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Sustainable aquaculture production for improved food security

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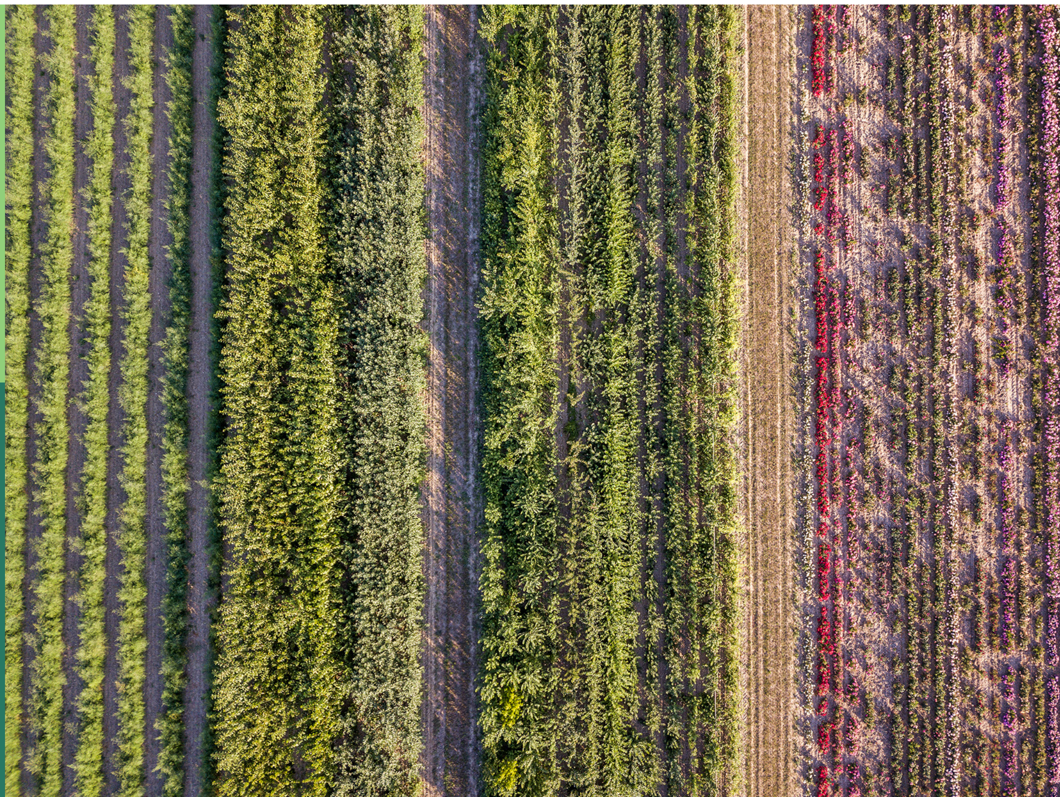
Published in
Frontiers in Sustainable Food Systems
Frontiers in Aquaculture



ISSN 1664-8714
ISBN 978-2-8325-5713-6
DOI 10.3389/978-2-8325-5713-6

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Sustainable aquaculture production for improved food security

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Citation
Obirikorang, K. A. A., Von Ahnen, M., Quagrainie, K., Kassah, J. E., eds. (2024). *Sustainable aquaculture production for improved food security*. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-5713-6

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frontiers | Frontiers in Sustainable Food Systems

TYPE Editorial
PUBLISHED 08 November 2024
DOI 10.3389/fsufs.2024.1485956

OPEN ACCESS

EDITED AND REVIEWED BY
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RECEIVED 25 August 2024
ACCEPTED 29 October 2024
PUBLISHED 08 November 2024

CITATION
Obirikorang KA, Quagrainie K, Kassah JE and Von Ahnen M (2024) Editorial: Sustainable aquaculture production for improved food security. *Front. Sustain. Food Syst.* 8:1485956.
doi: 10.3389/fsufs.2024.1485956

Editorial: Sustainable aquaculture production for improved food security

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KEYWORDS

aquaculture production, ecosystem-based management, environmental impact, food security, sustainable aquaculture

Editorial on the Research Topic
Sustainable aquaculture production for improved food security

Food security has been persistently recognized in global discourse as one of the world's main challenges. Despite some progress toward ensuring access to safe, nutritious, and sufficient food for all people year-round (SDG Target 2.1) or eradicating all forms of malnutrition (SDG Target 2.2), FAO et al. (2024) estimated that between 713 to 757 million individuals (8.9%—9.4% of the worldwide population) experienced undernourishment in 2023. Based on the mid-range figure of 733 million, about 152 million additional people may have faced hunger in 2023 compared to 2019. With outputs from capture fisheries stagnating over the past few decades, aquaculture holds the potential to play crucial roles in achieving food security (FAO, 2020). Global demands for fish are expected to increase in future decades to meet the needs and preferences of a growing human population (Jennings et al., 2016). With global populations projected to increase to over 9.7 billion by 2050 (United Nations, 2024), seafood in general and fish in particular will continue to play an important role in providing nutrition and food security globally, especially in developing countries (Cojocaru et al., 2022; Bjørndal et al., 2024).

Two separate but interconnected sectors contribute to global fish supply: capture or wild-caught fisheries and aquaculture or farmed fish. In fact, as capture fisheries have leveled off, continued increases in production from aquaculture will be required in order to maintain or increase per capita fish consumption (FAO, 2020). According to the FAO (2022), aquaculture has for several decades, been the fastest growing animal production sector in the world, contributing to 49% of total aquatic production (FAO, 2022). This rate of growth and the sector's contribution to global food security, however, appear to be much lesser than estimated when seaweeds (algal autotrophs) are excluded from the production statistics and comparisons to terrestrial livestock productions are made based on only edible yields (Edwards et al., 2019). This, notwithstanding, the sector still holds the potential to make important contributions to sustainable food futures although its rapid expansion has consequences relating to environmental sustainability. Additionally, the sector faces challenges relating to the high cost of aquafeeds for finfish and shellfish, post-harvest losses, and pathogen-induced mortalities.

The article submissions to this Research Topic make contributions to solving some of the problems the aquaculture sector faces through perspectives, reviews, and original research works focusing on various aspects of aquaculture, including sustainable production (Chen et al.; Shen et al.; Mizuta; N'Souvi et al.), aquaculture nutrition (Akter et al.; Andam et al.), postharvest processing technologies (Barros et al.), production systems (Rossignoli et al.), fish health and welfare (Stentiford et al.; Zornu, Tavornpanich, Brun, et al.; Zornu, Tavornpanich, Shimaa, et al.), and aquaculture finance (Munguti et al.). The primary data for the articles published under this Research Topic were sourced from 13 countries spread across three continents (Figure 1) and broadly fall under the three pillars of sustainability: environmental sustainability (production technologies that optimize fish production and/or minimize significant environmental disruptions or impacts), economic sustainability (private-public sector partnerships and multinational donor investments), and social and community sustainability (social dimensions of aquaculture, especially in developing countries).

The development of aquaculture hinges largely on the formulation and production of low-cost, but nutritionally balanced aquafeeds for finfish and shellfish culture, but aquafeed remains prohibitively expensive for many small-scale farmers. The aquafeed industry has long depended on fishmeal as a chief protein source, but unstable supplies and erratic price fluctuations have called for partial or total replacements with more sustainable raw materials (Roques et al., 2020). The studies by Akter et al. and Andam et al. thus highlight the advancements in aquaculture nutrition over the last two decades through continuous innovations in feed formulation to improve feed efficiency and sustainability. The replacement of fishmeal with mysid meal up to 65% in diets for the Pacific white shrimp (*Penaeus vannamei*) without negatively impacting growth performance, feed utilization efficiency, and body composition (Andam et al.) represents a cost-saving strategy that can increase the profitability of shrimp culture. The successful inclusions of mustard oil cake, soybean meal, and rice bran as fishmeal replacers in diets for *Labeo rohita* (Akter et al.) highlight the possibility of using these unconventional ingredients as dietary protein sources to minimize fish production costs and positively contribute to increased food security, particularly in developing countries.

Due to significant pathogen-induced mortalities, aquaculture, which provides half of the world's aquatic protein, faces difficulties in providing a safe and sustainable fish supply. Investigating the causes of fish mortalities (Zornu, Tavornpanich, Brun, et al.), extending the interpretations of diseases beyond the identification of disease agents to address host, environmental, and human factors (Stentiford et al.), and bridging knowledge gaps in fish health management through education and research (Zornu, Tavornpanich, Shimaa, et al.) can enhance aquatic animal health and foster a resilient and sustainable aquaculture industry. Sustainability in aquaculture development is further gaining prominence due to environmental issues like water pollution. Reducing the impacts of aquaculture production on the environment should be a key focus if the sector, which paradoxically is largely dependent on clean water, is to sustainably contribute to global food and nutrition security. The implementations of resource-efficient and environmentally-friendly approaches such as green total factor productivity (the efficiency of aquaculture production considering environmental sustainability) (Shen et al.) and the adoption of emerging green production technologies in production (Chen et al.) are key ways to ensure this.

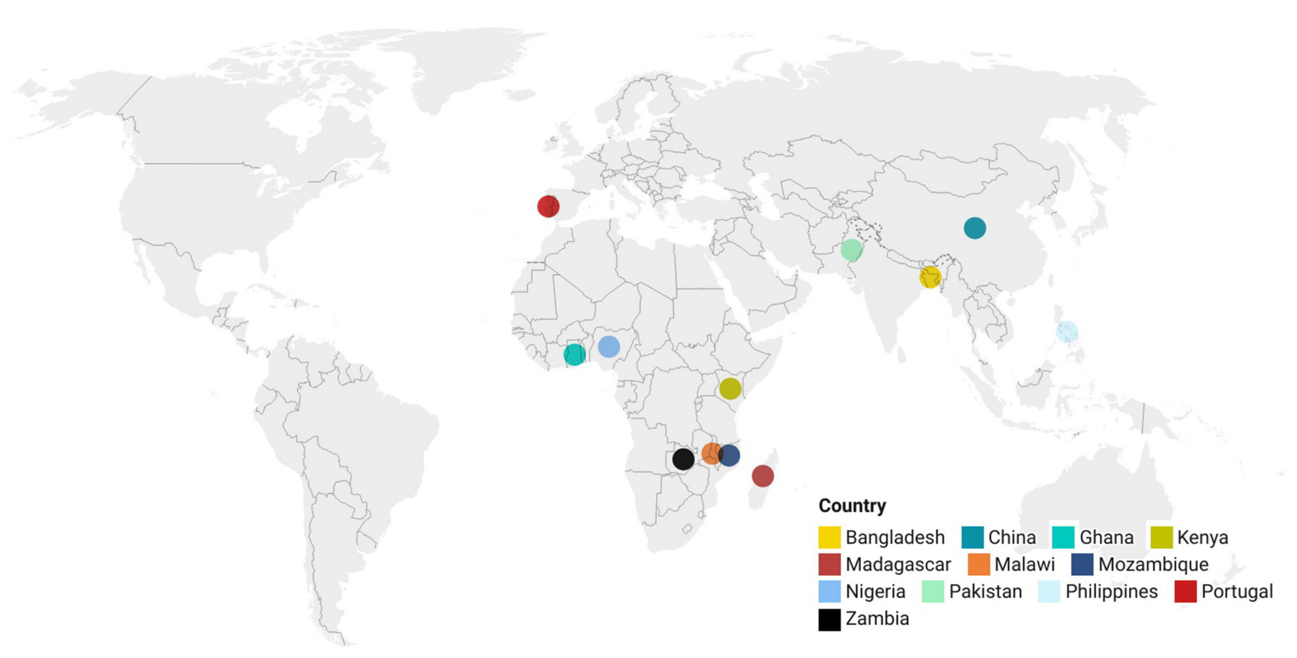

FIGURE 1
Geographic distribution of the countries from which primary data was sourced for the articles in this Research Topic.

To build resilience and sustain production in the face of climate change and environmental degradation, aquaculture producers must adapt to short-term available options such as shading ponds and aeration or make long-term adjustments to production practices, including diversifying production systems and areas (Maulu et al., 2021). By expanding the areas available for aquaculture production, the industry can increase its production capacity to meet the rising human demands for fish and other aquatic products. Aquaculture production in inland saline environments, also known as "desert aquaculture" in some jurisdictions, offers the potential to increase production of euryhaline and marine species. While commercial aquaculture production using saline groundwater is well-developed in countries such as the USA, Israel, India, and Australia (Allan et al., 2009), it remains underdeveloped in some developing countries such as Pakistan (Rossignoli et al.). Inland saline waters provide key resources for producing fish and other aquaculture products by employing otherwise unproductive resources while minimizing reliance on freshwater resources, which otherwise serve as potable water sources for humans. The study by Rossignoli et al. serves as key baseline data to address some of the information gaps crucial for the sustainable development of saline aquaculture in developing countries. There is the need to strengthen technical skills in saline aquaculture in tandem with the establishment of hatcheries for salt-tolerant species, aiming to reduce dependence on freshwater species in saline pond environments.

With several projections highlighting the vulnerability of the entire aquaculture value chain to climate change and environmental degradation, there are valid concerns about whether the sector is growing sustainably and fast enough to meet future demands, further exacerbated by the rapidly growing human population. The present shifts in human dietary patterns toward sustainable foods may further cause the demand for seafood to rise sharply over the next 10 years, necessitating further research on innovative aquafeeds in all areas of sustainability. Prioritizing research on low-cost and complementary ingredients in aquafeeds, especially for species in low-trophic production systems, will be an innovative way to stimulate the development of the sector. Additionally, there is the need to adopt innovative production methods, prioritize disease prevention measures, and minimize the environmental impacts to optimize the economic, social, and environmental efficiency of the aquaculture sector.

Author contributions

KO: Writing – original draft, Conceptualization. KQ: Writing – review & editing. JK: Writing – review & editing. MV: Writing – review & editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Allan, G. L., Fielder, D. S., Fitzsimmons, K. M., Applebaum, S. L., and Raizada, S. (2009). "Inland saline aquaculture," in *New Technologies in Aquaculture*, ed. G. Burnell, and G. Allan (Cambridge: Woodhead Publishing Ltd.), 1119–1147.

Bjørndal, T., Dey, M., and Tusvik, A. (2024). Economic analysis of the contributions of aquaculture to future food security. *Aquaculture* 578:740071. doi: 10.1016/j.aquaculture.2023.740071

Cojocaru, A. L., Liu, Y., Smith, M. D., Akpalu, W., Chávez, C., Dey, M. M., et al. (2022). The "seafood" system: aquatic foods, food security, and the Global South. *Rev. Env. Econ Policy* 16, 306–326. doi: 10.1086/721032

Edwards, P., Zhang, W., Belton, B., and Little, D. C. (2019). Misunderstandings, myths and mantras in aquaculture: its contribution to world food supplies has been systematically over reported. *Mar. Policy* 106:103547. doi: 10.1016/j.marpol.2019.103547

FAO (2020). *The State of World Fisheries and Aquaculture 2020. Sustainability in Action.* Rome: FAO. doi: 10.4060/ca9229en

FAO (2022). *The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation.* Rome: FAO. doi: 10.4060/cc0461en

FAO, IFAD, UNICEF, WFP and WHO (2024). *The State of Food Security and Nutrition in the World 2024 – Financing to end hunger, food insecurity and malnutrition in all its forms.* Rome: FAO. doi: 10.4060/cd1254en

Jennings, S., Stentiford, G. D., Leocadio, A. M., Jeffery, K. R., Metcalfe, J. D., Katsiadaki, I., et al. (2016). Aquatic food security: insights into challenges and solutions from an analysis of interactions between fisheries, aquaculture, food safety, human health, fish and human welfare, economy and environment. *Fish Fish.* 17, 893–938. doi: 10.1111/faf.12152

Maulu, S., Hasimuna, O. J., Haambiya, L. H., Monde, C., Musuka, C. G., Makorwa, T. H., et al. (2021). Climate change effects on aquaculture production: sustainability implications, mitigation, and adaptations. *Front. Sustain. Food Syst.* 5:609097. doi: 10.3389/fsufs.2021.609097

Roques, S., Deborde, C., Richard, N., Skiba-Cassy, S., Moing, A., and Fauconneau, B. (2020). Metabolomics and fish nutrition: a review in the context of sustainable feed development. *Rev. Aquac.* 12, 261–282. doi: 10.1111/raq.12316

United Nations (2024). *World Population Prospects: The 2024 Revision.* New York, NY: United Nations.

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 27 June 2023
DOI 10.3389/fsufs.2023.1211392

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OPEN ACCESS

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RECEIVED 24 April 2023
ACCEPTED 02 June 2023
PUBLISHED 27 June 2023

CITATION
Chen Q, Xu Q and Yu X (2023) Triple-hurdle model analysis of aquaculture farmers' multi-stage willingness to participate in green and healthy aquaculture actions in China: based on ecological cognition and environmental regulation perspectives.
Front. Sustain. Food Syst. 7:1211392.
doi: 10.3389/fsufs.2023.1211392

Triple-hurdle model analysis of aquaculture farmers' multi-stage willingness to participate in green and healthy aquaculture actions in China: based on ecological cognition and environmental regulation perspectives

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Implementing the action of green and healthy aquaculture is an important measure to ensure the stable and secure supply of crucial agricultural products and promote the green and high-quality development of the fishing industry in China. This article divides the willingness to participate in the green and healthy aquaculture actions (GHAAs) into three stages: whether to participate, mode of participation, and degree of participation based on the dynamic decision-making process of the farmers. Based on micro survey data of aquaculture households in Zhejiang Province, this paper applies the Triple-Hurdle model to analyze the effect of ecological cognition and environmental regulation on multi-stage participation willingness, with a particular emphasis on exploring the differences in participation willingness between two types of green aquaculture methods, traditional and emerging technologies. The results show that ecological cognition has a positive promoting effect on the willingness to participate in actions and the degree of willingness to participate in both types of technological methods, the constrained environmental regulation policies significantly positively affects the degree of willingness to participate in traditional technological methods, and the incentive environmental regulation policies significantly positively affects the willingness to choose emerging technological methods and its degree of willingness to participate. The analysis of the regulatory effect of environmental regulation shows that constrained regulation policies can enhance the willingness of high ecological cognition farmers to participate in actions, while incentive policies are helpful for high ecological cognition farmers' adoption willingness of emerging green production technology. In addition, there are scale and intergenerational differences in the effects of ecological cognition and environmental regulation on farmers' willingness to participate in actions.

KEYWORDS

aquaculture farmers, ecological cognition, environmental regulation, green and healthy aquaculture actions, multi-stage adoption willingness

1. Introduction

Since the reform and opening up, China's aquaculture industry has made leaps and bounds, becoming the world's largest aquaculture country, but the quality and safety of aquatic products and the resources and environmental problems brought about by aquaculture have not been effectively solved. To this end, China's Ministry of Agriculture and Rural Affairs and ten other ministries and commissions jointly issued in 2019 the first guidance document since the founding of the country, endorsed by the State Council, specifically for the aquaculture industry, "Several Opinions on Accelerating the Green Development of the Aquaculture Industry." Since then, on March 30, 2020, the Ministry of Agriculture and Rural Affairs specially issued the "Notice from the General Office of the Ministry of Agriculture and Rural Affairs 'Five Actions' Concerning the Implementation of the Green and Healthy Aquaculture in 2020 "(hereinafter referred to as the "Five Actions"), put forward five action plans including the promotion of ecological and healthy aquaculture mode, the promotion of aquaculture tail water treatment mode, the reduction of aquaculture drug, the replacement of juvenile miscellaneous fish with compound feed and the improvement of the quality of aquaculture seed industry, the greening and upgrading of aquaculture at a national level has thus kicked off. As the "main force" of aquatic production, aquaculture farmers scientifically regulate their production behavior, which is the crux link to realizing the green development of aquaculture from the source. However, in reality, influenced by smallholder consciousness, farmers are often reluctant to change their traditional production models, especially in aquaculture characterized by high input and risk (Han et al., 2007). Therefore, it is of great practical importance to explore the mechanisms influencing the participation in green and healthy aquaculture actions (GHAAs) by aquaculture farmers.

Studies have shown that the green production behavior of aquaculture farmers can be affected by many intrinsic and extrinsic factors. Among them, the internal factors are mainly regarding the resource endowment of the farmers. Resource endowment is a collection of various knowledge, cognitive abilities, and technical reserves that farmers innately possess or acquired accumulation that can be used for production and living, and can be classified into two types: non-physical resource endowment and physical resource endowment (Schreinemachers et al., 2017; Zhao et al., 2022). Studies have shown that individual characteristics such as farmers 'education level and green cognition level, as well as social capital such as social norms and social networks, are the prime non-physical resources that affect farmers 'green production behavior (Chen and Fang, 2011; Joffer et al., 2019). At the same time, the implementation of green production usually requires additional capital, equipment, and human input, while sufficient endowments of physical resources such as labor and capital are also necessary for farmers to choose green production behavior (Jin et al., 2022; Zhu and Deng, 2022). The external factors affecting the green production behavior of farmers are mainly based on various intervention policies formulated by the government. Information asymmetry is considered the fundamental reason why aquaculture farmers do not take the initiative to change their extensive production behavior. Specifically, farmers may be reluctant to implement pro-environmental behavior because they do not understand the hazards of environmental pollution, the benefits of environmental protection, and the use of green production technology (Xie et al., 2021). Reasonable intervention policies can effectively facilitate information transfer and guide pro-environmental behavior to develop in an orderly manner. Some studies have analyzed the effects of restrictive policies such as aquaculture product quality supervision and effluent regulation concerning the pro-environmental aquaculture behavior of aquaculture farmers. Some studies have also evaluated the effect of incentive-based policies such as green production knowledge dissemination, technical training, and government subsidies on the clean environmental behavior of aquaculture farmers (Li and Xu, 2018).

The above studies have examined the factors influencing aquaculture farmers' green production behavior from different perspectives, but there is still some room for expansion. In terms of research content, previous studies on green production behavior in aquaculture have focused on traditional green technology (TGT) models such as pesticide reduction and reduction of aquaculture density, while little attention has been paid to emerging green technology (EGT) methods such as feed substitution and aquaculture tailwater management. Currently, the connotation and requirements of green and healthy aquaculture have undergone significant changes. It not only demands the assurance of the quality and safety of aquatic products but also emphasizes the environmental friendliness and resource conservation in the aquaculture process (Tang et al., 2014). To this end, in 2020, China's Ministry of Agriculture and Rural Affairs proposed the "Five Actions," which include not only TGT methods such as reducing the use of drugs and controlling aquaculture capacity but also incorporate EGT methods such as feed substitution and aquaculture wastewater treatment. The replacement of juvenile miscellaneous fish with compound feed (feed substitution) is significant to alleviate the decline of offshore fishery resources (Lei, 2010; Liu and Peng, 2021), and the implementation of aquaculture tailwater treatment can improve the environmental quality of surrounding waters (Zhang and Ma, 2020). In reality, farmers often have little incentive to respond to such green production models with positive resource and environmental externalities (Hukom et al., 2020). In these regards, this paper examines the willingness of farmers to adopt traditional and emerging green production technology concerning the "Five Actions" program promulgated and implemented by the Ministry of Agriculture and Rural Affairs, to make up for the lack of existing research. Simultaneously, constrained by knowledge structure and information asymmetry, it is more difficult for farmers to form accurate cognitive perception and evaluation regarding novel green production technologies, which in turn affects their willingness to adopt. Therefore, it is necessary to build upon the new concepts and policies of modern green and healthy aquaculture to explore the differences in farmers' willingness to choose between traditional and emerging green technologies, and dig into the underlying influencing factors. This will provide references for identifying the key actions for promoting green and healthy aquaculture and enhancing the efficiency of technology promotion.

Based on the current background of China's GHAAs, this paper uses micro-survey data of aquaculture farmers in Zhejiang Province, China, and analyzes the impact of ecological cognition and environmental regulation on the willingness of aquaculture farmers to participate in GHAAs using the Triple-Hurdle model. The paper focuses on exploring the differences in willingness to participate in traditional and emerging green technologies and further discusses the regulatory role of the environmental regulation. The possible marginal contributions of this paper include three aspects. Firstly, unlike most previous studies that simply divide the willingness to participate in green production into a binary variable of "yes or no," this paper divides the decision-making process of aquaculture farmers' participation in green and healthy aquaculture into three dynamic decision-making stages of "whether to participate," "mode of participation" and "degree of participation," which more realistically reflects the decision-making process of aquaculture farmers and improves the reliability and reference value of the conclusions. Secondly, based on the GHAAs plan, this paper examines the differences in the willingness of aquaculture farmers to choose traditional and emerging green production technologies, making up for the research gap on emerging green production technologies such as feed substitution and aquaculture wastewater treatment, and providing strong references for current policy promotion and practice. Finally, this paper incorporates two categories of factors, ecological cognition and environmental regulation, into the analysis framework of green production intention, revealing the common mechanism of interaction between intrinsic and extrinsic factors. This further enriches and develops the research on the influencing factors of green production intention.

2. Theoretical analysis

2.1. The influence of ecological cognition and environmental regulation on participation willingness in GHAAs

Whether farmers participate in green and healthy aquaculture can be viewed as a decision-making problem for farmers to choose new technologies with significant positive externalities. As rational economic agents, farmers' choice of new production technology is a decision made by comparing the costs and benefits of the old and new technology to maximize profit (Yu et al., 2017). With the propagation and implementation of the green development concept, some scholars point out that farmers have ecological as well as economic rationality and can obtain public utility from agricultural non-economic functions (Yan et al., 2017). Farmers usually become concerned about ecological issues after their subsistence needs are met and incorporate eco-efficiency goals into their behavioral decisions (Hukom et al., 2020). Conducting green and healthy farming is conducive to food security and eco-environmental protection, and can satisfy farmers' demands for social and environmental benefits and other public interests, thus increasing their public utility. Therefore, farmers' participation willingness in GHAAs depends on maximizing their total utility after the sum of economic and ecological benefits.

According to the theory of planned action, cognition is the basis of behavior, and personal cognition determines preferences, which then influence final behavioral decisions (Cooke and Sheeran, 2004). Ecological cognition is an individual's basic understanding of the ecological environment and mastery of relevant ecological knowledge and technology, which can reflect individual ecological values, environmental perception ability, and the level of green production technology reserves (Zhang et al., 2019). Traditional farming practices can lead to eutrophication and drug contamination of the water body, which affects farmers' profits (Bbxa et al., 2021). When farmers can perceive the harm that traditional farming models may cause to aquatic product quality and the watershed environment, they are inclined to adopt green production technology driven by economic and ecological rationality (Li et al., 2020). In addition, the more knowledgeable farmers are about green production and technology, the more they can realize the importance of green farming and discover the possible economic and ecological benefits of traditional farming models, thus being more inclined to participate in green production (Obubuafo et al., 2008). Based on these, the following hypothesis is proposed:

> Hypothesis *H1*: Ecological cognition had a significant positive effect on farmers' participation willingness in GHAAs.

Farmers' production decisions are aimed at maximizing individual utility, but in practice, they are also constrained by external policies. Farmed tailwater treatment has typical positive environmental externalities and may face an imbalance between marginal private benefits and marginal social benefits. The implementation of green production usually involves additional capital and labor inputs, resulting in lower marginal private returns, but the marginal social benefits from green products may be higher. At this point, the government must internalize the externality problem by setting constraints and incentives to correct the marginal private costs or benefits and maximize the social benefits (Li et al., 2019). The restrictive environmental regulation policy is mainly based on pollution monitoring and penalties. Under the restrictive policy scenario, the probability of government penalties for excessive drug use and tailwater pollution by farmers increases, and the cost of not implementing green farming increases for farmers, who are driven by economic rationality to comply with regulatory objectives and choose to participate in green production (Kim et al., 2010). Incentive environmental regulation policies are mainly focused on green production subsidies. Financial subsidies can reduce the acquisition costs of farmers to participate in green production and increase their private benefits, thus promoting the implementation of green production by farmers (Chen and Mu, 2022). Based on these, the following hypothesis is proposed:

> Hypothesis *H2*: Restrictive and incentive environmental regulation policies have a significant positive effect on farmers' participation willingness in GHAAs.

Aquatic products pollution and environmental pollution caused by traditional farming models are typical negative externality problems, in the reality that responsibility is hard to identify and define, even if farmers recognize the hazards of traditional farming models, under the "free ride" motive usually still do not choose to take the initiative to participate in green production. Therefore, it is necessary to strengthen the ecological cognition of farmers through environmental regulation policies such as subsidies, supervision, and penalties to internalize externalities and promote their transformation from green cognition to green behavior. According to situational cognitive theory, different contexts may have an impact on the relationship between farmers' cognition and behavior (Guo and Zhao, 2014). Policy and institutional contexts are vital external contexts faced by farmers. It has been shown that providing both incentive and restrictive environmental regulations positively moderate the relationship between farmers' ecological cognition and green production behavior (Huang et al., 2020; Luo et al., 2022). In the environmental regulation context, farmers with a high level of ecological cognition are more willing to put their green cognition into practice under certain constraints and incentives to obtain the maximum individual utility. Based on these, the following hypothesis is proposed:

> Hypothesis *H3*: Restrictive and incentive environmental regulation policies can enhance the effect of ecological cognition on farmers' participation willingness in GHAAs.

2.2. The dynamic decision-making process of participation willingness in the GHAAs

According to the theory of behavioral stage change, behavioral decision-making is not a static event, but a dynamic multi-stage process (Prochaska and Diclemente, 1983). The complete green production decision process contains multiple stages from whether to decide to participate to decide the degree of participation (Dimara and Skuras, 2003; Doss, 2010; Chen et al., 2020). For green aquaculture, the first stage is for farmers to decide if they would like to participate in green and healthy aquaculture. Farmers usually have a high reliance on long-established aquaculture experience in the production and operation process (Figure 1). However, under traditional aquaculture models, high aquaculture densities, excessive medication, and tailwater discharge may cause pest and disease problems, affecting the yield and quality of aquatic products, as well as damaging the surrounding ecological environment. In this context, driven by economic and ecological rationality, farmers will decide whether to change their traditional aquaculture practices and adopt green production technology based on maximizing their utility. For farmers who are willing to participate, the second stage requires them to decide on the specific technical mode to adopt for green farming, including two methods: TGT and EGT. Furthermore, in the third stage, for those farmers who choose to adopt a specific green technology, it is necessary to further consider to what extent they are willing to apply these green technologies. This can be measured by investigating the cost that farmers are willing to invest in adopting green technology.

3. Methods and materials

3.1. Methods

According to the previous theoretical analysis section, the aquaculture farmers decisions related to green production technology adoption could be seen to be a dynamic stage process: whether to participate, mode of participation, and degree of participation. To explore the three-stage participation willingness and the associated influencing factors, a Triple-Hurdle model was employed for the empirical analysis. The Triple-Hurdle model can be used to analyze three-stage farmer behavior decisions and address all possible conditionally uncorrelated errors (Burke et al., 2015; Yang et al., 2020). The complete triple-hurdle model is expressed as:

$$y_1 = x_1\left(EV, CV\right) \quad (1)$$

$$y_2 = x_2\left(EV, CV\right) \quad (2)$$

$$y_3 = x_3\left(EV, CV\right) \quad (3)$$

$$y_4 = x_4\left(EV, CV\right) \quad (4)$$

In Eqs. (1)–(4), y1 is the binary variable of aquaculture farmers' willingness to participate in GHAAs, y2 is a binary variable of farmers' willingness to choose green technology mode (including TGT and EGT), y3 and y4 are the degree of willingness to adopt TGT and the degree of willingness to adopt EGT, respectively. x1, x2, x3, x4 are sets of explanatory variables, where EV is the core explanatory variable and CV is the control variable. Finally, the integration of the formulas

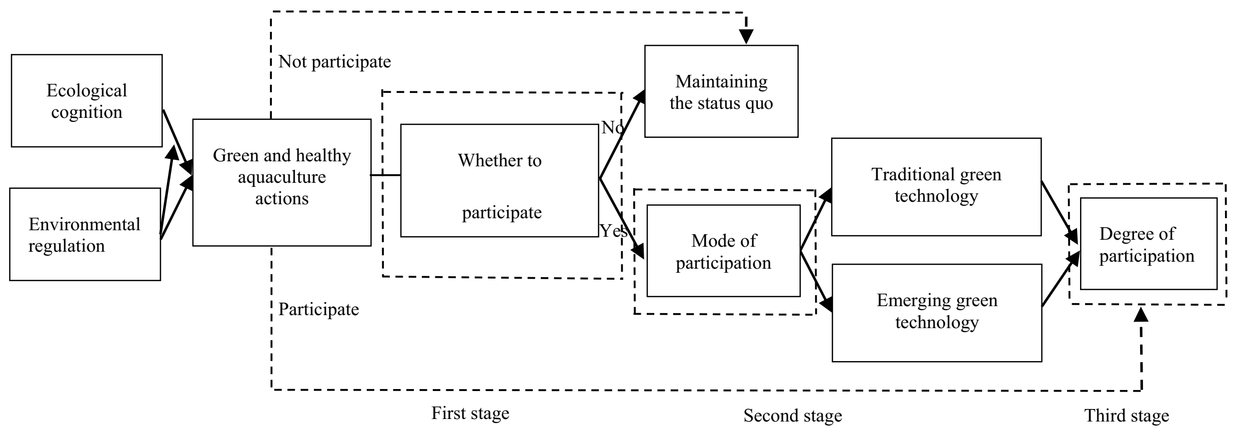

FIGURE 1
Theoretical framework.

established the triple-hurdle model likelihood function for each aquaculture farmer i:

$$f\left(y|\alpha,,,,,\beta,,,,,\delta_1,,,,,\delta_2,,,,,\sigma_1,,,,,\sigma_2\right)=\left[1-\Phi\left(\alpha x_1\right)\right]^{1[y_1=0]}\times\left[\Phi\left(\alpha x_1\right)\left\{\left[\frac{\Phi\left(\beta x_2\right)\phi\left(\frac{\ln y_3-\delta_1 x_3}{\delta_1}\right)}{\sigma_1 y_3}\right]^{1[y_2=0]}\left[\frac{\Phi\left(\beta x_2\right)\phi\left(\frac{\ln y_4-\delta_2 x_4}{\delta_2}\right)}{\sigma_2 y_4}\right]^{1[y_2=1]}\right\}\right]^{1[y_1=1]} \quad (5)$$

In Eq. (5), Φ(·) is the cumulative density function of the standard normal distribution, α is the parameter of the first decision stage explanatory variable x1, β is the parameter of the second decision stage explanatory variable x2, δ1 and δ2 are the parameters of the two variance explanatory variables x3 and x4 in the third decision stage, and σ1 and σ2 denote the standard deviation of the corresponding truncated normal distribution. 1[·] is an indicator function. If the expression given in brackets is true, the value is 1 and 0 otherwise. To address the sample selection bias, the inverse Mills ratio (IMR) was constructed using the results of the previous regression stage, respectively, and the IMR was added to the latter model for regression as a control variable along with other explanatory variables to obtain the estimated parameter W of the IMR. If W is not significant then the model is not subject to sample selection bias, otherwise IMR needs to be used as a control variable to correct for the sample selection problem. In addition, to ensure the identifiability of the model estimates, the previous stage equations need to contain at least one exclusive restrictive variable that does not appear in the latter equations.

3.2. Data source

The data in this paper are from a field study conducted by the research team from July to November 2021 in Zhejiang Province, China, among aquaculture farmers. Aquaculture includes pond aquaculture, net cage aquaculture, factory aquaculture, raft aquaculture and other modes, and the technical and economic characteristics of different aquaculture modes vary greatly. In this study, only pond aquaculture farmers were selected as respondents. According to the China Fisheries Statistical Yearbook, the proportion of pond aquaculture production in China accounted for about 48.84% of the total aquaculture production in 2019. Moreover, Pond aquaculture is also the hardest hit by excessive drug use and environmental pollution. Therefore, it is representative and relevant to use pond aquaculture farmers as the study object.

Zhejiang is one of the major provinces of pond aquaculture in China, with the second-highest production of marine pond aquaculture and the seventh-highest production of freshwater pond aquaculture in the country, according to the China Fisheries Statistical Yearbook. Zhejiang has consistently served as a leading demonstration area for implementing central policies. Following the requirements put forth by the central government and the Ministry of Agriculture and Rural Affairs to promote green development in aquaculture, Zhejiang took the initiative to formulate an action plan for green development in aquaculture and subsequently promoted the adoption of green and healthy aquaculture practices throughout the province. Considering the research purpose and research maneuverability, four major aquaculture production regions in Zhejiang Province, Ningbo, Hangzhou, Huzhou, and Taizhou, were chosen as the survey regions (Figure 2). On this basis, non-probability sampling methods were used to further determine the districts and villages for sample collection. Based on the geographical information map of the distribution of farmed water resources in Zhejiang Province (Chen, 2017), the districts and counties with relatively large pond aquaculture areas and production were identified among the above four regions, and six districts and counties were finally identified, namely Xiangshan and Ninghai counties in Ningbo, Qiantang and Xiaoshan districts in Hangzhou, Deqing County in Huzhou, and Sanmen County in Taizhou. A total of 410 questionnaires were distributed in the formal survey, and 370 valid questionnaires were obtained after eliminating invalid ones.

3.3. Variable selection

Dependent variable. The dependent variable in this paper is the willingness of farmers to participate in GHAAs. The decision-making process of aquaculture farmers' green technology adoption contains three stages, thus three dependent variables were set in this paper. The specific meanings and assigned values of the dependent variables are shown in Table 1. The willingness to participate or not to participate in the first decision stage was a dichotomous variable. During the survey, the four main green production technology models were first explained to the farmers, and then they were asked whether they were willing to participate in actions. In the second stage, farmers who were willing to participate actions were asked whether they would prefer to adopt TGT methods or EGT methods. Low-density aquaculture and drug reduction are green technology modes that have been promoted for a long time before the introduction of the "Five Actions," and these two types of technologies are defined as TGT methods in this study. The feed substitution and tailwater treatment are the key green technologies to be promoted by the government after the formulation of the "Five Actions" in 2020, and these two types of technologies are defined as emerging green technologies in this study. In the third stage, farmers who chose different technological methods were asked how much they were willing to invest in the chosen green technology.

Core explanatory variables. The core explanatory variables of this study are ecological cognition and environmental regulation. With reference to existing studies, ecological cognition can be divided into two variables: pollution perception and benefit perception. The questionnaire was designed to assess the pollution perception through the question "Do you agree that traditional aquaculture methods cause ecological pollution and contamination of aquatic products." The benefit perception was assessed by the question "Do you agree that green production technology can improve the

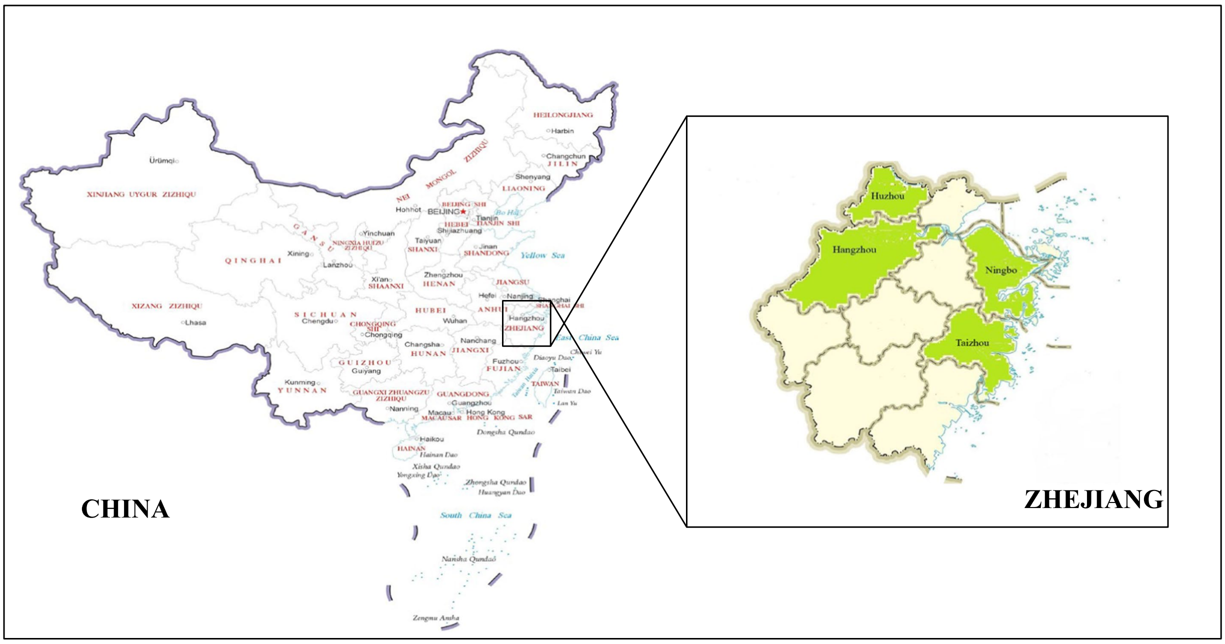

FIGURE 2
Map of Zhejiang Province showing the study area.

TABLE 1 Variable definition, assignment and descriptive statistics.

Variable name		Variable meaning and assignment	Mean value	Standard deviation
Willingness to participate in GHAAs	Whether to participate	Willing to participate in actions = 1; Unwilling to participate in actions = 0	0.722	0.448
	Mode of participation willingness	Prefer to adopt EGT = 1; Prefer to adopt TGT = 0	0.403	0.490
	Degree of participation	Logarithmic value of willingness to invest in the adoption of green technologies (CNY/hm^2 year)	10.902	0.670
Ecological cognition		Mean values of pollution perception and benefit perception scores	2.312	0.830
Environmental regulation	Restrictive environmental regulation policies	Policy strength: Very low = 1; Low = 2; Moderate = 3; High = 4; Very high = 5	3.582	0.627
	Incentive environmental regulation policies	Policy strength: Very low = 1; Low = 2; Moderate = 3; High = 4; Very high = 5	2.382	0.625
Individual characteristics	Age	Actual age / years	50.032	7.489
	Gender	Female = 0; Male = 1	0.773	0.419
	Education level	Elementary school and below = 1; Middle school = 2; High school = 3; College and above = 4	1.635	0.657
	Aquaculture experience	Years engaged in aquaculture / years	9.544	3.638
Household characteristics	Number of household laborers	Number of laborers in the household / person	2.478	0.816
	Annual household income	Total annual household income level / 10,000 CNY	16.659	11.931
	Aquaculture scale	Actual area of ponds operated by aquaculture households/hm^2	2.713	2.173
Social organization	Cooperatives	Not joined = 0; Joined = 1	0.295	0.456
	Village cadres	No one in the family is a village cadre = 0; Someone in the family is a village cadre = 1	0.111	0.314
Regional characteristics	Demonstration district (county)	Yes = 1; No = 0	0.568	0.495
Exclusive restrictive variables	Disease and pollution losses	Very small loss = 1; Small loss = 2; Medium loss = 3; Large loss = 4; Very large loss = 5	3.097	0.931
	Technology training experience	Yes = 1; No = 0	0.273	0.445

ecological environment and the quality of aquatic products." Both variables were measured using the Likert 5-point measure. Both variables were measured using the Likert 5-point scale. Then, the average of two variables, pollution perception and benefit perception, was taken as the score of ecological cognition variable. Environmental regulation is divided into two categories: restrictive environmental regulation policies and incentive environmental regulation policies. Drawing on existing studies, farmers' subjective perceptions of environmental regulation policies were used to assess policy intensity, i.e., to obtain farmers' evaluations of the strength of penalties for aquaculture pollution behavior and the strength of subsidies for green production.

Control variables. The following control variables are selected. First, individual characteristics variables, including age, gender, education level, and aquaculture experience. Second, household characteristics variables, including the number of household laborers, annual household income, and aquaculture scale. Third, social organization variables, including cooperatives and village cadres. The fourth is a regional variable, measured by whether the sample location is a national-level fishery health aquaculture demonstration district (county). In 2013, the Ministry of Agriculture and Rural Affairs decided to organize the establishment of national-level fishery health aquaculture demonstration district (county). The aim was to expand the scale of the demonstration of healthy aquaculture practices and ensure the quality and safety of aquaculture products. According to the list published by the Ministry of Agriculture, among the six sample areas selected for this study, Xiangshan County, Deqing County and Sanmen County belong to the national-level fishery health aquaculture demonstration district (counties), while the other three districts and counties do not. Fifth is the exclusive restrictive variable. Aquaculture diseases and environmental pollution can reduce farmers' profitability and lead to farmers' willingness to shift their original production methods and increase their willingness to adopt green production technologies, but they do not directly influence farmers' willingness to choose different green production technology model (traditional green production technology or emerging green production technology). Therefore, disease and pollution losses were used as an exclusive restrictive variable in the second stage decision equation. In the questionnaire, we designed the question "How much revenue is lost due to aquaculture diseases and environmental pollution in daily production and business activities "to measure this exclusive restrictive variable. Farmers have limited knowledge of green production technologies, especially emerging technologies such as compound feed use and aquaculture tailwater treatment. Relevant technical training experiences can help farmers better understand and master emerging green production technologies, which in turn may influence their willingness to choose the technical model, but have no direct effect on the adoption degree willingness. Therefore, drawing on existing research (Yang et al., 2020), we used technology training experience as an exclusive restrictive variable in the third stage of the decision equation. The value of the technology training experience variable was measured by the question "whether or not you have participated in training on emerging green production technologies such as compound feed use and aquaculture tailwater treatment."

The definitions and descriptive statistics of each variable are shown in Table 1.

4. Results

4.1. Analysis of the effects of ecological cognition and environmental regulations on participation willingness in GHAAs

To exclude possible covariance problems between variables, the variance inflation factor method was used to test for multiple covariances in all independent variables. The results show that the maximum variance inflation factor VIF is 1.81, which is much smaller than 10, so there is no multicollinearity problem in the model. Based on the triple-hurdle model, Stata software was used to estimate the data. First, two regression models were established by introducing two core explanatory variables, ecological cognition, and environmental regulation, respectively. Then, the third regression model was established by introducing ecological cognition and environmental regulation simultaneously. The coefficients and significance of the variables in the three models were found to be consistent, which means that the model estimation results were relatively robust. Table 2 shows the estimation results of introducing both ecological cognition and environmental regulation variables, and the subsequent analysis is based on these results. The results of the first-stage probit model estimation showed that the disease and pollution losses variable was significant at the 5% statistical level and thus was appropriate as an exclusive restrictive variable. Further, to test the existence of sample selection bias, the IMR obtained from the first-stage probit regression was brought into the second-stage regression model as a control variable. The results showed that the regression coefficient of IMR was 0.558 with $p > |z| = 0.385$, which did not pass the significance test, indicating that there was no sample selectivity bias and no correction was required.

Ecological cognition had a positive effect on farmers' willingness to participate or not to participate in the first stage and on their willingness to choose modes in the second stage, and had a significant positive effect on the degree of participation in EGT methods in the third stage, while it did not have a significant effect on the degree of participation in TGT methods. When farmers can accurately perceive that traditional aquaculture practices may cause environmental pollution and affect the quality of aquatic products, they will be willing to change their traditional production methods. In addition, farmers' perceptions of the potential benefits of green technology also contribute to the willingness of farmers to adopt it. The higher the level of ecological cognition, the more farmers tend to choose EGT and are also willing to invest more money in it. The possible reason is that the higher the level of ecological cognition, the higher the demand of farmers for public benefits such as ecological protection, and thus the higher the preference for emerging technological methods with typical positive resource-environmental externalities such as compound feed use and aquaculture tailwater treatment. The above results verified hypothesis *H1*.

Among the environmental regulation variables, restrictive policies had a significant positive effect on the willingness to participate or not to participate in the first stage and the degree of participation of TGT methods in the third stage. Increased environmental regulation and pollution penalties by the government mean higher costs for farmers for illegal drug use and tailwater discharge, which will increase farmers' willingness to adopt green technology. Restrictive policies significantly increased the willingness of farmers to adopt TGT

TABLE 2 Estimated results of the impact of ecological cognition and environmental regulation on participation willingness in GHAAs.

Variable	First stage (whether to participate)	Second stage (mode of participation)	Third stage (degree of participation)	
			TGT	EGT
Core explanatory variables				
Ecological cognition	0.236* (0.133)	0.432*** (0.120)	−0.011 (0.062)	0.093* (0.055)
Restrictive environmental regulation policies	0.907*** (0.130)	0.035 (0.130)	0.358*** (0.062)	0.072 (0.069)
Incentive environmental regulation policies	0.785*** (0.151)	0.413*** (0.156)	0.074 (0.076)	0.376*** (0.087)
Control variables				
Age	0.018 (0.014)	−0.017 (0.012)	−0.013** (0.006)	0.005 (0.007)
Gender	0.633*** (0.232)	0.271 (0.279)	−0.035 (0.112)	−0.388** (0.163)
Education level	−0.038 (0.166)	0.029 (0.146)	−0.06 (0.063)	−0.09 (0.101)
Aquaculture experience	0.159 (0.149)	−0.165 (0.119)	−0.028 (0.059)	0.016 (0.066)
Number of household laborers	−0.522*** (0.131)	0.410*** (0.136)	−0.017 (0.074)	0.02 (0.075)
Annual household income	−0.005 (0.007)	−0.01 (0.008)	−0.001 (0.003)	0.006 (0.005)
Aquaculture scale	0.018 (0.335)	0.131 (0.311)	0.182 (0.164)	0.027 (0.146)
Cooperatives	−0.119 (0.239)	−0.145 (0.218)	0.942 (0.101)	0.559*** (0.126)
Village cadres	0.429 (0.335)	−0.874*** (0.322)	0.135 (0.120)	0.208 (0.205)
Demonstration district (county)	0.477** (0.219)	0.340* (0.197)	0.084 (0.093)	0.148 (0.118)
Exclusive restrictive variables				
Disease and pollution losses	0.258** (0.120)			
Technology training experience		0.701*** (0.263)		
Constant	−5.814*** (0.972)	−2.727*** (0.967)	3.632*** (0.467)	2.804*** (0.544)
Log-likelihood	−116.971	−150.247	−101.357	−86.858
LR chi2	203.70***	67.99***	45.48***	51.71***
Observations	370	267	144	123

***, **, *Significant at the 1, 5, and 10% level. Standard errors in parentheses.

methods. The possible reason is that, before the Ministry of Agriculture promoted the "Five Actions" for green and healthy aquaculture, the long-term environmental regulation policy for aquaculture was mainly focused on the control of aquaculture capacity and regulation of drug use, which led to more pressure on farmers not to participate in TGT methods.

Incentive policies have a significant positive effect on the willingness to participate in the first stage, the willingness to choose the methods in the second stage and the willingness to invest in the extent of emerging green technologies in the third stage. The participation in GHAAs usually requires additional capital and manpower investment, which increases production and operating costs. Green production policy subsidies can directly relieve farmers' capital investment pressure, compensate for the external costs of adopting green technology, enhance the level of returns, and thus increase farmers' willingness to adopt it. The estimation results of the second and third stages indicated that the higher the farmers' perception of the incentive policy, the more inclined they were to choose to adopt the EGT and also to invest more money in the EGT. The possible reason is that, compared with the TGT method involving changes in aquaculture density and drug use habits, the adoption of EGT methods such as compound feed substitution and tailwater treatment does not involve changes in production habits, but mainly generates additional costs for the purchase of feed and facilities. Therefore, when farmers perceive that the subsidy policy can compensate for the adoption cost and improve the net income, they will be more willing to choose and invest more money to adopt the EGT. Hypothesis *H2* was verified.

4.2. Analysis of the interaction effect between ecological cognition and environmental regulation

According to situational cognitive theory, external contexts, especially policy contexts, may have an impact on the relationship between farmers' cognition and behavioral intentions (Guo and Zhao, 2014). For farmers with a high level of ecological awareness, the imposition of some environmental regulation policies can effectively stimulate their willingness to green production. To this end, this paper further explored the effect of the interaction between ecological cognition and environmental regulation on farmers' participation willingness in GHAAs. The interaction terms of ecological cognition with restrictive and incentive policies were introduced for regression analysis. The results are shown in Table 3.

The farmers' willingness in the first participation decision stage was significantly and positively influenced by the interaction term of ecological cognition and restrictive environmental regulation policies.

TABLE 3 Impact of the interaction between ecological cognition and environmental regulation on participation willingness in GHAAs.

Variable	First stage (whether to participate)	Second stage (mode of participation)	Third stage (degree of participation)	
			TGT	EGT
Ecological cognition	0.255* (0.140)	0.356** (0.120)	−0.007 (0.072)	0.034 (0.068)
Restrictive environmental regulation policies	1.161*** (0.169)	0.041 (0.130)	0.349*** (0.068)	0.090 (0.068)
Incentive environmental regulation policies	0.927*** (0.172)	0.394** (0.156)	0.082 (0.081)	0.306*** (0.089)
Ecological cognition × Restrictive environmental regulation policies	0.619*** (0.233)	0.104 (0.156)	−0.033 (0.087)	−0.028 (0.073)
Ecological cognition × Incentive environmental regulation policies	0.218 (0.217)	0.171 (0.193)	−0.021 (0.104)	0.246** (0.099)
Other variables	Control	Control	Control	Control
Log-likelihood	−112.034	−149.588	−101.270	−83.845
LR chi2	213.58***	69.31***	45.65***	57.74***
Observations	370	267	144	123

***, **, *Significant at the 1, 5, and 10% level. Standard errors in parentheses.

For farmers with a high level of ecological cognition, improving the strength of environmental supervision, pollution penalties, and other restrictive policies can help guide them to participate in actions. Farmers with a high level of ecological awareness, i.e., ecological-social rationality, are familiar with the hazards of aquaculture pollution and the benefits of green production, and restrictive policies can further stimulate the endogenous motivation of farmers to green production. The interaction term between ecological cognition and incentive policies had a significant impact on the degree of participation in EGT methods in the third stage. Government subsidies for green production can compensate farmers for the acquisition costs when implementing emerging green technologies such as compound feed use and tailwater treatment, improve expected returns, and solve the problem of farmers with high ecological cognition reducing green production inputs due to cost–benefit considerations. Hypothesis *H3* was verified.

4.3. Heterogeneity analysis

Previous studies have shown that differences in production scale and age of farmers may affect their ecological cognition and policy perceptions, which in turn affect their willingness to adopt green production technologies (Li et al., 2020; Chen and Mu, 2022). Referring to the "Criteria for the Identification of Other Producers of Agricultural Products of a Certain Scale" issued by the Zhejiang Provincial Department of Agriculture, farmers operating aquaculture with an area of 2 hm2 and above were classified as large-scale farmers, and those below 2 hm2 were classified as small-scale farmers. The division of generational differences was referred to existing studies (Duan et al., 2022), which categorized farmers born in 1975 and before as older generation farmers and those born after 1975 as new generation farmers.

Scale heterogeneity. The estimation results in Table 4 show that ecological cognition had a significant effect on the willingness to participate in actions in the first stage for large-scale farmers, while the effect was not significant for small-scale farmers. Large-scale farmers are more likely to achieve economies of scale and lower implementation costs when adopting green production technologies, while small-scale farmers may still be reluctant to adopt green production technologies due to cost–benefit considerations, even if they have a high level of ecological cognition. This research result is consistent with the findings of studies focused on green production behaviors among small-scale aquaculture farmers (Phong et al., 2021). In terms of environmental regulation, restrictive policies had a significant positive effect on the participate in EGT methods in the third stage of large-scale farmers, while the effect on small-scale farmers was not significant. The impact of incentive policies on the willingness of large-scale farmers to participate in actions was only reflected in the first stage, while the impact on small-scale farmers was felt throughout the three decision-making stages.

Intergenerational heterogeneity. The estimated results in Table 5 show that ecological cognition had a significant positive effect on the willingness to choose green technology methods in the second stage for both generations of farmers, and a non-significant effect on the willingness in the other stages. In terms of environmental regulation, the impact of restrictive policies on the willingness of farmers to participate in actions was consistent between the two generations, while the impact of incentive policies on the willingness of farmers in the second and third participation decision stages differed significantly between the two generations. Specifically, the incentive policies were able to significantly increase the willingness of the new generation of farmers to adopt TGT, while the effect on the older generation of farmers was not significant. This conclusion is consistent with the research findings of Pannell and Claassen (2020) and Guo et al. (2022). Incentive policies had a significant positive effect on the willingness of the older generation of farmers to adopt emerging green production technology, while the effect on the willingness of the new generation of farmers to adopt emerging green production technology was not significant.

4.4. Robustness tests

Robustness tests were conducted by constructing new variables to replace the original core explanatory variables and smoothing

TABLE 4 Scale differences in the impact of ecological cognition and environmental regulation on participation willingness in GHAAs.

Variable	Large-scale farmers				Small-scale farmers			
	First stage (whether to participate)	Second stage (mode of participation)	Third stage (degree of participation)		First stage (whether to participate)	Second stage (mode of participation)	Third stage (degree of participation)	
			TGT	EGT			TGT	EGT
Ecological cognition	0.601** (0.251)	0.234* (0.167)	−0.346 (0.088)	0.172** (0.070)	0.504 (0.317)	0.861*** (0.299)	0.043 (0.110)	0.262* (0.142)
Restrictive environmental regulation policies	1.041*** (0.187)	0.158 (0.169)	0.450*** (0.090)	0.143* (0.076)	0.971*** (0.268)	−0.233 (0.238)	0.281*** (0.070)	−0.002 (0.101)
Incentive environmental regulation policies	0.929*** (0.229)	0.203 (0.215)	−0.107 (0.117)	0.115 (0.099)	1.110*** (0.298)	0.687** (0.268)	0.274*** (0.083)	0.774*** (0.119)
Other variables	Control				Control			
Log-likelihood	−62.637	−89.358	−59.447	−36.970	−39.379	−51.899	−23.950	−26.398
LR chi2	112.35***	32.60***	37.99***	25.11**	120.55***	53.36***	38.92***	58.49***
Observations	207	153	82	71	163	114	62	52

***, **, *Significant at the 1, 5, and 10% level. Standard errors in parentheses.

TABLE 5 Intergeneration differences in the impact of ecological cognition and environmental regulation on participation willingness in GHAAs.

Variable	New generation farmers				Older generation farmers			
	First stage (whether to participate)	Second stage (mode of participation)	Third stage (degree of participation)		First stage (whether to participate)	Second stage (mode of participation)	Third stage (degree of participation)	
			TGT	EGT			TGT	EGT
Ecological cognition	0.144 (0.268)	0.410* (0.246)	0.043 (0.091)	0.136 (0.099)	0.263 (0.174)	0.592*** (0.173)	−0.013 (0.077)	0.048 (0.070)
Restrictive environmental regulation policies	0.940*** (0.240)	0.094 (0.276)	0.301*** (0.095)	−0.034 (0.175)	0.986*** (0.172)	0.270 (0.222)	0.378*** (0.080)	0.100 (0.076)
Incentive environmental regulation policies	0.928*** (0.267)	0.264 (0.312)	0.394** (0.145)	0.101 (0.126)	0.709*** (0.206)	0.578** (0.246)	0.019 (0.088)	0.559*** (0.110)
Other variables	Control				Control			
Log-likelihood	−40.351	−47.185	−21.495	−28.350	−68.837	−92.025	−66.762	−49.988
LR chi2	85.95***	33.17***	37.66***	14.22	132.05***	56.03***	32.03***	51.84***
Observations	134	92	46	46	236	175	98	77

***, **, *Significant at the 1, 5, and 10% level. Standard errors in parentheses.

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the sample singularities. First, the measure of restrictive environmental regulation policies was replaced from "the strength of penalties for aquaculture pollution behavior "to "the strength of aquaculture environmental monitoring," and the measure of incentive environmental regulation policies was replaced from "the strength of subsidies for green production "to "the support intensity of policy-based aquaculture insurance," and then the regression was repeated, and the results are shown in Table 6. Comparison with Table 2 shows that the direction and significance of the effects of the core explanatory variables of ecological cognition and environmental regulation in the three decision stages are basically the same, indicating that the estimation results are robust.

Respondents' evaluation of ecological cognition and environmental regulation in micro surveys may be influenced by subjective factors, resulting in underestimation or overestimation of data values, and thus generating sample singularities. In view of this, with reference to existing studies (Zhang et al., 2020; Fei et al., 2022), the maximum and minimum singular values of the observed values of the core explanatory variables were smoothed using the winsorized method and then regressed to further verify the robustness of the results, and the estimation results are shown in Table 7. Compared with the results in Table 2, the regression results after the smoothing of sample singular values did not change significantly, indicating that the study findings are more robust.

5. Conclusion and policy recommendations

5.1. Conclusion

In this paper, we divide farmers' participation willingness in GHAAs into three decision stages, namely, whether to participate, mode of participation, and degree of participation, and based on the survey data from 370 aquaculture farmers in Zhejiang province, the triple-hurdle model was applied to analyze the effects of ecological cognition, environmental regulation, and their interaction on farmers' multi-stage participation willingness of in GHAAs, and explored the scale and intergenerational differences. The main conclusions are as follows.

Ecological cognition and environmental regulation both have significant positive effects on farmers' willingness to participate in actions in the first stage, while the impacts on the participation willingness in the second and third stages are different. Specifically, ecological cognition has a significant positive effect on the farmers' three decision stages. In environmental regulation, restrictive policies have a significant positive impact on the willingness of farmers to participate in the first stage and the degree of willingness to participate TGT methods in the third stage. Incentive policies, on the other hand, have a significant positive effect on all three stages of decision-making.

Environmental regulation has a positive moderating effect on the influence of ecological cognition on the farmers' willingness to

TABLE 6 Regression results after replacing the core explanatory variables.

Variable	First stage (whether to participate)	Second stage (mode of participation)	Third stage (degree of participation)	
			TGT	EGT
Ecological cognition	0.513*** (0.116)	0.452*** (0.120)	0.091 (0.064)	0.093 (0.056)
Restrictive environmental regulation policies	0.269** (0.108)	0.169 (0.109)	0.169*** (0.058)	0.081 (0.057)
Incentive environmental regulation policies	0.246*** (0.082)	0.486** (0.094)	−0.041 (0.049)	0.151*** (0.054)
Other variables	Control	Control	Control	Control
Log-likelihood	−175.152	−139.433	−110.634	−92.451
LR chi2	87.34***	89.62***	26.92**	40.53***
Observations	370	267	144	123

TABLE 7 Regression results after smoothing sample singular values.

Variable	First stage (whether to participate)	Second stage (mode of participation)	Third stage (degree of participation)	
			TGT	EGT
Ecological cognition	0.229* (0.135)	0.432*** (0.120)	−0.011 (0.062)	0.093* (0.055)
Restrictive environmental regulation policies	0.910*** (0.133)	0.035 (0.130)	0.358*** (0.062)	0.072 (0.069)
Incentive environmental regulation policies	0.957*** (0.166)	0.413*** (0.156)	0.074 (0.076)	0.376*** (0.087)
Other variables	Control	Control	Control	Control
Log-likelihood	−115.940	−150.247	−101.357	−86.858
LR chi2	205.77***	67.99***	45.48***	51.71***
Observations	370	267	144	123

participate in actions. The restrictive policies will help raise the willingness of farmers with high ecological cognition to participate in GHAAs in the first stage, the incentive policy can promote the participation in EGT methods in the third stage of high ecological cognition farmers.

There are scale and intergenerational differences in the effects of ecological cognition and environmental regulation on farmers' participation willingness. In terms of scale difference, the willingness of large-scale farmers to participate was significantly affected by ecological cognition and restrictive policies, while the willingness of small-scale farmers was mainly affected by incentive policies. In terms of intergenerational differences, the effect of incentive policies on the new generation of farmers is mainly in enhancing the willingness to participate in TGT methods, while the incentive effect on the older generation of farmers is mainly in enhancing the willingness to participate in EGT methods.

5.2. Policy recommendations

Based on the above findings, the following policy recommendations are proposed.

In the promotion of GHAAs, we should further strengthen the publicity about the hazards of traditional farming methods and the benefits of green farming technology to improve the social responsibility of farmers to protect the environment, maintain food safety and stimulate their endogenous motivation for green production. Particularly for the substitution of complementary feed, aquaculture tailwater treatment, and other emerging green production technology relatively unfamiliar to farmers, with the help of training and advocacy, the network, television, and other channels to convey information about the purpose of the application of technology, potential benefits and so on, to improve the level of farmers' cognition, and to ensure that the policy objectives and farmers ecologically rational demand for unity.

Constrained policies can significantly increase the willingness of farmers to adopt green production technology, especially traditional green production technology. To this end, it is necessary to further improve the aquaculture quality and safety supervision system, increase the crackdown on illegal acts such as the use of fake and substandard veterinary drugs, banned drugs, and unlicensed additives, and improve the penalties for violations, timely disclosure of relevant supervision and inspection information, restraint and guide farmers to spontaneously adopt the reduction of drugs, aquaculture density control and other traditional green production technology.

The incentive policy plays a prominent role in promoting farmers' willingness to adopt new green production technology. On the one hand, focus on the substitution of compound feed, aquaculture tailwater treatment, and other emerging green production technology, and provide subsidy support in the procurement of compound feed, tailwater treatment equipment purchase, aquaculture pond renovation, and other aspects to reduce the cost of technology adoption by aquaculture farmers. On the other hand, the green aquatic product certification, pollution-free aquatic product certification, the acquisition of contractual arrangements, and other product market terminals, increase the examination of the use of compound feed, aquaculture tailwater treatment effect, improve the expected return on the adoption of emerging green production technology by farmers, and enhance farmers' technology adoption motivation.

In the process of green production technology promotion, based on different scales of technology adoption, differentiated supporting policies should made for different scales and different ages farmers. For farmers with the insufficient willingness to green production transformation, we should strengthen policy advocacy and play the guiding and supervising role of restrictive policies, and for farmers who already have the willingness to green production transformation, we should focus on the role of the incentive policies to boost and improve their technology adoption. At the same time, we should fully consider the difference in aquaculture scale and age, implement the policy combination of Propaganda, supervision, and incentives, and improve the efficiency of green production technology promotion.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

QC organized the database and wrote the first draft of the manuscript. QX performed the statistical analysis. QC, QX, and XY wrote parts of the manuscript. All authors contributed to the article and approved the submitted version.

Funding

This research was supported by Zhejiang Soft Science Research Program (2021C35063); National Social Science Foundation of China (19CGL039); Yongjiang Social Science Young Talent Cultivation Project.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Bbxa, B., Eds, C., and Qtkn, A. (2021). Stakeholder perceptions towards sustainable shrimp aquaculture in Vietnam – science direct. *J. Environ. Manag.* 290:112585. doi: 10.1016/j.jenvman.2021.112585

Burke, W. J., Myers, R. J., and Jayne, T. S. (2015). A triple-hurdle model of production and market participation in Kenya's dairy market. *Am. J. Agri. Econ.* 97, 1227–1246. doi: 10.1093/ajae/aav009

Chen, J. H., (2017). *Atlas of Aquaculture Regional Distribution and Water Resources in China-Zhejiang*. Shanghai Scientific & Technical Publishers, Shanghai.

Chen, Y. S., and Fang, R. J. (2011). Empirical analysis on factors affecting fishery drug application behavior of mariculturists. *Chin. Rural Econ.* 320, 72–80.

Chen, H. W., and Mu, Y. Y. (2022). Policy incentives, value perception and farmers' adoption of water-saving technologies: an empirical analysis based on 1188 farmers in Hebei, Shandong and Henan. *Resour Sci* 44, 1196–1211. doi: 10.18402/resci.2022.06.08

Chen, Y., Wang, F., Li, H. J., Aftab, S., and Liu, Y. Q. (2020). Triple-hurdle model analysis of the factors influencing biogas digester building, use and processing by Chinese pig farmers. *Sci. Total Environ.* 761:143259. doi: 10.1016/j.scitotenv.2020.143259

Cooke, R., and Sheeran, P. (2004). Moderation of cognition-intention and cognition-behaviour relations: a meta-analysis of properties of variables from the theory of planned behaviour. *Br. J. Soc. Psychol.* 43, 159–186. doi: 10.1348/0144666041501688

Dimara, E., and Skuras, D. (2003). Adoption of agricultural innovations as a two-stage partialobservability process. *Agric. Econ.* 28, 187–196. doi: 10.1111/j.1574-0862.2003.tb00137.x

Doss, C. R. (2010). Analyzing technology adoption using microstudies: limitations, challenges, and opportunities for improvement. *Agric. Econ.* 34, 207–219. doi: 10.1111/j.1574-0864.2006.00119.x

Duan, W., Jiang, Y. C., and Ouyang, B. (2022). Trend of conflict between community livelihood sand nature reserves: based on the intergenerational differences of rural households' natural resource utilization behavior. *Resour. Sci.* 44, 1267–1279. doi: 10.18402/resci.2022.06.13

Fei, H. M., Sun, L. M., and Wang, L. (2022). Decision making of farmers' black land conservation tillage behavior: value perception or policy driving? *J. Nat. Resour.* 37, 2218–2230. doi: 10.31497/zrzyxb.20220902

Guo, Z., Chen, X., and Zhang, Y. (2022). Impact of environmental regulation perception on farmers' agricultural green production technology adoption: a new perspective of social capital. *Technol. Soc.* 71:102085. doi: 10.1016/j.techsoc.2022.102085

Guo, L. J., and Zhao, J. (2014). Mechanisms of farmers' pro-environmental behavior and policy interventions: take straw treatment as an example. *Issues Agric Econ.* 35, 78–84+112. doi: 10.13246/j.cnki.iae.2014.12.010

Han, L. M., Ren, G. Y., and Qin, H. (2007). The basic connotation and specificity of the three-fishing-issues. *Issues Agric. Econ.* 112, 93–96. doi: 10.3969/j.issn.1000-6389.2007.06.020

Huang, Y. Z., Luo, X. F., Tang, L., and Yu, Z. W. (2020). Influence of market trust on farmers' application behavior of biological pesticides: regulatory effect analysis based on institutional environment. *Resour. Environ Yangtze Basin* 29, 2488–2497. doi: 10.11870/cjlyzyyhj202011016

Hukom, V., Nielsen, R., Asmild, M., and Nielsen, M. (2020). Do aquaculture farmers have an incentive to maintain good water quality? The case of small-scale shrimp farming in Indonesia. *Ecol. Econ.* 176:106717. doi: 10.1016/j.ecolecon.2020.106717

Jin, R. R., Li, S. P., and Nan, L. (2022). Effects of capital endowment, perceived value, and government subsidies on farming households' adoption behavior of clean heating. *Resour Sci.* 44, 809–819. doi: 10.18402/resci.2022.04.13

Joffer, O. M., Poortvliet, P. M., and Klerkx, L. (2019). To cluster or not to cluster farmers? Influences on network interactions, risk perceptions, and adoption of aquaculture practices. *Agric. Syst.* 173, 151–160. doi: 10.1016/j.agsy.2019.02.011

Kim, J., Goldsmith, P., and Thomas, M. H. (2010). Economic impact and public costs of confined animal feeding operations at the parcel level of Craven County, North Carolina. *Agric. Hum. Values.* 27, 29–42. doi: 10.1007/s10460-009-9193-x

Lei, J. L. (2010). Strategy consideration for industry construction of Chinese marine culture. *J. Fish. Sci. China* 17, 600–609.

Li, J., Feng, S., Luo, T., and Guan, Z. (2020). What drives the adoption of sustainable production technology? Evidence from the large-scale farming sector in East China. *J. Clean. Prod.* 257:120611. doi: 10.1016/j.jclepro.2020.120611

Li, B. W., and Xu, X. (2018). Spatial effect of cultivation agglomeration and technology supporter on farmers' adoption of new agricultural technology: take freshwater aquaculture as an example. *J. Nanjing Agric. Univ. (Soc. Sci. Ed).* 18, 124–136.

Li, F. N., Zhang, J. B., and He, K. (2019). Impact of informal institutions and environmental regulations on farmers' green production behavior: based on survey data of 1105 households in Hubei Province. *Resour. Sci.* 41, 1227–1239. doi: 10.18402/resci.2019.07.04

Liu, L. J., and Peng, K. (2021). Research progress on substitution of iced trash fish with aquatic compound feed. *Feed Res.* 44, 141–144. doi: 10.13557/j.cnki.issn1002-2813.2021.21.031

Luo, L., Yang, X. F., Niu, W. J., and Li, Y. (2022). Cognitive norms, institutional environment and multi-stage dynamic process of fruit farmers adopting green production technology: an analysis based on the triple-hurdle model. *J. Agrotech. Econ.* 330, 98–113. doi: 10.13246/j.cnki.jae.20211228.001

Obubuafo, J., Gillespie, J., Paudel, K., and Kim, S. A. (2008). Awareness of and application to the environmental quality incentives program by cow calf – producers. *J. Agric. Applied Econ.* 40, 357–368. doi: 10.1017/s1074070800028169

Pannell, D. J., and Claassen, R. (2020). The roles of adoption and behavior change in agricultural policy. *Appl. Econ. Perspect. Policy.* 42, 31–41. doi: 10.1002/aepp.13009

Phong, T. N., Thang, V. T., and Hoai, N. T. (2021). What motivates farmers to accept good aquaculture practices in development policy? Results from choice experiment surveys with small-scale shrimp farmers in Vietnam. *Econ. Anal. Policy.* 72, 454–469. doi: 10.1016/j.eap.2021.09.015

Prochaska, J. O., and Diclemente, C. C. (1983). Stages and processes of self-change of smoking: toward an integrative model of change. *J. Consult. Clin. Psychol.* 51, 390–395. doi: 10.1037/0022-006X.51.3.390

Schreinemachers, P., Chen, H.-P., Nguyen, T. T. L., Buntong, B., Bouapao, L., Gautam, S., et al. (2017). Too much to handle? Pesticide dependence ofsmallholder vegetable farmers in Southeast Asia. *Sci. Total Environ.* 593-594, 470–477. doi: 10.1016/j.scitotenv.2017.03.181

Tang, Q. S., Ding, X. M., Liu, S. L., Wang, Q. Y., Nie, P., He, J. G., et al. (2014). Safeguard measures and policy recommendations for green and sustainable development of Chinese aquaculture. *Chin. Fish. Econ.* 32, 5–11. doi: 10.3969/j.issn.1009-590X.2014.02.001

Xie, J. H., Yang, G. J., Zhang, J., and Wang, G. (2021). Mechanism of farmers' ecological cognition affecting their clean energy utilization behaviors in the Yangtze River Economic Belt: an empirical analysis of farmers in 5 districts(cities). *J. Huazhong Agric. Univ.* 40, 52–63. doi: 10.13300/j.cnki.hnlkxb.2021.03.007

Yan, T. W., Zhang, D. K., He, K., and Zhang, J. B. (2017). Study on farmers' decision behavior of crop straw recycling of returning to field: based on a survey in seven provinces including Anhui and Lu. *Issues Agric. Econ.* 38, 39–48+110–111. doi: 10.13246/j.cnki.iae.2017.04.005

Yang, Z. H., Wang, J., and Yang, X. (2020). Self-sufficiency or outsourcing: how does small rural household adopt the practice of soil conservation? Based on the perspective of social capital. *China Land Sci.* 34, 89–98. doi: 10.11994/zgtdkx.20200824.094427

Yu, W. Z., Luo, X. F., and Li, R. R. (2017). The paradox between farmer willingness and their adoption of green technology from the perspective of green cognition. *Resour. Sci.* 39, 1573–1583. doi: 10.18402/resci.2017.08.13

Zhang, H. N., Ge, X. H., Jie, Y. M., and Zheng, Y. C. (2019). A study on the influence of ecologicalcognition on river basin residents' willingness to participate in ecological compensation. *China Popul. Resour. Environ.* 29, 109–116. doi: 10.12062/cpre.20190606

Zhang, W. B., and Ma, X. Z. (2020). China's aquaculture development trends since 2000 and future directions. *J. Shanghai Ocean Univ.* 29, 661–674. doi: 10.12024/jsou.20190502673

Zhang, T. Y., Yan, T. W., and Wang, Z. (2020). Social networks, income uncertainty and the self-employedwomen's adoption behavior of conservation tillage technology. *J. Agrotech. Agrotech. Econ.* 304, 101–116. doi: 10.13246/j.cnki.jae.2020.08.008

Zhao, K., Zhang, R. H., and Sun, P. F. (2022). The impacts of capital endowment on farmers' adoption behaviors of agricultural socialization services: from the perspective of family life cycle. *Res. Agric. Mod.* 43, 121–133. doi: 10.13872/j.1000-0275.2021.0118

Zhu, J. F., and Deng, Y. Y. (2022). Green transformation of agricultural production: logic of formation, dilemma and practical strategy. *Reform Econ. Syst.* 234, 84–89.

frontiers | Frontiers in Sustainable Food Systems

TYPE Systematic Review
PUBLISHED 02 August 2023
DOI 10.3389/fsufs.2023.1208918

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OPEN ACCESS

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RECEIVED 19 April 2023
ACCEPTED 17 July 2023
PUBLISHED 02 August 2023

CITATION
Munguti JM, Obiero KO, Iteba JO, Kirimi JG, Kyule DN, Orina PS, Githukia CM, Outa N, Ogello EO, Mboya JB, Ouko KO, Liti D, Yossa R and Tanga CM (2023) Role of multilateral development organizations, public and private investments in aquaculture subsector in Kenya.
Front. Sustain. Food Syst. 7:1208918.
doi: 10.3389/fsufs.2023.1208918

Role of multilateral development organizations, public and private investments in aquaculture subsector in Kenya

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Rapid population and economic growth, increased health benefits of aquatic food, and changes in lifestyles and preferences as a result of rapid urbanization and globalization are all contributing to the rapid growth of aquaculture production in Kenya. Despite significant investment efforts from the national and devolved governments as well as donors and international organizations, smallholder aquaculture production is yet to result in a significant increase in incomes and improved food and nutrition security. We conducted a scoping review to investigate the roles of multilateral development organizations, international financial institutions, and public and private investments in Kenya's aquaculture subsector. We draw on lessons learned from previous projects implemented at the national, county, and farm levels to make recommendations for sustainable aquaculture intensification in Kenya. To unlock Kenya's aquaculture potential and improve its food and nutrition status, deliberate efforts must be made to create a conducive environment for public and private investment in the industry. First, there is a need to coordinate and clearly articulate the roles and responsibilities among devolved and national governments, donors, and financial institutions through public-private partnerships to ensure optimal allocation of financial, human, and infrastructure resources. Second, more collaborative research should be devoted to the design and construction of climate smart culture systems, developing new species to guarantee supply of high-quality products; developing and scaling low-cost and highly nutritious fish feeds based on novel ingredients; and enhancing resilient livelihoods through innovative aquaculture practices and market linkages to create employment opportunities for youth and women. Finally, the national and devolved governments should create an enabling policy environment through tax incentives and regulatory reforms to combat climate change, protect nature and biodiversity, sustain livelihoods, and mainstream food and nutrition initiatives into the design and implementation of future aquaculture projects.

KEYWORDS

aquaculture, role, multilateral donors, public, private, investments, Kenya

 10.3389/fsufs.2023.1208918

1. Introduction

More than 800 million people depend on fish and other aquatic foods and fish also contribute 20% of the global animal protein consumed by 3.3 billion people (FAO, 2022). According to Bush and Oosterveer (2019), aquaculture presently produces more than half of the fish consumed directly by humans and is projected to increase to 140 million tonnes by 2050 (FAO, 2018). Aquaculture generated US$264 billion in revenue in 2018 (WorldFish, 2020). Aquatic foods directly contribute US$24 billion to the African economy, as well as food and nutrition security (WorldFish, 2020). The need for fish as a food source is expected to increase as the world's population rises to 9.7 billion by 2050, placing further strain on the world's fisheries (United Nations, 2015). As a result of the ongoing and impressive development in the availability of fish for human consumption, aquaculture is progressively garnering attention as a solution to this shortage (FAO, 2022; Le Gouvello et al., 2022).

Fish and other aquatic foods have an array of roles in the food systems of Africa, including generating revenue and serving as a vital source of micronutrients, especially for women and young children (Chan et al., 2019; Tran et al., 2019). However, the value of fish and aquatic foods in Africa are often overlooked in development research, policy, and investment cycles (Chan et al., 2021). Indeed, the vital contribution of fish to food and nutrition security has largely been overlooked in high-level food policy dialogs and associated funding portfolios of major international organizations and actors (Bennett et al., 2021). For instance, between 1968 and 2018, World Bank investment in capture fisheries and aquaculture accounted for an average of 1.8% of all agricultural funding; although funding has increased to an average of 2.6% (and as high as 5.4% in 2018) over the past decade (Bennett et al., 2021).

Sustainable financing and investment are required to sustain capture fisheries and promote aquaculture expansion in Sub-Saharan Africa to shift the aquatic food chain towards healthier diets (Chan et al., 2021). Over the past decade, there has been increased investments aimed at intensifying culture systems and commercializing the aquaculture value chain on the continent (Kaminski et al., 2018; Chan et al., 2019). Despite its rich aquatic and biological diversity, the continent contributes less than 2.5% of total global aquaculture production (Satia, 2017; Obiero et al., 2019a). Many governments, donors and international organizations have spearheaded aquaculture development in Africa, primarily targeting smallholder farmers to increase food and nutrition security (Brummett et al., 2008; Kaminski et al., 2018). In addition, international financial institutions have made significant contributions to aquaculture development, particularly through human and institutional capacity building, funding applied and adaptive research, developing codes of practice, and provision of capital for investment in the production value chain (World Bank, 2007). Given that Africa's population is expected to more than double by 2050 and that an estimated 278 million people suffer from chronic hunger (FAO, IFAD, UNICEF, WFP and WHO, 2022), aquaculture is projected to play a significant role in providing critical animal protein foods to millions of people struggling to maintain decent livelihoods (Kobayashi et al., 2015; Golden et al., 2017).

Aquaculture has become well-integrated into the global food system over the past two decades (Verdegem et al., 2023). Since 2000, annual production has increased rapidly due to the expansion of production areas (Oyinlola et al., 2018), intensification of production systems (Verdegem et al., 2023), improved production management, and the adoption of new and improved technologies and innovations (Kumar and Engle, 2016; Henriksson et al., 2018). In recent years, more attention is focused on integration of aquaculture systems into local nutrition-sensitive, circular economy, and sustainable food systems. African countries should effectively harness the potential of aquaculture to meet increasing demand for fish while reducing poverty and stimulating economic growth by prioritizing investments in research, development, infrastructure, and capacity-building initiatives (Adeleke et al., 2020).

In Kenya, inland fisheries and aquaculture represent a vast potential to support local economic development in terms of fighting poverty, reduction of food insecurity and the generation of employment in Kenya (Schubert et al., 2021). Kenya's Vision 2030 development blueprint recognized fisheries and aquaculture subsector as a source of food security, poverty alleviation, and employment creation. The country has abundant inland and marine resources suitable for scaling up fisheries and aquaculture production and blue economy related industries and services to spur inclusive economic growth and development (Obiero et al., 2022). Kenya's fisheries and aquaculture sector contributes approximately 0.7% to country's gross domestic product (GDP). The sector supports about 1.5 million people directly and indirectly working as fishers, traders, processors, suppliers and merchants of fishing accessories and their dependents (GoK, 2022). The country's total fish production from capture fisheries and aquaculture was 174,000 tonnes, valued at KES 37.5 billion in 2022 (KNBS, 2023). The fisheries sector is over-reliant on wild catch, whose volumes are declining due to overfishing, biodiversity loss and pollution, especially in the territorial waters. As a result, the sector cannot meet the annual demand for fish in Kenya, currently estimated at 550,000 to 600,000 tonnes against a production base of 180,000 to 240,000 tonnes (Obiero et al., 2019b). There is a significant gap between projected demand and national fish production, which is partially offset by fish imports. Kenya's *per capita* fish consumption has stagnated at around 4.5 kg/person/year, compared to a global average of 21 kg/person/year. The country aims to increase *per capita* fish consumption to 10 kg per person per year by 2030, which would necessitate greater production, particularly through intensive and semi-intensive aquaculture systems (Obiero et al., 2019b).

Aquaculture production in Kenya has almost doubled over the past decade, resulting in increased income and employment opportunities, improved nutritional status among vulnerable communities and regional development in rural areas (Cheserek et al., 2022). Aquaculture production increased from 12,152 tonnes in 2010 to 22,140 tonnes in 2022, accounting for 12.7% of the country's total fish output (Figure 1). This growth was primarily due to the implementation of the Fish Farming Enterprise Productivity Project (FFEPP) under the Economic Stimulus Program (ESP) in which the Kenya Government allocated KES 3.986 billion in two phases for pond construction, supply of fingerlings and stocking of ponds, acquisition and supply of fish farming inputs and specialized equipment as well as capacity building and extension support services (Musa et al., 2012;

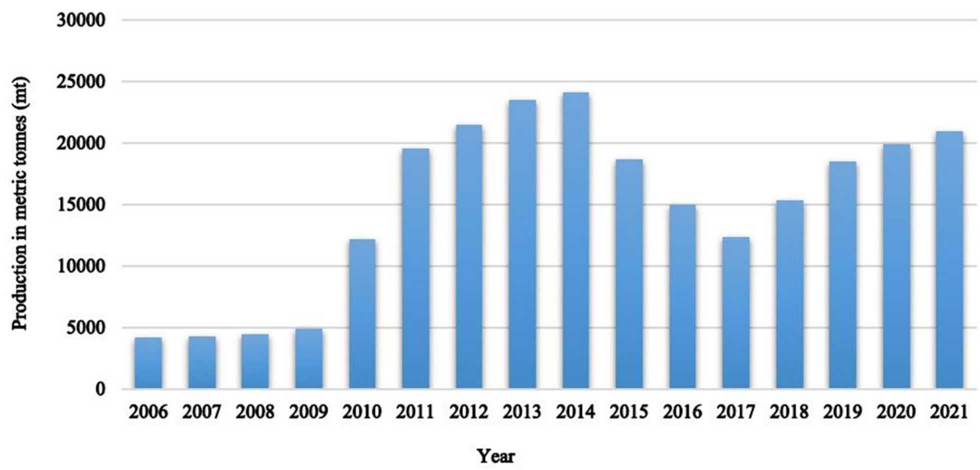

FIGURE 1
Trends in aquaculture production in Kenya from 2006 to 2021 (KNBS, 2022).

Munguti et al., 2021). The ESP was a massive high impact fish farming intervention that invested heavily in projects with both short-term and long-term benefits, and there are strong indications that aquaculture production will continue to grow rapidly, driven by the commercially oriented large-scale sector. In this regard, small-scale aquaculture producers should be organized into viable enterprises capable of realizing economies of scale and forging economic ties with input suppliers, product markets, technical service providers, and financial service providers.

Smallholder aquaculture production in Kenya has mostly remained stagnant, despite significant efforts from public and private sector institutions and actors at all nodes of the aquaculture value chain (Munguti et al., 2014). Previous aquaculture development initiatives have resulted in slow growth due to inadequate quality seed and feed, low uptake of appropriate technologies, poor market linkages, poor management of culture systems, heavy reliance on weak government extension and advisory services, low technical capacity in disease diagnostics and biosecurity, and importation of cheaper fish products (Ngugi and Manyala, 2009; Obiero et al., 2019c). Additionally, although existing universities and mid-level colleges offer fisheries and aquaculture degrees, current curricula and the aquaculture training landscape do not adequately address core skills and competencies, resulting in graduates who are not sufficiently skilled for the aquaculture job market and business, frequently exacerbated by inadequate financial and physical infrastructure in universities and technical vocational training centers (Nyonje et al., 2021). There is need to understand the multifaceted challenges in aquaculture development in Kenya in order to provide more context-specific solutions to address both opportunities and challenges for future development.

In this article, we review and synthesize existing literature to document the roles of multilateral development organizations, international financial institutions, public and private sector investments in the aquaculture subsector in Kenya. The goal is to provide lessons and recommendations for the design and implementation of future fisheries and aquaculture projects in the country by the relevant stakeholders in the sectors including policy and decision makers, private sector actors, academicians, and researchers in low-and middle-income countries, development organizations, input suppliers, farmers, processors, traders, and consumers.

2. Methodology

The present study adopted a scoping review methodology (Arksey and O'Malley, 2005; Levac et al., 2010) to conduct a comprehensive literature review on the involvement of international organizations, institutions from the public and private sectors, and actors in Kenya's aquaculture subsector. According to Arksey and O'Malley (2005), scoping studies *"aim to map rapidly the key concepts underpinning a research area and the main sources and types of evidence available."* Levac et al. (2010) expanded on Arksey and O'Malley (2005) methodological framework and made recommendations to improve consistency in conducting and reporting scoping studies.

As a starting point, we applied the Preferred Reporting Items for Systematic Reviews and Meta-Analyzes extension for Scoping Reviews (PRISMA-ScR) checklist to map relevant literature (Tricco et al., 2018). The steps were as follows: (1) identify relevant studies, (2) screen and select relevant publications, (3) chart the data and information, and (4) assemble, summarize, and report the results. Figure 2 illustrates the steps of the scoping review. To achieve the intended objectives, we used a set of keywords (related to aquaculture, development partners, national government, county governments and the private sector) to search scientific databases of Research Gate, Google Scholar, and The Lens to find published research articles, review papers, technical reports, books, book chapters, and dissertations/thesis. The literature review was conducted between January and February 2023.

We also searched for published material from international institutions that are directly and indirectly involved in aquaculture, e.g., FAO and WorldFish. The search terms used were "international donors," "aquaculture," "government," "public sector," "private sector," and "Kenya." Boolean operators ("OR," "AND," and "NOT") were appropriately used in databases and search engines to narrow down

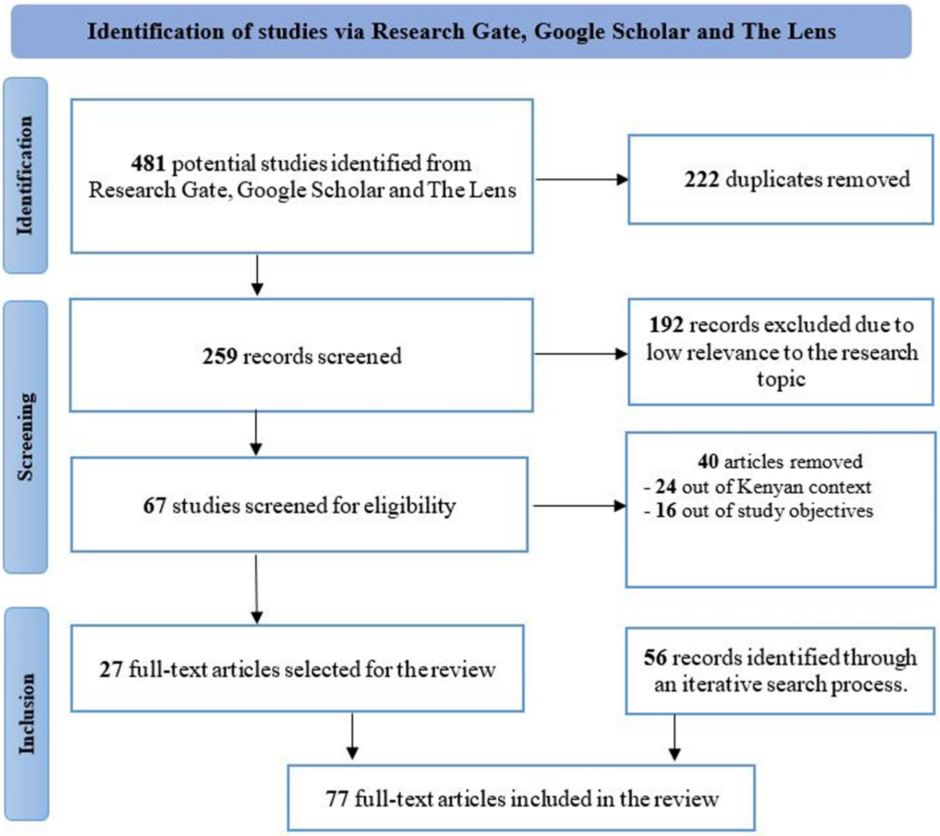

FIGURE 2
Flow chart of the selection process of studies examining the role of international organizations, public and private sector in aquaculture development in Kenya.

and refine the search. We used a five criteria checklist to include publications for literature review. Specifically, the publications were to (1) be topically relevant and focused on aquaculture, (2) meet academic quality, i.e., only scientific, technical, and academic documents were accepted, (3) be published in the last 12 years (2010 to 2022), (4) be written in English language, and (5) focus on geographic location of Kenya and its 47 counties.

The search approach yielded 481 publications including 167 works in Research Gate, 123 works in Google Scholar, and 191 works in The Lens. To reduce reporting bias, the full-text and abstract of each article were reviewed by at least two reviewers in accordance with suggested protocols for scoping reviews (Peters et al., 2015). After eliminating duplicates, 259 distinct works remained. Following a screening of the primary title and abstract, 67 articles were included as potentially relevant. After reading the full-text articles, 27 publications met the criterion for inclusion in this current review. Further, fifty-six (56) records were included in this review after a three-step iterative search process that involved (1) reviewing available literature, and selecting relevant articles to include in the search data, (2) evaluating the presented data and determining its relevance to the research goals, and (3) identifying knowledge gaps to inform future research needs (Figure 3). The relevant studies were then imported into the Mendeley® literature management software. Microsoft Excel was used to develop a data-charting form for analysis.

3. Results and discussion

3.1. Evolution of aquaculture in Kenya

According to Obwanga et al. (2020), the growth of aquaculture in Kenya is categorized into three development phases, i.e., introduction phase, public and donor supported phase, and private sector-investment phase as described in Table 1.

3.1.1. Introductory phase

Aquaculture was introduced in Kenya by the colonial government for sport fishing in 1920s (van Someren, 1960). The first fish introduced into static water pond culture were native tilapias, which were later followed by common carp and African catfish. Between 1940s and 1960s, aquaculture was promoted as sustainable aquatic production system to improve rural nutrition, wealth creation, diversify agriculture failure risks, and create jobs in rural areas (Adeleke et al., 2020). The initial efforts focused on fundamental research and development to produce appropriate technologies for culture of indigenous species (Brummett et al., 2008). The colonial administration set up the Sagana Fish Farm for warm-water species, i.e., tilapia and catfish and Kiganjo Trout Farm for cold-water species in 1948 to produce seed for stocking ponds, dams, and rivers (MoFD, 2010).

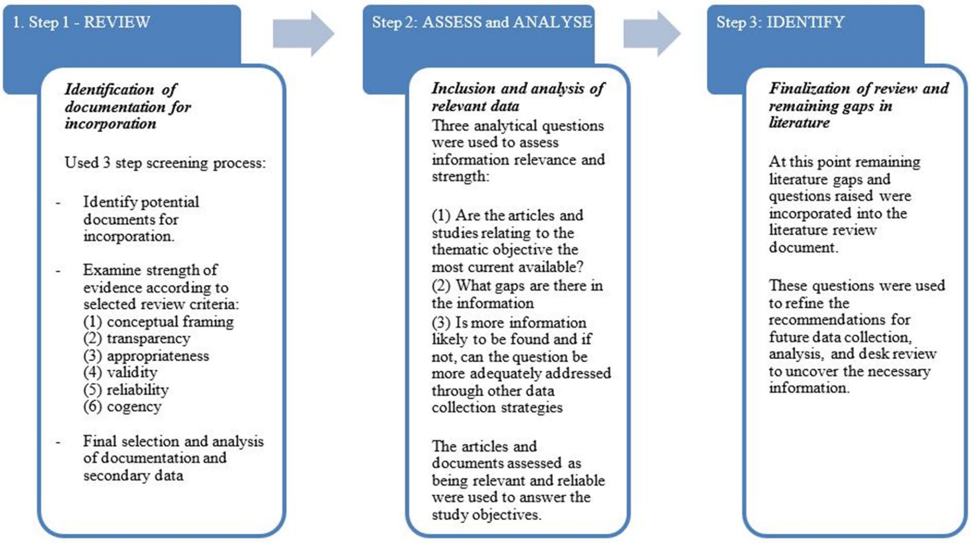

FIGURE 3
The iterative process utilized to conduct literature review.

3.1.2. Public funding and donor supported phase (1960 to 2010s)

Following Kenya's independence, the newly formed government established the Fisheries Department domiciled in the Ministry of Agriculture to spearhead fisheries development in the country. The Fisheries Department promoted the fledgling industry through "Eat More Fish Campaigns" resulting in the rapid development of rural pond fish farming in Kenya, mainly in the Lake Victoria region. Thus, by the early 1970s, Western and Nyanza Provinces had an estimated 30,000 ponds (Zonneveld, 1983). However, because the majority of the ponds were small, most of them were eventually abandoned (Kagai, 1975). This resulted in a rapid decrease in fish ponds in the region, owing to poor yields, inadequate high quality fingerlings and feeds, and limited technical know-how in fish farming husbandry (Okemwa and Getabu, 1996). According to Ngugi and Manyala (2009), there were 10,000 existing ponds in 1989, with approximately 5,000 actively managed based on a review of 28 District fisheries offices annual reports. In the late 1970s, Ngomeni Prawn Farm was established as a pilot project, marking the beginning of mariculture in the coastal region (Rothuis et al., 2011). Food security, poverty eradicating, and job creation in rural areas were the top priorities for donors and policymakers. Even with technical and financial support from numerous international and bilateral donors, as well as government provision of seed and extension services, subsistence fish farming in ponds dominated the subsector (Okemwa and Getabu, 1996). According to the national development plan for the industry developed in 1982, aquaculture was expected to produce 44,500 metric tonnes annually by 1990, or roughly 20% of the total fish production (GoK, 1982). However, by that time, aquaculture output was only 975 tonnes by 1990, far short of the target. Between 1970 and 2006, aquaculture production oscillated between 1,000–4,000 MT. In 2004, there were approximately 7,500 small-scale fish farmers producing fish from 10,371 ponds with a combined surface area of 168 hectares. Due to the low fish harvests and poor economic returns on and capital investments, many farmers regarded aquaculture as a risky business. In 2007, about 4,250 metric tonnes of fish was produced by 4,742 farmers from 7,477 ponds covering a surface area of 217 hectares (ha), 301 dams and reservoirs (497 ha), and 248 tanks and raceways countrywide (Nyandat and Owiti, 2013).

Between 2009 and 2013, the Kenya Government implemented the large-scale Fish Farming Enterprise Productivity Project under the ESP to promote smallholder aquaculture production through targeted assistance for input provision, farmed fish production, post-harvest handling technologies, and related activities (Ole-Moiyoi, 2017). In 2012, during the peak of the subsidy program, the number of smallholder farmers increased to 49,050 owning approximately 69,998 ponds occupying 2,063 Ha (Nyandat and Owiti, 2013). Furthermore, during the FFEPP implementation phase, a mapping of suitable aquaculture locations was carried out guided by water availability, climatic conditions, soil type, terrain, land use, and access to inputs and markets. The Western, Central, and Eastern parts of Kenya were reported as the most suitable areas for fish farming. As a result, some 9.58 million ha were identified as areas of high suitability, 40.56 million ha with medium suitability and 3.24 million ha with low suitability, especially in arid and semi-arid (ASAL) regions (Ogello and Munguti, 2016). The suitable regions are, however, at risk of climate change (Munguti et al., 2022b). The regions in Western Kenya are threatened by frequent heavy rainfall, which increases the risk of flooding of Lake Victoria, while the Central/Eastern area is under threat of drought, which makes pond farmers rely more heavily on natural water points.

3.1.3. Private sector led aquaculture development

Public-private producers' partnerships have been promoted as the best option for aquaculture growth in Kenya. This is due to an appropriate distribution of risks among the parties in these partnerships, which are funded by both the government and donors. Currently, several private investment organizations have been

TABLE 1 Historical phases of aquaculture development in Kenya.

Phase	Period	Description of activities
I – Introductory Phase	1900–1950s	• Introduction of fish farming by stocking trout in rivers for sport fishing by colonialist between 1910 and 1921 • Basic research and development (R&D) to provide practical technologies for culture of indigenous species • In 1948, the colonial government established Sagana and Kigango fish station for culture of catfish, tilapia, and trout
II – Government and donor support phase	1960–2010	• At independence, the new government established the Fisheries Department (FD) domiciled in Ministry of Agriculture • The FD popularized fish farming through "Eat More Fish Campaigns" • By early 1970s, there was a rapid spread of rural pond fish farming in Kenya (>30,000 fishponds) in Nyanza and Western Kenya • Between 1970–2006, aquaculture production oscillated between 1,000–4,250 tonnes. • Introduction of mariculture in 1980s with the establishment of the Ngomeni Prawn culture pilot project along the coastal region • The FAOIUNDP, in 1966, the World Bank in 1978, NORAD during 1970–1988, EEC - during 1984–1986, the Government of Belgium in 1984, USAID during 1983–1990 and IFS in 1974 have aided projects on aquaculture research and development • The 2010 Constitution established a devolved system of governance with most agriculture functions transferred to County Governments • During the 2009/2010 financial year, the Kenyan Government through the Economic Stimulus Program (ESP) launched the Fish Farming Enterprise Productivity Program (FFEPP) in 2009, with an initial budget of KES 2.2 billion (Charo-Karisa and Gichuri, 2010; Musyoka and Mutia 2016)
III – Donor supported projects and private sector led ventures	2010 – Present	• Establishment of cage culture in Lake Victoria and other reservoirs • The Third Medium Term Plan (MTP III) 2018–2022 of Vision 2030 identifies the Blue Economy (including the fisheries and aquaculture sector) as one of the priority areas with high potential to spur inclusive economic growth and development in Kenya • Substantial donor funding for aquaculture development, e.g., USD 143.3 million Aquaculture Business Development Program (ABDP) funded by IFAD from 2018–2026 and Kenya Marine Fisheries and Socio-Economic Development (KEMSFED) Project worth KSH 10 billion supported by the World Bank from 2020–2025 • Private sector support by the Dutch Government to explore business opportunities in aquaculture. The Dutch supported initiatives include FoodTechAfrica, Kenya Market Led Aquaculture Program (KMAP), IDH-Sustainable Trade Initiative and Lattice Aquaculture that have brought a consortium of partners to tackle different challenges facing smallholder producers • Gatsby Foundation, through Msingi East Africa identified aquaculture as a high potential sector to develop. Farm Africa also supported Aqua Shops Project, funded by DFID

established to tackle different challenges facing smallholder producers (Table 2; IDH, 2023).

3.2. Aquaculture production trends

Aquaculture in Kenya is viewed as a viable option for closing the growing gap between fish demand and its supply (Obiero et al., 2019b). Freshwater fish account for over 75% of Kenya's reported aquaculture production. Nile tilapia (75%) and African catfish (18%) make up the majority of aquaculture production while common carp (6%) and rainbow trout (1%) are two exotic cold-water species practiced in limited scope (Opiyo et al., 2018; Munguti et al., 2022a). Small scale pond farmers owning 1–2 ponds dominates fish farming in Kenya. However, small-scale farmers are not producing volumes presented in government projected statistics. In 2021, aquaculture production was 21,076 metric tonnes with a farm gate value of KES 6.714 billion compared to 19,945 metric tons valued at KES 6.303 billion in 2020 (GoK, 2022). In 2022, pond-based production was projected to reach 23,000 tonnes from 55,032 fish farmers owning 75,201 operational ponds and occupying 1,309 hectares (13,090,740 m^2). Furthermore, since limited resources are allocated to collect data from fisheries related activities, national statistics often underreport small-scale fisheries and aquaculture production. Farmers face multiple challenges because of the highly fragmented value chain, including limited

TABLE 2 Selected private sector investors in the aquaculture value chain in Kenya (IDH, 2023).

• *Victory Farms*: Victory Farms located in Sindo in Homa Bay, for example, is one of success stories of cage aquaculture in sub-Saharan Africa. The company is on track to produce around 20,000 tonnes of fish by 2023, working with over 20,000 market trading women who source from its 55 branches countrywide to supply to their consumers
• *Jewlet Enterprises*: Established in 2010 and located in the Western region of Kenya with a vision to become a leading freshwater aquaculture farm in EA region. Jewlet is involved in the production of fingerlings and market-size tilapia fish using RAS, ponds, and cages. The average fingerling production in the facility is currently at 500,000 fingerlings per month. The company has heavily invested in research and technology and currently uses Genetically Improved Farmed Tilapia (GIFT) in the production of fingerlings
• *Kamuthanga Farm Limited*: Located in the Eastern region, Kamuthanga is an EcoMark Africa certified farm that leverages RAS in the production of fingerlings and market-size fish. For instance, Kamuthanga Fish farm based in Machakos County was established in 2014 as a large-scale commercial RAS and currently produces approximately 100 metric tonnes of tilapia and 3 million fingerlings annually (IDH, 2023)
• *Hydro Victoria Fish Hatchery Farm (HVFHF)*: A private investment firm established in November 2016, with initial investments in pond and cage fish farming in Busia and Siaya Counties. Realizing the gaps in fish seed and feeds, the firm set up a hatchery and nursing system with an annual production capacity of 2,500,000 tilapia fingerling in March 2019 based at Port Victoria Town, Busia County. The goal of the firm is to use black soldier fly (BSF) as an environmentally friendly, sustainable, and economically viable fish feed to create job opportunities for women and youths
• *Aquaculture Academy (AA)*: This is the knowledge arm of Lattice Aquaculture established in 2021 with the goal to train and build 'aquapreneurs' able to run a sustainable and profitable business, inspire others to become fish farmers and spur economic prosperity throughout the sector. The academy currently has two locations at Kamuthanga Fish Farm located in Machakos county and Jewlet Fish farms in Homabay County. The academy is structured to provide both theoretical and practical training to fish farmers, with a target to reach about 1,000 farmers every year
• *Aquarech Limited*: This is a fish aggregation company established in 2019 in Kisumu, Kenya. Aquarech is building Africa's first fish farming platform leveraging on technology to enhance access to inputs, credit and facilitate market. Through the platform, fish farmers can buy top-quality feed, sell fish, and learn about best fish farming practices to improve their incomes. The company estimates its outreach to be about 2,000 farmers, 60% of whom are cage farmers
• *Tunga Nutrition (K) Limited*: Established in 2021 as a joint venture between Unga Group Ltd., Nutreco International BV's Aqua division, Skretting to provide quality fish feed to meet the growing demand of feeds in the wider East African region. The company has a production plant located in Nairobi with over 35 distribution outlets spread out in the region. The company is involved in the manufacturing, importation marketing, and distribution of fish feed
• *Great Lakes Feeds Limited*: A registered company located in Utonga Beach, Bondo, Siaya County. The company is a social for-profit enterprise which has been operating for the last 5 years. The company is engaged in the production of high-quality animal feeds majorly fish feeds, but also poultry, pig feeds and others. The company established a hatchery facility in 2020 specializing in Nile tilapia (*Oreochromis niloticus*) and African catfish (*Clarius gariepinus*) fingerlings and brood-stock production and sale
• *Labedcash Marine Enterprises*: Fish and fingerlings production farm in Malava, Kakamega County. The hatchery has been in operation for the last 12 years. The farm specializes in commercial production of Nile Tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*) fingerlings and ornamental. The farm has over 200 ponds and a hatchery that can produce up to 1 million fingerlings monthly
• *African Blue Limited* is producing very fresh and high-quality tilapia in cages in the clear and pristine waters of Lake Victoria. The company which was established in 2019 is located next to Uyawi Beach in Siaya County, Western Kenya, 15 km south of Bondo The company employs local community members to boost the Kenyan economy

access to quality and cost-effective inputs and premium markets. Since land and water are becoming scarce due to competition from other industries and resource users, technological advancements have been encouraged to accelerate aquaculture development (Obiero et al., 2019c). Recirculating aquaculture systems (RAS), tank-based systems, hydroponics, aquaponics, and installation of high-density cages in Lake Victoria are examples of technological innovations rolled out in recent years. However, the high initial investment costs, operating expenditures, and lower market pricing for farmed fish limit upscaling of RAS and other tank-based systems. Economic feasibility is frequently unsure due to the high investment prices, which may limit the adoption of these contemporary production systems, as seen in other locations (Ngoc et al., 2016).

In Kenya, cage culture has grown from relative obscurity over the past 10 years to become a significant method of producing Nile tilapia, primarily in rural and urban regions (Aura et al., 2018). Cage installations have spread throughout the five riparian counties, but their installation in terms of volume varies from county to county (Njiru et al., 2019). There are currently an estimated 4,800 active cages with a production capacity of 21,000 tonnes, but the projected carrying capacity using the best management practices is 110,000 tonnes annually (KMFRI, 2017). Even though cage culture holds great promise for boosting output, generating employment opportunities, and enhancing the economic wellbeing of rural communities, site suitability for installing cage is still poorly regulated. Over 45% of cage installations are made within 200 meters of fish breeding grounds, which may put other lake users in conflict (Njiru et al., 2019). Small water bodies (SWBs), such as dams and reservoirs, also provide a variety of livelihood options in Kenya, significantly contributing to economic growth, food security, and national development (Aura et al., 2022). Aura et al. (2021) calculated the carrying capacity of 74 SWBs in Western and Central Kenya. The study demonstrated that the central region had a capacity to produce 72,447 tonnes in 37 sampled SWBs, while the western region would only produce approximately 447 tonnes in the sampled sites.

4. Role and contribution of national and county governments in aquaculture growth in Kenya

National and county governments support aquaculture development through enacting and enforcing laws and regulations. According to Part 1 of Section 29 of the Fourth Schedule of the Constitution, the National Government is responsible for the "protection of the environment and natural resources with a view to establishing a durable and sustainable system of development." On the other hand, county governments are responsible for implementing national government policies that pertain to their respective counties (CoK, 2010). National and county governments prioritize and support the implementation of aquaculture policies and measures that advance, support, and increase sector production (Tracy et al., 2021). To ensure uniformity and national standards in the fisheries and aquaculture sector, each County government implements and play their role in accordance with national policy guidelines through legislation and administrative action (CoK, 2010).

Fisheries and aquaculture are being developed by a number of government institutions and organizations through policy development and implementation, training, research, and extension. These organizations have been implementing their mandate either independently or in cooperation with other state organizations. In areas with high potential for aquaculture, there are both research and extension facilities; however, a lack of funding to support the facilities and staff has hindered their effectiveness in providing services (Obwanga and Lewo, 2017). The government also collaborates with non-governmental organizations (NGOs) to spearhead the research agenda, provide funding, conduct research, and produce and disseminate research findings. The focus of NGOs involvement in educating farmers, extension agents, and research officers about a range of aquaculture subjects, such as market access, entrepreneurship, and value addition, has been on the development of simple, appropriate technologies and innovations, particularly at the rural level (Fonda et al., 2021; Obiero et al., 2021).

4.1. National government

In general, the national government has developed policies and measures to promote aquaculture development (GoK, 2015). In addition, the government has established a number of support services, such as extension services, fish health programs, and fishery management programs, as well as resources for infrastructure development and marketing operations (Orina et al., 2018). The Kenyan government approved funding of KES 1 billion in November 2022 to establish the Kabonyo Fisheries and Aquaculture Service and Training Centre of Excellence. The goal of the centre is to support training, research, innovation, and best practices in aquaculture through practical demonstrations and business incubations. A Nile Perch Development Center, an Aquaculture Resource Center, and the Kenya Fishing School will be built as part of the project. Domestication and selective breeding of Nile perch, tilapia, and catfish will also be conducted to increase the number of fish species available to small and large-scale fish farmers. The National Aquaculture Technology Development and Innovation Transfer Centre in Sagana is also being expanded and modernized as a national breeding nucleus for warm water culture species. There are also several county-level fish multiplication hatcheries, research centers throughout the country, the National Trout Hatchery at Kiganjo, several universities and technical and vocational education centers, and private sector investments in aquaculture infrastructure.

4.2. County governments

The Kenyan Constitution of 2010 fundamentally changed the country's governance system. The constitution established 47 Counties and delegated many functions of the National Government to them. Counties are semi-autonomous administrative units in charge of county legislation, executive duties, and public service delivery. As a result of the current division of responsibilities between the National Government and the Counties, they play an important role in the growth of the agriculture industry and the provision of related services. Furthermore, counties have positioned themselves as focal points for accelerating socioeconomic development across the country, with most of it reliant on the agri-food sector (Coninx and Kilelu, 2020). County governments are responsible for developing industry-supporting regulations and policies, promoting aquaculture product production and marketing, and allocating resources such as land and water to the sector (Odende et al., 2022). They are also in charge of providing infrastructure and services such as roads, energy, and market access to help the country's aquaculture industry grow. County governments are also responsible for promoting research and development, developing expertise, and providing financial and technical assistance to the aquaculture sector. County governments mobilize farmers, provide extension services, build market connections, build access roads, promote fish consumption, and promote fish quality sanitary standards and programs (Muwonge et al., 2022).

Several counties have invested in aquaculture development programs and initiatives through various projects. For instance, Busia County, through the directorate of fisheries, has put a lot of efforts and resources in promoting aquaculture as a business both in the lake through open water cage culture systems and aquaculture parks on land systems to meet the growing population and demand for fish as a food and protein source (Odende et al., 2022). The county has introduced cage fish farming in Bunyala and Samia sub counties in Lake Victoria waters to increase fish production and so far over 100 cages have been installed in the Lake Victoria waters of Busia County. Additionally, the land-based aqua park has been constructed in Kamarinyang' in Teso South Sub-county (100 fish ponds), ATC Aquapark in Matayos Sub-county (20 fish ponds), Bukani, Samia Sub-county (100 fish ponds), and Siunga in Butula Sub-county (70 fish ponds).[1] With the creation of these aqua parks by the County Government of Busia, fish production is estimated to increase from the current 1,080 MT valued at KES 200 million annually to at least 4,300 MT valued at KES. 1 billion by 2027 (see Footnote 1). This will also lead to increase in *per capita* fish consumption, improved income and trade in the county and reduced fishing pressure on the lake. In Kakamega County, a fish farming subsidy program for fish feeds and fingerlings has been launched to economically empower fish farmers and increase production of fish.

The County Government of Nyeri has actively extended support to fish farmers through various channels- providing fingerlings, feeds, dam liners and training. Nyeri County Government has facilitated the restocking of 266,000 fingerlings and supplied 16,825 Kg of feed to 3,000 farmers to enhance their operations. Further, these farmers have been equipped with 287 pond liners, which serve as essential equipment for their fish farming activities (CoG, 2023). Kisii County Government has embarked on an ambitious fish farming project to boost food security and improve earnings to farmers. Through the fisheries department, Kisii county government targets to construct 288 fish ponds in a project set to cost KES. 57 million (KCG, 2022). The objective of the initiative is to commercialize fish farming while improving food security. Kirinyaga County Government has supported 20 selected self-help groups with fishpond liners, fingerlings and feeds to enable them undertake fish farming through the Wezesha Kirinyaga Economic program that has been supporting farmers to diversify on their agricultural activities in order to increase their revenue streams (CGK, 2023). The project was informed by the huge deficit of fish which makes Kenya import fish since lake fishing cannot sustain the demand. All these comprehensive interventions in the above few highlighted county governments are carefully designed to empower fish farmers, enabling them to significantly improve their productivity and achieve greater success in the aquaculture sector. Devolution of government services has improved the efficiency of service provision to the Kenyan population, leading to several development projects in various parts of the country, especially in rural areas which are dominated by small-scale farming (Shimengah, 2018; Muwonge et al., 2022).

5. Donor supported aquaculture projects

Since the aquaculture industry was established in Kenya prior to independence, it has received significant support from the Government of Kenya (GoK), non-governmental organizations (NGOs), and bilateral and multilateral donor initiatives (Obwanga and Lewo, 2017). In recent years, donor funded support has shifted to commercialization of aquaculture through propagation of catfish and production of tilapia fingerlings as well as to establishment of semi-intensive and intensive culture systems. Although projects supported by bilateral and multilateral organizations have historically been marked by giveaways, subsidies, and other forms of assistance, farmers' over-reliance on free and/or subsidized inputs and services is one of their major challenges. Because of this, farmers have had a difficult time getting long-term autonomy, which has slowed the growth of the sub-sector. Therefore, incorporating donor supported programs into GoK activities has improved the initiatives' and programs' sustainability (Ngugi and Manyala, 2009).

According to Ngugi and Manyala (2009), ten donors contributed USD 13.25 million to Kenya's aquaculture industry between 1970 and 1990. Since 2000, the UK's Department for International Development (DFID), the Swedish International Development Cooperation Agency (SIDA), and other bilateral and multilateral donor organizations have funded aquaculture development projects. Furthermore, in 2010 there were reports of direct investments from Australia (USD 198.4 million), Israel (USD 49.6 million), the United Kingdom (USD 9.2 million), and India (USD 5.4 million) (Rothuis et al., 2011). The increased investments are also due to several non-governmental organizations support for technology transfers for improved fish farming practices. For example, since the 1990s, the USAID-funded Aquaculture CRSP in Kenya has been instrumental in advancing innovative fish production techniques. Donor support for aquaculture in Kenya is expected to promote long-term growth by giving small-scale producers access to financing, building their capacity, and providing technical assistance (Kaminski et al., 2018; ASDSP, 2019).

5.1. Selected donor funded aquaculture initiatives

Previously, three major donor-funded projects in Kenya were implemented, including the Lake Victoria Environmental Management Project (LVEMP), Trilateral Cooperation, and Kenya Market-Led Aquaculture Program (KMAP) programs in specific Kenyan counties. The lessons and results from these projects can be used to build on, expand, and improve future projects so that the benefits can reach a larger number of rural smallholder farmers in a sustainable way.

5.1.1. Lake Victoria Environment Management Program (LVEMP)

LVEMP was implemented to deal with the observed environmental problems experienced in the Lake Victoria basin (LVEMP, 2002). It did this by drawing the attention of East African Community (EAC) partner states and other stakeholders' attention to issues that threaten sustainable development, the use of lake basin resources, and the strengthening of governing institutions (Kolding et al., 2005; Mwanuzi et al., 2005). The goal of the project was to create a thriving society with fair opportunities and rewards in a healthy and sustainable manner. The LVEMP was implemented in two phases. Phase I from March 1997 to December 2005, and Phase II from September 2009 to December 2017. The World Bank (WB) funded Phase I through grants from the Global Environment Facility (GEF) and credits from the International Development Association (IDA). LVEMP II, which succeeded LVEMP I, aimed to reduce widespread poverty and improve people's quality of life by promoting sustainable management of the Lake Victoria Basin's shared natural resources. According to a 2018 World Bank report on aquaculture issues, LVEMP helped create (a) the East African Community's Fisheries and Aquaculture Policy (LVFO, 2018a), (b) the guidelines for setting up and operating cage fish farming in the EAC (LVFO, 2018b), (c) Harmonized Fisheries and Aquaculture Border Inspection Manual (LVFO, 2018c), and (d) Regional fishing

1 https://busiacounty.go.ke/index.php/fisheries

guidelines for species-specific licenses for Lake Victoria (LVFO, 2015). The new fisheries policy frameworks have been adopted at the national level in the three countries, especially in Kenya to facilitate implementation of the Fisheries Management and Development Act No. 35 (2016) (Bwathondi et al., 2014).

5.1.2. Kenya Aquaculture Productivity and Agribusiness Program (KAPAP)

The Kenyan Government in partnership with the World Bank and other partners supported the implementation of the KAPAP project to promote the growth of the country's aquaculture sector. The actual cost was $70.31 million, out of which the beneficiary communities contributed $0.57 million, $65.95 million in IDA credit, and $3.79 million in government funding over a five-year period (2009–2015). KAPAP aimed to "increase agricultural productivity and the incomes of participating smallholder farmers" in the project regions. Under the Competitive Grant System, the project also funded projects in the aquaculture value chain titled "Commercializing aquaculture production through sustainable technologies and market linkages." The goal of the aquaculture project was to establish a thriving and sustainable commercial aquaculture among rural impoverished people to improve livelihood, wealth development, and food safety and security. The overarching goal was to promote acceptable post-harvest handling techniques, increase productivity, and create market and information-sharing channels for Tilapia, Catfish, and *Ningu*. The project made significant progress in several areas, including the production and distribution of improved tilapia and catfish seed in 22 Kenyan counties; the formulation and production of 12 new fish feed diets for different developmental stages of tilapia, catfish, and *Ningu*; the development and adoption of 13 value-added farmed fish products; and the development of a web-based system to connect aquaculture farmers with different stakeholders by developing a web-based system to link aquaculture farmers with markets; capacity building and training of 287 aquaculture trainers and 922 fish farmers countrywide on different aquaculture systems and technologies; development of publications and value use documents; and organizing Eat More Fish campaigns in Kisii and Taita Taveta Counties (World Bank, 2018).

5.1.3. Trilateral Cooperation (TTC)

The TTC was a joint project implemented by Kenya, Germany, and Israel from 2012 to 2016. Its goal was to increase commercial aquaculture capacity through a targeted skills development program in aquaculture value chain technologies in the Lake Victoria region. The TTC pioneered an efficient and low-cost method of educating 8,000 farmers by selecting and outfitting the training facility, educating trainers including instructors, extension officers, and experienced farmers, and requesting farmers to contribute to the cost of education in order to secure their commitment. Students' understanding of aquaculture, aquafeeds, and fingerling production improved as a result of this educational strategy (Ngugi et al., 2013).

5.1.4. Kenya Market Led Aquaculture Program (KMAP)

KMAP was a four-year project (January 2016 to December 2019) funded by the Embassy of the Kingdom of the Netherlands in Kenya at a cost of EUR 4 million to address triple challenges in food production, i.e., food insecurity, nutrition, and income by engaging 1,100 fish farming enterprises in Kenya (Farm Africa, 2019). The program adopted a franchise model to create a commercially viable input and service distribution system comprised of aqua shops owned by local entrepreneurs that provided inputs and technical advice on best management practices in fish farming. Furthermore, the project engaged over 8,000 small-scale fish farmers by supporting household food needs and providing intermittent income from sale of fish surpluses. Building on the momentum created by KMAP, another Dutch funded public-private partnership (PPP) project, FoodTechAfrica combined the strengths of Dutch agrifood companies (primarily SMEs), knowledge institutions, government agencies, and their East African counterparts to improve food security in East Africa by establishing a fully integrated aquaculture supply chain (IDH, 2023). This project's contribution to Kenya's aquaculture sector cannot be overlooked, particularly in terms of transitioning mindset of smallholder farmers from subsistence to commercial aquaculture enterprises in rural communities. Furthermore, fish farmers were encouraged to invest in aquaculture by showcasing successful fish production systems and connecting them with experts to establish and operate these systems (KMAP, 2016).

5.2. Ongoing donor support aquaculture initiatives

5.2.1. EU-EAC project for promoting aquaculture in the Lake Victoria Basin (TRUE-FISH)

The True Fish Farming Story in the Lake Victoria Basin (TRUE-FISH) is a project financed under the 11th European Development Fund for a 5-year period (2019–2024) at a total cost of EUR10.15 million for the benefit of EAC countries, Kenya, Tanzania, and Uganda (LVFO, 2019). The main objective is to foster competitive, gender-equitable, and sustainable commercial aquaculture development in order to promote economic growth and long-term resource management in the Lake Victoria basin (Applestein et al., 2022). The overarching goal of the project is "to contribute to the development of a competitive, gender-equitable, and sustainable commercial aquaculture sector to support the economic development and sustainable management of natural resources in the Lake Victoria Basin." The project focuses on three specific objectives: 1) Improve capability in access to commercial networks at the national and regional levels for aquaculture-related businesses, 2) Build national capacity to use robust genetic screening consequently increase availability of skilled personnel thus addressing two of the most significant limiting factors for aquaculture development, and 3) Improve sustainability by mitigating risks related to the aquatic environment. To minimize the risk of accidental and/or intentional introduction of genetic material that could endanger native species, component 3.3 of the project is intended to deliver improved protection of biodiversity of the aquatic resources of the region (LVFO, 2019).

5.2.2. Kenya Climate Smart Agriculture Project (KCSAP)

The Government of Kenyan (GoK) acquired an International Development Association (IDA) credit facility from the World Bank amounting to US$250 million to finance the Kenya Climate Smart agriculture Project (KCSAP) for a five-year period (2017–2022), though the deadline was extended to 2023 due to the Covid-19 pandemic. The total cost of the project is US$ 279 million with a Government contribution of US$ 29 million. The project activities are implemented within five (5) components, namely (i) upscaling climate-smart agriculture practices, (ii) strengthening climate smart agricultural research and seed systems, (iii) supporting agro-weather, market, climate, and advisory services, (iv) project coordination and management; and contingency emergency services. Within Component 2, KCSAP developed, validated, and adopted context-specific climate smart-aquaculture technologies, innovations, and management practices (CSA-TIMPs) to target beneficiaries under Components 1 and 3 in 24 counties, as well as developed sustainable seed production and distribution systems. The project provided collaborative research grants (CRGs) to support implementation of adaptive and applied research through the Kenya Agriculture and Livestock Research Organization (KALRO)-led National Agricultural Research Systems (NARS) framework. The CRGs funded six (6) applied research projects, four (4) seed systems projects, and six (6) adaptive research projects within the aquaculture value chain to increase food and nutrition security in the counties of Busia, Siaya, Kakamega, Nyandarua, Isiolo, Marsabit, and Lamu. CSA-TIMPs development was followed by the creation of technical training materials and modules on the CSA-TIMPs, as well as subsequent training of community technical departments and service providers for effective CSA-TIMPs delivery. In the aquaculture value chain, the project inventoried 50 CSA-TIMPs and developed Training of Trainor (ToT) manuals and value use documents for training over 500 extension service providers and 2,500 lead and smallholder farmers (Obiero et al., 2021). The CSA-TIMPs were divided into six categories: (a) culture systems, (b) culture species and breeding, (c) fish feeds, nutrition, and feed management practices, (d) fish health management and biosecurity, (e) post-harvest loss reduction, (f) value addition, and (g) fish marketing, trade, and supply channels (Obiero et al., 2021). Furthermore, KCSAP has provided funding for sub-projects throughout the aquaculture value chain with the goal of increasing fish productivity and resistance to the hazards of climate change.

5.2.3. Aquaculture Business Development Program (ABDP)

The Aquaculture Business Development Program (ABDP) is a partnership between the Government of Kenya and the International Fund for Agricultural Development (IFAD), with the overall goal to contribute to the reduction of poverty and increased food security and nutrition in rural communities in Kenya (ABDP, 2021). The ABDP is being implemented for an eight-year period, from 2018 to 2026, with a total budget of US$ 143.3 million, which is approximately KES. 14.9 billion. The Program Development Objective is "to increase the incomes, food security and nutritional status of the wider communities of poor rural households involved in aquaculture in the target Counties." The Program targeted counties with high aquaculture activity, adequate research, processing and marketing infrastructure, and suitable aquatic resources (Obiero et al., 2019c). The Program began in six (6) Counties in the first year and has since expanded to a total of fifteen (15) counties, including Busia, Embu, Homa Bay, Kajiado, Kakamega, Kiambu, Kirinyaga, Kisii, Kisumu, Machakos, Meru, Migori, Nyeri, Siaya and Tharaka Nithi (ABDP, 2021).

The ABDP is comprised of two investment components aimed to strengthen the aquaculture value chains for the benefit of smallholder fish producers, service providers and rural communities. The program targets 35,500 households of aquaculture farmers, including 5,500 youth beneficiaries. According to third joint IFAD/GoK supervision and implementation support mission (ISM), the project has made some progress towards achieving the development objectives, but the implementation pace is slow and achievements in most cases falls short of the targets. The project has realized some progress in achieving its development objective. For instance, "the cumulative fish production from ponds was about 176,586 Kg while 53,957 Kgs were produced from dams that have received some support from the project. This translates to income from fish sales of about KES 64 million (approximately USD 557,000) from fish ponds and KES 19,576,050 (approximately USD 170,000) from dams, respectively" (IFAD, 2022). In general, progress has been experienced in various farm-level activities mainly in provision of pond liners to prevent water loss and predator control nets. Specifically, 9,420 farmers received a pond liner (3,973), or predator kit (5,447) and 6,291 farmers built, upgraded, or rehabilitated their ponds and stocked them with Tilapia, or Catfish fingerlings. The Program has also made significant investments to improve farmers' knowledge and skills in aquaculture through various approaches and interventions through extension support services and aquaculture field schools. Nonetheless, key value chain interventions are hampered by procurement-related issues and inefficient sequencing of project activities (IFAD, 2022).

5.2.4. Kenya Marine Fisheries and Socio-Economic Development (KEMSFED)

The Government of Kenyan in collaboration with the World Bank is implementing KEMFSED project through the State Department for Blue Economy and Fisheries. The project duration is 5 years (2020 to 2025) with a total cost of KES 10 billion. The PDO is being implemented in three complementary components: "(1) strengthen capacity in governance and management of marine fisheries, (2) Coastal community empowerment and livelihoods, and (3) project management. The project targets to support about 36,000 beneficiary households, 217,000 individual beneficiaries across 98 wards in five counties (Kwale, Kilifi, Lamu, Mombasa and Tana River). Currently, the project is fast tracking the developing of a marine hatchery—National Mariculture Training Centre (NAMARET) in Shimoni, which will incorporate a marine hatchery, wet and dry laboratory, training resource centre, administration block, accommodation, and museum. The marine hatchery is intended to provide a consistent supply of high-quality seed of finfish and shellfish for the growth of the industry. To step up mariculture farming, 27 extension officers, 43 fish (finfish and shellfish) and 60 sea-weed farmers were trained in mariculture production, while 6 ponds for three groups in Kilifi County were stocked with prawns and marine tilapia (KEMSFED, 2022).

5.3. Role of national and international research organizations

5.3.1. WorldFish

Since its inception in 1975 at the University of Hawaii as the International Center for Living Aquatic Resources Management (ICLARM), WorldFish initially focused on enhancing productivity of coastal fisheries and aquaculture through institutional and technological interventions in Southeast Asia and the Pacific. WorldFish is playing a significant role in bringing attention to issues revolving around the contribution of small-scale fisheries and aquaculture to food and nutrition security, as a member of the Consultative Group on International Agricultural Research (One CGIAR) and the sole global research center with over 45 years of experience in low- and middle-income countries (WorldFish, 2020; Kura and Kawarazuka, 2021). The original mandate has been expanded to include broader aspects of aquatic food systems and their essential role in sustaining human well-being and livelihoods. WorldFish has a long history of working in Africa, including the establishment of country offices in Egypt, Nigeria, Tanzania, and Zambia, in order to strengthen the continent's aquaculture sector through research and training.

WorldFish in partnership with ICIPE, CORAF, Aller Aqua, Swedish University of Agricultural Sciences and Natural Resource Development College is implementing a new project *Development and Scaling of Sustainable Feeds for Resilient Aquatic Food Systems in Africa (FASA)"* that seeks to develop low-cost, highly nutritious fish feeds based on novel ingredients and enable 5,000 smallholder fish farmers in 3 African countries – Nigeria, Zambia, and Kenya to test and adopt these ingredients and feeds, leading to increased income, improved food security, and reduced waste and pollution. Specifically, FASA expected outcomes in Kenya include: (i) Enhanced capacity of stakeholder groups in Kenya to integrate best practices toward a more sustainable feed sector, and to adopt new knowledge on nutrient requirements of multiple improved strains of tilapia and African catfish, (ii) Established the quality of at least 5 local ingredients for improvement through various processing techniques and the ingredients that are used by stakeholders in Kenya, including local millers and farmers, to produce 9 novel, cost-efficient insect-based feed formulations, to improve aquaculture productivity and resilience, (iii) Develop databases and digital solutions to be used by farmers for formulating and adapting new insect- based local feeds on a "real-time" basis, and (iv) 3,000 farmers directly or indirectly linked to the project access, test, and use novel fish feeds and feed solutions using the knowledge and innovations developed by the project, with the support of a range of strategic scaling partners and other stakeholders.

5.3.2. International Centre of Insect Physiology and Ecology (*icipe*)

The International Centre of Insect Physiology and Ecology (*icipe*) is a Pan-African Center of Excellence in insect and arthropod research. Over the past 50 years, *icipe* has pioneered and applied world class science and innovation to address issues related to food and nutrition security, human and environmental health for the continent's rural and urban communities (Icipe, 2020). The Center conducts state of the art research on the use of insects for food, feed, and other applications, and then applies this knowledge to create creative, cost-effective, accessible, and simple solutions to address food insecurity and malnutrition while promoting mitigation action to lower greenhouse gas emissions (Kelemu et al., 2015). These initiatives have been aided by a vast collaboration network, extensive capacity- and awareness-building, the adoption of national rules and standards, and fostering of marketing alliances for insect goods, particularly those derived from black soldier flies, in Kenya and East Africa. Since insect-based businesses can be operated with minimal labor inputs, they are ideal for women, young people, and low-income households, who frequently constrained by inadequate access to agricultural resources. In response to these research opportunities and needs, ICIPE established the Insects for Food, Feed and Other Uses Program (INSEFF) to translate the latent benefits of insects in transforming the food system into sustainable and viable circular economy (Tanga et al., 2021). To this end, several medium- to large-scale black soldier fly (BSF) farms have been established (Tanga et al., 2021). Furthermore, ICIPE collaborates with its partners to promote insect-based farming enterprises. Some of the projects include:

- *SiPFeed*: Testing Business Models for Scaling Insect-Based Protein Feed for Use in Poultry Farming and Aquaculture in Kenya, funded by Rockefeller Foundation; whose objective is "to implement and promote the use of insect-based protein as feed additives in poultry and aquaculture among smallholder farmers, small- and medium-scale enterprises (SMEs) and other actors along the value chain."
- *INSFEED*: Insect feed for poultry, fish and pig production in sub-Saharan Africa – Phase 1&2 funded by International Development Research Centre, Canada (IDRC) and Australia Centre for International Agricultural Research (ACIAR).
- *PROTeinAfrica*: Upscaling the benefits of insect animal feed technologies for sustainable agriculture intensification in Africa funded by the ACIAR.
- *ILIPA*: Improving livelihood by increasing livestock production in Africa: An agribusiness model to commercially produce high quality insect-based protein ingredients for chicken, fish and pig industries.
- *INSFeedFish*: Upscaling insect-based protein-rich feeds for enhanced nutrition and health of fish in Kenya, funded by KCSAP. The specific objectives were to: (i) evaluate the viability of insect-based fish feeds, (ii) validate mass production, harvesting, and primary processing of protein from black soldier fly larvae, (iii) validate ration formulations for nutrient-rich insect-based feeds for fish production, and (iv) validate production protocols for safe insect-based fish feeds/diets in accordance with established standards in Busia, Siaya, and Kakamega.

6. Conclusions and priorities for action

The aquaculture sector in Kenya is gaining momentum due to rapid population and economic growth, increased awareness of the health benefits of eating fish, and changes in lifestyles and preferences brought about by rapid urbanization and globalization, among other factors. We successfully assessed the roles of multilateral development organizations, the public and private sectors in aquaculture development in Kenya. The study findings depict the significance of synergistic interventions from development organizations, the public and private sectors for the expansion of aquaculture output to meet the rising food demand in the country. The actors complement each other through the combined use of resources towards achieving the goal of aquaculture development for improved food and nutrition security. By letting the various actors focus on what they are good at, the quality of the service is strengthened. Government acts as the regulator and focuses on planning services and monitoring performance. Both the national and county governments play critical roles with respect to the formulation of pro-aquaculture policies and creation of favorable financial environment for the potential investors in the sector. The public and private sectors complement the efforts of international donors and development agencies by investing more resources to policy research, aquaculture research and educational initiatives in the sector. In addition, international donors and development agencies' role should not be limited to technology transfer, and capacity building, but they should collaborate with the national and county governments in developing innovative financial models that favor sustainable aquaculture enterprises.

To unlock Kenya's aquaculture potential and improve its food and nutrition status, deliberate efforts must be taken to create a conducive environment for public and private investment in the industry. First, there is a need to coordinate and clearly articulate the roles and responsibilities among devolved and national governments, donors, and financial institutions through public-private partnerships to ensure optimal allocation of financial, human, and infrastructure resources. Second, more collaborative research should be devoted to design and construction of climate smart culture systems, developing new species to guarantee supply of high-quality products; develop and scale low cost and highly nutritious fish feeds based on novel ingredients; and to enhance resilient livelihoods through innovative aquaculture practices and market linkages to create employment opportunities for youths and women. More importantly, research, training, extension, and advisory services should be strengthened to improve capability and preparedness for emergencies such as the recent fish kills in cages in Lake Victoria. Third, national and devolved governments should create an enabling policy environment through tax incentives and regulatory reforms to combat climate change, protect nature and biodiversity, sustain livelihoods, and mainstream food and nutrition initiatives into design of international financial institution supported projects. The county government can also build links between the private and public sectors through the County Integrated Development Plans (CIDPs) and allocate budgets to promote aquaculture development as a devolved function. Finally, private sector investment is critical for sustained aquaculture growth through creating innovative and inclusive financing mechanisms to increase access to financial services, such as micro credit to fund small aqua businesses. Hence, donors and funding agencies should focus on developing gender-inclusive and pro-youth interventions to increase employment opportunities and deliver value for money along the value chain nodes.

7. Limitations of the study

There were limitations in our research approach. First, regarding rigor and quality, the literature in our review covered an extensive spectrum. This, in our opinion, is a limitation of the review approach and is noted as such since scoping reviews do not evaluate the rigor or quality of studies (Hanneke et al., 2017). Second, when seeking to define the scope of the study, the incorporation of gray literature posed challenges. The challenge in defining the study scope was also a result of the heterogeneity in terminology and the ambiguous definitions of key terms. Although the scoping review process appears to be linear, following the five steps, Arksey and O'Malley (2005) state that the steps are "not linear but iterative." This view was supported by the iterative and sometimes repetitive nature of our scoping approach. The research questions, search technique, and selection criteria had to be defined and redefined in an iterative manner leading to increase in time and resources needed. Owing to the wide scope and unclear boundaries, we had a lot of data which presented challenges for feasibility as the process was tedious and took longer than expected. Third, in as much as we reduced reporting bias by engaging at least two reviewers in reviewing the full full-text and abstract of each article, the process still had a risk of bias of included literature.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JMM, KOb, JI, CT, and RY put together the manuscript with contributions from all co-authors. All authors involved the literature review and conceptualization of the manuscript and read and approved to the published version.

Funding

This work was supported by the Kenya Climate-Smart Agriculture Project (KCSAP) Collaborative Adaptive Projects (Grant No. GA02-4/3, Grant No. GA02-4/4 & Grant No. GA02-4/5), Australian Centre for International Agricultural Research (ACIAR) (ProteinAfrica – Grant No: LS/2020/154), IKEA Foundation (G-2204-02144), Novo Nordic Foundation (RefIPro: NNF22SA0078466), the Rockefeller Foundation (WAVE-IN—Grant No: 2021 FOD 030); Bill & Melinda Gates Foundation (INV-032416); Horizon Europe (NESTLER - Project: 101060762 - HORIZON-CL6-2021-FARM2FORK-01), the Norwegian Agency for Development Cooperation (NORAD) (Grant No: SAFA-21/0004.), the Curt Bergfors Foundation Food Planet Prize Award; Norwegian Agency for Development Cooperation, the Section for research, innovation, and higher education [Grant number RAF–3058 KEN–18/0005 (CAP–Africa)]; the Swedish International Development Cooperation Agency (Sida); the Swiss Agency for Development and Cooperation (SDC); the Federal Democratic Republic of Ethiopia and the Government of the Republic of Kenya. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. The views expressed herein do not necessarily reflect the official opinion of the donors.

Acknowledgments

The authors appreciate the financial assistance from Kenya Climate-Smart Agriculture Project (KCSAP), Australian Centre for International Agricultural Research (ACIAR), IKEA Foundation, Novo Nordic Foundation, the Rockefeller Foundation, Bill & Melinda Gates Foundation, Horizon Europe, the Norwegian Agency for

Development Cooperation (NORAD), the Curt Bergfors Foundation Food Planet Prize Award, the Swedish International Development Cooperation Agency (Sida); the Swiss Agency for Development and Cooperation (SDC), Norwegian Agency for Development Cooperation, the Section for research, innovation, and higher education, the Federal Democratic Republic of Ethiopia and the Government of the Republic of Kenya.

Conflict of interest

RY was employed by WorldFish.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

ABDP (2021). *Aquaculture Blue Pages - an Assessment of the Aquaculture Value Chain Players in ABDP Implementing Counties*. Kisumu: Aquaculture Business Development Programme.

Adeleke, B., Robertson-Andersson, D., Moodley, G., and Taylor, S. (2020). Aquaculture in Africa: a comparative review of Egypt, Nigeria, and Uganda Vis-a-Vis South Africa. *Rev. Fish. Sci. Aquac.* 29, 167–197. doi: 10.1080/23308249.2020.1795615

Applestein, C., Caughlin, T., and Germino, M. J. (2022). *Sectoral Training Needs Assessment for Aquaculture Business Operators and Employees at the Lake Victoria Basin (Kenya, Tanzania and Uganda)*. Lattice Aquaculture Trust *1*, 1–73. Nairobi

Arksey, H., and O'Malley, L. (2005). Scoping studies: towards a methodological framework. *Int. J. Soc. Res. Methodol.* 8, 19–32. doi: 10.1080/1364557032000119616

ASDSP (2019). *Agricultural Sector Development Support Programme (ASDSPII) 2019–2022*. Nairobi: ASDSP.

Aura, C. M., Musa, S., Yongo, E., Okechi, J. K., Njiru, J. M., Ogari, Z., et al. (2018). Integration of mapping and socio-economic status of cage culture: towards balancing lake-use and culture fisheries in Lake Victoria. Kenya. *Aquac. Res.* 49, 532–545. doi: 10.1111/are.13484

Aura, C. M., Mwarabu, R. L., Nyamweya, C. S., Owiti, H., Ongore, C. O., Guya, F., et al. (2022). Exploring the potential of small water bodies as an integrative management tool for fisheries production. *Fish. Manag. Ecol.* 29, 254–268. doi: 10.1111/fme.12529

Aura, M. C., Nyamweya, C. S., Owiti, H., Odoli, C., Musa, S., Njiru, J. M., et al. (2021). Citizen science for bio-indication: development of a community-based index of ecosystem integrity for assessing the status of Afrotropical riverine ecosystems. *Front. Water* 2:609215. doi: 10.3389/frwa.2020.609215

Bennett, A., Basurto, X., Virdin, J., Lin, X., Betances, S. J., Smith, M. D., et al. (2021). Recognize fish as food in policy discourse and development funding. *Ambio* 50, 981–989. doi: 10.1007/s13280-020-01451-4

Brummett, R. E., Lazard, J., and Moehl, J. (2008). African aquaculture: realizing the potential. *Food Policy* 33, 371–385. doi: 10.1016/j.foodpol.2008.01.005

Bush, S. R., and Oosterveer, P. (2019). *Governing Sustainable Seafood*. New York: Taylor & Francis Group.

Bwathondi, P. O. J., Ogutu Ohwayo, R., and Ogaari, J. (2014). Lake Victoria fisheries management plan. Lake Victoria Fisheries Organization (LVFO). Technical Document, 79. Available at: http://www.lvfo.org/index.php/lvfo/lvfo-secretariat/23-the-implementation-of-a-fisheries-management-plan-ifmp

CGK. (2023). Boost for farmers as county Govt gives them fishpond liners, fingerlings and feeds. County government of Kirinyaga. Available at: https://kirinyaga.go.ke/boost-for-farmers-as-county-govt-gives-them-fishpond-liners-fingerlings-and-feeds/

Chan, C. Y., Tran, N., Cheong, K. C., Sulser, T. B., Cohen, P. J., Wiebe, K., et al. (2021). The future of fish in Africa: employment and investment opportunities. *PLoS One* 16:e0261615. doi: 10.1371/journal.pone.0261615

Chan, C. Y., Tran, N., Pethiyagoda, S., Crissman, C. C., Sulser, T. B., and Phillips, M. J. (2019). Prospects and challenges of fish for food security in Africa. *Glob. Food Sec.* 20, 17–25. doi: 10.1016/j.gfs.2018.12.002

Charo-Karisa, H., and Gichuri, M. (2010). *Overview of the Fish Farming Enterprise Productivity Program. End of year report. Fish Farming Enterprise Productivity Program Phase I, Aquaculture Development Working Group*. Kenya: Ministry of Fisheries Development.

Cheserek, M. J., Obiero, K. O., Menach, E., and Ogello, E. O. (2022). Fish and fish products consumption behaviours and attitudes of farmers in Western Kenya. *African J. Food, Agric. Nutr. Dev.* 22, 21503–21527. doi: 10.18697/ajfand.114.21550

CoG. (2023). Harnessing the potential of blue economy: Nyeri County supports sustainable fish farming in Kieni east sub-county. Council of Governors. Maarifa Centre. 7. Available at: https://maarifa.cog.go.ke/county-initiatives/harnessing-potential-blue-economy-nyeri-county-supports-sustainable-fish-farming

CoK (2010). *The constitution of the Republic of Kenya, 2010. Republic of Kenya, KEN-2010-C-8478*. Rome: Food and Agriculture Organization.

Coninx, I., and Kilelu, C., (2020). Counties as hubs for stimulating investment in agrifood sectors in Kenya; a review of aquaculture, dairy and horticulture sectors in selected counties. Wageningen environmental research, report 3008.

FAO (2018). *The State of World Fisheries and Aquaculture 2018-Meeting the Sustainable Development Goals*. Rome: FAO.

FAO (2022). *The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation*. Rome: FAO, 1–11.

FAO, IFAD, UNICEF, WFP and WHO (2022). *The State of Food Security and Nutrition in the World 2022. Repurposing Food and Agricultural Policies to make Healthy Diets more Affordable*. Rome: FAO.

Farm Africa (2019). Kenya market-led aquaculture Programme (KMAP). A 2019 guide to profitable fish farming. 6(1), 1–18. Available at: https://www.farmafrica.org/downloads/2019/kenya-market-led-aquaculture-programme-business-cases-compressed.pdf

Fonda, J. A., Opiyo, M. A., Obiero, K. O., Munguti, J. M., Abwao, J., Nyonge, B. M., et al. (2021). Aquaculture extension service in Kenya: farmers and extension officers' perspectives. *J. Agric. Ext. Rural Dev.* 13, 14–22. doi: 10.5897/JAERD2020.1203

GoK (1982). *Fisheries Department Statistical Bulletin: 1982*. Nairobi: Ministry of Tourism and Wildlife.

GoK (2015). *Fish Quality Assurance Guidelines for Fish Business Operators in Kenya*. Nairobi: Government of Kenya. State Department of Fisheries.

GoK (2022). *Fisheries Annual Statistical Bulletin 2021. Kenya Fisheries Service*. Nairobi: State Department for Fisheries and the Blue Economy.

Golden, C. D., Seto, K. L., Dey, M. M., Chen, O. L., Gephart, J. A., Myers, S. S., et al. (2017). Does aquaculture support the needs of nutritionally vulnerable nations? *Front. Mar. Sci.* 4:159. doi: 10.3389/fmars.2017.00159

Hanneke, R., Asada, Y., Lieberman, L. D., Neubauer, L. C., and Fagan, M. C. (2017). The scoping review method: mapping the literature in "structural change" public health interventions. doi: 10.4135/9781473999008

Henriksson, P. J. G., Belton, B., Jahan, K. M., and Rico, A. (2018). Measuring the potential for sustainable intensification of aquaculture in Bangladesh using life cycle assessment. *Proc. Natl. Acad. Sci.* 115, 2958–2963. doi: 10.1073/pnas.1716530115

Icipe (2020). Vision and strategy 2021–2025. Nairobi, Kenya. Available at: http://www.icipe.org/system/files_force/about/corporate_publications_files/icipe_Vision_and_Strategy_2021-2025.pdf

IDH. (2023). An ecosystem approach for tilapia value chain development in Kenya: service delivery model analysis. Available at: https://www.idhsustainabletrade.com/publication/sdm-case-study-lattice-kenya/

IFAD (2022). *Kenya: Aquaculture Business Development Programme Supervision Report. Project no. 2000001132 and Report no. 6182-KE*. Rome: International Fund for Agricultural Development.

Kagai, J. K. (1975). *National Plan for Development of Aquaculture in Kenya. FAO Aquaculture Planning in Africa, ADCP/REP/75/1*. Rome: FAO, 61–65.

Kaminski, A. M., Genschick, S., Kefi, A. S., and Kruijssen, F. (2018). Commercialization and upgrading in the aquaculture value chain in Zambia. *Aquaculture* 493, 355–364. doi: 10.1016/j.aquaculture.2017.12.010

KCG. (2022). Kisii County government embarks on fish farming project. Kisii County government. Available at: https://www.kisii.go.ke/index.php/item/1781-kisii-county-government-embarks-on-fish-farming-project

Kelemu, S., Niassy, S., Torto, B., Fiaboe, K., Affognon, H., Tonnang, H., et al. (2015). African edible insects for food and feed: inventory, diversity, commonalities and contribution to food security. *J. Insects Food Feed* 1, 103–119. doi: 10.3920/JIFF2014.0016

KEMSFED (2022). *Kenya marine fisheries and socio economic development (KEMFSED) project.Annual Progress Report 2021-2022*. Nairobi: National Project Coordination Unit.

KMAP (2016). *Report on Market Study of the Aquaculture Market in Kenya. In Kenya Market-Led Aquaculture Programme (KMAP)*. Nairobi: KMAP.

KMFRI. (2017). Kenya's aquaculture brief 2017: status, trends, challenges and future outlook. African Journal of Food, Agriculture, Nutrition and Development. Available at: https://www.kmfri.co.ke/images/pdf/Kenya_Aquaculture_Brief_2017.pdf

KNBS. (2022). Economic survey report 2022. Kenya National Bureau of Statistics. Available at: https://www.knbs.or.ke/wp-content/uploads/2022/05/2022-Economic-Survey1.pdf

KNBS. (2023). Economic survey report 2023. Kenya National Bureau of Statistics. Available at: https://www.knbs.or.ke/download/economic-survey-2023/

Kobayashi, M., Msangi, S., Batka, M., Vannuccini, S., Dey, M. M., and Anderson, J. L. (2015). Fish to 2030: the role and opportunity for aquaculture. *Aquac. Econ. Manag.* 19, 282–300. doi: 10.1080/13657305.2015.994240

Kolding, J., van Zwieten, P., Manyala, J., Okedi, J., Mgaya, Y. D., and Orach-Mesa, F. (2005). *Regional synthesis report on fisheries research and management: Status, trends and processes. Final report, Maun, Wageningen, Dar Es Salaam, December 2005*.

Kumar, G., and Engle, C. R. (2016). Technological advances that led to growth of shrimp, salmon, and tilapia farming. *Rev. Fish. Sci. Aquac.* 24, 136–152. doi: 10.1080/23308249.2015.1112357

Kura, Y., and Kawarazuka, N. (2021). Fish in sustainable food systems of the 21st century: role of WorldFish research on food and nutrition security, gender equity, and natural resource conservation. *Jpn. Agric. Res. Q.* 55, 553–558. doi: 10.6090/jarq.55.553

Le Gouvello, R., Brugere, C., and Simard, F. (2022). Aquaculture and nature-based solutions. Identifying synergies citation: Between sustainable development of coastal communities, aquaculture, and marine and coastal conservation. Gland, Switzerland: IUCN. Available at: https://portals.iucn.org/library/efiles/documents/2022-005-En.pdf

Levac, D., Colquhoun, H., and O'Brien, K. K. (2010). Scoping studies: advancing the methodology. *Implement. Sci.* 5, 1–9. doi: 10.1186/1748-5908-5-69

LVEMP. (2002). A report on the implementation status of Lake Victoria environmental management project in Kenya, Tanzania and Uganda from and way forward. Regional Secretariat, Lake Victoria Environmental Management Project. (Issue August), 1–35. Available at: http://repository.eac.int/bitstream/handle/11671/722

LVFO (2015). *Fisheries Management Plan III (FMP III) for Lake Victoria Fisheries 2016–2020*. Jinja, Uganda: Lake Victoria Fisheries Organization.

LVFO (2018a). *Fisheries and Aquaculture Policy for the East African Community*. Jinja, Uganda: Lake Victoria Fisheries Organization.

LVFO (2018b). *Guidelines for Establishment and Operation of Cage Fish Farming in the East African Community*. Jinja, Uganda: Lake Victoria Fisheries Organization.

LVFO (2018c). *Harmonized Fisheries and Aquaculture Border Inspection Manual for East African Community*. Jinja, Uganda: Lake Victoria Fisheries Organization.

LVFO. (2019). EU-EAC True Fish Farming Story in Lake Victoria Basin (TRUEFISH). Lake Victoria Fisheries Organization. Available at: https://lvfo.org/content/eu-eac-true-fish-farming-story-lake-victoria-basin-truefish

MoFD. (2010). National Aquaculture Strategy and development plan, November 2. Ministry of Fisheries Development. Available at: http://www.kilimo.go.ke/fisheries/wp-content/uploads/2015/05/National-Aquaculture-Strategy-Plan.pdf

Munguti, J. M., Kim, J. D., and Ogello, E. O. (2014). An overview of Kenyan aquaculture: current status, challenges, and opportunities for future development. *Fish. Aquatic. Sci.* 17, 1–11. doi: 10.5657/FAS.2014.0001

Munguti, J. M., Kirimi, J. G., Kariuki, C. M., Mbaabu, P., Liti, D., Obiero, K. O., et al. (2022b). Role of aquaculture in climate-smart food production systems–a review. *East Afr. Agric. For. J* 85, 176–186. Available at: http://repository.tharaka.ac.ke/xmlui/handle/1/3448

Munguti, J. M., Nairuti, R., Iteba, J. O., Obiero, K. O., Kyule, D., Opiyo, M. A., et al. (2022a). Nile tilapia (*Oreochromis niloticus* Linnaeus, 1758) culture in Kenya: emerging production technologies and socio-economic impacts on local livelihoods. *Aquaculture Fish Fish.* 2, 265–276. doi: 10.1002/aff2.58

Munguti, J., Obiero, K., Orina, P., Mirera, D., Kyule, D., Mwaluma, J., et al. (2021). *State of Aquaculture Report 2021: Towards Nutrition Sensitive Fish Food Production Systems*. Nairobi: Techplus Media House.

Musa, S., Aura, C., Owiti, G., and Nyonje, B. (2012). Fish farming enterprise productivity program (FFEPP) as an impetus to *Oreochromis niloticus* (L.) farming in Western Kenya: lessons to learn. *Afr. J. Agric. Res.* 7, 1324–1330. doi: 10.5897/AJAR11.1606

Musyoka, S. N., and Mutia, G. M. (2016). The status of fish farming development in arid and semi-arid counties of Kenya: case study of Makueni County. European Journal of physical and agricultural sciences. Kenya: South Eastern Kenya University.

Muwonge, A., Williamson, T. S., Owuor, C., and Kinuthia, M. (2022). *Making Devolution Work for Service Delivery in Kenya*. Washington, DC: World Bank Publications.

Mwanuzi, F., Abuodha, J., Muyodi, F., and Hecky, R. (2005). *Lake Victoria regional water quality synthesis report (LVEMP)*. Kampala, Uganda: Lake Victoria Environmental Management Programme Secretariat.

Ngoc, P. T. A., Meuwissen, M. P. M., Le, T. C., Bosma, R. H., Verreth, J., and Lansink, A. O. (2016). Adoption of recirculating aquaculture systems in large pangasius farms: a choice experiment. *Aquaculture* 460, 90–97. doi: 10.1016/j.aquaculture.2016.03.055

Ngugi, C. C., and Manyala, J. O. (2009). *Assessment of National Aquaculture Policies and Programmes in KENYA*. Eldoret: SARNISSA.

Ngugi, C., Domenica, L. D., Meijberg, A., Manyala, J., and Bejerano, I. (2013). *Development of Nile Tilapia (Oreochromis niloticus) value chain under governments of Kenya, Germany and Israel trilateral arrangement for increased aquaculture production and conservation of dwindling stocks of Lake Victoria, Kenya. Paper presented during the 10th International Symposium on Tilapia in Aquaculture – ISTA10 from 6-10 October 2013, Jerusalem, Israel.*

Njiru, J. M., Aura, C. M., and Okechi, J. K. (2019). Cage fish culture in Lake Victoria: a boon or a disaster in waiting? *Fish. Manag. Ecol.* 26, 426–434. doi: 10.1111/fme.12283

Nyandat, B., and Owiti, G. O. (2013). *Aquaculture needs assessment mission report. Report/rapport: SF-FAO/2013/24*. Ebene, Mauritius: FAO-SmartFish Programme of the Indian Ocean Commission.

Nyonje, B., Nangulu, A., Van Stappen, G., Obiero, K., Opiyo, M. A., Awuor, J. F., et al. (2021). *Policy Framework for Aquaculture Education in Kenya*. Kenya: KMFRI.

Obiero, K., Cai, J., Abila, R., and Ajayi, O. (2019b). Kenya: High aquaculture growth needed to improve food security and nutrition, Rome, Italy. Available at: http://www.fao.org/3/ca4693en/ca4693en.pdf

Obiero, K., Meulenbroek, P., Drexler, S., Dagne, A., Akoll, P., Odong, R., et al. (2019a). The contribution of fish to food and nutrition security in eastern Africa: emerging trends and future outlooks. *Sustainability* 11:1636. doi: 10.3390/su11061636

Obiero, K., Munguti, J., Liti, D., Ani, J., Njiru, J., Wamuongo, J., et al. (2021). *Inventory of Climate Smart Technologies, Innovations and Management Practices (TIMPs) for Aquaculture Value Chain*. Nairobi: Kenya Agricultural and Livestock Research Organization.

Obiero, K. O., Achieng, A. O., Nyamweya, C. S., Onyango, H. O., Opaa, B., Ajode, Z. M., et al. (2022). Societal implications of Kenya's inland and marine waters *Encyclopedia of Inland Waters* (T. Mehner & (S. E. Tockner 450–463). Elsevier. Amsterdam

Obiero, K. O., Waidbacher, H., Nyawanda, B. O., Munguti, J. M., Manyala, J. O., and Kaunda-Arara, B. (2019c). Predicting uptake of aquaculture technologies among smallholder fish farmers in Kenya. *Aquac. Int.* 27, 1689–1707. doi: 10.1007/s10499-019-00423-0

Obwanga, B., and Lewo, M. R. (2017). *From Aid to Sustainable Trade: Driving Competitive Aquaculture Sector Development in Kenya; Quick Scan of Robustness, Reliability and Resilience of the Aquaculture Sector*. Wageningen: Wageningen University and Research.

Obwanga, B., Soma, K., Ayuya, O. I., Rurangwa, E., van Wonderen, D., Beekman, G., et al. (2020). *Exploring Enabling Factors for Commercializing the Aquaculture Sector in Kenya; 3R Research Report/Centre for Development Innovation 3R Research Report 011*. Wageningen: Wageningen Centre for Development Innovation.

Odende, T., Ogello, E. O., Iteba, J. O., Owori, H., Outa, N., Obiero, K. O., et al. (2022). Promoting sustainable smallholder aquaculture productivity through landscape and seascape aquapark models: a case study of Busia County, Kenya. *Front. Sustain. Food Syst.* 6, 1–16. doi: 10.3389/fsufs.2022.898044

Ogello, E. O., and Munguti, J. M. (2016). Aquaculture: a promising solution for food insecurity, poverty and malnutrition in Kenya. *Afr. J. Food Agric. Nutr. Dev.* 16, 11331–11350. doi: 10.18697/ajfand.76.15900

Okemwa, E., and Getabu, A. (1996). Fish farming in Kenya with particular reference to the Lake Victoria basin. Paper read by the authors at the seminar on the management of integrated freshwater agro-piscicultural ecosystems in tropical areas (Brussels, 16-19 may 1994) organized by the Royal Academy of overseas sciences (Brussels), the technical Centre for Agricultural and Rural co-Operation and the food and agriculture Organization of the United Nations.

Ole-Moiyoi, L. K. (2017). *Fishing for Answers: Can Aquaculture Transform Food Security in Rural Kenya*. Doctoral dissertation. Stanford, CA: Stanford University.

Opiyo, M. A., Marijani, E., Muendo, P., Odede, R., Leschen, W., and Charo-Karisa, H. (2018). A review of aquaculture production and health management practices of farmed fish in Kenya. *Int. J. Vet. Sci. Med.* 6, 141–148. doi: 10.1016/j.ijvsm.2018.07.001

Orina, S., Ogello, E. O., Kembenya, E. M., and Muthoni, C. (2018). *State of Cage Culture in Lake Victoria, Kenya*. Mombasa: Kenya Marine and Fisheries Research Institute.

Oyinlola, M. A., Reygondeau, G., Wabnitz, C. C., Troell, M., and Cheung, W. W. (2018). Global estimation of areas with suitable environmental conditions for mariculture species. *PLoS One* 13:e0191086. doi: 10.1371/journal.pone.0191086

Peters, M. D., Godfrey, C. M., Khalil, H., McInerney, P., Parker, D., and Soares, C. B. (2015). Guidance for conducting systematic scoping reviews. *JBI Evid. Implementation*, 13, 141–146.

Rothuis, A. J., van Duijn, A. P., van Rijsingen, J. C. M., van der Pijl, W., and Rurangwa, E. (2011). *Business Opportunities for Aquaculture in Kenya, with Special Reference to Food Security. LEI Report 2011-067/IMARES Report C131/11*. Wageningen: Wageningen UR.

Satia, B. P. (2017). *Regional Review on Status and Trends in Aquaculture Development in Sub-Saharan Africa–2015, FAO Fisheries and Aquaculture Circular no. 1135/4*. Rome, Italy: FAO.

Schubert, A., Nyingi, W., Tuda, P., Aura, C. M., Obiero, K., Manyala, J., et al. (2021). Reconstructing Kenya's total freshwater fisheries catches: 1950–2017. *Mar. Freshw. Res.* 73, 57–70. doi: 10.1071/MF21189

Shimengah, M. M. (2018). Influence of strategic leadership practices on service delivery within county governments in Kenya: a literature review. *Strateg. Manag. J.* 3, 1–13. doi: 10.47672/jsm.326

Tanga, C. M., Egonyu, J. P., Beesigamukama, D., Niassy, S., Emily, K., Magara, H. J., et al. (2021). Edible insect farming as an emerging and profitable enterprise in East Africa. *Curr. Opin. Insect Sci.* 48, 64–71. doi: 10.1016/j.cois.2021.09.007

Tracy, D., Gouse, M., Kirimi, L., Meyer, F., Thurlow, J., and Odhiambo, N. (2021). *Prioritising Policies for Inclusive Agricultural Transformation in Kenya – Aquaculture Value Chain Deep Dive Report*. Pretoria, South Africa: Bureau for Food and Agricultural Policy.

Tran, N., Chu, L., Chan, C. Y., Genschick, S., Phillips, M. J., and Kefi, A. S. (2019). Fish supply and demand for food security in Sub-Saharan Africa: An analysis of the Zambian fish sector. *Marine Policy*, 99, 343–350. doi: 10.1016/j.marpol.2018.11.009

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., and Levac, D., et al. (2018). PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. *Ann. Intern. Med.* 169, 467–473. doi: 10.7326/M18-0850

United Nations (2015). Transforming our world: The 2030 agenda for sustainable development. Seventieth session. Available at: https://www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E

van Someren, V. D. (1960). The inland fishery research station, Sagana, Kenya. *Nature* 186, 425–426. doi: 10.1038/186425a0

Verdegem, M., Dalsgaard, A. J. T., Buschmann, A. H., Lovatelli, A., and Latt, U. W. (2023). The contribution of aquaculture systems to global aquaculture production. *J. World Aquac. Soc.* 54, 206–250. doi: 10.1111/jwas.12963

World Bank (2007). *Changing the face of the waters: The promise and challenge of sustainable aquaculture. Agriculture and rural development*. Washington, DC: World Bank.

World Bank (2018). *Kenya-agricultural productivity program (KAPP I AND II). Independent Evaluation Group, Project Performance Assessment Report 133838.* Washington, DC: World Bank, 131.

WorldFish. (2020). 2020 annual report – building forward better with aquatic foods. Available at: https://worldfishcenter.org/annual-report2020/

Zonneveld, N. (1983). *Study of the Pre-Conditions of Commercial Fish Farming in the Lake Victoria Basin*. Kisumu, Kenya: Lake Basin Development Authority (LBDA) Report.

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 15 September 2023
DOI 10.3389/fsufs.2023.1249898

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OPEN ACCESS

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RECEIVED 29 June 2023
ACCEPTED 04 September 2023
PUBLISHED 15 September 2023

CITATION
Zornu J, Tavornpanich S, Brun E, van Zwieten PAM, van de Leemput I, Appenteng P, Anchirinah J and Cudjoe KS (2023) Understanding tilapia mortalities and fish health management in Lake Volta: a systematic approach.
Front. Sustain. Food Syst. 7:1249898.
doi: 10.3389/fsufs.2023.1249898

Understanding tilapia mortalities and fish health management in Lake Volta: a systematic approach

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Unusual fish mortalities in aquaculture threaten global food security and carry significant socio-economic burdens. In 2018, Nile tilapia (*Oreochromis niloticus*) suffered unusual patterns of mortalities, attributed to disease-causing agents in Lake Volta cage aquaculture. In recent times, disease investigations have shifted from single to consideration of multiple factors to understand the puzzling range of causal risk factors. This study therefore aimed at expanding on tilapia mortality risk factors, while documenting fish health and Lake Volta management practices for sustainable aquaculture. We interviewed relevant aquaculture stakeholders operating on Lake Volta and conducted thematic analysis on their responses to map out mortality risk factors and management practices. The identified risk factors were conceptualized in established models of causation web and Social-Ecological System to explain the practical significance of the findings. The results showed that the risk factors of tilapia mortalities are a combination of pathogens and non-infectious factors mediated by weak law enforcement. The results further suggested mortality reinforcing mechanisms through the horizontal transmission of pathogens, namely, *Streptococcus agalactiae* and Infectious Spleen and Kidney Necrosis Virus. Moreover, the recognition of weak enforcement as a possible factor reinforcing human activities is a non-infectious route that can be deleterious to fish health. Health management practices comprised phytotherapy, vaccination, heat shock treatment, biological controls, and best husbandry practices. Lake management involves creating a waterfront buffer of 85.34 m, surveillance, and executing the framework guiding aquaculture development on the Lake. The findings are suggestive of complementary quantitative studies that augment the qualitative evidence herein. Such follow up studies can disclose precise mortality risk factors to inform policy directives and effective remedial strategies that can secure fish and lake health.

KEYWORDS

Nile tilapia (*Oreochromis niloticus*), mortalities, Lake Volta, systemic approach, reinforcing mechanisms, pathogens, non-infectious factors, management practices

1. Introduction

Lake Volta is a man-made system primarily purposed for generating hydroelectric power in Ghana. Over the years, the Lake evolved to support other commercial activities among which capture fisheries and aquaculture are dominant. The Lake has become the hub of cage aquaculture in Ghana, producing Nile tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*), and African arowana (*Heterotis niloticus*) (Béné, 2007; Rurangwa et al., 2015). Nile tilapia accounts for 80% of Ghana's total fish production, while African catfish and African arowana together represent 20% (Fisheries Commission, 2021). In 2016, Ghana produced 47,174 MT of fish from 8,415 floating cages, majority of which were concentrated on Lake Volta (Ragasa et al., 2018). Currently, 1,200 of these cages were reportedly abandoned on the Lake, due to fish mortalities driven by poor water quality and disease outbreaks (Mantey et al., 2020). In mid-October 2018, disease-induced mortalities in cage-farmed tilapia significantly hampered the species' contributions to total fish production. Two pathogens, namely *Streptococcus agalactiae* and Infectious Spleen and Kidney Necrosis Virus (ISKNV), have been introduced through imports of live biological materials and incriminated in these mortalities (Verner-Jeffreys et al., 2018; Ramírez-Paredes et al., 2021). These pathogens are currently prevalent and are occurring in coinfections to cause diseases, a finding consistent with gross pathologies in cage-farmed tilapia examined on the Lake (Ramírez-Paredes et al., 2021). While *S. agalactiae* and ISKNV are recognized as economically important fish pathogens in Lake Volta, it remains uncertain whether other risks factors from the Lake Environment and fish farms contribute to an increased likelihood of fish diseases and mortalities.

During the early 20th century, diseases occurring in animals and humans were often attributed to single agents (e.g., pathogens) (Barreto, 2005). However, the focus of disease investigation has shifted from singular agents to considering the involvement of multiple agents. The shift started in 1960 with the development of the web of causation model, which allowed rethinking the potential causalities or risks factors in contracting diseases (MacMahon et al., 1960). Moving forward, the web of causation has been applied in mapping the potential diseases risk factors and examining the interrelationship among risk factors to design effective interventions (MacMahon and Pugh, 1970; Joffe et al., 2012). The causation web provided the first evidence of lung cancer's multiple risks, ranging from tobacco smoking to environmental, behavioral, and hereditary factors. The environmental factors include exposure to chemicals such as arsenic or asbestos and unintentional inhalation of smoke from burning tobacco products (Pope et al., 1995). The behavioral factors are characterized by people's attitude of excessively smoking tobacco, while hereditary factors entail the transmission of disease variants to offspring (Fichtenberg and Glantz, 2002; Benusiglio et al., 2021). By adopting the web of causation, this study wants to broaden the understanding of disease and mortality risk factors of cage-farmed tilapia to move beyond the focus solely on pathogens. The primary aim of this study therefore is to leverage on the causation web model to elucidate the practical implications of risk factors while substantiating the presence of multiple contributing factors to Nile tilapia diseases and mortalities.

Streptococcus agalactiae and ISKNV pose threats to Nile tilapia throughout the production chain in Lake Volta. For instance, tilapia hatcheries sourcing water from Lake Volta experience a loss of >50% fry due to ISKNV infections (Ramírez-Paredes et al., 2021). Likewise, *S. agalactiae* infections cause 40–70% tilapia mortalities during the grow-out phases in submerged cages (Verner-Jeffreys et al., 2018). There has been no study conducted in Lake Volta to explain the underlying mechanisms driving consistent tilapia mortalities apart from the wide attribution to pathogenic risks. Reinforcing mechanism is a conceptual model within the broader social ecological systems (SES) that drives growth or decline processes (Downing et al., 2014). Growth processes could involve increased chemical use in agro farms at a Lake front thereby producing increase nutrient loading through surface runoffs. Increased nutrient loading causes algal blooms in the aquatic ecosystem. High algae blooms damages fish gills and reduce oxygen uptake with a resultant fish population decline, an example of a decline process.

This study conceptualize the SES model to study reinforcing mechanisms for tilapia diseases and mortalities in Lake Volta. Disease and mortality risk factors must be managed for a sustainable aquaculture industry. There is however, limited information on management practices initiated by fish farmers and regulators to counteract risk factors associated with diseases and mortalities in the Lake. Hence, the secondary aim of this study is to ascertain reinforcing mechanisms of Nile tilapia diseases and mortalities and document management practices initiated by stakeholders to attenuate the risk factors. Qualitative interviews to fish farmers and regulatory institutions managing aquaculture and lake resources were used to respond to the research aims. Studies on SES entail qualitative and quantitative modeling whereby the latter is dependent on the type of data, their availability or the possibility to collect the data (Haraldsson et al., 2020). The qualitative approach bridges these barriers by allowing the incorporation of variables that are difficult to measure and to sacrifice precision for generality and realism (Levins, 1966).

2. Materials and methods

2.1. Conceptualization

Risk factors are broadly categorized into environmental, behavioral, physiological, genetic, and demographic components (Virolainen et al., 2022). Building upon this background information on risk factors, we examined the drivers of cage-farmed tilapia mortalities by looking at risk factors influencing, shaping, or bringing about mortalities (Hammersley, 2012).

Risk factors are intricately related hence studying their relationship is essential in understanding their contributions to a particular outcome (Vial et al., 2020). The concept developed by MacMahon et al. (1960) on lung cancer has been adapted to study the relationships among risk factors and their contributions to cage-farmed tilapia mortalities in Lake Volta. The risk factors identified in this study served as foundational elements in building the causation web. Some controversies have been raised on using qualitative research to infer on causal relationships. Therefore, Maxwell (2019) recommended literature to complement qualitative data in giving causal explanations. This study complemented the qualitative data with relevant literature to support how risk factors are related or influence each other in establishing mortalities, as exemplified by Odhiambo et al. (2020).

Risk factors carry wider ecological implications and disrupt the overall balance and functioning of ecosystems (Myers et al., 2013). A single risk factor can trigger a cascade of changes in an ecosystem. The cascade effects of risk factors are modeled in a SES to demonstrate their far-reaching effects across social and ecological domains (Ann et al., 2006). The cascade effects of risk factors represented in a SES model can produce positive and negative feedbacks based on the relationships among the risk factors (Nassl and Löffler, 2015). Positive feedback relationships among risk factors represent reinforcing mechanisms that carry the potential to destabilize the overall balance and functioning of ecosystems (Levins, 1974; Downing et al., 2014). A negative feedback loop is a stabilizing mechanism capable of limiting the disturbances of risk factors to preserve the balance and functioning of ecosystems (Levins, 1974; Downing et al., 2014). In light of this, we will adopt the concept of positive and negative feedback within the larger SES model to establish how cage-farmed tilapia mortalities and diseases have been uninterrupted in Lake Volta.

2.2. Study area

Lake Volta has a mean depth of 19 m, covers 3.6% of Ghana's surface area, and lies between longitude 1° 30° W and 0° 20° E and latitude 6° 15′ N and 9° 10′ N. Most cage farms on the Lake are found in the Asuogyaman District of the Eastern Region, with clusters of developing farms in the South Dayi District - Volta Region (Kassam, 2014). This subsequently informed the selection of Eastern and Volta region, and their respective districts for the study (Figure 1).

2.3. Description of participants

This study employed a participatory research approach conducted in two stages: (1) online interviews from March–July 2021 and (2) a stakeholder workshop in May 2022. The interviews and stakeholder workshop targeted fish farmers, regulators, and researchers, as they represent the key stakeholders with a vested interest in Lake Volta aquaculture. The participants in the online interviews were selected purposively from the two study districts. The selection was based on long-term experiences and knowledge in Lake Volta cage aquaculture and the related fish health challenges. The interviews were conducted online due to Covid-19 traveling restrictions. In total, we encountered a sample size of 26 participants (Figure 2) determined through data saturation (Coenen et al., 2012). Based on the methodology of Coenen et al. (2012), we reached data saturation after three consecutive interviews when no new themes on risk factors and management practices were realized. Of the 26 interview participants, 15 are cage farmers, eight regulators, and three researchers. The stakeholder workshops ($n = 40$) validated the perspectives of the 26 interviewees. Of the 40 participants, 6 were cage farmers, 32 regulators, and 2 researchers (Figure 2).

The participating fish farms were small (<50 tonnes), medium (50–100 tonnes), and large-scale (>100 tonnes) tilapia producers. The regulator institutions were Fisheries Commission (FC), Water Resource Commission (WRC), Volta River Authority (VRA),

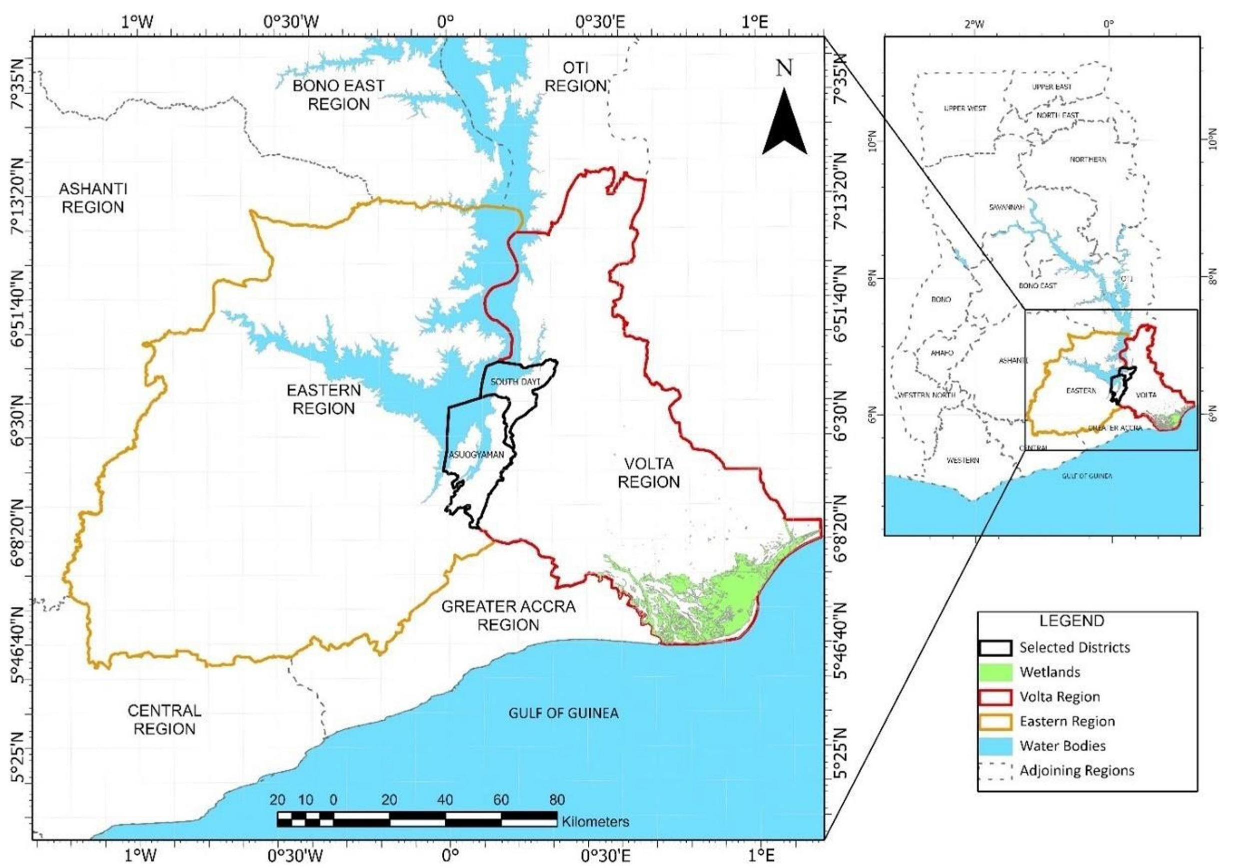

FIGURE 1
Map of Ghana showing Eastern region (Asuogyaman district) and Volta region (South Dayi district).

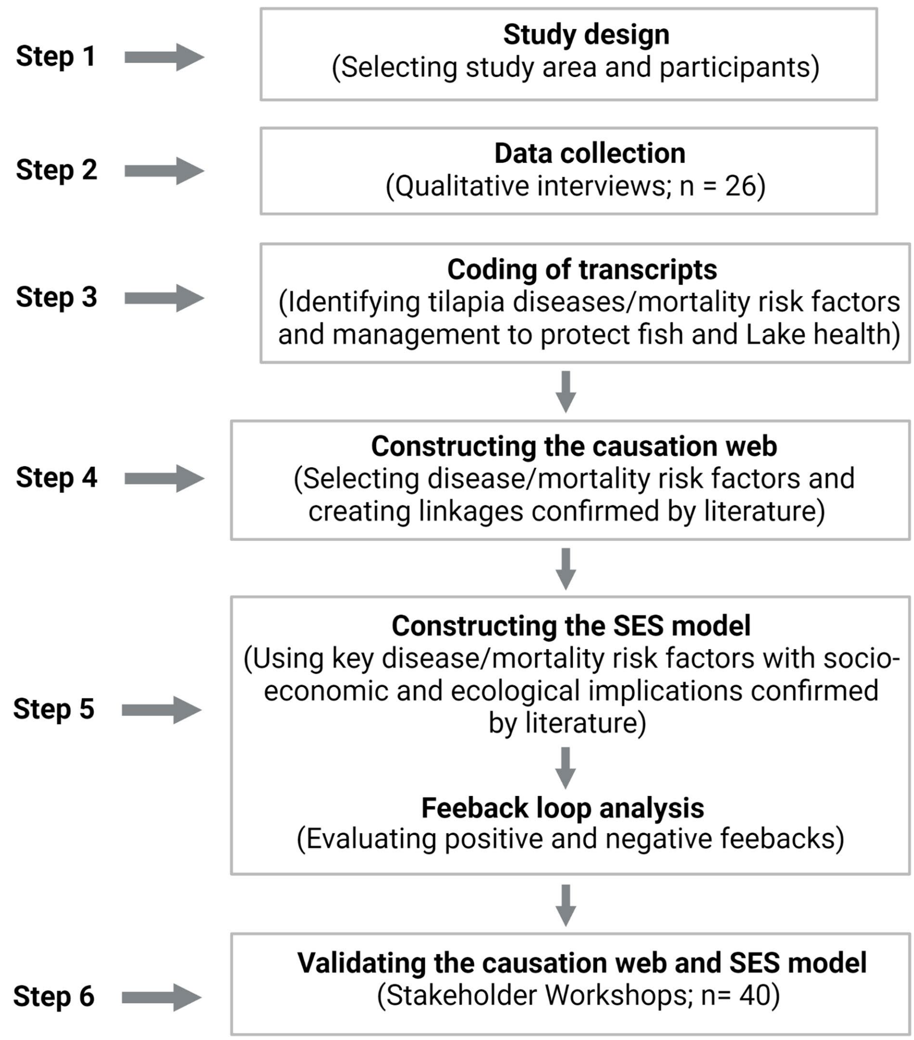

FIGURE 2
Flowchart to develop and validate the causation web and SES model.

Environmental Protection Agency (EPA), and District Assembly (DA). These institutions were selected because of their mandate to regulate the Lake environment, cage aquaculture activities, and other economic activities along the lake. The researchers were represented by the Aquaculture Research and Development Center (ARDEC), including other aquaculture education and research institutions with an interest in cage aquaculture on the Lake.

2.4. Online interviews

The participants completed an ethical clearance form prior to the online interviews in Microsoft Teams. Data was collected through open questions categorized in four themes: (a) farm information (b) risk factors of tilapia diseases and mortalities, (c) fish health management practices and (d) Lake Volta management practices. Open-ended questions enabled the provision of broad information and allowed the use of follow-up questions to clarify responses from interviewees. To ensure confidentiality, personal information regarding farms and participants are withheld, while focusing on risk factors of fish mortalities/diseases and management practices. The digital recordings from the interviews were transcribed and complemented with handwritten notes for further processing.

2.5. Analyzing interview data

We conducted thematic analyzes through three stages to analyze interview data (Krippendorff, 2004; Creswell, 2014; Sarku et al., 2020). The thematic analysis was done in Atlas.ti to identify themes relevant to the study objectives. Firstly, the transcripts were analyzed by identifying responses to specific questions, realigning sentence structures, and clarifying sentence structures (Wolfinger, 2002; Dey, 2003). Secondly, we applied inductive coding to identify initial codes (Krippendorff, 2004; Creswell, 2014; Sarku et al., 2020). The initial codes are common responses in the narrations relating to (a) risk factors of tilapia diseases and mortalities, (b) fish health management practices, and (c) Lake Volta management practices. For example, we encountered initial codes such as

ISKNV (virus), *S. agalactiae* (bacteria), agro-chemicals (herbicides and pesticides), overfeeding, and overstocking during the inductive coding of risk factors. Subsequently, the initial codes were grouped into various themes such as pathogens, water pollution, dietary factors, and husbandry factors. Thirdly, the themes identified were visualized graphically using the number of responses on each initial codes as a percentage of the total responses to each question.

2.6. Synthesizing interview data to construct causation web and SES model

We adapted the methodology of Scavarda et al. (2006) to construct the causation web from the interview data. Through an iterative consensus-driven process, we reflected on the interview narrations and coded data on diseases and mortality risk factors to identify factors that can be mapped to create the causation web. The mapping was done by examining how two or more disease/mortality risk factors can influence each other. For example, the informants revealed the continuous release of agro-chemical contaminants, including herbicides and pesticides from nearby farms into the Lake. This subsequently led to a reduction in water quality, which was consistent with past instances of fish mortality events, as described by the participants. This narration was evaluated by the study team using literature, leading to a consensus that chemical pollutants can degrade water quality to stress the fish and render them vulnerable to mortalities (Chinnadurai et al., 2022). These iterative consensus-driven processes aided in building an initial causation web for subsequent evaluation in an expert group workshop.

Similarly, the approach outlined by Hossain et al. (2020) was adopted to construct the SES model as an attempt, to ascertain the social and ecological implications of the diseases and mortality risk factors. This was done in four stages: (a) Identifying key disease and mortality risk factors in terms of social and ecological implications (b) Creating linkages among key risk factors in terms of their probability to influence diseases and mortalities (c) Determine the outcomes of the relationships among risk factors considering both positive and negative feedbacks, and (d) Analyze positive and negative feedback loops using the methodologies of Downing et al. (2014) and Cooper and Dearing (2019). By following the four stages, the study team first synthesized the responses to the open questions, which were telling to deduce social and ecological implications of the disease and mortality risk factors. For example, the informants went beyond merely mentioning risk factors like pathogens. They provided narratives detailing the pathway through which the pathogens were introduced, including the socio-economic and ecological consequences.

Literature information contributed to broadening the socio-economic and ecological components by incorporating spillover effects induced by the risk factors. For example, the informants revealed the practice of utilizing unprocessed tilapia cadavers as feed for catfish. Subsequently, literature information was consulted to validate this scenario in the form of cross-infections between tilapia and catfish (Wise et al., 2021). Secondly, through an iterative consensus-driven process, the study team created linkages among risk factors, considering their potential to influence diseases and mortalities. The linkages were also supported with literature information under the framework of social and ecological implications of the risk factors. Next, we determined the outcomes of the relationships among the disease and mortality risk factors by considering how increasing one risk factor could trigger an increase in the second or successive risk factors. If an increase in one risk factor causes an increase in the succeeding risk factor, the sign is positive (+). On the other hand, if an increase in one risk factor causes a decrease in the succeeding risk factor, the sign is negative (−).

Lastly, we conducted qualitative loop analyses to identify feedback loops in the SES model. A loop is a pathway through a number of system risk factors (or elements). When initiating with any given element, the pathway will eventually circle back to the initial element, thereby creating a loop in the process. The individual signs (+/−) between connected elements in a loop cancel each other to arrive at an overall positive or negative sign (e.g., overall + = − + − +). An overall positive sign in a closed loop is a positive feedback loop with the potential of reinforcing disturbances that can change the equilibrium state of a system. An overall negative sign is a negative feedback loop which can self-regulate disturbances to keep systems in their equilibrium state (Levins, 1974; Downing et al., 2014). By adopting the concepts of negative and positive feedback loops, we determined the reinforcing mechanisms of fish diseases/mortalities and identified stabilizing mechanisms for adoption in management practices.

2.7. Validating causation web and SES model

In the stakeholder workshop, the study team presented the research aims and the risk factors gathered from the online interviews to create the draft causation web and SES model. Thereafter, expert discussions were initiated to examine the strengths and interrelationships among the risk factors in both the causation web and SES model. The expert discussions aided the study team to refine the linkages between risk factors, which were created as a draft from the interview narratives. This helped in finalizing the causation web and SES model. Additionally, the final SES model produced new feedback loops that were assessed in a consensus-driven manner during the workshop (Figure 2).

Figure 2 encapsulates the step-by-step procedures followed in creating and validating the causation web and SES model.

3. Results

3.1. Risk factors of tilapia diseases and mortalities

The results of the study indicate that water pollution in the lake was the highest risk factor of tilapia diseases/mortalities at 34.6% followed by pathogens (*S. agalactiae* and ISKNV) at 30.8% (Figure 3). Water pollution is caused by human-mediated pollutants from mining sand and minerals, aquaculture waste, wood processing, agrochemicals, and domestic waste (Figure 4). Weak enforcement drives fish mortalities through uncontrolled human activities as the regulations and laws governing aquaculture and lake users are poorly implemented (Figure 4). The responses during the interviews highlighted enforcement as an important confounding variable. Although complex, enforcement plays a major role in influencing the pollution of the Lake. Moreover, weak enforcement also facilitated the importation of infected live fish and eggs that were banned in Ghana (Figure 4). The fish farmers do not have good physical structures to contain the infected live fish and eggs, resulting in the transfer of exotic pathogens, and inbreeding among imported tilapia and the local tilapia strain for aquaculture in Ghana. Furthermore, the occurrence of escapees in aquaculture facilitates the movement of fish from the cages into the wild environment, leading to admixed fish populations in the lake and potential gene pollution of wild tilapia population (Figure 4). Gene pollution implies a loss of genetic integrity arising from unregulated breeding activities among exotic and local tilapia strains. Following this, pathogen load and gene pollution, along with stress from water pollution can cause impaired fish immunity to induce fish mortalities. Furthermore, husbandry and dietary factors influencing fish diseases/mortalities were recorded at 15.4 and 7.7%, respectively, (Figure 3). In the causal web, husbandry and dietary factors were collectively termed husbandry practices. These practices encompass the utilization of dead fish and rancid feed as food sources, overfeeding, overstocking, and the manner in which fish are handled (Figure 4). The respondents perceived these husbandry practices as factors contributing to fish stress, which in turn could compromise fish immunity, leading to diseases and mortalities (Figure 4). A fraction of the stakeholders (11.5%) who gave "no response" upon follow up questions, were oblivious to risk factors of tilapia diseases and mortalities (Figure 3).

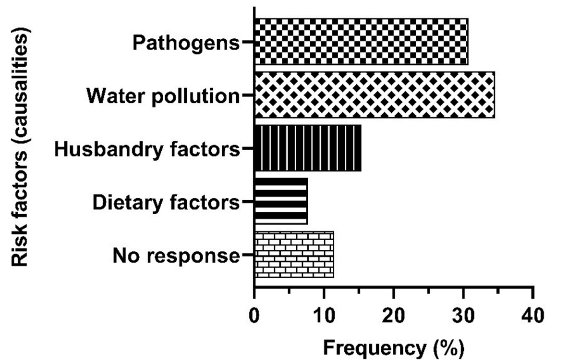

FIGURE 3
Risk factors of Nile tilapia diseases and mortalities in Lake Volta cage aquaculture.

3.2. Social and ecological system

The SES model encompassed Lake Volta cage aquaculture including a snapshot of land-based activities. The land-based activities were included in the model, because of their influence on overall fish health status in Ghana's aquaculture. The risk factors constituting the model were assigned IDs (Table 1). The social components of the SES model include disease and mortality risk factors such as enforcement, human activities, and husbandry practices. Conversely, the ecological components include biological fitness, fish stress, genetic diversity, and cross-infection.

The SES model is driven externally by enforcement (EF), which leads to multiple pathways of tilapia diseases and mortalities in Lake Volta. The multiple pathways consist of elements leading to decreased water quality in the lake, reduced fish immunity,

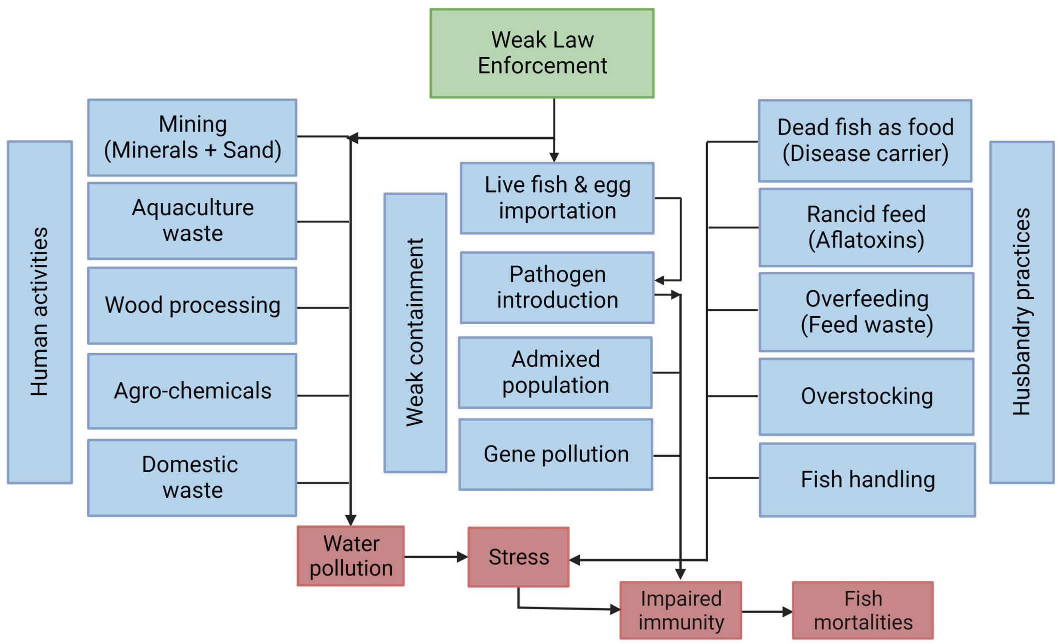

FIGURE 4
Causation web of Nile tilapia diseases and mortalities in Lake Volta cage aquaculture. The causal web was created with BioRender.com.

TABLE 1 The risk factors elicited from interviews served as inputs for the Social-Ecological System (SES) model.

Risk factors	Risk ID	Definition
1. Enforcement	EF	Enforcement is the implementation of laws binding aquaculture and lake exploitation.
2. Live Fish & Egg Importation	LF&EI	Importation of exotic fishery products such live fish and eggs
3. Pathogen Load	PL	Concentration of pathogens in fish or Lake Volta as a whole.
4. Fish Transport	FT	Domestic transport of live fish among aquaculture farms.
*5. Cross-infection	CI	The transfer of pathogens from an infected fish to a non-infected fish
*6. Biological Fitness	BF	The ability of fish to survive and reproduce or bring economic gains.
*7. Fish Immunity	FI	The ability of fish to maintain a potent immunity against infectious pathogens.
8. Fish Diseases	FD	Diseases that arise in fish upon exposure to infectious factors.
9. Fish Mortality	FM	Death of fish leading to reduced biomass.
*10. Admixed Population	AP	New fish generations due to inbreeding between local and exotic fish strains.
*11. Genetic diversity	GD	Genetic variability in cultured and wild fish in Lake Volta.
12. Human Activities	HA	Human-mediated activities that generate pollutants to reduce water quality.
13. Water Quality	WQ	Condition of water (physical, chemical or biological) supporting ecosystem services in Lake Volta.
14. *Fish Stress	FS	Stress in fish characterized by reduced welfare and susceptibility to infections and death.
15. Husbandry Practices	HP	Husbandry practices favorable for fish welfare, health and increase production.
16. Fish Farmer's Output	FFO	Total fish production and economic gains of farmers

*Risk factors added based on literature information.

diseases and mortalities. The interaction between two elements were assessed independently by considering their effect(s) on the succeeding element if the preceding element increases. For instance, EF is governance structure regulating aquaculture activities and lake development. Hence, an increase in EF decreased live fish and importation (LF&EI) and decreased human activities (HA) around the lake (Figure 5). In practice, high enforcement will lead to no LF&EI nor unacceptable human practices (identified by blue arrows). However, high LF&EI increased pathogen load (PL) in the lake and fish, shown with a positive sign (identified by green arrow) as a growth process. From the interview narratives, LF&EI was driven by the perceived underperforming local tilapia seeds compared to the purportedly superior performing foreign seeds for improved fish production. The SES model accounted for fish production as Fish Farmer's Output (FFO). It became evident from the narratives that FFO is dependent on farmers' husbandry practices (HP). Additionally, farmers rely on the authorities to enforce regulations binding sustainable Lake exploitation, including regulations on ban of LF&EI to have high FFO. The enforcement of these regulations is however low, thereby reducing FFO through imported diseases and deteriorated water quality. In consequence, farmers have lost trust in the regulatory authorities and are antagonistic to regulations being enforced. This informed the linkages created to unite FFO with HP, LF&EI, and EF. We emphasize that some elements in the model were added using literature information. For example, the inclusion of biological fitness (BF) and fish stress (FS) were informed by literature. Increased pathogen load in the aquatic environment decreases fish biological fitness (e.g., immune potential) by lowering survival and reproduction rates (Walker and Winton, 2010; Iregui et al., 2014). Through literature, we also accounted for genetic impacts of interbreeding between imported and local strains denoted as Genetic Diversity (GD) in the model (Anane-Taabeah et al., 2019).

3.3. Loop analyzes of the qualitative SES model

The SES model encompassed sixteen (16) feedback loops representing Lake Volta aquaculture and land-based activities (Figure 5). The self-reinforcing loops and self-regulating loops are, respectively, eight in number (Table 2). Redundant feedback loops were excluded because they yielded the same feedback signs (+/−) without additional information. For instance, LF&EI and HA are key findings, but we did not include separate loops for these variables. This is because LF&EI and HA are embedded in the major feedback processes driven by enforcement. We included Pathogen Load (PL) because it has a direct influence on fish diseases and mortalities. Moreover, Fish Farmer's Output (FFO) was included because it has an influence on enforcement of aquaculture laws. In this context, fish farmers will not obey regulations perceived to be limiting their outputs.

3.4. Management practices for fish and lake health

Table 3 is a summary of key responses from stakeholders during online interviews on the management practices for fish and Lake Health.

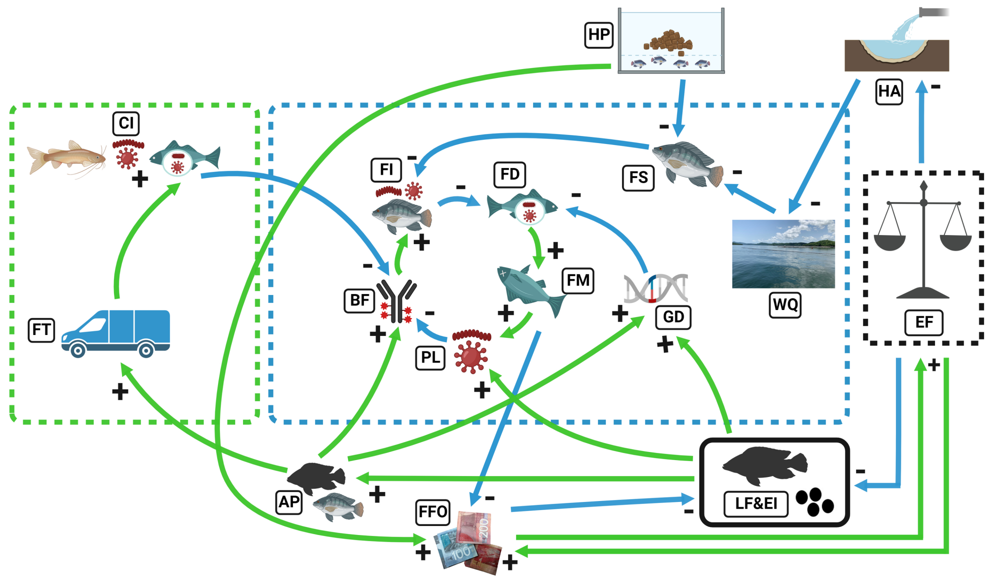

FIGURE 5
Qualitative SES model of Lake Volta aquaculture and land-based activities. Blue dotted lines encompass aquaculture-ecological interactions in Lake Volta; green dotted lines represent land-based activities; blue continuous arrows represent reduction processes (– signs); and green continuous arrows represent growth processes (+ signs). EF, Enforcement; HA, Human Activities; WQ, Water Quality; HP, Husbandry Practices; FS, Fish Stress; FI, Fish Immunity; FD, Fish Diseases; FM, Fish Mortality; PL, Pathogen Load; FFO, Fish Farmer's Output; LF&EI, Live Fish and Egg Importation; AP, Admixed Population; GD, Genetic Diversity; FT, Fish Transport, CI, Cross-Infection and BF, Biological Fitness. The SES image was created with BioRender.com. Additional image citation: (WQ- Duodu et al., 2022).

TABLE 2 Reinforcing (+) and self-regulating (–) feedback loops.

Feedback loops	Signs
1. [c]EF➔LF&EI➔AP➔FT➔CI➔BF➔FI➔FD➔FM➔FFO➔EF	+
2. EF➔LF&EI➔PL➔BF➔FI➔FD➔FM➔FFO➔EF	+
3. EF➔HA➔WQ➔FS➔FI➔FD➔FM➔FFO➔EF	+
4. FFO➔EF➔HA➔WQ➔FS➔FI➔FD➔FM➔FFO	+
5. [c]FFO➔EF➔LF&EI➔AP➔FT➔CI➔BF➔FI➔FD➔FM➔FFO	+
6. FFO➔ LF&EI➔AP➔FT➔CI➔BF➔FI➔FD➔FM➔FFO	+
7. [a]PL➔BF➔FI➔FD➔FM➔PL	+
8. PL➔BF➔FI➔FD➔FM➔FFO➔LF&EI➔PL	+
9. EF➔LF&EI➔AP➔GD➔FD➔FM➔FFO➔EF	–
10. [b]EF➔LF&EI➔AP➔BF➔FI➔FD➔FM➔FFO➔EF	–
11. EF➔LF&EI➔GD➔FD➔FM➔FFO➔EF	–
12. [b]FFO➔EF➔LF&EI➔AP➔BF➔FI➔FD➔FM➔FFO	–
13. FFO➔EF➔LF&EI➔AP➔GD➔FD➔FM➔FFO	–
14. FFO➔EF➔LF&EI➔GD➔FD➔FM➔FFO	–
15. [a]GD➔FD➔FM➔FFO➔EF➔GD	–
16. AP➔GD➔FD➔FM➔FFO➔LF&EI➔AP	–

EF, Enforcement; LF&EI, Live Fish & Egg Importation; AP, Admixed Population; FT, Fish Transport; CI, Cross-Infection; BF, Biological Fitness; FI, Fish Immunity; FD, Fish Diseases; FM, Fish Mortality; FFO, Fish Farmer's Output; HA, Human Activities; WQ, Water Quality; FS, Fish Stress; HP, Husbandry Practices; PL, Pathogen Load; and GD, Genetic Diversity. [a]Short feedback loops that may be stronger than longer ones. [b]Long negative feedback loops that can be destabilizing. [c]Long positive feedback loops that can be destabilizing.

4. Discussion

Our findings consolidate and confirm the results of other studies regarding the risk factors of tilapia diseases and mortalities (Verner-Jeffreys et al., 2018; Ramírez-Paredes et al., 2021). The findings also hint at reinforcing mechanisms that warrant consideration in the design of management practices aimed at addressing fish health challenges in Lake Volta.

TABLE 3 Management practices for fish and lake health quoted from stakeholder responses.

Stakolder group	Managemet practices for fish and lake health
Fish farmers	*"We are increasing biosecurity and not willing to compromise." "We scale down production by reducing the stocking density." "We grind neem tree leaves with salt solution that is mixed with the feed when we notice diseases." "Good water quality management, nutrition, vaccination, and sanitation. "The way we are dealing with ISKNV is we are now heat shocking the fish." "We transfer fish in smaller volumes to minimize mortalities."*
Regulators	*"We screen people working on aquaculture farms." "We sensitize farmers on biosecurity measures, good aquaculture practices, and do not encourage them to use any chemicals." "Adopting appropriate stocking density, providing approved fish feed and observing changes in water quality." "Regular monitoring of fish farms and mass vaccination exercises." "VRA developed framework of aquaculture guidelines which spells out the Dos and Don'ts on the lake." "VRA collaborates with Environmental Protection Agency, Water Resource Commission, Fisheries Commission, and District Assemblies to carry out surveillance monitoring on the lake." VRA is planting special bamboos to demarcate no structure should be established within the 280 ft. contour/85.34 m." The intervals between any two farms should not be less than 1 km."*
Researchers	*"Have quarantine sections for in-coming and out-going fish. Report any disease condition to the relevant authorities." "A well written and followed disease management plan." "Farmers are advised to reduce stocking density in the cages during cold seasons or either stock before or after the cold season." "We also explore other alternatives by using herbal extracts from neem tree leaves to treat the fish." "They use potassium permanganate, or normal salt (sodium chloride) to change the chemistry of the environment for which the fungus or disease causing organism grow."*

4.1. Risk factors of tilapia mortalities

This study categorizes the risk factors contributing to tilapia diseases and mortalities in Lake Volta aquaculture into two main groups. These are pathogens and non-infectious factors, attributable to inadequate law enforcement measures. The Aquaculture Regulations of Ghana (Aquaculture and Fisheries Regulations, 2020) is legally binding and must be enforced for responsible aquaculture operations. The regulations are poorly enforced resulting in the violation of the ban on importing live fish, exotic fish species, and eggs/gametes, except with permit from the Fisheries Commission. The opinion-based evidence in the study suggest that failed enforcement of the regulations allowed *S. agalactiae* and ISKNV to be introduced into Ghana's aquaculture industry through imports of fishery products (Figure 4). These pathogens have been confirmed in Lake Volta for causing recurrent diseases and mortalities in cage farmed tilapia (Verner-Jeffreys et al., 2018; Ramírez-Paredes et al., 2021). Other infectious risk factors were revealed through the husbandry practices of using dead fish and rancid feed as feed sources in catfish and tilapia production, respectively (Figure 4). Catfish mortalities were recorded from using unprocessed tilapia cadaver as feed source. Reportedly, the cadavers employed as catfish feed were believed to be contaminated with *S. agalactiae* and ISKNV during tilapia production process. This narrative lacked substantial evidence as it was founded solely on participants' opinions. However, fish cadaver carrying infectious factors is a source of pathogenic stress that can impair fish immunity and cause fish mortalities (Novoslavskij et al., 2016). Additionally, feeding tilapia with rancid feed increases the likelihood of introducing mycotoxins that can induce tilapia mortality. In fish, high concentrations of mycotoxins can lead to a myriad of effects, namely reduced weight, compromised immune system, and impaired liver function, ultimately leading to mortalities (Anater et al., 2016; Marijani et al., 2019).

Non-infectious risk factors that can influence the occurrence of tilapia diseases and mortalities have been identified as water pollution in the lake, and husbandry practices of improper handling, overfeeding, and overstocking (Figure 4). Interestingly, findings from a quantitative study suggested that the Lake has a fairly good chemical health status (Tay, 2021). However, the results from a qualitative study corroborate the findings in this study, as water quality was purported to have aggravated disease incidences in farmed fish on the Lake (Abarike et al., 2022). The results in this study thus suggest the need to formulate testable hypothesis on specific water quality contaminants, such as herbicides and pesticides, as disclosed by the participants. Information on quantifiable water quality contaminants in the Lake and their effects on fish health can guide the formulation of specific management policies and remedial measures. Nevertheless, Tay (2021) recommended the continuous monitoring of the Lake water quality by competent authorities to preserve it for human and animal use. Stress due to the husbandry practices of overstocking and improper handling can manifest into diseases and mortalities. This observation is consistent with the findings of Wanja et al. (2020), where the occurrence of diseases and tilapia mortalities were consistent with overstocking and improper handling. Overstocking and improper handling can lead to competition for space and injuries that can serve as entry points for opportunistic pathogens to establish diseases and mortalities. The husbandry practice of overfeeding does not directly result in fish mortalities. This notion is supported by Kamler et al. (2006), who reported no confirmed fish mortalities in a feeding trial with different feed concentrates in Trench fish. However, overfeeding can contribute to the accumulation of uneaten feed, excess nutrients and organic matter to deteriorate water quality. This in turn can cause stress, diseases, and mortalities in fish species (Riche et al., 2004; Kamler et al., 2006; Gao et al., 2015). The qualitative evidence gathered in this study suggests that the risk factors of tilapia diseases and mortalities are a combination of both pathogens and non-infectious factors.

4.2. Reinforcing mechanisms behind tilapia diseases and mortalities

Reinforcing mechanisms represent positive feedbacks that amplify negative changes in a system rather than reverse them. Such changes happen within stable systems when they encounter disturbances induced naturally or by human interventions. Natural disturbances are not limited to windstorms, landslides, droughts, and flooding. Human disturbances include among others, deforestation, pollution, and overpopulation (White and Pickett, 1985; Spagnuolo et al., 2009; Dornelas, 2010). These disturbances could be likened to the risk factors of tilapia diseases and mortalities in Lake Volta. In fact, mortality is an essential effect of disturbances in an ecosystem (Sousa, 1984). Within the framework of the SES model, we examined the feedback loops to identify positive feedback mechanisms that might be reinforcing the risk factors associated with tilapia diseases and mortalities.

Aquatic ecosystems like Lake Volta host a myriad of naturally occurring pathogens where aquatic life have adapted and coexisted with them over the years. The introduction of new pathogens can disturb the balance that have been established between fish and the *in-situ* microbial community. The introduction of new pathogens parallels the introduction of invasive species, both of which holds the potential of disturbing the stability of species communities and affect the balanced food web (Downing et al., 2014). The introduction of *S. agalactiae* and ISKNV serves as an evidence of invasive pathogens within Lake Volta, resulting in the establishment of a short and strong feedback loop (Loop 7; Table 2). Short and strong feedbacks are known for causing rapid ecosystem changes (Soto-Ortiz, 2015). The short feedback loop stemming from pathogen load may have reduced the biological fitness of farmed fish and compromised their immune potential, thereby making the fish susceptible to diseases and mortalities. Fish mortalities caused by pathogens in cage aquaculture pose the risk of shedding pathogens into the water body. According to Zhu et al. (2017), this process is a horizontal disease transmission pathway with the potential of re-infecting new fish. This study hints at the occurrence of horizontal pathogen transfers as a reinforcing mechanism, which can manifest through shedding of pathogens from dead tilapia into the water column. Ultimately, this could lead to re-infection of non-infected tilapia that are farmed on the Lake. Ayiku et al. (2022) confirmed the horizontal transfer of *S. agalactiae* and ISKNV among farmed tilapia in Lake Volta. This underscores how the Lake may be functioning as a pathogen reservoir, thereby reinforcing tilapia diseases and mortalities. Therefore, timely removal of fish cadaver in aquaculture becomes imperative.

The identified confounding variable of weak enforcement has the potential of reinforcing anthropogenic activities through non-infectious pathways that impact fish mortalities. The non-implementation of the laws and regulations binding sustainable lake could potentially contribute to anthropogenic wastes in the lake as a reinforcement of low water quality. Low water quality induced by built-up of anthropogenic wastes can persist once there is non-enforcement of laws binding lake users. Loop 3 exemplifies the role of weak enforcement in a positive feedback loop as it reinforces human activities to reduce water quality, cause fish stress, reduce immunity, establish diseases/mortalities, and reduces fish production (Table 2). As fish production reduces among farmers, a loss of trust in regulators occurs. This exacerbates the challenges of enforcement to ultimately reinforce the introduction of anthropogenic wastes into the Lake. The perceived loss of trust in regulators have been reported in Ghana's aquaculture industry by Agyei (2022). Regulators are encouraged to partner with aquaculture stakeholders in their regulatory processes for efficient enforcement (Lebel et al., 2019). This can be applied in a comprehensive manner to all stakeholders engaged in the exploitation of lake resources to dampen reinforcing processes conflicting fish and lake health.

All the feedback loops involving Genetic Diversity (GD) and Admixed Population (AP) resulted in stabilizing feedbacks. Stabilizing feedback processes serve to limit disturbances to preserve equilibrium states (Downing et al., 2014). This suggests that GD and AP may be self-regulating the negative impacts of LF&EI to preserve genetic integrity and maintain fish health. From Table 2, GD and AP can stimulate fish biological fitness to reduce diseases and mortalities caused by LF&EI (Loop 9: GD➔FD; Loop 10: AP➔BF). In practice, intentional breeding programs as reported by Eszterbauer et al. (2015), should be implemented to deliberately select favorable alleles that can enhance the fish's ability to withstand disease impacts. This way, genetic variabilities in tilapia through breeding programs can reduce disease-induced mortalities while increasing the growth rate of fish. Nevertheless, if fish disease-induced mortalities persist in the Lake, mortalities can become a self-regulating mechanism to depopulate the number of cage farmers. New fish farmers who are privy to the mortality risks of lake production will be compelled to pursue inland production in ponds and other closed systems. Fish farmer's output which is dependent on good enforcement and husbandry practices takes a complicated pathway to produce both reinforcing and stabilizing feedbacks (loop 5 and 12, Table 2). This suggest that fish farmer's output is intrinsically linked to other confounding variables to either reinforce fish mortalities or dampen risk factors of tilapia diseases and mortalities.

4.3. Management practices for fish and lake health

Small-scale farmers practice phytotherapy by grinding neem tree (*Azadirachta indica*) leaves with salt solution and mixing it with the feed. Fish farmers have trust in this practice because from experience it offers treatment and protection against *S. agalactiae* and ISKNV infections. Neem tree leaves can enhance immune responses in tilapia due to bioactive ingredients serving as antioxidant, anti-inflammatory, immunomodulatory, and apoptotic agents (Kapinga et al., 2018; Mondal et al., 2020; Sarkar et al., 2021). Heat shock treatment is also administered when tilapia (<5 g) is ISKNV positive. The optimum temperature of the fish is nonlethally manipulated by the farmers around ±10°C. This practice enhances tilapia immunity by producing heat shock proteins (Dini et al., 2006; Chen et al., 2014). Additionally, farmers use ducks as biological controls that feed on debris on the production net to enhance water circulation and improve dissolved oxygen. Using animals as biological controls demand precautionary measures because of their disease vector abilities. Moreover, farmers improve water quality by reducing feeding levels during disease outbreaks. This practice can reduce organic wastes and nitrogenous compounds to improve water quality, prevents fish stress, and maintains good immunity (Amirkolaie, 2011). Finally, farmers minimize fish stress through best husbandry practices such as reduce fish handling, and optimal stocking density combined with biosecurity measures. To reduce transport-related stress and minimize mortalities, farmers transport fish in smaller batches.

The Ghana Fisheries Commission launched vaccination exercises to control the infectious pathogens in tilapia. According to farmers, the vaccination exercise was partially successful. Fish must be vaccinated with a potent vaccine ahead of exposure to give sufficient time to develop immunity (Ayalew and Fufa, 2018). As reported by farmers, fish vaccination was carried out during an outbreak. This is an incorrect practice that will create skepticism to vaccination and give vaccination bad reputations. Depending on the vaccine type, boosters are usually recommended for better protection (Tobar et al., 2015; Thu Lan et al., 2021). VRA governs lake resources by reinforcing the lake buffer of 280 ft. (85.3440 meters) to control developments along the lakefront. As an example, special bamboo trees are planted to create a waterfront buffer against encroachment. Furthermore, VRA organizes joint surveillance programs in collaboration with FC, EPA, DA, and WRC to monitor fish farmers and other lake users. Monitoring fish farms is guided by VRA's framework for aquaculture development. We therefore recommend registering and licensing lake users, law enforcement, and awareness on sustainable lake exploitation. These regulatory measures should be accompanied with biosecurity measures and surveillance programs to effectively anticipate the risk factors of tilapia diseases and mortalities.

The method of data saturation was used to determine the sample size ($n = 26$) of online interviewees (Hennink and Kaiser, 2022). Saturation emerged as the 'gold standard' in qualitative inquiry at which point investigators do not realize any new data or themes after a consecutive number of interviews and focus group discussions (Guest et al., 2006; Fusch and Ness, 2015; Nelson, 2017). Statistically, 26 is considered not representative in comparison to the population of relevant stakeholders associated with Lake Volta aquaculture. The findings must therefore be interpreted with caution as it only offers a glimpse into risk factors and management practices through the opinions of relevant stakeholders involved in the study. People's opinion are rooted in their experiences, culture, feelings, and beliefs, often lacking scientific validation (Douglas and Wildavsky, 1983; Grimble and Wellard, 1997; Commodari and La Rosa, 2020). Nonetheless, the study has discerned mortality and disease risks factors that merit testable hypothesis through quantitative research for conclusive remarks.

Standardized quantitative methods that could be applied are ecological risk assessment, quantitative microbial risk assessment, hazard identification, exposure assessment, and probabilistic risk assessment (Yeak et al., 2022; Domínguez et al., 2023; Hunt et al., 2023; Ma et al., 2023; Ntakiyisumba et al., 2023). Despite these limitations, this study pioneers the conceptualization of causation web and social-ecological system models to explain the practical implications of risk factors associated with fish health. A further limitation was the 15 fish farmers out of 26 participants. This is a clear misrepresentation since it does not accurately reflect the overall representation of the different stakeholder groups in the study. The dominant farmer group may introduce some biases even though the study is grounded in expert consensus and literature validation. In retrospect, the predominant representation of farmers disclosed their pleas, which can be useful for government to know policies that are likely to support farmers. While we recognize the limitations of opinion-based approaches in risk determination, complementing personal perspectives with quantitative analyzes can offer broader outlooks to build robust remedial measures (Hodgson et al., 2019).

5. Conclusion

Based on the opinion-based evidence, the risk factors of tilapia diseases and mortalities in Lake Volta cage aquaculture are a combination of pathogens and non-infectious factors. The pathogenic factors are *S. agalactiae* and ISKNV, which aligns with quantitative evidence in literature. Conversely, the qualitative evidence regarding non-infectious factors are improper handling, overfeeding, overstocking, water pollutants (e.g., herbicides, and pesticides). These non-infectious factors require testable hypotheses in future studies to establish conclusive insights into their roles in exacerbating tilapia diseases and mortalities. This must include a quantitative study to investigate the assertions of horizontal transfer of *S. agalactiae* and ISKNV from tilapia cadaver to catfish, along with the study of mycotoxins and their permissible limits in tilapia. While the study hints at some management practices, complementary quantitative studies on the risk factors can be pivotal in shaping policy directives and strategies aimed at effectively managing fish and lake health.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

JZ: conceptualization, methodology, data collection, data analysis, visualization, writing–original draft, and review and editing. ST, EB, PZ, and IL: conceptualization, methodology, and writing–review and editing. PA and JA: methodology, data collection, and writing–review and editing. KC: conceptualization, methodology, resources, writing–review and editing, and supervision. All authors contributed to the article and approved the submitted version.

Funding

This study contributed to the Ghana Fish for Development (FfD) project funded by Norwegian Agency for Development Cooperation (NORAD). The workshop and article processing charge were funded by NORAD (Grant No. GHA 17/0005).

Acknowledgments

The first author appreciates the Norwegian Veterinary Institute for the opportunity as an intern on the NORAD-funded Fish for Development Program to conduct this work as part of a Master's program in Wageningen University. The authors are indebted to the stakeholders for participating in the interviews and workshop; Geert Wiegertjes (Wageningen University) for technical feedback on the conceptual models; Jacob Adzikah (Chamber of Aquaculture Ghana) and Derrick Kwesi Asare (Ghana Fisheries Commission) for organizing fish farmers to participate; Rebecca Sarku (ClimAgri-Food Consult) for guidance in analyzes; and Michael Yeboah and Grace Darling Atopah (Wageningen University) for peer discussions on the conceptual models.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Abarike, E., Atuna, R. A., Dandi, S. O., Agyekum, S., Appenteng, P., Alhassan, E. H., et al. (2022). *Preliminary survey on the health and management practices among small-scale cage Tilapia farmers on Lake Volta*.

Agyei, B. P. (2022). *Sustainability of pond and cage fish farming Systems in the Ashanti, bono, eastern and Volta regions in Ghana (unpublished master's thesis)*. Norway: Norwegian University of Life Sciences.

Amirkolaie, A. K. (2011). Reduction in the environmental impact of waste discharged by fish farms through feed and feeding. *Rev. Aquac.* 3, 19–26. doi: 10.1111/j.1753-5131.2010.01040.x

Anane-Taabeah, G., Frimpong, E. A., and Hallerman, E. (2019). Aquaculture-mediated invasion of the genetically improved farmed Tilapia (GIFT) into the lower Volta Basin of Ghana. *Diversity* 11:188. doi: 10.3390/d11100188

Anater, A., Manyes, L., Meca, G., Ferrer, E., Luciano, F. B., Pimpão, C. T., et al. (2016). Mycotoxins and their consequences in aquaculture: a review. *Aquaculture* 451, 1–10. doi: 10.1016/j.aquaculture.2015.08.022

Ann, P. K., Paul, R., Michel, E., Helen, A., Thomas, E., and Brian, H. W. (2006). Resilience and regime shifts: assessing cascading effects. *Ecol. Soc.* 11:20. doi: 10.5751/ES-01678-110120

Aquaculture and Fisheries Regulations. (2020). *L. I. 1968, Fish seed production certificate and fish transfer permit*. Available at: https://faolex.fao.org/docs/pdf/gha151991.pdf. (Accessed June 25, 2023).

Ayalew, A., and Fufa, A. (2018). Maintenance of fish health in aquaculture: review of epidemiological approaches for prevention and control of infectious disease of fish. *Vet. Med. Int.* 2018, 1–10. doi: 10.1155/2018/5432497

Ayiku, A., Adelani, A., Appenteng, P., Nkansah, M., Ngoi, J. M., Collins, M., et al. (2022). Molecular epidemiology of infectious spleen and kidney necrosis virus (ISKNV). *bioRxiv* 2022:516701. doi: 10.1101/2022.11.15.516701

Barreto, M. (2005). Epidemiologists and causation in an intricate world. *Emerg. Themes Epidemiol.* 2, 2–3. doi: 10.1186/1742-7622-2-3

Béné, C. (2007). *Diagnostic study of the Volta Basin fisheries: part 1 overview of the fisheries resources*. WorldFish p. 31.

Benusiglio, P. R., Fallet, V., Sanchis-Borja, M., Coulet, F., and Cadranel, J. (2021). Lung cancer is also a hereditary disease. *Eur. Respir. Rev.* 30:210045. doi: 10.1183/16000617.0045-2021

Chen, M., Wang, R., Liping, L., Liang, W., Wang, Q., Huang, T., et al. (2014). Immunological enhancement action of endotoxin-free tilapia heat shock protein 70 against *Streptococcus iniae*. *Cell. Immunol.* 290, 1–9. doi: 10.1016/j.cellimm.2013.12.008

Chinnadurai, K., Prema, P., Veeramanikandan, V., Kumar, K. R., Nguyen, V. H., Marraiki, N., et al. (2022). Toxicity evaluation and oxidative stress response of fumaronitrile, a persistent organic pollutant (pop) of industrial waste water on tilapia fish (*Oreochromis mossambicus*). *Environ. Res.* 204:112030. doi: 10.1016/j.envres.2021.112030

Coenen, M., Stamm, T. A., Stucki, G., and Cieza, A. (2012). Individual interviews and focus groups in patients with rheumatoid arthritis: a comparison of two qualitative methods. *Qual. Life Res.* 21, 359–370. doi: 10.1007/s11136-011-9943-2

Commodari, E., and La Rosa, V. L. (2020). Adolescents in quarantine during COVID-19 pandemic in Italy: perceived health risk, beliefs, psychological experiences and expectations for the future. *Front. Psychol.* 11:2480. doi: 10.3389/fpsyg.2020.559951

Cooper, G. S., and Dearing, J. A. (2019). Modelling future safe and just operating spaces in regional social-ecological systems. *Sci. Total Environ.* 651, 2105–2117. doi: 10.1016/j.scitotenv.2018.10.118

Creswell, J. W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches*. *4th Edn.* Thousand Oaks, CA: SAGE Publications.

Dey, I. (2003). *Qualitative data analysis: A user friendly guide for social scientists*. Abingdon: Routledge.

Dini, L., Lanubile, R., Tarantino, P., Mandich, A., and Cataldi, E. (2006). Expression of stress proteins 70 in tilapia (*Oreochromis mossambicus*) during confinement and crowding stress. *Ital. J. Zool.* 73, 117–124. doi: 10.1080/11250000600679652

Domínguez, R. C., Guadian, J. E. R., Guerrero, J. L., and Mares, J. I. P. (2023). Hazard identification for risk assessment using the pra technique in the automotive industry. *Saf. Sci.* 160:106041. doi: 10.1016/j.ssci.2022.106041

Dornelas, M. (2010). Disturbance and change in biodiversity. *Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci.* 365, 3719–3727. doi: 10.1098/rstb.2010.0295

Douglas, M., and Wildavsky, A. (1983). *Risk and culture - an essay on the selection of technological and environmental dangers*, Berkeley, CA: University of California Press.

Downing, A. S. E., Van Nes, J., Balirwa, J., Beuving, P., Bwathondi, L. J., Chapman, I. J. M., et al. (2014). Coupled human and natural system dynamics as key to the sustainability of Lake Victoria's ecosystem services. *Ecol. Soc.* 19:190431. doi: 10.5751/ES-06965-190431

Duodu, S., Jansen, M. D., Nkansa, M., Ayiku, A. N. A., Adelani, A. A., Erkinharju, T., et al. (2022). *Fish for Development baseline study to map the disease occurrence in tilapia farms on Lake Volta*. Report, 36/2022.

Eszterbauer, E., Forró, B., Tolnai, Z., Guti, C., Zsigmond, G., Hoitsy, G., et al. (2015). Parental genetic diversity of brown trout (*Salmo trutta* m. fario) brood stock affects offspring susceptibility to whirling disease. *Parasit. Vectors* 8:141. doi: 10.1186/s13071-015-0744-2

Fichtenberg, C. M., and Glantz, S. A. (2002). Effect of smoke-free workplaces on smoking behaviour: systematic review. *Br. Med. J.* 325:188. doi: 10.1136/bmj.325.7357.188

Fisheries Commission. (2021). *National Fisheries and aquaculture policy*. Fisheries Commission.

Fusch, P. I., and Ness, L. R. (2015). Are we there yet? Data saturation in qualitative research. *Qual. Rep.* 20, 1408–1416. doi: 10.46743/2160-3715/2015.2281

Gao, Y., Wang, Z., Hur, J. W., and Lee, J. Y. (2015). Body composition and compensatory growth in Nile tilapia *Oreochromis niloticus* under different feeding intervals. *Chin. J. Oceanol Limnol.* 33, 945–956. doi: 10.1007/s00343-015-4246-z

Grimble, R., and Wellard, K. (1997). Stakeholder methodologies in natural resource management: a review of principles, contexts, experiences and opportunities. *Agric. Syst.* 55, 173–193. doi: 10.1016/S0308-521X(97)00006-1

Guest, G., Bunce, A., and Johnson, L. (2006). How many interviews are enough? An experiment with data saturation and variability. *Field Methods* 18, 59–82. doi: 10.1177/1525822X05279903

Hammersley, M. (2012). "Qualitative causal analysis: grounded theorizing and the qualitative survey" in *Challenging the qualitative-quantitative divide: Explorations in case-focused causal analysis*. eds. B. Cooper, J. Glaesser, R. Gomm and M. Hammersley (London, England: Continuum), 72–95.

Haraldsson, M., Raoux, A., Riera, F., Hay, J., Dambacher, J., and Niquil, N. (2020). How to model social-ecological systems? – a case study on the effects of a future offshore wind farm on the local society and ecosystem, and whether social compensation matters. *Mar. Policy* 119:104031. doi: 10.1016/j.marpol.2020.104031

Hennink, M., and Kaiser, B. N. (2022). Sample sizes for saturation in qualitative research: a systematic review of empirical tests. *Soc. Sci. Med.* 292:114523. doi: 10.1016/j.socscimed.2021.114523

Hodgson, E. E., Essington, T. E., Samhouri, J. F., Allison, E. H., Bennett, N. J., Bostrom, A., et al. (2019). Integrated risk assessment for the blue economy. *Front. Mar. Sci.*:6:609. doi: 10.3389/fmars.2019.00609

Hossain, M. S., Ramirez, J., Szabo, S., Eigenbrod, F., Johnson, F. A., Speranza, C. I., et al. (2020). Participatory modelling for conceptualizing social-ecological system dynamics in the Bangladesh delta. *Reg. Environ. Chang.* 20, 1–14. doi: 10.1007/S10113-020-01599-5/TABLES/3

Hunt, K., Doré, B., Keaveney, S., Rupnik, A., and Butler, F. (2023). A quantitative exposure assessment model for norovirus in oysters harvested from a classified production area. *Microb. Risk Anal.* 23:100247. doi: 10.1016/j.mran.2023.100247

Iregui, C., Barato, P., Rey, A., Vasquez, G., and Verjan, N. (2014). "Epidemiology of *Streptococcus agalactiae* and Streptococcosis in tilapia (*Oreochromis* sp.)" in *Epidemiology 1: theory, research and practice*. ed. M. Jansen (Hong Kong: iConcept Press), 251–268.

Joffe, M., Gambhir, M., Chadeau-Hyam, M., and Vineis, P. (2012). Causal diagrams in systems epidemiology. *Emerg. Themes Epidemiol.* 9, 1–18. doi: 10.1186/1742-7622-9-1

Kamler, E., Myszkowski, L., Kamiński, R., Korwin-Kossakowski, M., and Wolnicki, J. (2006). Does overfeeding affect tench *Tinca tinca* (L.) juveniles? *Aquac. Int.* 14, 99–111. doi: 10.1007/s10499-005-9018-x

Kapinga, I. B., Limbu, S. M., Madalla, N. A., Kimaro, W. H., and Tamatamah, R. A. (2018). *Aspilia mossambicensis* and *Azadirachta indica* medicinal leaf powders modulate physiological parameters of Nile tilapia (*Oreochromis niloticus*). *Int. J. Vet. Sci. Med.* 6, 31–38. doi: 10.1016/j.ijvsm.2018.03.003

Kassam, L. (2014). *Aquaculture and food security, poverty alleviation and nutrition in Ghana: case study prepared for the aquaculture for food security, Poverty Alleviation and Nutrition project*. Penang, Malaysia: WorldFish

Krippendorff, K. (2004). *Content analysis: An introduction to its methodology*. Thousand Oaks, CA: SAGE Publications, p. 93.

Lebel, L., Lebel, P., and Chuah, C. J. (2019). Water use by inland aquaculture in Thailand: stakeholder perceptions, scientific evidence, and public policy. *Environ. Manag.* 63, 554–563. doi: 10.1007/s00267-019-01143-0

Levins, R. (1966). The strategy of model building in population biology. *Am. Sci.* 54, 421–431.

Levins, R. (1974). The qualitative analysis of partially specified systems. *Ann. N. Y. Acad. Sci.* 231, 123–138. doi: 10.1111/j.1749-6632.1974.tb20562.x

Ma, X., Xu, J., Pan, J., Yang, J., Wu, P., and Meng, X. (2023). Detection of marine oil spills from radar satellite images for the coastal ecological risk assessment. *J. Environ. Manag.* 325:116637. doi: 10.1016/j.jenvman.2022.116637

MacMahon, B., and Pugh, T. F. (1970). *Epidemiology principles and methods*. Boston: Little Brown and Co.

MacMahon, B., Pugh, T. F., and Ipsen, J. (1960). *Epidemiological methods*. Boston, MA: Little, Brown and Co.

Mantey, V., Mburu, J., and Chumo, C. (2020). Determinants of adoption and disadoption of cage tilapia farming in southern Ghana. *Aquaculture* 525:735325. doi: 10.1016/j.aquaculture.2020.7353

Marijani, E., Kigadye, E., and Okoth, S. (2019). Occurrence of Fungi and mycotoxins in fish feeds and their impact on fish health. *Int. J. Microbiol.* 2019, 1–17. doi: 10.1155/2019/6743065

Maxwell, J. A. (2019). *Causality in qualitative research*. Thousand Oaks, CA: SAGE Publications Ltd.

Mondal, P., Garai, P., Chatterjee, A., and Saha, N. (2020). Toxicological and therapeutic effects of neem (*Azadirachta indica*) leaf powder in hole-in- the- head (HITH) disease of fish *Anabas testudineus*. *Aquac. Res.* 52, 715–723. doi: 10.1111/are.14928

Myers, S. S., Gaffikin, L., Golden, C. D., Ostfeld, R. S., Redford, K. H., Ricketts, T., et al. (2013). Human health impacts of ecosystem alteration. *Proc. Natl. Acad. Sci.* 110, 18753–18760. doi: 10.1073/pnas.1218656110

Nassl, M., and Löffler, J. (2015). Ecosystem services in coupled social-ecological systems: closing the cycle of service provision and societal feedback. Ambio: a journal of the human. *Environment* 44, 737–749. doi: 10.1007/s13280-015-0651-y

Nelson, J. (2017). Using conceptual depth criteria: addressing the challenge of reaching saturation in qualitative research. *Qual. Res.* 17, 554–570. doi: 10.1177/1468794116679873

Novoslavskij, A., Terentjeva, M., Eizenberga, I., Valciņa, O., Bartkevičs, V., and Bērziņš, A. (2016). Major foodborne pathogens in fish and fish products: a review. *Ann. Microbiol.* 66, 1–15. doi: 10.1007/s13213-015-1102-5

Ntakiyisumba, E., Lee, S., and Won, G. (2023). Identification of risk profiles for salmonella prevalence in pig supply chains in South Korea using meta-analysis and a quantitative microbial risk assessment model. *Food Res. Int.* 170:112999. doi: 10.1016/j.foodres.2023.112999

Odhiambo, E., Angienda, P. O., Okoth, P., and Onyango, D. (2020). Stocking density induced stress on plasma cortisol and whole blood glucose concentration in nile tilapia fish (*Oreochromis niloticus*) of Lake victoria, Kenya. *Int. J. Zool.* 2020, 1–8. doi: 10.1155/2020/9395268

Pope, C. A., Thun, M. J., Namboodiri, M. M., Dockery, D. W., Evans, J. S., Speizer, F. E., et al. (1995). Particulate air pollution as a predictor of mortality in a prospective study of U.S. adults. *Am. J. Respir. Crit. Care Med.* 151, 669–674. doi: 10.1164/ajrccm/151.3_Pt_1.669

Ragasa, C., Andam, K., Kufoalor, D., and Amewu, S. (2018). *A blue revolution in sub-Saharan Africa? Evidence from Ghana's tilapia value chain*. Report number: IFPRI GSSP working paper 49.

Ramírez-Paredes, J. G., Paley, R. K., Hunt, W., Feist, S. W., Stone, D. M., Field, T. R., et al. (2021). First detection of infectious spleen and kidney necrosis virus (ISKNV) associated with massive mortalities in farmed tilapia in Africa. *Transbound. Emerg. Dis.* 68, 1550–1563. doi: 10.1111/tbed.13825

Riche, M., Oetker, M., Haley, D. I., Smith, T., and Garling, D. L. (2004). Effect of feeding frequency on consumption, growth, and efficiency in juvenile tilapia (*Oreochromis niloticus*). *Israel J. Aquacult.* 56, 247–255. doi: 10.46989/001c.20386

Rurangwa, E., Agyakwah, S. K., Boon, H., and Bolman, B. C. (2015). *Development of aquaculture in Ghana: Analysis of the fish value chain and potential business cases*, (Ser. Imares report, c021/15). IMARES Wageningen UR. Available at: http://edepot.wur.nl/337344. (Accessed September 4, 2023).

Sarkar, S., Singh, R. P., and Bhattacharya, G. (2021). Exploring the role of *Azadirachta indica* (neem) and its active compounds in the regulation of biological pathways: an update on molecular approach. *3 Biotech* 11:178. doi: 10.1007/s13205-021-02745-4

Sarku, R., Gbangou, T., Dewulf, A., and Slobbe, E. (2020). *Beyond "expert knowledge": Locals and experts in a joint production of weather app and weather information for farming in the Volta Delta, Ghana*.

Scavarda, A., Bouzdine-Chameeva, T., Goldstein, S., Hays, J., and Hill, A. (2006). A methodology for constructing collective causal maps. *Decis. Sci.* 37, 263–283. doi: 10.1111/j.1540-5915.2006.00124.x

Soto-Ortiz, L. (2015). The regulation of ecological communities through feedback loops: a review. *Res. Zool.* 5, 1–15. doi: 10.5923/j.zoology.20150501.01

Sousa, W. P. (1984). The role of disturbance in natural communities. *Annu. Rev. Ecol. Syst.* 15, 353–391. doi: 10.1146/annurev.es.15.110184.002033

Spagnuolo, V., Terracciano, S., and Giordano, S. (2009). Trace element content and molecular biodiversity in the epiphytic moss *Leptodon smithii*: two independent tracers of human disturbance. *Chemosphere* 74, 1158–1164. doi: 10.1016/j.chemosphere.2008.11.080

Tay, C. K. (2021). Integrating water quality indices and multivariate statistical techniques for water pollution assessment of the Volta lake, Ghana. *Sustain. Water Resour. Manag.* 7, 1–23. doi: 10.1007/s40899-021-00552-6

Thu Lan, N. G., Salin, K. R., Longyant, S., Senapin, S., and Dong, H. T. (2021). Systemic and mucosal antibody response of freshwater cultured Asian seabass (*Lates calcarifer*) to monovalent and bivalent vaccines against *Streptococcus agalactiae* and *Streptococcus iniae*. *Fish Shellfish Immunol.* 108, 7–13. doi: 10.1016/j.fsi.2020.11.014

Tobar, I., Arancibia, S., Torres, C., Vera, V., Soto, P., Carrasco, C., et al. (2015). Successive oral immunizations against *Piscirickettsia salmonis* and infectious salmon anemia virus are required to maintain a long-term protection in farmed salmonids. *Front. Immunol.* 6:244. doi: 10.3389/fimmu.2015.00244

Verner-Jeffreys, D., Wallis, T., Cano, I., Ryder, D., Haydon, D., Domazoro, J. F., et al. (2018). *Streptococcus agalactiae* multilocus sequence type 261 is associated with mortalities in the emerging Ghanaian tilapia industry. *J. Fish Dis.* 41, 175–179. doi: 10.1111/jfd.12681

Vial, A., Van der Put, C., Stams, G. J. J., Assink, M., and Kossakowski, J. (2020). Exploring the interrelatedness of risk factors for child maltreatment: a network approach. *Child Abuse Negl.* 107:104622. doi: 10.1016/j.chiabu.2020.104622

Virolainen, S. J., VonHandorf, A., Viel, K. C. M. F., Weirauch, M. T., and Kottyan, L. C. (2022). Gene–environment interactions and their impact on human health. *Genes Immunity* 24, 1–11. doi: 10.1038/s41435-022-00192-6

Walker, P., and Winton, J. R. (2010). Emerging viral diseases of fish and shrimp. *Vet. Res.* 41:51. doi: 10.1051/vetres/2010022

Wanja, D., Mbuthia, P., Waruiru, R., Mwadime, J., Bebora, L., Nyaga, P., et al. (2020). Fish husbandry practices and water quality in Central Kenya: potential risk factors for fish mortality and infectious diseases. *Vet. Med. Int.* 2020, 1–10. doi: 10.1155/2020/6839354

White, P. S., and Pickett, S. T. A. (1985). "Natural disturbance and patch dynamics: an introduction" in *The ecology of natural disturbance and patch dynamics*. ed. S. T. A. Pickett (Orlando, FL: Academic Press)

Wise, A. L., LaFrentz, B. R., Kelly, A. M., Khoo, L. H., Xu, T., Liles, M. R., et al. (2021). A review of bacterial co-infections in farmed catfish: components, diagnostics, and treatment directions. *Animals* 11:3240. doi: 10.3390/ani11113240

Wolfinger, N. H. (2002). On writing fieldnotes: collection strategies and background expectancies. *Qual. Res.* 2, 85–93. doi: 10.1177/1468794102002001640

Yeak, K. Y. C., Palmont, P., Rivière, G., Bemrah, N., den Besten, H. M. W., and Zwietering, M. (2022). Microbial and chemical Hazard identification in infant food chains. *Glob. Pediatr.* 2:100010. doi: 10.1016/j.gpeds.2022.100010

Zhu, Y.-G., Gillings, M., Simonet, P., Stekel, D., Banwart, S., and Penuelas, J. (2017). Microbial mass movements. *Science (New York, N.Y.)* 357, 1099–1100. doi: 10.1126/science.aao3007

frontiers | Frontiers in Sustainable Food Systems

TYPE Perspective
PUBLISHED 28 September 2023
DOI 10.3389/fsufs.2023.1281447

OPEN ACCESS

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RECEIVED 22 August 2023
ACCEPTED 08 September 2023
PUBLISHED 28 September 2023

CITATION
Stentiford GD, Tyler CR, Ellis RP, Bean TP, MacKenzie S, Brugere C, Holt CC, Peeler EJ, Christison KW, Rushton J and Bass D (2023) Defining and averting syndemic pathways in aquaculture: a major global food sector. *Front. Sustain. Food Syst.* 7:1281447. doi: 10.3389/fsufs.2023.1281447

Defining and averting syndemic pathways in aquaculture: a major global food sector

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Aquaculture now provides half of all aquatic protein consumed globally—with most current and future production occurring in low- and middle-income countries (LMICs). Concerns over the availability and application of effective policies to deliver safe and sustainable future supply have the potential to hamper further development of the sector. Creating healthy systems must extend beyond the simple exclusion of disease agents to tackle the host, environmental, and human drivers of poor outcomes and build new policies that incorporate these broader drivers. Syndemic theory provides a potential framework for operationalizing this One Health approach.

KEYWORDS
aquaculture, food, disease, sustainable, health

What is a syndemic?

Syndemic theory extends our interpretation of disease beyond traditional medical definitions of morbidity, co-morbidity, and multi-morbidity to include societal, economic, and environmental drivers contributing to, and exacerbating, detrimental health outcomes (Singer et al., 2017). This "biosocial" concept of disease, first applied to SAVA (substance abuse, violence, and AIDS) in individuals and groups from low-income urban environments (Singer, 1996), has subsequently been deployed where infectious and non-infectious conditions interface with prevailing political, societal, and environmental factors (Moussavi et al., 2007; Zinsstag et al., 2011; Mendenhall, 2013). Syndemic theory was re-animated by the COVID-19 pandemic, with a diverse outcome disease state associated with infection by a novel viral pathogen and the differing political, environmental, and demographic landscapes operating across susceptible human host communities (Mendenhall, 2020; Fronteira et al., 2021). Syndemic theory has important consequences for human health policy, identifying the need to move beyond biomedical intervention to simultaneously focus on tackling socio-economic disparities underlying poor health (Singer et al., 2017; Horton, 2020).

Syndemic pathways in aquaculture

In this study, we consider how syndemic theory may be applied elsewhere—specifically, to animal health outcomes within food systems. Aquaculture, one of the fastest-growing food sectors, predominates in LMICs (Stentiford and Holt, 2022). Interacting biological, environmental, social, and political factors have contributed to diseases that have seriously limited yield, benefits, profit, and food security from the sector, both in LMICs and in higher-income nations, over recent decades (Faruk et al., 2004; Solomieu et al., 2015; Abolofia et al., 2017; Tang and Bondad-Reantaso, 2019; Stentiford et al., 2020, 2022; Patil et al., 2021; Ward et al., 2021). The role of animal disease as a poverty trap for LMIC farmers, in particular, has been discussed in this context—an improved biosocial evidence basis to understand causality, to design policy, and to drive public–private investment are cornerstones of the Global Burden of Animal Diseases (GBAD) approach to reducing risk (Huntington et al., 2021; Rushton et al., 2021). The discourse on the role of disease in aquaculture has shifted focus from the presence of the pathogen (Stentiford et al., 2017) to the traditional epidemiological triad model for disease (Snieszko, 1974) revised to acknowledge that hosts and pathogens are elements of, and not distinct from, the environment (Dohoo et al., 2009). However, now the need to extend beyond this paradigm seems critical for averting losses (Stentiford et al., 2020). Instead, we propose that a "syndemic pathway" is driving poor health outcomes in aquaculture (Figure 1), and we urge that wider-ranging factors from biological to systemic failings of the institutional environment be incorporated into national strategies aimed at underpinning sustainability in the sector.

Pathogens

Diverse pathogen taxa are implicated in aquaculture disease outbreaks, with international legislation aimed at limiting the spread and further establishment of specific (listed) diseases (i.e., transboundary diseases) via the trade in animals and products (WOAH, 2022). Single pathogens are important in syndemic pathways (Munkongwongsiri et al., 2022; Niu et al., 2022), but the need for wider consideration of the symbiome within which known pathogens exist is acknowledged (Bass et al., 2019). In aquaculture, disrupted endemic microbial consortia co-contribute to "crop production" (non-listed) diseases that are significant drivers of

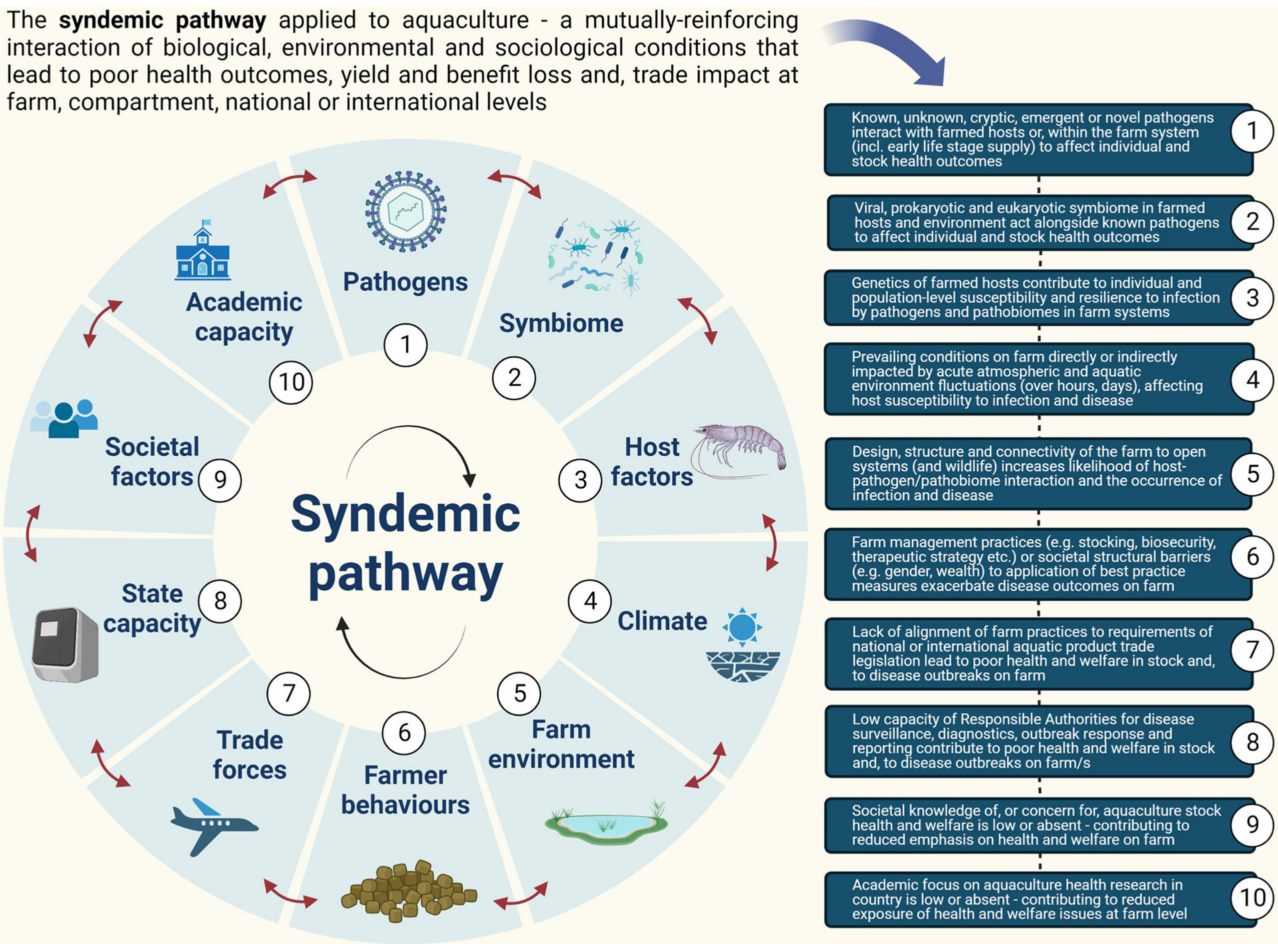

FIGURE 1
Elements of the syndemic pathway in aquaculture.

farm losses (Kooloth Valappil et al., 2021; Delisle et al., 2022). Diagnostic innovations used to profile these consortia in hosts, feeds, and water are influencing better microbial management practices on the farm, which leads to improved health, welfare, and yield (Bentzon-Tilia et al., 2016; Heyse et al., 2021; Holt et al., 2021). For averting syndemic pathways in aquaculture, profiling (and managing) microbial consortia conducive to healthy outcomes is likely to be as important as doing so during outbreaks (**Elements 1 and 2**, Figure 1).

Hosts

Sub-optimal water quality, nutrition, and the microbial ecosystem catalyse disease outbreaks in susceptible hosts (Murray and Peeler, 2005; Bateman et al., 2020). Susceptibility is also rooted in the genetics of farmed individuals and populations at local, national, and global levels. Selective breeding (Gjedrem and Rye, 2018; Houston et al., 2020), gene editing (Gratacap et al., 2019; Potts et al., 2021), and vaccinology (Ma et al., 2019) are critical tools for promoting health (Stentiford et al., 2017, 2020)—resilient populations being those in which effective genetic management reduces disease burden, reduces susceptibility to environmental change, and maintains diversity (You and Hedgecock, 2018). Resilience extends beyond single traits (Frank-Lawale et al., 2014), but it can be situation specific. For example, genetics for environmentally controlled biosecure farming may focus on enhanced growth traits, whilst for open systems, resilience to multiple stressors, and pathogens in combination may be required (Sae-Lim et al., 2016; Houston et al., 2020). Understanding functional bases for genetic resilience in major farmed aquatic species across the range of environments in which they are cultured is a critical component for sustainability in the sector (**Element 3**, Figure 1).

Environment

The immediate farm environment, farm management practices, and the impact of high-level forcing factors (e.g., climate change) play key roles in aquaculture syndemic pathways (Naylor et al., 2021; Panicz et al., 2022). On farms, sub-optimal water quality causes physiological stresses that can lead to immunological damage to stock, whilst also driving pathogen virulence (Kennedy et al., 2016). Farming intensity (Oddsson, 2020), mismanagement of waste (Granada et al., 2016), and poor biosecurity (Subasinghe et al., 2019; Reverter et al., 2020; Stentiford et al., 2020, 2022) combine to create conditions conducive to disease. Vulnerability to outbreaks is further compounded by the incursion of wildlife and vegetation, surrounding land use, pollution, erosion, and the presence of disease vectors (Soto et al., 2019; Bouwmeester et al., 2021; Stentiford et al., 2022). Preventing the development of syndemic pathways in aquaculture requires minimizing the impact of these complex environmental factors on the farmed stock. Spatial planning is critical to ensuring that aquaculture develops where environmental impacts on and from aquaculture are minimal. In some cases, physical separation of the farm from the environment or emerging precision technologies is needed to minimize environmental interactions (Føre et al., 2018) (**Elements 4, 5**, Figure 1).

People and society

The socio-cultural and economic context sets rules and enforcement mechanisms that shape a very specific institutional environment (Rushton and Leonard, 2009). This can create structural barriers (e.g., gender, language, knowledge, wealth, age, and access to facilities) that prevent farm operatives from obtaining adequate training and adopting practices to de-risk production. These barriers exacerbate pathogen, host, and environmental elements of the syndemic pathway—and *vice versa*, resulting in catastrophic disease losses in the sector (Kumar and Engle, 2016). Farmer behavior also directly influences the effectiveness of disease management and reporting decisions (Brugere et al., 2017; Hidano et al., 2018). The globalized nature of trade and diversity in forms of seafood consumption increase the risk of disease spread and exposure to human pathogens (Macpherson, 2005; Rodgers et al., 2011; FAO, 2012, 2020; Rinanda, 2015; Stentiford et al., 2022). National policy choices and priorities for disease surveillance, reporting, and control (including compensation for lost income), investments in animal health research, standard enforcement (notably regulation of trade), choice of farmed species, land use planning, and development (e.g., location of farms in the wider landscape), and public health policies and institutions' funding and outreach are often insufficient and disharmonized (van Herten et al., 2019; FAO, 2020). This not only has direct negative outcomes for animal and human health (Rushton et al., 2007) but also catalyses the formation of syndemic pathways that indirectly impact human prosperity (**Elements 6–10**, Figure 1).

Averting syndemic pathways

Whilst control of disease in aquaculture is a responsibility shared by the government and producers, the operationalization of One Health Aquaculture (Stentiford et al., 2020) can only be led by the government. By holistically conceptualizing human, environmental, and organism health, the syndemic pathway provides a framework for the government to operationalize One Health Aquaculture. Alongside national aspirations for expanded aquaculture output (Stentiford and Holt, 2022), it should catalyze the co-development of policies that extend well beyond attempts to exclude or manage the hazard (pathogen) to ones that drive investment in developing resilient hosts, protecting farms from the environment, and (particularly) exposing the core potential of humans operating within food systems to avert syndemic pathways from forming (Brugere et al., 2017).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

GS: Conceptualization, Funding acquisition, Methodology, Writing—original draft, Writing—review and editing. CT: Conceptualization, Writing—original draft, Writing—review and editing. RE: Conceptualization, Writing—original draft, Writing—review and editing. TB: Conceptualization, Writing—original draft, Writing—review and editing. SM: Conceptualization, Writing—original draft, Writing—review and editing. CB: Conceptualization, Writing—original draft, Writing—review and editing. CH: Conceptualization, Writing—original draft, Writing—review and editing. EP: Conceptualization, Writing—original draft, Writing—review and editing. KC: Conceptualization, Writing—original draft, Writing—review and editing. JR: Conceptualization, Writing—original draft, Writing—review and editing. DB: Conceptualization, Funding acquisition, Methodology, Writing—original draft, Writing—review and editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was funded by the Department for Environment, Food and Rural Affairs, UK Government under contracts FX001, FD002, and C8376 to GS, EP, and DB.

Conflict of interest

CB was employed by Soulfish Research and Consultancy.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Abolofia, J., Asche, F., and Wilen, J. E. (2017). The cost of lice: quantifying the impacts of parasitic sea lice on farmed salmon. *Mar. Res. Econ.* 32, 329–349. doi: 10.1086/691981

Bass, D., Stentiford, G. D., Wang, H. C., Koskella, B., and Tyler, C. (2019). The Pathobiome in animal and plant diseases. *Trends Ecol. Evolut.* 34, 996–1008. doi: 10.1016/j.tree.2019.07.012

Bateman, K. S., Bignell, J. P., Feist, S. W., Bass, D., and Stentiford, G. D. (2020). "Marine pathogen diversity and disease outcomes," in *Marine Disease Ecology,* eds. C. Donald, D. C. Behringer, B. R. Silliman, K. D. Lafferty (Oxford, UK: Oxford University Press). doi: 10.1093/oso/9780198821632.003.0001

Bentzon-Tilia, M., Sonnenschein, E. C., and Gram, L. (2016). Monitoring and managing microbes in aquaculture - towards a sustainable industry. *Microb. Biotechnol.* 9, 576–584. doi: 10.1111/1751-7915.12392

Bouwmeester, M. M., Goedknegt, M. A., Poulin, R., and Thieltges, D. W. (2021). Collateral diseases: aquaculture impacts on wildlife infections. *J. Appl. Ecol.* 58, 453–464. doi: 10.1111/1365-2664.13775

Brugere, C., Onuigbo, D. M., and Morgan, K. L. (2017). People matter in animal disease surveillance: Challenges and opportunities for the aquaculture sector. *Aquaculture.* 467, 158–169. doi: 10.1016/j.aquaculture.2016.04.012

Delisle, L., Laroche, O., Hilton, Z., Burguin, J. F., Rolton, A., Berry, J., et al. (2022). Understanding the dynamic of POMS infection and the role of microbiota composition in the survival of Pacific Oysters, *Crassostrea gigas*. *Microbiol. Spectr.* 31, e0195922. doi: 10.1128/spectrum.01959-22

Dohoo, I., Martin, W., and Stryhn, H. (2009). *Veterinary Epidemiologic Research.* VER Inc. ISBN 10:0919013600,0919013865.

FAO (2012). *Food and Agriculture Organization of The United Nation (FAO), 2012 The state of world fisheries and aquaculture.* Available online at: www.fao.org/docrep/016/i2727e.pdf (accessed June 2, 2022).

FAO (2020). *The State of World Fisheries and Aquaculture 2020: Sustainability in Action.* Rome: FAO.

Faruk, M. A. R., Sarker, M. M. R., Alam, M. J., and Kabir, M. B. (2004). Economic loss from fish diseases on rural freshwater aquaculture of Bangladesh. *Pak. J. Biol. Sci.* 7, 2086–2091. doi: 10.3923/pjbs.2004.2086.2091

Føre, M., Frank, K., Norton, T., Svendsen, E., Alfredsen, J. A., Dempster, T., et al. (2018). Precision fish farming: A new framework to improve production in aquaculture. *Biosyst. Engineer.* 173, 176–193. doi: 10.1016/j.biosystemseng.2017.10.014

Frank-Lawale, A., Allen, S. K., and Dégremont, L. (2014). Breeding and domestication of eastern oyster (Crassostrea virginica) lines for culture in the mid-Atlantic, USA: line development and mass selection for disease resistance. *J. Shellfish Res.* 33, 153–165. doi: 10.2983/035.033.0115

Fronteira, I., Sidat, M., Magalhães, J. P., Cupertino de Barros, F. P., Delgado, A. P., Correia, T., et al. (2021). The SARS-CoV-2 pandemic: A syndemic perspective. *One Health.* 12, 100228. doi: 10.1016/j.onehlt.2021.100228

Gjedrem, T., and Rye, M. (2018). Selection response in fish and shellfish: a review. *Rev. Aquacult.* 10, 168–179. doi: 10.1111/raq.12154

Granada, L., Sousa, N., Lopes, S., and Lemos, M. F. (2016). Is integrated multitrophic aquaculture the solution to the sectors' major challenges? A review. *Rev. Aquacult.* 8, 283–300. doi: 10.1111/raq.12093

Gratacap, R. L., Wargelius, A., Edvardsen, R. B., and Houston, R. D. (2019). Potential of genome editing to improve aquaculture breeding and production. *Trends Genet.* 35, 672–684. doi: 10.1016/j.tig.2019.06.006

Heyse, J., Props, R., Kongnuan, P., De Schryver, P., Rombaut, G., Defoirdt, T., et al. (2021). Rearing water microbiomes in white leg shrimp (*Litopenaeus vannamei*) larviculture assemble stochastically and are influenced by the microbiomes of live feed products. *Environ. Microbiol.* 23, 281–298. doi: 10.1111/1462-2920.15310

Hidano, A., Enticott, G., Christley, R. M., and Gates, M. C. (2018). Modeling dynamic human behavioral changes in animal disease models: challenges and opportunities for addressing bias. *Front. Vet. Sci.* 5, 137. doi: 10.3389/fvets.2018.00137

Holt, C. C., Bass, D., Stentiford, G. D., and van der Giezen, M. (2021). Understanding the role of the shrimp gut microbiome in health and disease. *J. Invertebr. Pathol.* 186, 107387. doi: 10.1016/j.jip.2020.107387

Horton, R. (2020). Offline: COVID-19 is not a pandemic. *Lancet* 396, 10255–10874. doi: 10.1016/S0140-6736(20)32000-6

Houston, R. D., Bean, T. P., Macqueen, D. J., Gundappa, M. K., Jin, Y., Jenkins, T. L., et al. (2020). Harnessing genomics to fast-track genetic improvement in aquaculture. *Nat. Rev. Genet.* 21, 389–409. doi: 10.1038/s41576-020-0227-y

Huntington, B., Bernardo, T. M., Bondad-Reantaso, M., Bruce, M., Devleesschauwer, B., Gilbert, W., et al. (2021). Global Burden of Animal Diseases: a novel approach to understanding and managing disease in livestock and aquaculture. *Rev. Sci. Tech.* 40, 567–584. doi: 10.20506/rst.40.2.3246

Kennedy, D. A., Kurath, G., Brito, I. L., Purcell, M. K., Read, A. F., Winton, J. R., et al. (2016). Potential drivers of virulence evolution in aquaculture. *Evolut. Applic.* 9, 344–354. doi: 10.1111/eva.12342

Kooloth Valappil, R., Stentiford, G. D., and Bass, D. (2021). The rise of the syndrome–sub-optimal growth disorders in farmed shrimp. *Rev. Aquacult.* 13, 1888–1906. doi: 10.1111/raq.12550

Kumar, G., and Engle, C. R. (2016). Technological advances that led to growth of shrimp, salmon, and tilapia farming. *Rev. Fish Sci. Aquacult.* 24, 136–152. doi: 10.1080/23308249.2015.1112357

Ma, J., Bruce, T. J., Jones, E. M., and Cain, K. D. (2019). A review of fish vaccine development strategies: Conventional methods and modern biotechnological approaches. *Microorganisms.* 7, 569. doi: 10.3390/microorganisms7110569

Macpherson, C. N. L. (2005). Human behaviour and the epidemiology of parasitic zoonoses. *Internat. J. Parasitol.* 35, 1319–1331. doi: 10.1016/j.ijpara.2005.06.004

Mendenhall, E. (2013). *Syndemic Suffering: Social Distress, Depression, and Diabetes Among Mexican Immigrant Women.* Walnut Creak, CA: Left Coast, Press.

Mendenhall, E. (2020). The COVID-19 syndemic is not global: context matters. *Lancet.* 396, 1731. doi: 10.1016/S0140-6736(20)32218-2

Moussavi, S., Chatterji, S., Verdes, E., Tandon, A., Patel, V., Ustun, B., et al. (2007). Depression, chronic diseases, and decrements in health: results from the World Health surveys. *Lancet.* 370, 851–858. doi: 10.1016/S0140-6736(07)61415-9

Munkongwongsiri, N., Prachumwat, A., Eamsaard, W., Lertsiri, K., Flegel, T. W., Stentiford, G. D., et al. (2022). *Propionigenium* and *Vibrio* species identified as possible component causes of shrimp white feces syndrome (WFS) associated with the microsporidian *Enterocytozoon hepatopenaei*. *J. Invertebr. Pathol.* 192, 107784. doi: 10.1016/j.jip.2022.107784

Murray, A. G., and Peeler, E. J. (2005). A framework for understanding the potential for emerging diseases in aquaculture. *Prevent. Vet. Med.* 67, 223–235. doi: 10.1016/j.prevetmed.2004.10.012

Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., et al. (2021). A 20-year retrospective review of global aquaculture. *Nature.* 591, 551–563. doi: 10.1038/s41586-021-03308-6

Niu, G. J., Yan, M., Li, C., Lu, P. Y., Yu, Z., and Wang, J. X. (2022). Infection with white spot syndrome virus affects the microbiota in the stomachs and intestines of kuruma shrimp. *Sci. Total Environ.* 839, 156233. doi: 10.1016/j.scitotenv.2022.156233

Oddsson, G. V. A. (2020). definition of aquaculture intensity based on production functions—The aquaculture production intensity scale (APIS). *Water.* 12, 765. doi: 10.3390/w12030765

Panicz, R., Całka, B., Cubillo, A., Ferreira, J. G., Guilder, J., Kay, S., et al. (2022). Impact of climate driven temperature increase on inland aquaculture: application to land-based production of common carp (*Cyprinus carpio L*). *Trans. Emerg. Dis.* 69, e2341–e2350. doi: 10.1111/tbed.14577

Patil, P. K., Geetha, R., Ravisankar, T., Avunje, S., Solanki, H. G., Abraham, T. J., et al. (2021). Economic loss due to diseases in Indian shrimp farming with special reference to *Enterocytozoon hepatopenaei* (EHP) and white spot syndrome virus (WSSV). *Aquaculture.* 533, 736231. doi: 10.1016/j.aquaculture.2020.736231

Potts, R. W. A., Gutierrez, A. P., Penaloza, C. S., Regan, T., Bean, T. P., Houston, R. D., et al. (2021). Potential of genomic technologies to improve disease resistance in molluscan aquaculture. *Phil. Transact. Roy. Soc. B.* 376, 20200168. doi: 10.1098/rstb.2020.0168

Reverter, M., Sarter, S., Caruso, D., Avarre, J. C., Combe, M., Pepey, E., et al. (2020). Aquaculture at the crossroads of global warming and antimicrobial resistance. *Nat. Comm.* 11, 1–8. doi: 10.1038/s41467-020-15735-6

Rinanda, T. (2015). Aquatic animals and their threats to public health at human-animal-ecosystem interface: a review. *AACL Bioflux.* 8, 784–789.

Rodgers, C. J., Mohan, C. V., and Peeler, E. J. (2011). The spread of pathogens through trade in aquatic animals and their products. *OIE Scient. Techn. Rev.* 30, 241–256. doi: 10.20506/rst.30.1.2034

Rushton, J., Huntington, B., Gilbert, W., Herrero, M., Torgerson, P. R., Shaw, A. P. M., et al. (2021). Roll-out of the global burden of animal diseases programme. *Lancet* 397, 1045–1046. doi: 10.1016/S0140-6736(21)00189-6

Rushton, J., and Leonard, D. (2009). "New institutional economics and the assessment of disease control," in *The Economics of Animal Health and Production*, ed. J. Rushton (Wallingford, UK: CABI) 144–148. doi: 10.1079/9781845931940.0144

Rushton, J., Viscarra, R., Otte, J., McLeod, A., and Taylor, N. (2007). Animal health economics where have we come from and where do we go next? *CABI Rev.* 2, 10. doi: 10.1079/PAVSNNR20072031

Sae-Lim, P., Gjerde, B., Nielsen, H. M., Mulder, H., and Kause, A. (2016). A review of genotype-by-environment interaction and micro-environmental sensitivity in aquaculture species. *Rev. Aquac.* 8, 369–393. doi: 10.1111/raq.12098

Singer, M. (1996). A dose of drugs, a touch of violence, a case of AIDS: conceptualizing the SAVA syndemic. *Free Inq. Creat. Sociol.* 24, 99–110.

Singer, M., Bulled, N., Ostrach, B., and Mendenhall, E. (2017). Syndemics and the biosocial concept of health. *Lancet.* 389, 941–950. doi: 10.1016/S0140-6736(17)30003-X

Snieszko, S. F. (1974). The effects of environmental stress on outbreaks of infectious diseases of fishes. *J. Fish Biol.* 6, 197–208. doi: 10.1111/j.1095-8649.1974.tb04537.x

Solomieu, V. B., Renault, T., and Travers, M.-., A. (2015). Mass mortality in bivalves and the intricate case of the Pacific oyster, Crassostrea gigas. *J. Invertebr. Pathol.* 131, 2–10. doi: 10.1016/j.jip.2015.07.011

Soto, D., León-Muñoz, J., Dresdner, J., Luengo, C., Tapia, F. J., and Garreaud, R. (2019). Salmon farming vulnerability to climate change in southern Chile: understanding the biophysical, socioeconomic and governance links. *Rev. Aquacult.* 11, 354–374. doi: 10.1111/raq.12336

Stentiford, G. D., Bateman, I. J., Hinchliffe, S. J., Bass, D., Hartnell, R., Santos, E. M., et al. (2020). Sustainable aquaculture through the One Health lens. *Nat. Food.* 1, 468–474. doi: 10.1038/s43016-020-0127-5

Stentiford, G. D., Flegel, T. W., Bass, D., Williams, B. A., Withyachumnarnkul, B., Itsathitphaisarn, O., et al. (2017). New paradigms to solve the global aquaculture disease crisis. *PLoS Pathog.* 13, e1006160. doi: 10.1371/journal.ppat.1006160

Stentiford, G. D., and Holt, C. (2022). Global adoption of aquaculture to supply seafood. *Environ. Res. Lett.* 17, 041003. doi: 10.1088/1748-9326/ac5c9f

Stentiford, G. D., Peeler, E. J., Tyler, C. R., Bickley, L. K., Holt, C., Bass, D., et al. (2022). A seafood risk tool for assessing and mitigating chemical and pathogen hazards in the aquaculture supply chain. *Nat. Food.* 3, 169–178. doi: 10.1038/s43016-022-00465-3

Subasinghe, R. P., Delamare-Deboutteville, J., Mohan, C. V., and Phillips, M. J. (2019). Vulnerabilities in aquatic animal production. *Rev. Scientif. Tech.* 38, 423–436. doi: 10.20506/rst.38.2.2996

Tang, K. F. J., and Bondad-Reantaso, M. G. (2019). Impacts of acute hepatopancreatic necrosis disease on commercial shrimp aquaculture. *Rev. Sci. Tech.* 38, 477–490. doi: 10.20506/rst.38.2.2999

van Herten, J., Bovenkerk, B., and Verweij, M. (2019). One Health as a moral dilemma: Towards a socially responsible zoonotic disease control. *Zoonoses Public Health.* 66, 26–34. doi: 10.1111/zph.12536

Ward, G. M., Kambey, C. S. B., Faisan, J. P., Tan, P.-L., Matoju, I., Stentiford, G. D., et al. (2021). Ice-ice disease: an environmentally and microbiologically driven syndrome in tropical seaweed. *Rev. Aquacult.* 14, 414–439. doi: 10.1111/raq.12606

WOAH (2022). *Aquatic Animal Health Code, World Organisation for Animal Health, online publication, Paris.* Avaiolable online at: https://www.woah.org/en/what-we-do/standards/codes-and-manuals/aquatic-code-online-access/ (accessed June 2, 2022).

You, W., and Hedgecock, D. (2018). Boom-and-bust production cycles in animal seafood aquaculture. *Rev. Aquacult.* 11, 1045–1060. doi: 10.1111/raq.12278

Zinsstag, J., Schelling, E., Waltner-Toews, D., and Tanner, M. (2011). From "one medicine" to "one health" and systemic approaches to health and well-being. *Prevent. Vet. Med.* 101, 148–156. doi: 10.1016/j.prevetmed.2010.07.003

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 07 November 2023
DOI 10.3389/fsufs.2023.1281366

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RECEIVED 22 August 2023
ACCEPTED 24 October 2023
PUBLISHED 07 November 2023

CITATION
Shen W, Ge H and Bao J (2023) Green total factor productivity growth and its driving forces in China's fisheries sector.
Front. Sustain. Food Syst. 7:1281366.
doi: 10.3389/fsufs.2023.1281366

Green total factor productivity growth and its driving forces in China's fisheries sector

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The rapid development of China's fisheries sector has brought about significant environmental problems, which are detrimental to the sustainable development of the sector. Balancing environmental protection while promoting fisheries development has become an urgent issue in China. Based on data from 30 provincial-level administrative regions in China from 2004 to 2019, this study utilizes the Epsilon-based Measure (EBM) model considering undesirable outputs and the global Malmquist-Luenberger (GML) index to measure the green total factor productivity (GTFP) growth in China's fisheries sector. Furthermore, it explores the spatiotemporal evolution and driving forces of fisheries GTFP growth using spatial Durbin model (SDM). The results indicate that ignoring the resource and environmental costs in fisheries production would overestimate the growth of total factor productivity (TFP) by 1.3%. The growth of fishery output primarily comes from the increase in input factors, exhibiting extensive characteristics that have been gradually diminishing over time. During the sample period, the provinces with the fastest growth in GTFP shifted from being mainly concentrated in the central and western regions to the eastern region. The local driving forces behind the improvement of fisheries GTFP include internet penetration rate, transportation convenience, education level of rural residents. The driving forces from economically similar provinces include the positive spatial interplay between provinces, fishery disaster rate, fisherman training, fishery trade openness, and urbanization rate. Overall, these finds offer a novel approach to reexamine the growth of China's fisheries and provide valuable insights for the future fisheries development.

KEYWORDS

fisheries, green total factor productivity, driving forces, epsilon-based measure, global malmquist-luenberger, spatial durbin model

1. Introduction

TFP has received significant research attention in the literature on economic growth as a driving force for economic development beyond input factors (Solow, 1957; Pan et al., 2022). In the field of fisheries research, TFP has also been the subject of significant focus and is commonly used to measure the quality of fisheries development (Asche et al., 2013; Aponte, 2020; Zhong et al., 2022). Therefore, improving the TFP of the fisheries sector has become one of the key issues for achieving high-quality development. However, in the face of resource and environmental challenges in fisheries development, it is not enough to focus solely on improving TFP. Prolonged extensive development in the fisheries sector has led to severe resource and environmental problems. In response, the Chinese government has introduced a series of laws and regulations to promote sustainable fisheries development. In 2013, the State Council issued

"Several Opinions on Promoting the Sustainable and Healthy Development of Marine Fisheries," which emphasized the protection of marine fishery resources and the ecological environment. With a focus on aquaculture, the Ministry of Agriculture and Rural Affairs, the Ministry of Ecology and Environment, and other departments jointly issued "Several Opinions on Accelerating the Green Development of Aquaculture" in 2019, which outlined the direction for the green development of the aquaculture industry from various perspectives such as spatial layout, farming methods, and environmental considerations. Considering the current situation of fisheries development and policy directions, green development will be the primary direction for the future of China's fisheries. The measurement and analysis of GTFP in the fisheries sector take into account the costs of resources and environmental factors, thus reflecting the resource and environmental constraints faced in fisheries development. Therefore, assessing and analyzing fisheries GTFP is of significant importance in promoting sustainable development in the industry.

Currently, research on TFP in the fishing industry focuses on two main aspects. The first aspect is the measurement and analysis of fisheries TFP. The measurement can be broadly classified into two categories: parametric estimation and non-parametric estimation (Ye et al., 2023). Parametric estimation is primarily based on production functions and involve estimating residuals from the production function relationship to measure TFP (Van Beveren, 2012; Van Nguyen and See, 2023). In the fishing industry, it is more common to combine production functions with Törnqvist index to measure total factor productivity (Squires, 1992; Wang and Walden, 2021). Non-parametric estimation primarily refers to the combined use of data envelopment analysis (DEA) and the malmquist index (Asche et al., 2013; Zhang et al., 2023). When looking at specific sectors, the measurement of TFP in the fishing sector is mostly estimated using parametric methods. For example, Wang and Walden (2021) used a constructed production function to measure the TFP of the US commercial fishing industry. They found that improvements in biomass growth can lead to higher output growth or lower input growth. In the aquaculture sector, both parametric and non-parametric methods are commonly used in research for measuring TFP. Indeed, there is a temporal sequence in the application of these two measurement methods in the aquaculture sector (See et al., 2021). In the early stages of research, the focus was primarily on using stochastic frontier analysis, such as the stochastic logarithmic production function, to measure technical efficiency, an important component of TFP in aquaculture. It was only later that studies began to incorporate the use of DEA for TFP estimation. Both measurement methods have their respective advantages, and the choice of which method to use depends on factors such as research objectives, data, production process type, and numbers of output (Pascoe and Tingley, 2007; Van Nguyen et al., 2021). This study will utilize an evolved methodology based on DEA, known as EBM, in conjunction with the GML index, to measure the GTFP growth in China's fisheries sector. Additionally, it is important to emphasize that the fisheries sector mentioned in this study refers to both aquaculture and fishing sectors.

Another type of research focuses on explaining the factors causing changes in fisheries TFP. These factors involve specific policies, fleet characteristics, environmental and farm characteristics, but they exhibit variations in the fishing and aquaculture sectors. In the fishing sector, fishery resource management policies are crucial (McClanahan et al., 2015). These fishery resource management policies primarily focus on the management of fisheries capture and vessels, such as individual fishing quotas (Sanchirico et al., 2006; Solís et al., 2014), transferable quotas (Newell et al., 2005; Pincinato et al., 2021), Vessel Capacity Reduction Programs (Holland et al., 1999, 2017). Among these, most studies have affirmed the positive effects of these policies on fishing vessel TFP (Pascoe et al., 2012; Solís et al., 2015; Nielsen et al., 2023), while a few studies have found that some policies have not achieved the intended outcomes (Walden et al., 2012). Additionally, factors such as total kW, total fishing days per year, and the stock of physical capital also influence vessel TFP (Jin et al., 2002; Pipitone and Colloca, 2018). In comparison to the fishing sector, there are more factors that affect the TFP in the aquaculture sector. These factors include education level, experience, age and credit constraints of the farmer (Kareem et al., 2009; Iliyasu et al., 2016; Mitra et al., 2019; See et al., 2021), adoption of new production technology or production process innovation (Dey et al., 2010), pond characteristics (Long et al., 2020; Mitra et al., 2020), family characteristics (Iliyasu et al., 2016), and government regulations (Shao et al., 2021).

In this study, the GTFP of the fisheries sector was measured, and subsequently, its driving forces were explored. This study contributes to existing research in three aspects. Firstly, previous studies have mainly focused on either the fishing or aquaculture sector, and often explored the total factor productivity (TFP) of specific fish species production, which fails to provide a comprehensive view of the TFP of the entire fisheries sector. This study combines the fishing and aquaculture sectors to investigate the overall TFP of the fisheries sector. Secondly, it departs from the traditional understanding of fisheries growth, shifting from a focus on productivity growth to a balance between productivity growth and sustainable resource-environment considerations. Previous studies on fisheries productivity often neglected the environmental externalities associated with fishing activities. This study takes into account the environmental costs associated with fisheries production in calculating the TFP. Additionally, considering the carbon sequestration function of fisheries, the study incorporates the economic value of carbon sequestration in desirable outputs. Thirdly, this study analyzes the driving forces of fisheries GTFP based on five dimensions: natural environment, infrastructure, human capital, market size, and government governance. It also explores the spatial spillover effects of these dimensions on fisheries GTFP.

The rest of the paper is organized as follows. Section 2 provides theoretical analysis and proposes relevant hypotheses. Section 3 introduces the methodology, indicator selection and data sources. Results are presented in Section 4. Section 5 summarizes the conclusions and provides policy implications.

2. Methods and materials

2.1. Measuring GTFP growth for the fishery sector

By utilizing input and output data, DEA can be used to evaluate the efficiency of decision-making units. DEA primarily consists of two types: radial measurement-based models and non-radial measurement-based models. Radial measurement-based models do not consider slack variables and assume that all factors change proportionally. However, this assumption does not align with reality. Non-radial measurement-based models incorporate slack variables and avoid the strict assumptions of radial measurement by identifying points that are far from the frontier to maximize input and output inefficiency. This means that the original ratio information of the efficiency frontier projection is lost. To address the issues faced in non-radial measurement, Tone and Tsutsui (2010) proposed the EBM in 2010. Based on this model, and following the approach of Wu et al. (2019), we have developed an EBM that incorporates undesirable outputs. The formula is as follows:

$$k^* = \min_{\theta,\eta,\lambda,s^-,s^{+g},s^{-b}} \frac{\theta - \varepsilon_x \sum_{i=1}^{m} \frac{w_i^- s_i^-}{x_{i0}}}{\eta + \varepsilon_y \left[\sum_{i=1}^{s1} \frac{w_i^{+s1} s_i^{+g}}{y_{i0}} + \sum_{i=1}^{s2} \frac{w_i^{-s2} s_i^{-b}}{y_{i0}} \right]} \quad (1)$$

$$\text{s.t.} \begin{cases} \theta X_0 - X\lambda - s^- = 0 \\ \eta Y_0 - Y^{+g}\lambda + s^{+g} = 0 \\ \eta Y_0 - Y^{-b}\lambda - s^{-b} = 0 \\ \lambda_1 + \lambda_2 + \ldots + \lambda_n = 1 \\ \lambda \geq 0, s^- \geq 0, s^{+g} \geq 0, s^{-b} \geq 0, \theta \leq 1, \eta \leq 1 \end{cases}$$

Where s^- represents the slack variable. s^{+g} and s^{-b} are both redundant variables. W_i^- represents the weight of the i-th input, with $\sum W_i^- = 1$ $(\forall_i\ W_i^- \geq 0)$. W_i^+ represents the weight of the s-th output, with $\sum W_i^{+S1} + \sum W_i^{-S2} = 1$ $(\forall_i\ W_i^+ \geq 0)$.

Relying solely on the EBM model is insufficient for measuring fisheries GTFP growth; the use of index methods is also necessary. The Malmquist-Luenberger (ML) index has long been used to measure productivity growth incorporating undesirable outputs. However, this index can encounter cases where linear programming has no solution and suffer from non-transitivity issues. To overcome the limitations of the ML index, Oh (2010) proposed the GML index. This study considers the combination of the EBM model with the GML index, incorporating undesirable outputs, to measure China's fisheries GTFP growth. Existing studies decomposes the GML index into two dimensions: efficiency change and technological change. The formula for the GML index is as follows:

$$GML^{t,t+1}\left(x^t, y^t, b^t, x^{t+1}, y^{t+1}, b^{t+1}\right) = \frac{1 + D^G\left(x^{t+1}, y^{t+1}, b^{t+1}\right)}{1 + D^G\left(x^t, y^t, b^t\right)} \quad (2)$$

$$= \frac{1 + D^{t+1}\left(x^{t+1}, y^{t+1}, b^{t+1}\right)}{1 + D^t\left(x^t, y^t, b^t\right)} \times \left(\frac{\left(1 + D^G\left(x^{t+1}, y^{t+1}, b^{t+1}\right)\right) / \left(1 + D^{t+1}\left(x^{t+1}, y^{t+1}, b^{t+1}\right)\right)}{(1 + D^G\left(x^t, y^t, b^t\right) / \left(1 + D^t\left(x^t, y^t, b^t\right)\right)} \right)$$

$$= EC^{t,t+1} \times TC^{t,t+1}$$

Where $D^t\left(x^t, y^t, b^t\right)$ and $D^G\left(x^t, y^t, b^t\right)$ represent the current and global EBM directional distance function, respectively. b^t represents the undesirable output of the decision-making unit in period t. $GML^{t,t+1}$ represents the growth in fisheries GTFP from period t to t + 1. $EC^{t,t+1}$ represents the change in efficiency from period t to t + 1, and $TC^{t,t+1}$ represents the change in technology from period t to t + 1. When $GML^{t,t+1}$, $EC^{t,t+1}$, and $TC^{t,t+1}$ are greater than 1, it indicates growth from period t to t + 1. If they are equal to 1, it means no change, and if they are less than 1, it indicates a decline.

2.2. Methods for testing the drivers of fisheries GTFP growth

This study will employ spatial econometric model to examine the drivers of fisheries GTFP growth. Spatial econometric model is advantageous as it can effectively handle the spatial correlation among spatial units and test the spatial spillover effects. Prior to estimating the spatial econometric model, it is necessary to test the spatial autocorrelation of the dependent variable to determine the need for employing spatial econometric model. In this study, the Global Moran's I index will be used to test the spatial autocorrelation of fisheries GTFP growth. The expression for the Global Moran's I index is as follows:

$$\text{Moran's I} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(Y_i - \bar{Y}\right)\left(Y_j - \bar{Y}\right)}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}}, (i \neq j) \quad (3)$$

$$S^2 = \frac{\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2}{n}$$

Where Y_i and Y_j represent the fisheries GTFP growth of province i and province j, respectively. W_{ij} is the spatial weight matrix based on inverse economic distance, which captures the interconnections between provinces. The value of the Moran's I index is between 0 and 1. A positive Moran's I index indicate the presence of spatial autocorrelation in fisheries GTFP, implying that high values tend to cluster with high values and low values tend to cluster with low values. Conversely, a negative Moran's I index suggests the existence of spatial heterogeneity, where high values (low values) tend to cluster with low values (high values). When Moran's I index equal to zero, it signifies the absence of spatial correlation, indicating a random distribution of fisheries GTFP growth among provinces. Spatial correlation represents a form of spatial dependence, reflecting the first law of geography, which states that geographically proximate entities are more likely to be related.

If the estimation of the Global Moran's I index suggests the presence of spatial correlation in fisheries GTFP growth, it is essential to employ spatial econometric models to examine the driving factors of this productivity. The three classical specifications of spatial econometric models are the SDM, spatial autoregressive model (SAR), and spatial error model (SEM). To determine the appropriate model specification among these, it is common practice to conduct tests using the SDM as the baseline model and employing the WALD, LR, and LM tests. In this study, the SDM specification is as follows:

$$\mathrm{FGTFP}_{\mathrm{it}} = \rho W * \mathrm{FGTFP}_{\mathrm{jt}} + \alpha X_{\mathrm{it}} + \beta W * \mathrm{X}_{\mathrm{jt}} + \gamma_{\mathrm{i}} + \varphi_{\mathrm{t}} + \mu_{\mathrm{it}} \quad (4)$$

Where $FGTFP_{it}$ denotes the fisheries GTFP growth of province i in year t. $W * FGTFP_{jt}$ represents the spatial lag term of fisheries GTFP growth, and the corresponding coefficient ρ captures the strength of spatial interaction among provinces regarding GTFP growth. X_{it} represents the vector of independent variables, encompassing five categories of variables, namely, natural environment, infrastructure, human capital, market size, and government governance. W represents the spatial weight matrix based on inverse economic distance. $W * X_{jt}$ is the spatial lag term of X_{it}. The parameters α and β are the coefficients to be estimated. The subscripts γ_i and φ_t represent province and year fixed effects, respectively. The term $\propto_{it}$ represents the random disturbance.

2.3. Variable and data

2.3.1. Indicators used to measure fisheries GTFP

For input, this study extends the traditional framework of capital, land, and labor by incorporating resource, taking into account the specific characteristics of the fisheries sector. For the measurement of capital, land, and labor, we employ indicators such as fishery capital stock, aquaculture area, and the number of individuals employed in the fisheries sector. As for resource inputs, we consider the unique aspects of both the aquaculture and fishing. In the case of aquaculture, we measure resource inputs using the quantity of fish fry. However, in the context of the fishing, where data on fishery resource stocks across Chinese provinces are unavailable, the common approach of measuring resource pressure using fishery resource stocks is not feasible. Instead, we utilize the tonnage of fishing vessels as a proxy, as it provides insights into the pressure exerted by the fishing on fishery resources.

It is important to note that the currently available public data does not include information on fishery capital stock. While some studies have used the year-end quantity of fishing vessels as a proxy for fishery capital stock (Sun et al., 2017), it should be acknowledged that the number of vessels alone does not fully capture the comprehensive capital inputs in the fisheries sector. Firstly, fisheries production involves not only fishing vessels but also fixed assets such as aquaculture or fishing equipment. Secondly, fishing vessels vary significantly in size and power, and relying solely on vessel counts to measure capital stock can introduce significant measurement errors. Lastly, the approach of using vessel counts often overlooks the issue of capital depreciation.

To address these limitations, this study follows the approach proposed by Li et al. (2018). We calculate the capital stock for the fisheries sector in each province. Then, we estimate the provincial fishery capital stock using the following formula:

$$\text{Fishery Capital Stock} = \text{Provincial capital stock} * \frac{\text{Provincial fishery gross output}}{\text{Provincial gross domestic product}} \quad (5)$$

For output, existing research has predominantly focused on economic outputs (Álvarez et al., 2020; Mitra et al., 2020). However, production not only generates economic outputs but also entails the generation of pollutants. While these pollutants are not desired outcomes, they impose a burden on society. Therefore, fisheries output indicators should encompass both desirable outputs, such as economic production, and undesirable outputs, such as pollution. Economic output represents the desirable outputs and can be understood as fishery value-added. On the other hand, the emission of pollutants constitutes the undesirable outputs. The primary challenge lies in quantifying the undesirable outputs. In this study, fisheries are defined to include both aquaculture and fishing. In practice, pollution emissions predominantly arise from aquaculture, while fishing activities have a more significant impact on fishery resources. This distinction is evident in the regulatory policies implemented by China, where regulations for aquaculture primarily focus on pollution prevention and control, while fishing regulations mainly aim to prevent overfishing and preserve fishery resources (Chang et al., 2022). Therefore, this study primarily focuses on the undesirable outputs related to pollution generated by aquaculture activities. However, currently, direct data on provincial-level aquaculture pollution emissions is unavailable. Consequently, an indirect estimation approach is employed to obtain this information.

For the undesirable outputs, we draw on the methods used by Li (2014), Guo and Liu (2021), and Ren and Zeng (2021). We estimate the emissions of total nitrogen, total phosphorus, and chemical oxygen demand (COD) from aquaculture in each province from 2004 to 2019 based on the pollutant emission coefficients provided in the "Manual of Pollutant Source Emission Coefficients for Aquaculture in the First National Pollution Source Census" and the production data from the "China Fishery Statistical Yearbook." The specific steps are as follows: Firstly, we obtain the pollutant emission coefficients for over 20 freshwater fish species (including sturgeon, eel, carp, and tilapia) in four different freshwater aquaculture modes, as well as for over 20 marine fish species in five different marine aquaculture modes from the "Manual of Pollutant Source Emission Coefficients for Aquaculture in the First National Pollution Source Census." Additionally, we gather production data for different fish species in freshwater and marine aquaculture from the "China Fishery Statistical Yearbook." Secondly, we calculate the mean emission coefficients for freshwater fish species in the four freshwater aquaculture modes and for marine fish species in the five marine aquaculture modes. Thirdly, we combine the emission coefficients for freshwater aquaculture with the production data for freshwater fish farming. For each freshwater fish species, we multiply its production by the corresponding emission coefficients for total nitrogen, total phosphorus, and COD. By summing up these calculations, we obtain the total nitrogen, total phosphorus, and COD emissions from freshwater aquaculture. The same approach is applied to estimate the emissions from marine aquaculture. Finally, we aggregate the total nitrogen, total phosphorus, and COD emissions from both freshwater and marine aquaculture to obtain the overall emissions of from the total nitrogen, total phosphorus, and COD in aquaculture.

The desirable outputs consist of two main components. Firstly, following the practice of existing research (Zhang et al., 2020; Lee and Lee, 2022; Yu et al., 2022) and select fishery output value as one of the desirable outputs. Secondly, we consider the economic value of carbon sequestration in marine aquaculture. Considering the unique characteristics of fisheries, bivalve and seaweed aquaculture exhibit significant carbon sequestration capabilities, as they can utilize their carbon-fixing capacity to remove or absorb carbon dioxide from water bodies (Sea et al., 2022). Specifically, seaweed aquaculture in marine environments can absorb carbon dioxide through photosynthesis, reducing the carbon dioxide partial pressure in seawater and promoting its absorption, thus facilitating carbon sequestration. Bivalves contribute to carbon sequestration through carbon fixation during shell growth and the conversion of organic carbon during soft tissue growth. Drawing on the methods proposed by Shao et al. (2019) and Le et al. (2023), we estimate the carbon sequestration in fisheries at the provincial level in China. Subsequently, we apply the calculation methodology introduced by Sun et al. (2020) to determine the economic value of carbon sequestration in marine aquaculture. Table 1 provides an overview of the indicators used in the calculation of fisheries GTFP growth.

2.3.2. Indicators used in the analysis of driving forces

In the analysis of driving forces, the dependent variable is the fishery GTFP growth. It is important to note that the fishery GTFP, derived from the EBM model of non-desired outputs and the GML index, represents the concept of year-on-year growth rate and cannot be directly used as the dependent variable. Following previous studies, the cumulative growth of fishery GTFP is calculated using the initial year of the research sample as the base year, which is used as the dependent variable (Yan et al., 2020; Lee and Lee, 2022). To examine the spatial correlation of fishery GTFP growth and its decomposition components, the corresponding Moran's I index is calculated, and the results are presented in Table 2. It indicates that most years show a positive Moran's I index, but only in 2013, 2014, 2015, and 2016 are the results statistically significant. For the fishery efficiency growth, the Moran's I index is positive and statistically significant in most years, while for the fishery technology growth, the Moran's I index is positive in most years, but statistically significant only in 2007, 2009, and 2019. These results suggest that fishery efficiency growth exhibits a more significant spatial correlation compared to fishery technology growth. Fisheries efficiency typically involves issues related to fisheries production management, and the diffusion of management knowledge can occur more rapidly through collaboration and exchange among fisheries producers in different provinces. In contrast, fisheries technological advancements involve technical aspects and may involve patent-related issues, resulting in relatively weaker spillover effects. The findings in Table 2 indicate the existence of spatial correlation. Therefore, it is necessary to employ spatial econometric models in the analysis of driving forces.

The independent variables are selected based on five dimensions: natural environment, infrastructure, human capital, market size, and government governance. The natural environment is measured by variables such as temperature (temp) and the incidence of fisheries disasters (natdis). Infrastructure is assessed using indicators such as internet penetration rate (internet) and transportation convenience (trans). Human capital is captured through indicators such as the education level of fishermen (aedu) and the provision of fisheries technical training (lnpeop). Market size is represented by trade openness (fishopen) and urbanization rate (urban. Government governance is evaluated by the proportion of environmental governance investment to gross domestic product (envir).

TABLE 1 The indicators used in the measurement of fisheries GTFP growth.

Category	Primary indicator	Secondary indicator	Unit
Input	Capital	Fishery capital stock	Billion yuan
	Land	Aquaculture area	Hectares
	Labor	Fishery employment	10,000 people
	Resource	Fingerling quantity	100 million
		Fishing Vessel Tonnage Gross	Tons
Output	Undesirable	Total nitrogen emissions	Tons
		Total phosphorus emissions	Tons
		COD emissions	Tons
	Desirable	Real fishery production value	100 million yuan
		Economic value of carbon sequestration	100 million yuan

2.3.3. Data source

China's fisheries GTFP growth is calculated using data from 30 provincial-level administrative region for the period of 2004–2019. The chosen time frame is based on the availability of data, as data prior to 2004 and after 2019 have significant gaps. Provincial-level administrative region such as Tibet, Hong Kong, Macau, and Taiwan were not included in the analysis due to limited data availability.

Data on aquaculture area, fisheries employment, fry quantity, and fishing vessel tonnage are sourced from the "China Fishery Statistical Yearbook" for input indicators. Fisheries capital input calculation utilizes fixed capital formation, fixed asset investment price index, and regional GDP data from the "China Statistical Yearbook." undesirable output, including total nitrogen, total phosphorus, and COD emissions, are calculated using production data for different fishery species from the "China Fishery Statistical Yearbook," combined with pollutant emission coefficients from the "Handbook of Pollutant Generation and Discharge Coefficients for Aquaculture in the First National Pollution Source Census." Desirable output, represented by fishery value-added, is obtained from the "China Fishery Statistical Yearbook," while the economic value of carbon sequestration is estimated using production data for shellfish and algae from the "China Fishery Statistical Yearbook."

In the section on driving force analysis, data for calculating provincial average temperature is obtained from the "China Meteorological Science Data Sharing Service Platform." To derive provincial average temperature, spatial interpolation is applied to convert daily observations from various weather stations into grid-point data, which is then regionally averaged. Fishery disaster area, aquaculture area, fishery technical training attendance, fishery trade, and total fishery output are sourced from the "China Fishery Statistical Yearbook." Internet penetration rate is obtained from the "Statistical Report on Internet Development in China." Grade highway is sourced from the "China Transport Statistics Yearbook." Rural labor force education level is derived from the "China Population and

TABLE 2 Spatial correlation test of fisheries GTFP growth and its decomposed components.

	Fisheries GTFP growth		Fisheries efficiency growth		Fishery technology growth	
Year	Moran	*P*-value	Moran	*P*-value	Moran	*P*-value
2005	−0.195	0.133	−0.242	0.036	−0.120	0.316
2006	−0.093	0.371	−0.227	0.120	−0.143	0.269
2007	0.116	0.194	0.246	0.033	0.317	0.024
2008	0.096	0.234	−0.018	0.463	0.170	0.128
2009	0.056	0.308	0.318	0.022	0.260	0.053
2010	0.111	0.210	0.273	0.039	−0.084	0.391
2011	0.145	0.162	0.368	0.011	−0.095	0.368
2012	0.030	0.361	0.356	0.012	0.182	0.111
2013	0.232	0.065	0.473	0.002	0.050	0.305
2014	0.360	0.012	0.443	0.003	0.015	0.391
2015	0.229	0.064	0.443	0.003	−0.094	0.369
2016	0.230	0.064	0.349	0.014	0.019	0.381
2017	0.134	0.169	0.362	0.011	0.105	0.216
2018	0.055	0.306	0.389	0.007	−0.121	0.313
2019	−0.048	0.469	0.342	0.015	−0.286	0.078

Employment Statistics Yearbook." Exchange rate from the "China Statistical Yearbook" is used to convert fishery trade volume reported in USD to CNY. Urbanization rate data is sourced from the "China Statistical Yearbook." Environmental governance investment is obtained from the "China Environmental Statistics Yearbook."

3. Results

3.1. Measurement of TFP and GTFP growth in China's fisheries sector

Based on the EBM model and the GML index, this study estimated China's fishery GTFP growth and its decomposition from 2004 to 2019. The estimation results are presented in Table 3. The results show that the annual average fishery GTFP experienced positive growth in 11 provincial-level administrative regions, including Qinghai, Hubei, Ningxia, Chongqing, Gansu, Fujian, Guizhou, Shaanxi, Beijing, Shanxi, and Jiangsu. Among them, Qinghai had the highest growth rate, reaching 4.7%. Compared to most provinces, Qinghai has a lower level of fishery development, which allows it to have greater growth potential than some other provinces. By learning from more developed provinces in the field of fisheries, Qinghai can access opportunities for rapid growth. Meanwhile, 19 provincial-level administrative regions, including Shanghai, Yunnan, Inner Mongolia, Jilin, Sichuan, Tianjin, Anhui, Shandong, Guangdong, Guangxi, Xinjiang, Jiangxi, Hebei, Henan, Zhejiang, Hainan, Hunan, Liaoning, and Heilongjiang, experienced a decline in annual average fishery GTFP. Among them, Henan had the fastest decline rate, with an average annual decrease of −4.2%. Looking at the decomposition components, efficiency showed positive growth in 10 provincial-level administrative regions, while technology exhibited positive growth in 27 regions. Moreover, in 23 regions, the rate of technological progress was faster than the rate of efficiency improvement. Overall, the growth of fishery GTFP was mainly driven by technological progress.

In addition, an interesting finding from Table 3 is that coastal provinces such as Shandong, Guangdong, and Zhejiang, known for their developed coastal areas, exhibit negative growth rates in fishery GTFP. These rates are significantly lower than those observed in some less-developed inland provinces. This finding may seem counterintuitive, as coastal provinces typically possess better technological conditions and institutional foundations. Several factors could account for this divergence. The decline in fishery GTFP in coastal provinces can be partially attributed to the substantial scale of fishing and aquaculture operations in these regions. The heightened strain on fishery resources and the environment might impede the overall fishery TFP level, particularly considering the environmental challenges specific to coastal areas. Another contributing factor could be the structural issues in resource allocation. Given their natural advantages as coastal regions, these provinces tend to prioritize marine aquaculture in resource allocation decisions. Consequently, the proliferation of marine ranches or blue grain storages, which require significant financial support, may inadvertently lead to a crowding-out effect on the development of freshwater aquaculture in coastal provinces. This phenomenon, in turn, might result in a relatively slower growth rate of freshwater aquaculture and ultimately impede the overall growth of fishery GTFP in these regions.

To further support this analysis, Table 4 provides additional insights by presenting the average annual growth rates of freshwater aquaculture and marine aquaculture GTFP for the 11 coastal provincial-level administrative regions. Averagely, the growth rate of marine aquaculture GTFP in coastal provinces from 2004 to 2019 was 9%, surpassing the average growth rate of 1.6% observed in freshwater aquaculture. These findings underscore the substantial divergence between the growth rates of marine and freshwater aquaculture GTFP.

Examining the provinces individually, except for Fujian and Liaoning, the growth rate of marine aquaculture TFP is higher than that of freshwater aquaculture TFP in all provinces. Combining the information from Tables 3, 4, it can be concluded that the lower growth rate of fishery TFP in coastal provinces is primarily due to the relatively lower growth rate of freshwater aquaculture TFP. This may reflect the crowding out effect of the rapid development of marine aquaculture on the development of freshwater aquaculture in coastal provinces, highlighting the contradiction in resource allocation between marine and freshwater aquaculture.

To compare the differences between fishery GTFP growth and TFP growth, Table 5 presents the estimation results of fishery TFP growth. By comparing these results with those in Table 3, it is evident that, on average, fishery GTFP has a growth rate of −0.5%, while TFP has a growth rate of 0.8%, indicating a difference of 1.3 percentage points. Therefore, disregarding the negative environmental externalities associated with fishery production can lead to an overestimation of fishery TFP growth. Similar conclusions have been drawn in studies from the agricultural sector (Pan and Ying, 2013), highlighting the tendency to overestimate TFP when environmental factors are not considered. Furthermore, substantial variations in efficiency are observed. When considering the negative environmental externalities, the growth rate stands at −0.6%, in contrast to the growth rate of 1.3% without such considerations, signifying a

TABLE 3 Average annual growth rates of fishery GTFP by province, 2004–2019.

Province	GTFP	EC	TC	Province	GTFP	EC	TC
Shanghai	−0.300	0.000	−0.300	Jiangxi	−0.900	−0.900	2.700
Yunnan	−0.900	−2.400	3.300	Hebei	−3.100	−2.900	0.300
Inner Mongolia	−1.100	−0.300	4.800	Henan	−4.200	−4.500	1.900
Beijing	0.500	0.000	0.500	Zhejiang	−0.400	−2.000	2.400
Jilin	−0.200	0.200	4.400	Hainan	−1.900	−2.300	1.200
Sichuan	−0.900	0.000	−0.900	Hubei	3.700	0.000	3.700
Tianjin	−3.900	−4.100	1.100	Hunan	−1.500	0.700	−0.700
Ningxia	2.100	2.400	0.600	Gansu	1.100	2.300	1.000
Anhui	−1.400	0.200	1.300	Fujian	1.300	0.000	1.300
Shandong	−1.400	−2.700	1.800	Guizhou	0.100	0.600	0.400
Shanxi	0.200	0.000	0.200	Liaoning	−2.800	−3.200	0.700
Guangdong	−0.600	−1.700	1.600	Chongqin	1.500	0.700	3.200
Guangxi	−3.100	−3.000	0.800	Shaanxi	1.200	2.700	4.400
Xinjiang	−1.700	1.300	4.600	Qinghai	4.700	3.500	1.100
Jiangsu	0.500	0.000	0.500	Heilongjiang	−2.100	−3.000	2.300
				Mean	−0.500	−0.600	1.500

TABLE 4 Average growth rate of fishery GTFP in coastal provinces from 2004 to 2019.

Province	Mariculture TFP	Freshwater aquaculture TFP	Province	Mariculture TFP	Freshwater aquaculture TFP
Shanghai	6.100	2.500	Hebei	8.600	−2.400
Tianjin	7.600	−4.200	Zhejiang	12.400	−9.600
Shandong	10.500	1.300	Hainan	5.300	−3.200
Guangdong	11.500	−3.700	Fujian	7.300	12.600
Guangxi	6.400	−2.900	Liaoning	13.200	28.100
Jiangsu	10.200	−1.400	Mean	9.000	1.600

significant discrepancy of 1.9 percentage points. A noteworthy distinction arises from the fact that the fishery technological progress displays negative growth when environmental externalities are overlooked, while it exhibits positive growth when accounting for these factors. This phenomenon may be attributed to the increasing emphasis on environmentally friendly-oriented technological advancements within China's marine aquaculture sector during the examined time frame (Ren and Zeng, 2021).

3.2. Comparison of TFP and GTFP growth trend in China's fisheries sector

Figure 1 presents the trends in fisheries TFP and GTFP. It also depicts the growth trend of fisheries output in constant prices (using 2004 as the base year). It is worth noting that the TFP (GTFP) calculated based on the GML index represents the relative change from the previous period and does not directly reflect the absolute change. To address this limitation, this study follows the approach suggested by previous studies (Li and Tao, 2012; Liu et al., 2022), where the TFP (GTFP) in 2004 is set as the reference point (equal to 1), and subsequent TFP (GTFP) values are computed by multiplying the TFP (GTFP) growth rate in each year by the corresponding GML index. This methodology is also applied to measure the growth of fisheries output to ensure comparability.

It can be found that the fisheries sector's output exhibits an overall upward trend. However, both TFP and GTFP show a slight decline, indicating that the growth in fisheries is driven by intensive factor inputs rather than contributions from TFP. In China's aquaculture industry, the majority of fish farmers operate on a small scale, resulting in a limited degree of scale efficiency. Their strategy for achieving higher output often involves increasing input factors such as feed and fingerlings per unit area, while investments in technology and management practices remain inadequate. In the fishing industry, increased inputs such as fishing vessels and labor are often utilized to enhance catch volumes, ultimately depleting fishery resources. The East China Sea has even experienced a situation where there are "no fish to catch," reflecting the extensive nature of fishing practices.

Additionally, an interesting phenomenon is observed. Before 2007, fisheries output growth was similar to TFP growth. However, a significant divergence occurred after 2007, with fisheries output continuing to increase while TFP experienced a slight decline. This phenomenon suggests that the contribution of input factors to fisheries growth is expanding, while the contribution of TFP is

TABLE 5 Average annual growth rates of fishery TFP by province, 2004–2019.

Province	TFP	EC	TC	Jiangxi	TFP	EC	TC
Shanghai	−1.300	0.000	−1.300	Hebei	1.000	0.000	1.000
Yunnan	−0.300	1.200	−1.500	Henan	−2.100	0.100	−2.200
Inner Mongolia	0.700	3.000	−2.200	Zhejiang	−5.100	−2.000	−3.200
Beijing	−0.500	0.000	−0.500	Hainan	1.800	0.000	1.800
Jilin	7.200	6.500	0.700	Hubei	1.100	−0.500	1.600
Sichuan	−1.200	0.000	−1.200	Hunan	1.500	0.000	1.500
Tianjin	−0.600	0.000	−0.600	Gansu	−2.300	0.000	−2.300
Ningxia	0.000	0.000	0.000	Fujian	1.900	0.000	1.900
Anhui	−0.500	−0.200	−0.300	Guizhou	1.100	0.000	1.100
Shandong	5.100	0.000	5.100	Liaoning	2.500	5.200	−2.600
Shanxi	−1.500	0.000	−1.500	Chongqin	7.100	3.600	3.400
Guangdong	−1.000	0.000	−1.000	Shaanxi	1.100	2.800	−1.700
Guangxi	−1.900	−1.000	−0.900	Qinghai	1.100	7.300	−5.800
Xinjiang	1.200	0.000	1.200	Heilongjiang	2.600	−0.200	2.800
Jiangsu	5.400	13.600	−7.200	Mean	0.000	0.000	0.000
				Jiangxi	0.800	1.300	−0.500

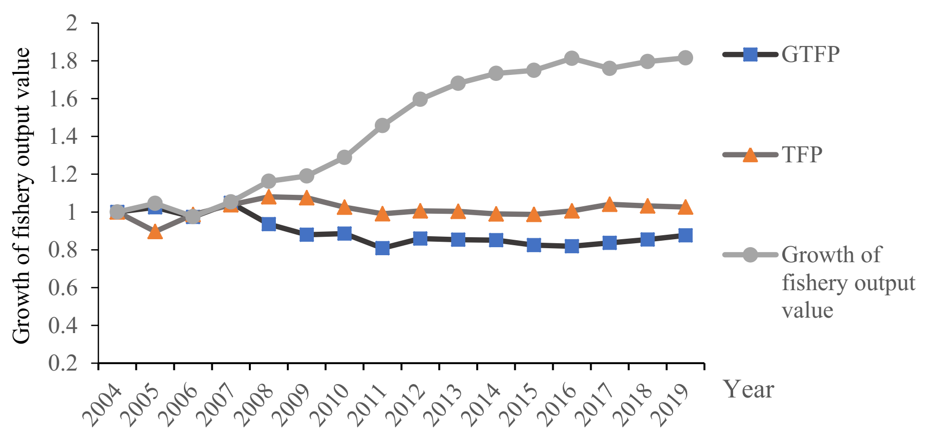

FIGURE 1
The trends of fishery TFP and GTFP growth.

diminishing. This may be related to China's previous extensive economic development pattern. Following the global financial crisis in 2008, the Chinese government initiated large-scale investments to mitigate the crisis, contributing to the extensive nature of China's economic development to some extent. Additionally, the economic growth pressure resulting from financial crises may lead to a relaxation of environmental regulatory.

3.3. Spatial evolution of GTFP growth in China's fisheries sector

Figure 2 presents the spatial distribution of the GTFP growth in the Chinese fisheries sector for the years 2004–2005 and 2018–2019. According to Figure 2A, during the period of 2004–2005, the provincial-level administrative region with positive growth in fisheries GTFP are Xinjiang, Qinghai, Inner Mongolia, Jilin, Yunnan, Hunan, Anhui, Liaoning, Shandong, Shaanxi, Chongqing, Guizhou, Hubei, Jiangxi, Shanghai, Zhejiang, and Guangdong, totaling 17 provincial-level administrative regions. Among them, Xinjiang, Qinghai, Shaanxi, Chongqing, Guizhou, Hubei, Liaoning, Jilin, Shandong, Jiangxi, Guangdong, Zhejiang, and Shanghai exhibited the fastest growth, belonging to the first tier. However, 13 provinces and cities including Heilongjiang, Gansu, Sichuan, Ningxia, Shanxi, Henan, Hebei, Beijing, Tianjin, Jiangsu, Guangxi, Hainan, and Fujian experienced a negative growth in GTFP in their fisheries sector.

According to Figure 2B, by 2019, there have been significant changes in the spatial distribution pattern of GTFP in China's fisheries sector. In terms of quantity, compared to the period of 2004–2005, the number of provincial-level administrative regions with positive growth rates in GTFP increased significantly during 2018–2019, with a total of 24 regions experiencing positive growth. However, the

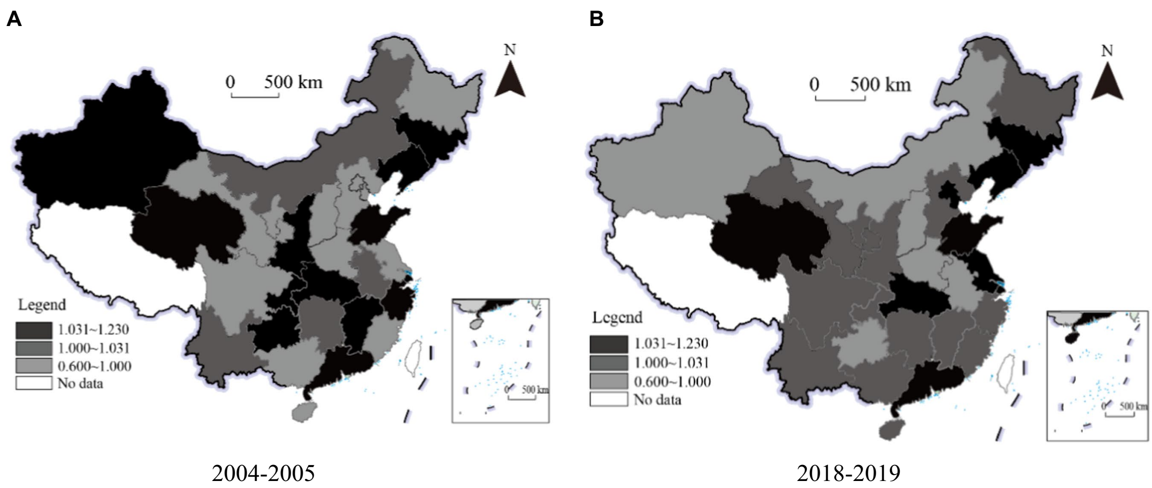

FIGURE 2
Spatial distribution and evolution of GTFP growth in China's fisheries industry. China's administrative system, Beijing, Shanghai, Tianjin, and Chongqing are considered municipalities directly under the central government and are at the same administrative level as provincial-level regions. Therefore, when referring to "cities" in the text, we are specifically talking about these four direct-administered municipalities.

TABLE 6 Model test results.

Null hypothesis	Test type	Statistics	P-value
Supporting random effects	Hausman	62.38	0.000
Supporting individual fixed effects	LR	61.33	0.000
Supporting time fixed effects	LR	348.35	0.000
SDM model can degenerate into the SEM	Wald	95.92	0.000
SDM model can degenerate into the SAR	Wald	92.39	0.000
SDM model can degenerate into the SEM	LR	41.65	0.000
SDM model can degenerate into the SAR	LR	43.30	0.000

number of regions belonging to the first tier in terms of growth decreased from 13 to 10.

Furthermore, examining the evolution of spatial distribution, it can be found that during the 2004–2005 period, the provincial-level administrative regions with the fastest growth rates were mainly located in the central and western regions. However, by 2018–2019, the provincial-level administrative regions with the fastest growth rates were primarily concentrated in the eastern coastal areas, with 8 out of the top 10 fastest-growing situated in the eastern region. Since China's accession to the WTO in 2001, the pace of opening up to the outside world has accelerated. As a forefront of openness, the eastern region has gained unprecedented development opportunities. The export volume of aquatic products has also increased significantly. However, the development of the fisheries sector has been relatively extensive, and the increase in export volume may have further solidified this development mode. Consequently, the growth of GTFP in certain provinces in the eastern region were relatively lower during the 2004–2005 period. However, since the new government took office in 2013, there has been a shift toward advocating high-quality development in the fisheries sector at the policy level. On the practical front, there have been continuous efforts to promote technological innovation and management practices. Leveraging better technological and industrial foundations, the eastern region has been at the forefront among all provinces and cities, leading to a rapid growth in GTFP in the fisheries sector.

3.4. Drivers of GTFP growth in China's fisheries sector

3.4.1. Estimation results of spatial econometric models

In this section, the initial model used is the SDM. The Hausman test is employed to determine whether the fixed effects should be included. The *p*-value based on the Hausman test, as shown in Table 6, is 0.000, rejecting the use of the Random Effects (RE) model. The Likelihood Ratio test is conducted to choose between individual fixed effects, time fixed effects, and the combination of both. The LR test results indicate that the *p*-values for all the options are 0.000, rejecting the use of only individual fixed effects or time fixed effects. Thus, the appropriate choice is the two-way fixed effects that includes both individual and time fixed effects. The three traditional spatial econometric model specifications are SDM, SAR, and SEM. For the same research question, these models may yield different estimation results. Therefore, before conducting model estimation, it is necessary to determine the specific model form. This study follows the testing strategy proposed by LeSage (2008) as well as Elhorst (2010). The SDM model is initially tested to examine whether it can degenerate into the SAR and SEM models. According to the results of the Wald test and LR test presented in Table 3, it is concluded that the SDM model cannot degenerate into the SEM and SAR models. Hence, the appropriate model choice is the SDM model. Considering all the testing results, this study adopts the SDM with two-way fixed effects. All subsequent empirical analyzes in this study will be based on this model.

Table 7 presents the estimation results of the model, columns (1) show that the spatial autoregressive coefficients ρ are all significantly positive. This suggests that provinces with similar levels of economic development in terms of their fisheries sector tend to mutually enhance their TFP, demonstrating a beneficial spatial interactive pattern.

Columns (1) to (2), present the estimated results of the effects of natural environment, infrastructure, human capital, macroeconomic conditions, and government governance factors, as well as their spatial lag terms, on fisheries GTFP. Considering that the effect of rising temperature on fisheries GTFP may not be linear, the quadratic term of temperature is included in the model. The results show that the coefficient of the quadratic term of temperature is negative and statistically significant, indicating a "inverted U-shaped" relationship between temperature and fisheries GTFP. This suggests that excessively high temperatures are detrimental to the improvement of GTFP. Internet penetration rate and transportation convenience both show significant positive correlations with fisheries GTFP. On one hand, internet usage helps fisheries producers access market information, management information, innovative knowledge, and fisheries technology, thereby improving the productivity of fisheries units. On the other hand, the widespread use of the internet enables fisheries producers to reduce financing costs, influencing fisheries production. Additionally, Ankrah Twumasi et al. (2021) mentioned another positive mechanism of internet usage influencing fisheries GTFP, which is the income effect brought by non-agricultural work that can improve productivity. The increase in non-agricultural income promotes agricultural household income growth, allowing agricultural producers to have more funds to invest in better machinery, equipment, higher-quality feed, or fertilizers, thereby stimulating productivity improvement (Ma et al., 2018).

Regarding human capital, the average education level of rural labor and fisheries technical training are positively correlated with fisheries GTFP, but only the average education level shows statistical significance based on significance tests. According to Wang et al. (2020), there are issues such as insufficient funds, outdated personnel structure, and inefficient management system in the promotion of aquaculture technology in China. This could be an important reason why fisheries technical training has not fully realized its potential. The level of trade openness has a negative correlation with fisheries GTFP, which is contrary to expectations. The potential reason for this is that the increase in trade openness not only expands the market size faced by fisheries producers but also increases the risks and uncertainties they face. The increase in uncertainty associated with trade openness outweighs the benefits it brings to GTFP, resulting in an inhibitory effect. Additionally, the negative impact may be related to the disproportionate increase in input costs such as aquaculture feed, labor, and land, and the price increase of exported fisheries products. The rise in input costs exceeds the increase in output prices, resulting in decreased output per unit of input and lowered fisheries GTFP. Another unexpected result is the estimated effect of environmental governance investment intensity. The result shows that the increase in environmental pollution control investment intensity has an inhibitory effect on fisheries TFP. This may be because environmental pollution control investment partly reflects government environmental regulations. According to existing studies (Ryan, 2012; He et al., 2020), in the short term, environmental regulations force producers to reduce pollution emissions, but they also increase the cost expenditure for producers, which hinder the improvement of GTFP.

The spatial lag coefficients for fisheries disaster rate, fisheries technical training person-times, fisheries trade openness, and urbanization rate are all positive and statistically significant. This indicates that an increase in these variables in one province has a positive spatial spillover effect on the fisheries GTFP of its economically similar provinces. The spatial lag coefficient for transportation convenience is negative and statistically significant,

TABLE 7 Estimated results of the SDM.

	(1)		(2)
	FGTFP		FGTFP
Temp	0.056	W*temp	−0.020
	(0.057)		(0.059)
Temp2	−0.004**	W*temp2	0.002
	(0.002)		(0.002)
Natdis	−0.000	W*natdis	0.001*
	(0.000)		(0.000)
Internet	0.004***	W*internet	0.002
	(0.002)		(0.002)
Trans	0.042**	W*trans	−0.059**
	(0.020)		(0.024)
Aedu	0.064**	W*aedu	0.054
	(0.030)		(0.043)
Lnpeop	0.008	W*lnpeop	0.022*
	(0.009)		(0.011)
Fishopen	−0.048*	W*fishopen	0.115***
	(0.026)		(0.033)
Urban	−0.000	W*urban	0.008*
	(0.003)		(0.004)
Envir	−0.032***	W*envir	−0.026
	(0.011)		(0.017)
ρ	0.117***		
	(0.040)		
Province fixed effects	YES		
Year fixed effects	YES		
Observations	480		
Within R^2	0.161		

Standard errors are shown in parentheses; ***, **, and * indicate significance at the 1, 5, and 10% levels, respectively.

suggesting an improvement in transportation convenience in one province has a negative spatial spillover effect on the fisheries GTFP of its economically similar provinces.

3.4.2. Decomposition of spatial effects

Despite the estimation results of the SDM provided in Table 7, which reflect the directions of the effects of natural environment, infrastructure, human capital, market size, and government governance on fishery GTFP, the point estimates of the coefficients do not capture the magnitude of the marginal effects of each factor on fishery GTFP. Therefore, following the approach presented by Lesage and Pace (2010), the effect of the five categories of factors on fishery GTFP is decomposed into direct effect, indirect effect, and total effect. The direct effect refers to the changes in fishery GTFP within a province caused by itself independent variables, including the spatial feedback effect on fishery GTFP. The indirect effect refers to the effect of the independent variables of a province on fishery GTFP in provinces with similar levels of economic development. The total effect is the sum of the direct and indirect effect. The decomposition is presented in Table 8.

The results of the direct effect in column (1) indicate that the estimated coefficients and significance of the quadratic term for temperature do not exhibit significant changes compared to Table 7. The estimated coefficient and statistical significance of internet penetration rate also remain unchanged. This result suggests that for every one-percentage-point increase in internet penetration rate, fishery GTFP will increase by 0.4%. The estimated coefficient for transportation convenience is 0.040, and it is statistically significant. This implies that for every one-percentage-point increase in the ratio of paved road mileage to land area, fishery GTFP will increase by approximately 0.04%. An increase of 1 year in the average years of education for rural residents will lead to a 6.8% increase in fishery GTFP. For every one-percentage-point increase in the ratio of fishery import and export trade to the total value of fishery production, fishery GTFP will decrease by approximately 0.04%. An increase of one percentage point in the proportion of environmental pollution control investment to GDP will result in a 3.4% decrease in fishery GTFP.

For indirect effect, for every one-percentage-point increase in the average fishery disaster rate of provinces with similar levels of economic development to the province being analyzed, the fishery GTFP of the province being analyzed will increase by approximately 0.1%. For every one-percentage-point increase in the ratio of paved road mileage to land area in provinces with similar levels of economic development to the province being analyzed, the fishery GTFP of the province being analyzed will decrease by approximately 0.06%. For every one-percentage-point increase in the number of technical training sessions for fishermen in provinces with similar levels of economic development to the province being analyzed, the fishery TFP of the province being analyzed will increase by approximately 0.03%. For every one-percentage-point increase in the ratio of import and export trade to the total value of fishery production in provinces with similar levels of economic development to the province being analyzed, the fishery GTFP of the province being analyzed will increase by approximately 0.12%. For every one-percentage-point increase in the urbanization rate in provinces with similar levels of economic development to the province being analyzed, the fishery GTFP of the province being analyzed will increase by approximately 0.8%.

Due to the different scales of the original variables, it is not possible to directly compare the estimated coefficients of the variables in columns (1) to (3) of Table 8. To determine which factor among the five factors of natural environment, infrastructure, human capital, market size, and government governance has the greatest promoting effect on fishery GTFP, all variables are standardized to unify the scales, and the model is re-estimated based on the standardized variables. The results are shown in columns (4) to (6) of Table 8. In column (4), the standardized coefficients of internet penetration rate and transportation convenience are the largest among all variables. Therefore, infrastructure has the largest positive direct effect on China's fishery GTFP, followed by human capital. Specifically, for every one-standard-deviation increase in internet penetration rate and transportation convenience, the growth rate of fishery GTFP in a province will increase by approximately 0.46 standard deviations and 0.29 standard deviations, respectively. In column (5), the standardized results show that the urbanization rate has the largest positive indirect effect on China's fishery GTFP, followed by the number of technical training sessions for fishermen and the degree of fishery trade openness. Therefore, in combination, market size has the largest positive indirect effect on China's fishery GTFP. For every one-standard-deviation increase in the urbanization rate, the number of technical training sessions for fishermen, and the degree of fishery trade openness in a province, the growth rate of fishery GTFP in provinces with similar levels of economic development to this province will increase by approximately 0.57, 0.22, and 0.21 standard deviations, respectively.

4. Conclusions and policy implications

Over the years, the inclusion of negative environmental externalities resulting from aquaculture pollution has posed a challenge in assessing fishery TFP growth at the provincial level in China. This study bridges this gap by estimating the negative environmental externalities associated with aquaculture, utilizing pollutant discharge coefficients from the "Handbook of Pollutant Generation and Discharge Coefficients for Aquaculture in the First National Pollution Source Census," and aquaculture production data from the "China Fishery Statistical Yearbook." By amalgamating the fishery capture and aquaculture sectors and integrating the estimations of aquaculture pollution emissions, this study endeavors to measure the GTFP growth of the entire fishery sector while meticulously examining the driving forces behind it.

Our study reveals that disregarding the environmental cost entailed by fishery production activities leads to an overestimation of fishery TFP growth. In comparison to GTFP growth that consider these costs, the growth rate of fishery TFP is inflated by 1.3% when such considerations are disregarded. In terms of its decomposition, the growth of fishery efficiency is overestimated by 0.7%, while fishery technological growth is underestimated by 1% in the absence of accounting for environmental costs. The expansion of fishery output primarily stems from augmented input factors rather than the TFP growth, indicative of an extensive pattern. Nonetheless, considering the progressively decelerating pace of fishery output growth, the contribution of increased input factors is gradually waning. Examining

TABLE 8 The decomposition of spatial effect.

	Standardized			Unstandardized		
	(1)	(2)	(3)	(4)	(5)	(6)
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
Temp	0.057	−0.017	0.040	1.3799	−0.4136	0.9663
	(0.057)	(0.056)	(0.040)	(1.3694)	(1.3626)	(0.9670)
Temp2	−0.004**	0.002	−0.001	−2.4929**	1.5193	−0.9736
	(0.002)	(0.002)	(0.002)	(1.2574)	(1.4350)	(1.1544)
Natdis	−0.000	0.001*	0.001	−0.0111	0.0818*	0.0707
	(0.000)	(0.001)	(0.001)	(0.0279)	(0.0468)	(0.0562)
Internet	0.004***	0.002	0.007***	0.4639***	0.2643	0.7282***
	(0.001)	(0.003)	(0.002)	(0.1579)	(0.2760)	(0.2697)
Trans	0.040**	−0.060**	−0.020	0.2880**	−0.4345**	−0.1466
	(0.019)	(0.025)	(0.035)	(0.1405)	(0.1824)	(0.2548)
Aedu	0.068**	0.067	0.136**	0.2504**	0.2466	0.4969**
	(0.030)	(0.048)	(0.062)	(0.1082)	(0.1751)	(0.2252)
Lnpeop	0.009	0.025**	0.034**	0.0752	0.2191**	0.2943**
	(0.009)	(0.012)	(0.017)	(0.0788)	(0.1076)	(0.1450)
Fishopen	−0.043*	0.117***	0.075	−0.0750*	0.2059***	0.1309
	(0.025)	(0.037)	(0.046)	(0.0444)	(0.0646)	(0.0812)
Urban	0.000	0.008*	0.008*	0.0191	0.5679*	0.5870*
	(0.003)	(0.004)	(0.004)	(0.2254)	(0.3235)	(0.3071)
Envir	−0.034***	−0.031	−0.065***	−0.1216***	−0.1133	−0.2349***
	(0.012)	(0.020)	(0.024)	(0.0422)	(0.0713)	(0.0881)

Standard errors are shown in parentheses; ***, **, and * indicate significance at the 1, 5, and 10% levels, respectively.

spatial distribution and evolution, we observe that in 2005, provinces and municipalities boasting the swiftest growth rates in GTFP were predominantly situated in China's central and western regions. Among the 12 provinces with the highest growth rates, 7 were concentrated in these areas. By 2019, the provinces and municipalities leading in growth rates were predominantly found in the eastern region, with 8 out of the top 10 provinces located there.

From the analysis of driving forces, provinces with similar levels of economic development in terms of their fisheries sector tend to mutually enhance their GTFP growth, demonstrating a beneficial spatial interactive pattern. The enhancement of fishery GTFP in a specific province can be facilitated by the improvement of factors such as internet penetration rate, transportation convenience, and rural residents' education level. Moreover, the fishery disaster rate, fisherman training, fishery trade openness, and urbanization rate in a province exhibit positive spatial spillover effects on the fishery GTFP growth of provinces with similar levels of economic development. When comparing the direct and indirect effects of these driving factors, it becomes apparent that infrastructure factors, including internet penetration rate and transportation convenience, exert the most significant direct influence on fishery GTFP growth. Market size factors, including trade openness and urbanization rate, on the other hand, exhibit the largest indirect effects on fishery GTFP growth.

The enhancement of GTFP in the fishery sector holds significant implications for achieving high-quality economic development in fisheries. Our study offers valuable policy insights to guide the advancement of China's fishery sector. Firstly, while prioritizing economic gains, it is imperative to ensure a balanced consideration of environmental benefits. This entails intensifying efforts to regulate pollution emissions arising from aquaculture activities and implementing stringent controls to prevent overfishing, thus safeguarding fishery resources. Secondly, the government should amplify its investments in foundational infrastructure, such as internet connectivity and road networks. This strategic approach aims to reduce information exchange costs and enhance logistical efficiency within the fishery sector. Thirdly, fostering regional market integration and bolstering inter-regional collaboration are pivotal. By promoting constructive interactions among different regions, we can stimulate the elevation of fishery GTFP and propel sustainable development.

There are still some areas that need further improvement in this study. Due to the difficulty in obtaining data on fishery resource stocks, this study directly uses the tonnage of fishing vessels as a measure of the pressure exerted by fishery production on fishery resources. However, this indicator may not be entirely accurate. For example, under different fishery resource stocks, the same tonnage of fishing vessels may exert different pressures on fishery resources. If we can collect data on fishery resource stocks in the future, it will enable us to estimate China's fishery GTFP more accurately and providing stronger support for the formulation of more effective fishery management and policies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

WS: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. HG: Supervision, Writing – review & editing, Data curation, Funding acquisition, Software. JB: Visualization, Data collection.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This research was supported by Zhejiang Province Philosophy and Social Science Planning Project (23NDJC255YB).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Álvarez, A., Couce, L., and Trujillo, L. (2020). Does specialization affect the efficiency of small-scale fishing boats? *Mar. Policy* 113:103796. doi: 10.1016/j.marpol.2019.103796

Ankrah Twumasi, M., Jiang, Y., Zhou, X., Addai, B., Darfor, K. N., Akaba, S., et al. (2021). Increasing Ghanaian fish farms' productivity: does the use of the internet matter? *Mar. Policy* 125:104385. doi: 10.1016/j.marpol.2020.104385

Aponte, F. R. (2020). Firm dispersion and total factor productivity: are Norwegian salmon producers less efficient over time? *Aquac. Econ. Manage.* 24, 161–180. doi: 10.1080/13657305.2019.1677803

Asche, F., Guttormsen, A. G., and Nielsen, R. (2013). Future challenges for the maturing Norwegian salmon aquaculture industry: an analysis of total factor productivity change from 1996 to 2008. *Aquaculture* 396-399, 43–50. doi: 10.1016/j.aquaculture.2013.02.015

Chang, Y.-C., Zhang, X., and Khan, M. I. (2022). The impact of the COVID-19 on China's fisheries sector and its countermeasures. *Ocean Coastal Manage.* 216:105975. doi: 10.1016/j.ocecoaman.2021.105975

Dey, M. M., Paraguas, F. J., Kambewa, P., and Pemsl, D. E. (2010). The impact of integrated aquaculture–agriculture on small-scale farms in southern Malawi. *Agric. Econ.* 41, 67–79. doi: 10.1111/j.1574-0862.2009.00426.x

Elhorst, J. P. (2010). Applied spatial econometrics: raising the bar. *Spat. Econ. Anal.* 5, 9–28. doi: 10.1080/17421770903541772

Guo, H., and Liu, X. (2021). Spatial and temporal differentiation and convergence of china's agricultural green total factor productivity. *J. Quant. Technol. Econ.* 38, 65–84. doi: 10.13653/j.cnki.jqte.2021.10.004

He, G., Wang, S., and Zhang, B. (2020). Watering down environmental regulation in China. *Q. J. Econ.* 135, 2135–2185. doi: 10.1093/qje/qjaa024

Holland, D., Gudmundsson, E., and Gates, J. (1999). Do fishing vessel buyback programs work: a survey of the evidence. *Mar. Policy* 23, 47–69. doi: 10.1016/S0308-597X(98)00016-5

Holland, D. S., Steiner, E., and Warlick, A. (2017). Can vessel buybacks pay off: an evaluation of an industry funded fishing vessel buyback. *Mar. Policy* 82, 8–15. doi: 10.1016/j.marpol.2017.05.002

Iliyasu, A., Mohamed, Z. A., and Terano, R. (2016). Comparative analysis of technical efficiency for different production culture systems and species of freshwater aquaculture in peninsular Malaysia. *Aquac. Rep.* 3, 51–57. doi: 10.1016/j.aqrep.2015.12.001

Jin, D., Thunberg, E., Kite-Powell, H., and Blake, K. (2002). Total factor productivity change in the New England groundfish fishery: 1964–1993. *J. Environ. Econ. Manag.* 44, 540–556. doi: 10.1006/jeem.2001.1213

Kareem, R. O., Aromolaran, A. B., and Dipeolu, A. O. (2009). Economic efficiency of fish farming in Ogun state, Nigeria. *Aquac. Econ. Manage.* 13, 39–52. doi: 10.1080/13657300802679145

Le, C.-Y., Feng, J.-C., Sun, L., Yuan, W., Wu, G., Zhang, S., et al. (2023). Co-benefits of carbon sink and low carbon food supply via shellfish and algae farming in China from 2003 to 2020. *J. Clean. Prod.* 414:137436. doi: 10.1016/j.jclepro.2023.137436

Lee, C.-C., and Lee, C.-C. (2022). How does green finance affect green total factor productivity? Evidence from China. *Energy Econ.* 07:105863. doi: 10.1016/j.eneco.2022.105863

LeSage, J. P. (2008). An introduction to spatial econometrics. *Rev. Econ. Ind.* 123, 19–44. doi: 10.4000/rei.3887

Lesage, J., and Pace, R. (2010). *Spatial econometric models*. Berlin, Heidelberg: Springer.

Li, G. (2014). The green productivity revolution of agriculture in China fr0m 1978 to 2008. *China Econ. Q.* 13, 537–558. doi: 10.13821/j.cnki.ceq.2014.02.011

Li, C., Feng, W., and Shao, G. (2018). Spatio-temporal difference of total carbon emission efficiency of fishery in China. *Econ. Geogr.* 38, 179–187. doi: 10.15957/j.cnki.jjdl.2018.05.022

Li, L., and Tao, F. (2012). Selection of optimal environmental regulation intensity for chinese manufacturing industry-based on the greenTFP perspective. *China Ind. Econ.* 30, 70–82. doi: 10.19581/j.cnki.ciejournal.2012.05.006

Liu, W., Du, M., and Bai, Y. (2022). Impact of environmental regulations on green total factor productivity. *China Popul. Resour. Environ.* 32, 95–107.

Long, L. K., Van Thap, L., Hoai, N. T., and Pham, T. T. T. (2020). Data envelopment analysis for analyzing technical efficiency in aquaculture: the bootstrap methods. *Aquac. Econ. Manage.* 24, 422–446. doi: 10.1080/13657305.2019.1710876

Ma, W., Abdulai, A., and Ma, C. (2018). The effects of off-farm work on fertilizer and pesticide expenditures in China. *Rev. Dev. Econ.* 22, 573–591. doi: 10.1111/rode.12354

McClanahan, T., Allison, E. H., and Cinner, J. E. (2015). Managing fisheries for human and food security. *Fish Fish.* 16, 78–103. doi: 10.1111/faf.12045

Mitra, S., Khan, M. A., and Nielsen, R. (2019). Credit constraints and aquaculture productivity. *Aquac. Econ. Manage.* 23, 410–427. doi: 10.1080/13657305.2019.1641571

Mitra, S., Khan, M. A., Nielsen, R., and Islam, N. (2020). Total factor productivity and technical efficiency differences of aquaculture farmers in Bangladesh: do environmental characteristics matter? *J. World Aquacult. Soc.* 51, 918–930. doi: 10.1111/jwas.12666

Newell, R. G., Sanchirico, J. N., and Kerr, S. (2005). Fishing quota markets. *J. Environ. Econ. Manag.* 49, 437–462. doi: 10.1016/j.jeem.2004.06.005

Nielsen, R., Hoff, A., and Andersen, J. L. (2023). Structural and productivity changes from introducing strong user rights in the Danish demersal fisheries. *Mar. Policy* 147:105385. doi: 10.1016/j.marpol.2022.105385

Oh, D. H. (2010). A global Malmquist-Luenberger productivity index. *J. Prod. Anal.* 34, 183–197. doi: 10.1007/s11123-010-0178-y

Pan, W., Xie, T., Wang, Z., and Ma, L. (2022). Digital economy: an innovation driver for total factor productivity. *J. Bus. Res.* 139, 303–311. doi: 10.1016/j.jbusres.2021.09.061

Pan, D., and Ying, R. (2013). Agricultural total factor productivity growth in China under the binding of resource and environment. *Resour. Sci.* 35, 1329–1338.

Pascoe, S., Coglan, L., Punt, A. E., and Dichmont, C. M. (2012). Impacts of vessel capacity reduction programmes on efficiency in fisheries: the case of australia's multispecies northern prawn fishery. *J. Agric. Econ.* 63, 425–443. doi: 10.1111/j.1477-9552.2011.00333.x

Pascoe, S., and Tingley, D. (2007). "Capacity and technical efficiency estimation in fisheries: parametric and non-parametric techniques" in *Handbook of operations research in natural resources*. eds. A. Weintraub, C. Romero, T. Bjørndal, R. Epstein and J. Miranda (Boston, MA: Springer US), 273–294.

Pincinato, R. B. M., Asche, F., Cojocaru, A. L., Liu, Y., and Roll, K. H. (2021). The impact of transferable fishing quotas on cost, price, and season length. *Mar. Resour. Econ.* 37, 53–63. doi: 10.1086/716728

Pipitone, V., and Colloca, F. (2018). Recent trends in the productivity of the Italian trawl fishery: the importance of the socio-economic context and overexploitation. *Mar. Policy* 87, 135–140. doi: 10.1016/j.marpol.2017.10.017

Ren, W., and Zeng, Q. (2021). Is the green technological progress bias of mariculture suitable for its factor endowment? Empirical results from 10 coastal provinces and cities in China. *Mar. Policy* 124:104338. doi: 10.1016/j.marpol.2020.104338

Ryan, S. P. (2012). The costs of environmental regulation in a concentrated industry. *Econometrica* 80, 1019–1061. doi: 10.3982/ECTA6750

Sanchirico, J. N., Holland, D., Quigley, K., and Fina, M. (2006). Catch-quota balancing in multispecies individual fishing quotas. *Mar. Policy* 30, 767–785. doi: 10.1016/j.marpol.2006.02.002

Sea, M. A., Hillman, J. R., and Thrush, S. F. (2022). The influence of mussel restoration on coastal carbon cycling. *Glob. Chang. Biol.* 28, 5269–5282. doi: 10.1111/gcb.16287

See, K. F., Ibrahim, R. A., and Goh, K. H. (2021). Aquaculture efficiency and productivity: a comprehensive review and bibliometric analysis. *Aquaculture* 544:736881. doi: 10.1016/j.aquaculture.2021.736881

Shao, G., Liu, B., and Li, C. (2019). Evaluation of carbon dioxide capacity and the effects of decomposition and spatio-temporal differentiation of seawater in China's main sea area based on panel data from 9 coastal provinces in China. *Acta Ecol. Sin.* 39, 2614–2625.

Shao, Y., Wang, Y., Yuan, Y., and Xie, Y. (2021). A systematic review on antibiotics misuse in livestock and aquaculture and regulation implications in China. *Sci. Total Environ.* 798:149205. doi: 10.1016/j.scitotenv.2021.149205

Solís, D., Agar, J. J., and del Corral, J. (2015). IFQs and total factor productivity changes: the case of the Gulf of Mexico red snapper fishery. *Mar. Policy* 62, 347–357. doi: 10.1016/j.marpol.2015.06.001

Solís, D., del Corral, J., Perruso, L., and Agar, J. J. (2014). Evaluating the impact of individual fishing quotas (IFQs) on the technical efficiency and composition of the US Gulf of Mexico red snapper commercial fishing fleet. *Food Policy* 46, 74–83. doi: 10.1016/j.foodpol.2014.02.005

Solow, R. M. (1957). Technical change and the aggregate production function. *Rev. Econ. Stat.* 39, 312–320. doi: 10.2307/1926047

Squires, D. (1992). Productivity measurement in common property resource industries: an application to the pacific coast trawl fishery. *Rand J. Econ.* 23, 221–236. doi: 10.2307/2555985

Sun, K., Cui, X., Su, Z., and Wang, Y. (2020). Spatio-temporal evolution and influencing factors of the economic value for mariculture carbon sinks in China. *Geogr. Res.* 39, 2508–2520.

Sun, K., Ji, J., Li, L., Zhang, C., Liu, J., and Fu, M. (2017). Marine fishery economic efficiency and its spatio- temporal differences based on undesirable outputs in China. *Resour. Sci.* 39, 2040–2051. doi: 10.18402/resci.2017.11.03

Tone, K., and Tsutsui, M. (2010). An epsilon-based measure of efficiency in DEA–a third pole of technical efficiency. *Eur. J. Oper. Res.* 207, 1554–1563. doi: 10.1016/j.ejor.2010.07.014

Van Beveren, I. (2012). Total factor productivity estimation: a practical review. *J. Econ. Surv.* 26, 98–128. doi: 10.1111/j.1467-6419.2010.00631.x

Van Nguyen, Q., Pascoe, S., Coglan, L., and Nghiem, S. (2021). The sensitivity of efficiency scores to input and other choices in stochastic frontier analysis: an empirical investigation. *J. Prod. Anal.* 55, 31–40. doi: 10.1007/s11123-020-00592-8

Van Nguyen, Q., and See, K. F. (2023). Application of the frontier approach in capture fisheries efficiency and productivity studies: a bibliometric analysis. *Fish. Res.* 263:106676. doi: 10.1016/j.fishres.2023.106676

Walden, J. B., Kirkley, J. E., Färe, R., and Logan, P. (2012). Productivity change under an individual transferable quota management system. *Am. J. Agric. Econ.* 94, 913–928. doi: 10.1093/ajae/aas025

Wang, P., Ji, J., and Zhang, Y. (2020). Aquaculture extension system in China: development, challenges, and prospects. *Aquac. Rep.* 17:100339. doi: 10.1016/j.aqrep.2020.100339

Wang, S. L., and Walden, J. B. (2021). Measuring fishery productivity growth in the northeastern United States 2007–2018. *Mar. Policy* 128:104467. doi: 10.1016/j.marpol.2021.104467

Wu, P., Wang, Y., Chiu, Y. H., Li, Y., and Lin, T.-Y. (2019). Production efficiency and geographical location of Chinese coal enterprises - undesirable EBM DEA. *Resour. Policy* 64:101527. doi: 10.1016/j.resourpol.2019.101527

Yan, Z., Zou, B., Du, K., and Li, K. (2020). Do renewable energy technology innovations promote China's green productivity growth? Fresh evidence from partially linear functional-coefficient models. *Energy Econ.* 90:104842. doi: 10.1016/j.eneco.2020.104842

Ye, F., Qin, S., Nisar, N., Zhang, Q., Tong, T., and Wang, L. (2023). Does rural industrial integration improve agricultural productivity? Implications for sustainable food production. *Front. Sustain. Food Syst.* 7:1024. doi: 10.3389/fsufs.2023.1191024

Yu, D., Liu, L., Gao, S., Yuan, S., Shen, Q., and Chen, H. (2022). Impact of carbon trading on agricultural green total factor productivity in China. *J. Clean. Prod.* 367:132789. doi: 10.1016/j.jclepro.2022.132789

Zhang, M., Cheng, Z., and Fan, Y. (2023). Exploring the impact of insect-resistant transgenic cotton application on agriculture total factor productivity under climate change. *J. Agrotech. Econ.* 42, 17–34.

Zhang, X., Shan, Z., and Yu, L. (2020). Green efficiency measurement and spatial spillover effect of china's marine carbon sequestration fishery. *Chinese Rural Econ.* 36, 91–110.

Zhong, S., Li, A., and Wu, J. (2022). The total factor productivity index of freshwater aquaculture in China: based on regional heterogeneity. *Environ. Sci. Pollut. Res.* 29, 15664–15680. doi: 10.1007/s11356-021-16504-8

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 13 November 2023
DOI 10.3389/fsufs.2023.1256860

OPEN ACCESS

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RECEIVED 11 July 2023
ACCEPTED 27 October 2023
PUBLISHED 13 November 2023

CITATION
Zornu J, Tavornpanich S, Shimaa AE, Addo S, Nyaga P, Dverdal MJ, Norheim K, Brun E and Cudjoe KS (2023) Bridging knowledge gaps in fish health management through education, research, and biosecurity.
Front. Sustain. Food Syst. 7:1256860.
doi: 10.3389/fsufs.2023.1256860

Bridging knowledge gaps in fish health management through education, research, and biosecurity

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Education, research, and biosecurity have global recognition as strong pillars of sustainable aquaculture development. In many developing countries, insufficient knowledge and awareness among stakeholders regarding the relevance of education, research, and biosecurity have influenced aquaculture sustainability negatively. To uncover the gaps in education, research, and biosecurity practices in aquatic animal health management, we conducted a questionnaire-based study in various East and West African countries. By adopting the methodology of self-reporting data, we invited a significant number of individuals to participate in the study. In the end, 88 respondents contributed, with the majority from Ghana (47) and Kenya (20), and 21 respondents from five other East and West African nations. The results revealed substantial educational gaps, including the need for practical training in aquatic animal health management, nutrition, and genetics. Respondents also emphasized the importance of creating additional national aquaculture research institutions and augmented funding to enable them to address industry needs. Governments of the represented nations should actively intervene by providing the essential logistics and capacity to support aquaculture research and development. Informed government involvement is paramount for bridging the disconnection among all stakeholders, as revealed in the results. Furthermore, the lack of biosecurity measures and the understanding of the importance of biosecurity measures in the industry addressed through awareness creation. Creating awareness on biosecurity underpinned with national aquaculture biosecurity policies can prevent disease incidences in the industry. The outcomes of this study can serve as a vital working document to enhance aquatic animal health management in East and West Africa, thereby fostering sustainable and resilient aquaculture.

KEYWORDS

African aquaculture, fish health management, education, research, biosecurity

1. Introduction

Severe exploitation of wild fish stocks in several geographical areas against the growing global human population, is expected to reach 9 billion by 2050 (United Nations, 2007; Oidtmann et al., 2011). This has increased pressure and demand on aquaculture to supplement capture fisheries to meeting the deficit in fish production. The aquaculture industry is already playing a key role in providing animal protein to support global food security. Egypt in North

Africa is the leading producer of farmed fish on the Africa continent, followed by East and West Africa, at second and third position, respectively (Hinrichsen et al., 2022). The adoption and implementation of better management practices for routine control, disease prevention and surveillance has not matched the intensification of aquaculture production (Kyule-Muendo et al., 2022). As a result, aquaculture in Africa and other regions have been subjected to many disease incidents of bacterial, viral, mycotic, and parasitic in nature.

Proper aquatic animal health management must accompany aquaculture practices to sustain the industry (Chinabut, 2001; Opiyo et al., 2018; Peeler and Ernst, 2019). Health services in aquatic animals are relatively undeveloped as compared to health services in terrestrial animals (Peeler and Taylor, 2011; Scarfe and Palić, 2020). In many of the developing countries, inadequate or lack of fish health services stems from the perception that fish do not get sick. However, this perception is changing particularly in Africa when the economic impacts of fish disease outbreaks have been devastating. Stakeholders are consequently gaining interest in fish health management through a myriad of national and regional projects (Kyule-Muendo et al., 2022) in the wake of these outbreaks. It is worthy to note that several related NORAD (Norwegian Agency for Development Cooperation)-financed projects aimed at boasting sustainable aquaculture production in East and West Africa have been initiated. For example, the ongoing Aquatic Animal Health in Africa project (AHA). AHA aims at increasing sustainability and resilience in the aquaculture sector by improving aquatic animal health management in East and West Africa (WorldFish, 2021). The beneficiary countries of the project are principally Ghana and Kenya but includes some neighbouring countries, due to recent economic losses caused by disease-causing vectors in their aquaculture sectors (Abarike, 2018; Opiyo et al., 2018). Among these other East and West African countries were Madagascar, Mozambique, Malawi, Zambia, Nigeria, and Mali as beneficiaries through training programs aimed at building a network of competent practitioners in aquatic animal health management across the continent. Central in the AHA project is the enhancement of education and the capacity-building in research and biosecurity to improve aquatic animal health management.

Education and training are essential for developing the right set of skills for aquatic animal health management. It is therefore paramount to identify the appropriate level of knowledge and technical skills needed in the curricular of educational institutions to effectively manage aquatic animal health (Weber et al., 2009; Scarfe et al., 2021). This will ensure that education focusses on providing not only degrees but the competencies and skills needed by aquatic animal health professionals. Educational institutions must provide competencies and skills that match the needs of the growing aquaculture industry in developing countries (Subasinghe et al., 2001). For this to happen, there should be effective partnership between public and private sectors, where expectations of all parties are clearly defined (Scutt and Ernst, 2019). Similarly, research institutions need public-private sector partnerships to undertake studies that inure to the benefit of the industry. The need to set up research institutions, co-funded through public-private sector collaborations to conduct targeted research in fish health management is essential (Anon, 2001; Bondad-Reantaso et al., 2005; Scutt and Ernst, 2019). Some of the essential research areas for fish health management include among others, hazards identification, transmission patterns, host susceptibility, and interventions (Peeler et al., 2007).

Identifying indispensable research areas is essential not only for conducting targeted research in fish health management but can inform specific biosecurity measures. Biosecurity is a fundamental component in fish health management practice to reduce the risk of introduction, establishment, and spread of diseases [World Organization for Animal Health (WOAH), 2019]. However, many developing countries have been lacking, inadequately implementing, or poorly applying biosecurity measures (Adah et al., 2023; Georges et al., 2023). These countries are increasingly recognizing the importance of aquaculture biosecurity and conducting sensitization programs. Yet, additional efforts are required to maintain this awareness through education and research (Osborn and Henry, 2019). In essence, education and research can form the foundation of fish health management by generating the necessary knowledge for creating robust biosecurity plans, which are critical for the success of aquaculture. The AHA project argues that by leveraging the power of education, research, and biosecurity in East and West Africa, we can promote aquatic animal health management for resilient aquaculture. This study therefore aims at identifying the gaps in education, research, and biosecurity practices to underpin capacity building initiatives in fish health management in East and West Africa.

2. Materials and methods

2.1. Study design and data collection

This is a cross-sectional study that collected data relevant to identifying the knowledge gaps in education, research, and biosecurity practices in East (Kenya) and West (Ghana) Africa. The data was collected using an online survey consisting of unstructured and structured questions (Table 1). The majority of the structured questions require nominal responses (e.g., Yes/No/Do not Know), including other responses based on predetermined categories (e.g., Likert scale, educational levels, etc.). There was an unstructured question conceived to investigate the major challenges affecting research quality and suggestions for improvement. The online survey was disseminated widely to aquaculture stakeholders in Ghana and Kenya, through emails and follow-up telephone calls to aquaculture associations and public sector institutions. These stakeholders working along the aquaculture value chain in academia, including private and public sector institutions are the target population of the study. The responses to the online survey were based on self-reporting leading to diverse respondents from the target countries, and other respondents in East and West Africa with aquaculture interest. Apart from collating diverse respondents, self-report studies are less expensive, not always time consuming, and representative of the target population for findings to be used in drawing general inferences (Short et al., 2009). The self-reporting of data through the online survey started in August 2021 and closed in May 2022 for data analysis.

2.2. Data analysis

The responses to the online survey were collated in Microsoft Excel and filtered to remove all blanks caused by unanswered questions. The diverse aquaculture respondents were then grouped into academia, private, and public sector based on a structured question that investigated their sector affiliations. This grouping became relevant in visualizing the distributions of nominal responses (Yes/No/Do not Know) across sectors. The nominal response data was categorized into contingency table, and then the Chi-square statistic ($\alpha = 0.05$) was calculated in SPSS to assess the association between the independent variables (sectors) and the dependent variables of Yes, No, and Do not Know. Chi-square statistic is a non-parametric test that analyzes group differences when the dependent variable is measured at a nominal level (McHugh, 2013). We therefore investigated whether the "Yes, No, and Do not Know" responses were independent or influenced by sector affiliations. Subsequently, the results were visualized in graphs using the number of respondents to the response categories, as a percentage of the total respondents to each question. The responses to some of the structured questions such as those on Likert scale were pooled together to draw general conclusions across sectors. This was necessary because the data becomes much more complex when analyzed in sectors yet did not produce any emergent information. The comments on the open-ended question were summarized including quoting of some selected comments as evidence of originality.

3. Results

3.1. Respondent characteristics

The final respondent sample consisted of 88 participants, comprising twenty (20) Kenyans, forty-seven (47) Ghanaians, and additional respondents from Madagascar (3), Mozambique (4), Nigeria (5), Malawi (4), and Zambia (5). In total, the response rate for all the questions was 97%. The lowest response rate was 36 out of 88 (Table 1; footer note), with an average response rate of 82.7 for the online survey questions. Table 2 shows the number of respondents in academia, private, and public sector, with 24, 16, and 48 individuals, respectively. This included the percentage of respondents per occupation according to their respective sectors.

3.2. Education

More than half of the respondents (55.2%) reported the introduction of aquaculture education at the university level. Twenty-eight percent (28.7%) selected the introduction of aquaculture education at the high school level, while 16.1% selected diploma level (Figure 1A). Aquatic animal health is taught through bachelor courses (64.4%) compared to 19.5%, 9.20%, and 6.9% for Master courses, infrequent courses, and "others" respectively (Figure 1B). At the high school level, 58% of the participants selected 'more than 40 students' as the percentage of students graduating each year. The number of aquaculture graduates with bachelor's degrees is 'more than 40 students' (73%) per year. The highest number of aquaculture graduates with master's degrees is distributed among "less than 20 students" and "20–40 students" as reported by 41% and 38% of correspondents, respectively. The number of graduates with aquaculture PhD degrees is less than 20 students (80%) per year (Figure 1C). In Figure 1D, majority of the respondents in academia (92%) and public (83%) sector confirmed the presence of aquatic animal health in the aquaculture curriculum, while the private sector showed some uncertainty (67%). The three most important gaps to consider in aquaculture curriculum planning for industry needs are aquatic animal health management (95.3%), aquatic animal nutrition (51.2%), and aquatic animal genetics (45.3%) (Figure 1E). The Pearson Chi-square statistics show that the responses were not influenced by sector affiliations (Figure 1D).

According to respondents (Figure 2A), the three most important gaps to consider in aquaculture curriculum planning to support government needs are controlling diseases and improving aquatic animal health management (77.9%), improving the regulatory aspects of aquaculture (38.4%), and increasing education related to aquatic animal genetics (33.7%). Across sectors, there were no responses indicating the exclusive teaching of aquatic animal health through practical courses alone. The private sector primarily views courses as theoretical (53%) but acknowledges that some practical training elements (47%) are included in the theoretical courses. Respondents from academia (58%) and the public (57%) sector confirmed a blend of practical and theoretical lessons (Figure 2B). The private sector takes the lead (67%) in providing entry-level training for newly hired technical staff. For academia and public sector, there is no clear evidence to affirmatively indicate entry-level training for newly hired technical staff, given the prevalence of "No" and "Do not Know" responses, which exceed "Yes" responses in both sectors (Figure 2C). Across all sectors, more than 40% of the respondents confirmed the absence of on-the-job training for technical staff. The private (43%) and public (42%) sectors confirmed presence of on-the-job training, whereas academia (24%) had a relatively lower rate (Figure 2D). Most of the respondents are inclined towards easy employability of graduates in the aquaculture industry. However, in national and provincial institutions, obtaining employment is not easy (Figure 2E). Pearson Chi-square statistics indicate that the responses were not influenced by sector affiliations (Figures 2B–D).

3.3. Research

More than 90% of the respondents confirmed the existence of institutions engaged in aquaculture research (Figure 3A). Over 60% of the respondents stated that the number of aquaculture research institutes is insufficient to support the industry needs (Figure 3B). Of the respondents, 55.2% indicated that aquaculture research questions were generated to meet academic interests, while, 27.6% mentioned that research questions addressed industry needs. About 17.2% of the responses pointed out that research primarily serves authority needs (Figure 3C). Aquaculture research is funded mainly by international organisations (41.9%) and through international collaboration (38.4%). National research funds for aquaculture was attributed to 18.5% of the respondents (Figure 3D). The Pearson Chi-square statistics indicated that the responses were not influenced by sector affiliations (Figures 3A,B).

More than 45% of the respondents from academia and private sectors indicated the absence of functional national laboratories dedicated to fish health diagnostics. Nonetheless, the public sector tend to confirm the presence of functional laboratories (56%), a clear bias to indicate a semblance of their usefulness (Figure 4A). The three main diagnostic laboratories available for confirming field diagnoses include public laboratories (46.5%), national reference laboratory (29.1%), and foreign laboratories (24.4%) (Figure 4B). There is

TABLE 1 Online survey questions to evaluate gaps in education, research, and biosecurity.

Theme	Question	Response categories	Response rate (a/b)*
Education	- At which academic level is the aquaculture education introduced?	High school; Diploma; University	87/88
	- At which level is aquatic animal health taught?	Bachelor courses; Master courses; Infrequent courses; others	87/88
	- At the national level, what is the average number of students graduating from these courses/year [High school; Bachelor; Master; PhD]#	Less than 20; 20–40; More than 40	252/264
	- Is aquatic animal health part of the aquaculture curriculum?	Yes; No; Do not know aquaculture curriculum?	87/88
	- What would you consider the 3 most important gaps to fill in the present aquaculture curriculum to support industry needs?	Aquatic animal nutrition; Aquatic animal genetics; Diseases and aquatic animal health management; to support industry needs? Basic farming knowledge; Technical knowhow; Environmental issues; Marketing and consumer perceptions; Food hygiene and quality; Economy; Others	86/88
	- What would you consider the 3 most important gaps to fill in the present aquaculture curriculum to support governmental needs?	Aquatic animal nutrition; Aquatic animal genetics; Diseases and aquatic animal health management; Basic farming knowledge; Technical knowhow; Environmental issues; Marketing and consumer perceptions; Food hygiene and quality; Economy; Regulatory aspects; Others	86/88
	- Are the aquatic animal health courses practical, theoretical, or both?	Practical; Theoretical; Both	86/88
	- Are newly hired technical staff given entry-level training?	Yes; No; Do not know	86/88
	- Are technical staff regularly called for continuation and on-the-job training?	Yes; No; Do not know	83/88
	- Graduates easily get employment in the following sectors [Aquaculture industry; National institutions; Provincial institutions]¤	Neutral; Agree; Disagree; Strongly agree; Strongly disagree	253/264
Research	- Are there any research Institutions doing aquaculture research as a primary focus?	Yes; No; Do not know	87/88
	- If yes, are they enough to support aquaculture industry in the country?	Yes; No; Do not know	87/88
	- In general, how are research questions generated?	Industry interest; Authority interest;	87/88
	- How is aquaculture research funded?	International organizations; International collaborations; National research funds; Industry funded	86/88
	- Are there dedicated national fish health diagnostic laboratories in service?	Yes; No; Do not know	87/88
	- What type of diagnostic laboratories confirm field diagnoses?	Foreign laboratories; National reference laboratory; Public laboratories; private laboratories; Do not know	86/88
	- Do research institutions meet farmers and industry expectations in terms of providing science-based solutions for aquaculture problems?	Yes; No; Do not know	87/88
	- Results from research are easily available for all stakeholders?	Neutral; Agree; Disagree; Strongly disagree; Strongly agree; Do not know	87/88
	- What are the major challenges affecting research quality? Any suggestions for improvement?	None (open-ended answers)	78/88
Biosecurity	- Are there regulations that guide government and industry's engagement in aquaculture?	Yes; No; Do not know	87/88
	- Are there legislation that mandate biosecurity on farms?	Yes; No; Do not know	86/88
	- Do you think there is high compliance to mandated biosecurity measures?	Yes; No; Do not know	86/88
	- How do competent authorities monitor biosecurity on farms?	Never; Do not know; When necessary; Annually	87/88
	- Is there a national aquatic animal biosecurity policy or plan?	Yes; No; Do not know	87/88
	- Are there biosecurity checklists to which farms must comply? [National biosecurity; Industry biosecurity; Farm biosecurity]α	Yes; No; Do not know	246/264
	- How do competent authorities monitor biosecurity on farms?	Questionnaires; Farmers self-reporting; Inspector extension service; Do not know; Other	86/88
	- Are farmers given any biosecurity specific training?	Yes; No; Do not know	86/88

*Response rate (a – number of respondents; b – total number of respondents). #36/88 – high school; 74/88 – bachelor; national institutions; 84/88 – provincial institutions. α85/88 – national biosecurity; 79/88 – industry biosecurity; 82/88 – farm biosecurity.

TABLE 2 Demographic information of sector respondents.

Sector (*N*)	Occupation	Percentage of respondents (n)
Academia (*N* = 24)	- Lecturer	62.5 (*n* = 15)
	- Student	16.7 (*n* = 4)
	- Research scientist	20.8 (*n* = 5)
Private (*n* = 16)	- Fish farmer	50 (*n* = 8)
	- Research scientist	31.1 (*n* = 5)
	- Feed producer	6.3 (*n* = 1)
	- Student	6.3 (*n* = 1)
	- Veterinarian/epidemiologist	6.3 (*n* = 1)
Public (*n* = 48)	- Compliance officer	52 (*n* = 25)
	- Research scientist	12.5 (*n* = 6)
	- Lecturer	14.6 (*n* = 7)
	- Veterinarian/epidemiologist	14.6 (*n* = 7)
	- Fish farmer	2.1 (*n* = 1)
	- Technician	2.1 (*n* = 1)
	- Unspecified	2.1 (*n* = 1)

N = total respondents/sector; *n* = subtotal of respondents/occupation.

insufficient evidence from academia regarding the sharing of science-based solutions, as 38% of responses were recorded for both "Yes" and "No" respectively. Majority (50%) of the private sector answered "Yes" while majority (46%) of the public sector answered "No" (Figure 4C). Regarding the availability of research findings, 20.7% of the respondents stated that research findings are made available to all stakeholders, with some respondents expressing neutrality (32.2%) and disagreement (33.3%). A small percentage of the respondents (9.2%) strongly disagreed on the availability of research findings (Figure 4D). Pearson Chi-square statistics indicated that the responses were not influenced by sector affiliations (Figures 4A,C).

3.3.1. Major challenges affecting research quality and suggestions for improvement

Funding is a major challenge affecting research quality. Respondents expressed concerns about inadequate funding from government and industry for purchasing equipment/tools, and supporting diagnostic and research works. Some responses provided evidence of reliance on international bodies for funding instead of receiving sufficient national funding to address industry needs through research. Here are some examples of comments supporting this concern: "*(1) Poor funding from the government and lack of logistics and (2) Most research funds come from external sources, therefore, research projects are often tailored to meet donors' needs.*" Some respondents mentioned problems related to weak infrastructural development and shortage of human resources. This includes antiquated laboratories and a limited number of fish health experts which in turn affect research quality. Comments supporting these limitations include: "*(1) The institutions conducting research are understaffed, which hinders their ability to conduct rigorous research that will result in accurate information and (2) Unavailability of essential equipment for conducting analyses*".

Other responses revealed the inadequacy of research bodies focusing on aquatic animal health. As a result, a recommendation was made for the establishment of Centres of Excellence in various universities dedicated to research and training in aquatic animal health management. Some respondents further suggested that these research centres could act as liaisons between the industry and government. Comments supporting these arguments include: "*(1) The establishment of a Centre of Excellence in a university dedicated to aquatic animal health, with the goal of spearheading research and training while acting as a liaison between industry and government and (2) The provision of infrastructure for aquatic animal health diagnostics and surveillance, including the establishment of a national reference laboratory*".

The respondents have also identified weak cooperation between researchers and the industry, as well as issues with poor research techniques and experimental designs. Some respondents have suggested establishing researcher-farmer partnerships to better understand industry needs. These partnerships are believed to inform the development of appropriate methodologies and experimental designs to generate research-based information necessary for industry use. According to some respondents, research quality has been compromised due to lack of trust between researchers and farmers. The respondents attributed this lack of trust to a failure to communicate research findings to the farmers who cooperated during data collection. Other responses have buttressed the weak linkage between universities, research institutes, and the industry. Supporting comments from the transcripts include: "*(1) Lack of effective coordination between the industry and academia, (2), Poor research techniques that affect the results of research, and (3) Weak linkages between research and the industry*".

3.4. Biosecurity

More than 80% of respondents across all sectors confirmed the presence of aquaculture regulations guiding government and industry engagements. However, about 10% of public sector respondents expressed a lack of knowledge ("Do not Know") regarding regulatory instruments, probably because they may not feel the effects of their

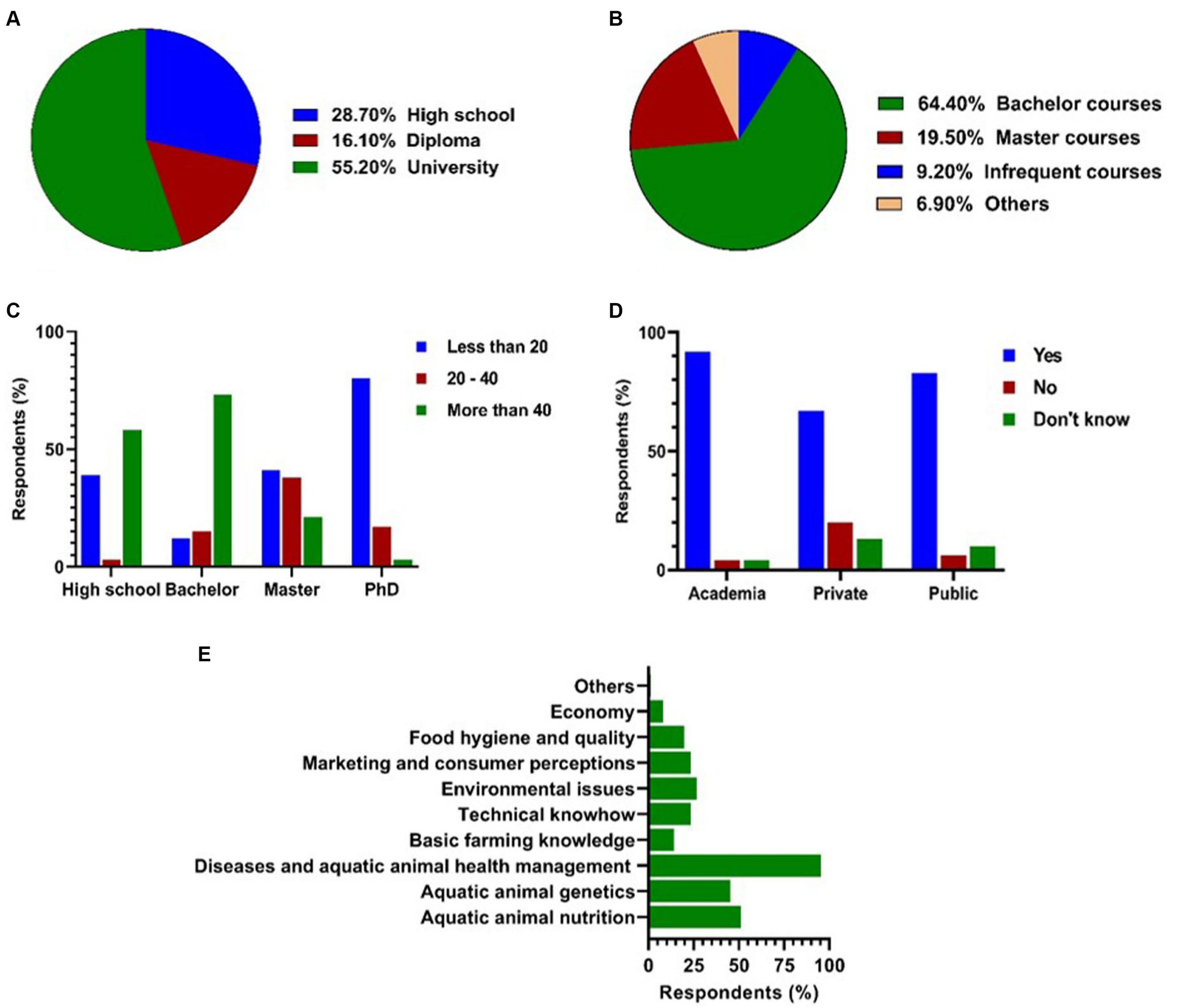

FIGURE 1
Overview of aquaculture and aquatic animal health education, aquaculture graduates, and aquaculture curriculum for industry needs. **(A)** Introduction of aquaculture education at different academic levels. **(B)** Level at which aquatic health education is acquired. **(C)** Number of aquaculture graduates per year. **(D)** Inclusion of aquatic animal health within the aquaculture curriculum. **(E)** Important gaps to fill in aquaculture curriculum to support industry needs [Pearson Chi-square test = **(D)**: 1.000, $p > 0.05$].

enforcement (Figure 5A). Over 50% of respondents from all sectors confirmed the existence of legislation mandating biosecurity on farms. Nonetheless, some respondents in public (30%) and private (27%) sectors disagreed about the presence of legislation mandating biosecurity on the farms exists (Figure 5B). From Figure 5C, the responses across all sectors are more than 65% to confirm non-compliance to biosecurity, while the academic respondents (17%) expressed lack of knowledge ("Do not Know") that is significantly higher compared to the responses from the other sectors. The respondents (52.9%) confirmed the monitoring of farm biosecurity when necessary, while 26.4% responded 'Do not Know' regarding the frequency of such monitoring (Figure 5D). Pearson Chi-square statistics indicated that the responses were not influenced by sector affiliations (Figures 5A–C).

More than 40% of the respondents from all sectors confirmed the presence of a national biosecurity policy. This was disputed by more than 20% of respondents from all sectors who disagreed, with more than 15% expressing "Do not Know" on the matter. It is concerning that academia had a high percentage (58%) of "Do not know" responses and confirmed the absence of national aquatic animal biosecurity policy (Figure 6A). In sum, "No" and "Do not know" responses collectively accounted for 50 and 75% respectively, confirming the absence of national and industry biosecurity checklist. However, "No" and "Do not know" responses combined were relatively low (49%) as compared to "Yes" (51%), confirming the presence of farm biosecurity checklist (Figure 6B). The majority of the respondents (65.1%) claimed that biosecurity is monitored during extension service delivery by inspectors. In contrast, only 14% of the respondents suggested farmers' self-reporting as a confirmation of farm biosecurity monitoring in practice (Figure 6C). There is high certainty among academic and private sector as more than 35% confirmed biosecurity specific training for farmers. Nonetheless, the public sector remained uncertain since 38% of the respondents agreed, but was disputed by 44% of the respondents

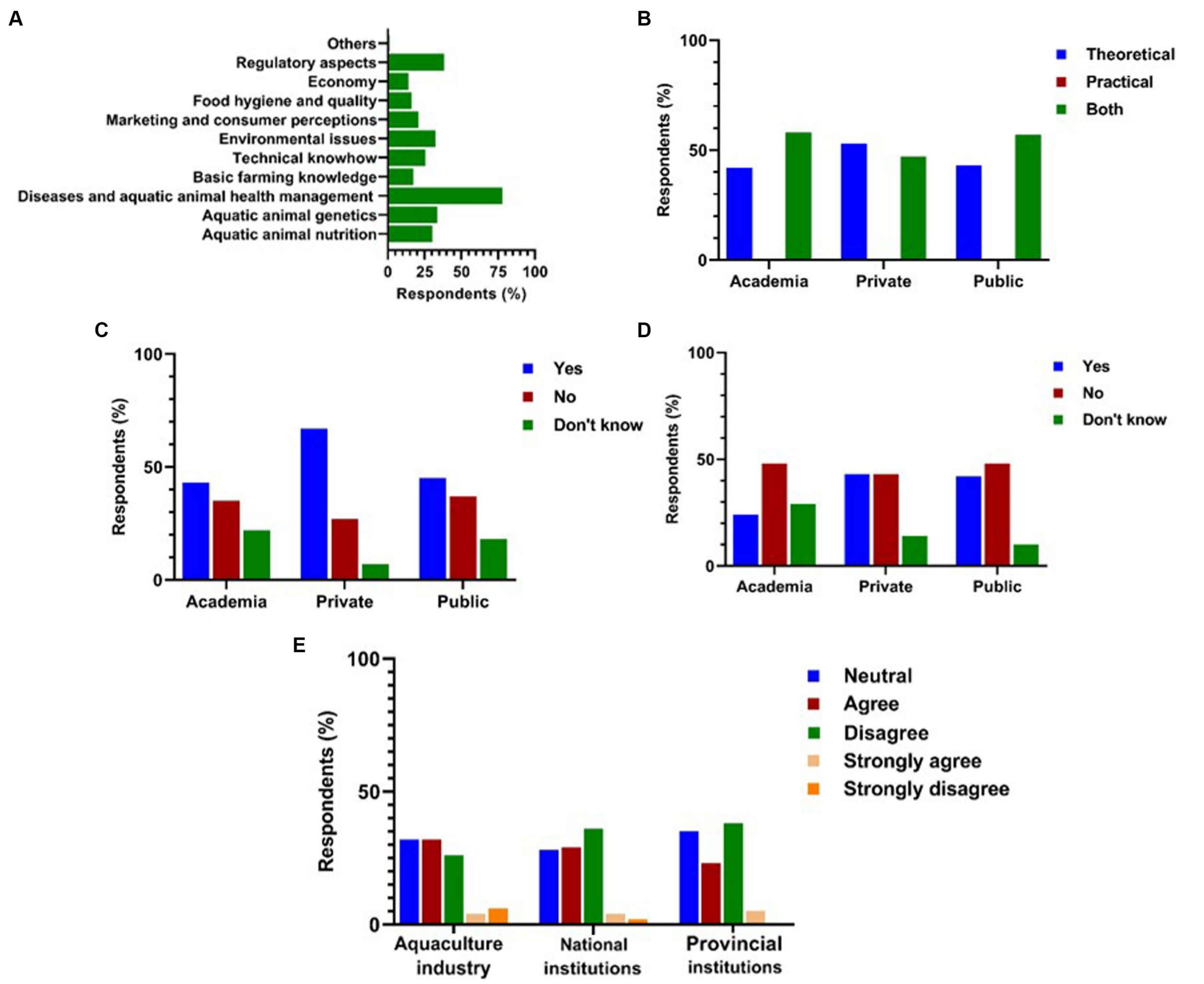

FIGURE 2
Enhancing aquaculture and aquatic animal health education, and workforce development to meet government and sector needs. **(A)** Important gaps to fill in aquaculture curriculum to support governmental needs. **(B)** The nature of aquatic animal health courses. **(C)** Entry-level training for newly hired technical staff. **(D)** On-the-job training for technical staff. **(E)** Graduates employability in the sector [Pearson Chi-square test = **(B)**: 0.871; **(C)**: 0.595; **(D)**: 0.352, $p > 0.05$].

(Figure 6D). The Pearson Chi-square statistics show that the responses were not influenced by sector affiliations (Figures 6A,D).

4. Discussion

Aquaculture is increasingly practiced in African countries to address food security needs and to generate personal incomes. The enterprise is however fraught with risks of major losses due to diseases. The sustainability of the industry has been negatively impacted by insufficient knowledge and awareness among stakeholders regarding the relevance of education, research and biosecurity practices. In this study, we aimed to bridge the knowledge gaps in research, education, and biosecurity, specifically in East and West Africa, with a focus on Ghana and Kenya. We conducted a questionnaire-based study, some of which were analyzed using tests of independence to investigate whether the responses were influenced by sector affiliations. The tests showed that the responses were independent of sector affiliations (for instance, Figures 3A, 4A, etc.).

4.1. Education

The health challenges in the growing field of aquaculture require educational reforms and training programs to improve the skills and services of health personnel in the industry (Dehaven and Scarfe, 2011). Based on the results and recommendations from the respondents, veterinary medicine education should include aquatic animal health rather than focusing solely on terrestrial animal health. This approach encourages education in aquatic animal health management, addressing the imbalance in veterinary medicine education, which often emphasizes competence in terrestrial animals (Hartman et al., 2006; Scarfe and Palić, 2020). Training in aquaculture and fish health management typically occurs at the tertiary level through Bachelor's and Master's Programs. This is

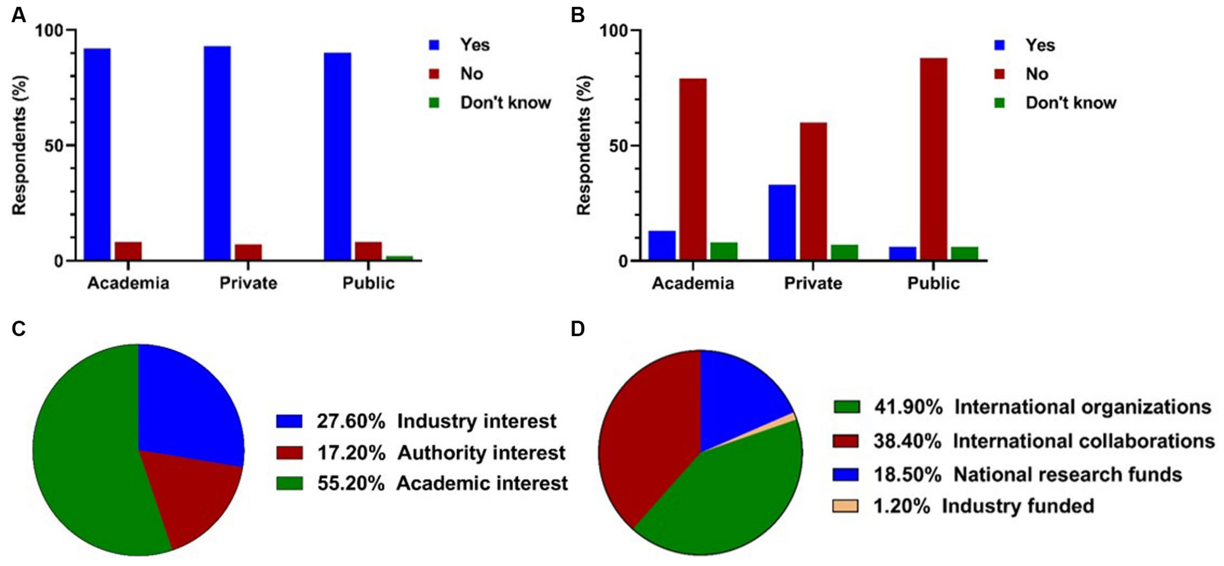

FIGURE 3
Mapping aquaculture research institutions: research questions and funding. **(A)** Presence of institutions pursuing aquaculture research. **(B)** Satisfactory presence of institutions supporting aquaculture research. **(C)** Means of formulating research questions. **(D)** Means of funding aquaculture research [Pearson Chi-square test = **(A)**: 1.000; **(B)**: 0.093, $p > 0.05$].

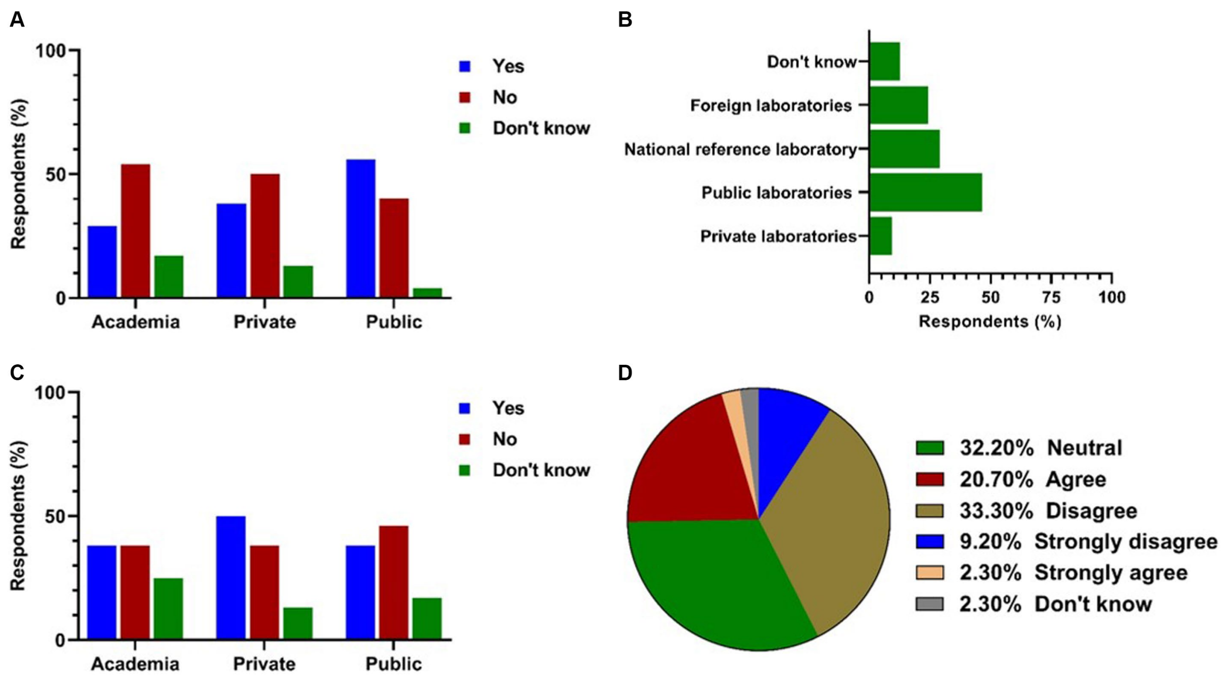

FIGURE 4
Comprehensive overview of fish health labs and knowledge exchange. **(A)** The presence of national fish health diagnostic laboratories. **(B)** Types of fish diagnostic laboratories. **(C)** Disseminating science-based solutions by research institutions to meet farmers and industry expectations. **(D)** Sharing of research findings among stakeholders [Pearson Chi-square test = **(A)**: 0.144; **(C)**: 0.784, $p > 0.05$].

evident from the strong representation of graduates from Bachelor's and Master's Programs. This presupposes that High School and Diploma graduates may not be adequately prepared for Bachelor's or Master's Programs in aquaculture and fish health management. The results also provide strong evidence for the inclusion of aquatic animal health in the aquaculture curriculum (Figure 1D). This inclusion is primarily at the Bachelor's level, with fewer representations at the Master's level (Figure 1B). It is clear from the foregoing that Bachelor's degree holders should be encouraged to pursue postgraduate programs in aquatic animal health to enhance their competence in managing emerging diseases that challenge the industry. Postgraduate programs require a diverse curriculum of

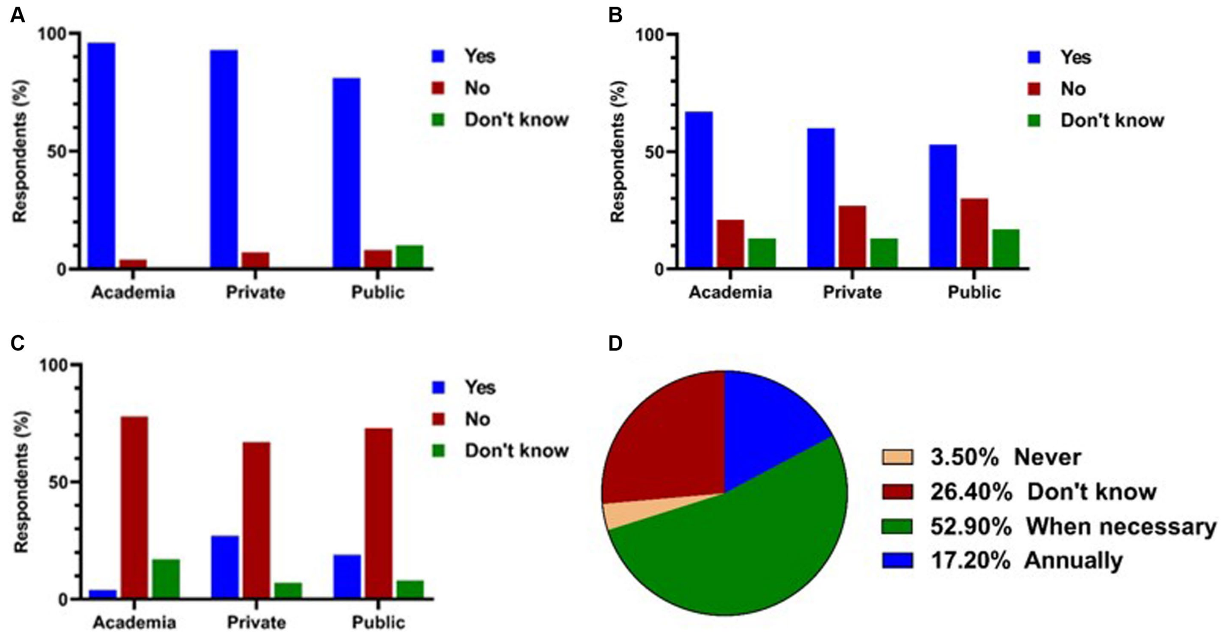

FIGURE 5
Examining monitoring and compliance to aquaculture regulations and biosecurity. **(A)** The existence of aquaculture regulations. **(B)** The presence of legislation mandating farm biosecurity. **(C)** Level of compliance to biosecurity measures. **(D)** How often competent authorities monitor biosecurity [Pearson Chi-square test = **(A)**: 0.298; **(B)**: 0.931; **(C)**: 0.316, $p > 0.05$].

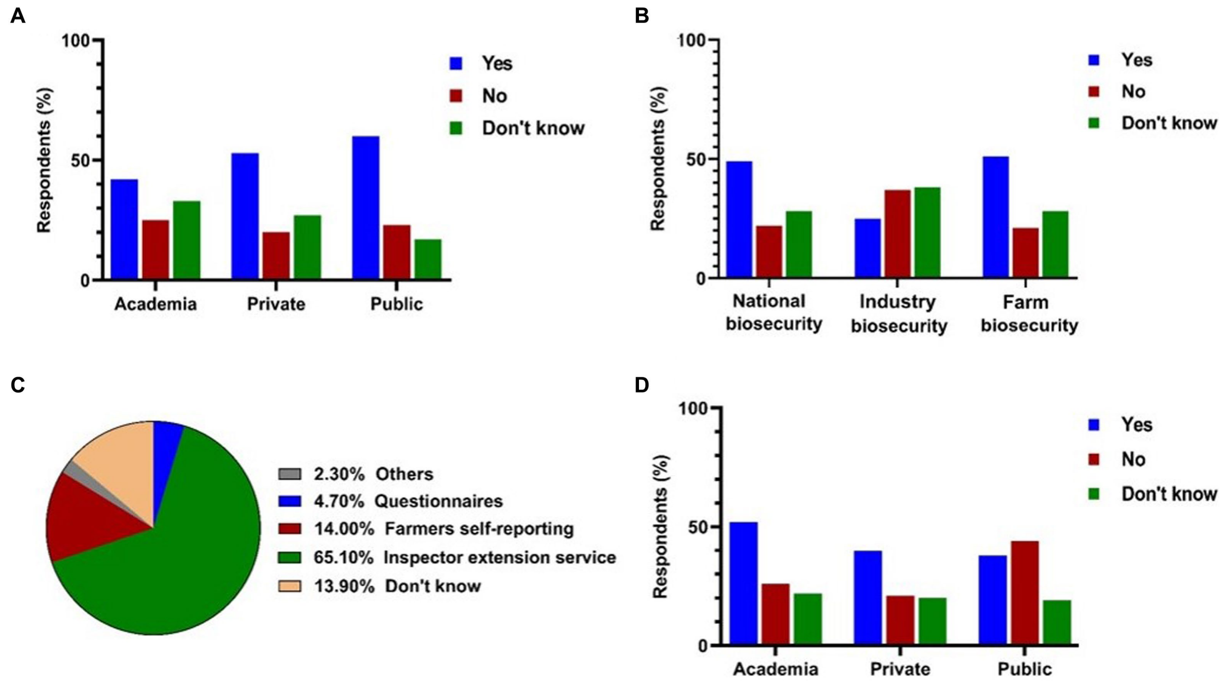

FIGURE 6
Examining presence of policy and checklists on biosecurity, its compliance, and level of biosecurity training. **(A)** Presence of a national policy on biosecurity for aquatic animals. **(B)** Presence of aquaculture biosecurity checklists. **(C)** Ways of monitoring farm biosecurity. **(D)** Biosecurity specific training offered to fish farmers [Pearson Chi-square test = **(A)**: 0.533, **(D)**: 0.587].

courses on aquatic animal health to produce a continuum of health professionals for the industry (Weber et al., 2009). In this study, the most relevant educational gaps to address in the current aquaculture curriculum include the training of more personnel in health management, nutrition and genetics. This approach will not only address the deficiencies in expertise related to health, nutrition, and genetics but facilitate the development of competencies in quality feed and seeds. Additionally, graduates with expertise in both health and nutrition will play a crucial role in developing balanced diets necessary for the optimal growth and health of fish (Oliva-Teles, 2012; Prabu et al., 2017).

The responses from the private sector suggest that there is an overemphasis on theoretical lessons (53%) compared to the preference for practical lessons in aquaculture education (Figure 2B). This may imply that graduates working with private sector institutions may have exhibited limited practical skills at the industry level. As a result, the private sector appears to recognize the importance of entry-level training and on-the-job training (Figures 2C,D), which they have incorporated into their employment practices. Through internal in-house training programs, employees can accumulate invaluable skills and knowledge that will mature over time as they gain long-term working experiences (Scarfe et al., 2021). It is therefore necessary to provide entry level and in-service training for technical persons across sectors to keep them abreast on emerging industry issues and strategies to overcome them. For example, farmers and extensions officers should be offered trainings that can enhance their knowledge of biosecurity and competence in controlling viral, bacterial, and parasitic diseases in aquatic animals (Lusiastuti et al., 2020). Additionally, academic institutions in represented countries are encouraged to pursue practical oriented aquaculture education. Educational strategies tailored to the needs of a country should be formulated through joint efforts involving all stakeholders. Government efforts should be focused on giving strategic policy direction based on a deep understanding of industry's needs, rather than relying on *ad hoc* measures. When educational institutions are tasked with meeting real industry needs while aligning with government strategic goals, a balanced triad is developed, providing the predictability and sustainability that the industry desperately needs. In summary, we recommend the inclusion of basic aquaculture education at the high school level. This can serve as preparation and motivation for students to pursue advanced aquaculture or related programs at the tertiary level. At the tertiary level, adequate infrastructural logistics are required to ensure that aquatic animal health education is practical oriented. The government can also offer scholarships as incentives to stimulate interest in pursuing education in aquatic animal health. Lastly, enhancing the skills of fish farmers and professionals in the field of aquaculture and fish health management can be achieved through robust educational curricular and routine training workshops.

4.2. Research

Research informs science-based decisions in any life science enterprise. While aquaculture research institutions exist in respondent countries, there is evidence to suggest that they are not meeting the country's research needs. This underscores the need for increased aquaculture research that addresses a wide range of topics to meet industry demands. Consequently, building interdisciplinary research competencies will enable collaboration and networking within and across participating countries. The results also show that aquaculture research questions are often formulated to align with academic interests rather than providing direct benefits to the industry (Figure 3C). The lack of direct government involvement in providing strategic national direction and funding is a major bottleneck to research development. In many African countries, government funding for aquaculture development has generally been low (Olapade, 2020; Ragasa et al., 2022). To address industry needs effectively, it is crucial to have national research funding accompanied by comprehensive research questions. This will enable academia and other research institutions to align with industry expectations and provide science-based solutions. International organizations collaborating with country-specific institutions are the primary sponsors of aquaculture research (Figure 3D). However, relying solely on international funding for research, without substantial government involvement can lead to skewed priorities that primarily serve foreign donors' demands to the disadvantage of recipient countries. This has been reported by Natsios (2005), suggesting that aid programs often prioritise the objectives of donor countries rather than addressing specific needs of recipient countries.

The availability of best aquaculture research infrastructures are paramount for conducting research and gaining new knowledge and technological advancements in aquaculture [Brugere et al., 2021; Ministry of Marine Affairs and Fisheries (MMAF), 2022; Further Africa, 2023]. In this study, research quality is impacted by weak infrastructure and human resource base, and it is limited in scope because research questions are not holistic and multidisciplinary. This is evident in Figure 3B concerning the unsatisfactory presence of institutions supporting aquaculture research. This also includes the uncertainty regarding the existence of national fish health diagnostic laboratories (Figure 4A). More than 45% of respondents from academia and private sector indicated the absence of functional national fish health diagnostic laboratories. In contrast, the public sector tends to confirm the presence of functional laboratories (56%), which indicates a bias towards acknowledging their potential usefulness (Figure 4A). These conflicting responses highlight a disconnection between industry, academia, and government. Furthermore, the existing laboratories are publicly owned (Figure 4B) with obsolete equipment, insufficient number of technicians and researchers. The government of represented countries need to intervene by providing the necessary logistics and human resources to support diagnostics, education, and research services. As highlighted by Hansen (2023), biological and technological developments in aquaculture require modern infrastructure to improve education and research services for the industry. Additionally, the results from this survey suggested that the establishment of national reference laboratories is essential to confirm results and establish protocols that guide diagnostic and research works. The recommendations for the establishing research centres in universities to serve as liaisons between industry and government should be implemented. These centres can guide the development of specific training courses for students and industry personnel, equipping them with the skills necessary for the growth of the industry.

The private aquaculture sector is at the forefront and is directly impacted by industry sustainability challenges such as disease outbreaks. However, the results suggest that research institutions are not effectively disseminating science-based solutions among fish farmers to solve industry problems (Figure 4C). Meanwhile, fish farmers appreciate the culture of sharing information and discussing solutions with relevant stakeholders to adopt coping strategies for the ongoing uncertainties in the industry (Tonje et al., 2017). Research bodies and academia are knowledge-based institutions that should play a crucial role in transferring science-based information to address sustainability issues. Collaborative research is essential in represented countries, where close partnerships between researchers, research institutions, universities, and farmers are needed. Such collaborations will keep researchers in the loop of industry problems and make their findings useful for sustainable growth. Presently, there is a lack of trust, which may have stemmed from insufficient communication between researchers and industry personnel for sharing research findings (Figure 4D). This aligns with earlier findings suggesting that lack of communication in sharing information can lead to mistrust among fish farmers and stakeholders in the industry (Agyei, 2022; Falconer et al., 2023). Researchers should prioritise effective communication of research findings to stakeholders throughout the aquaculture value chain in a user-friendly manner.

4.3. Biosecurity

Practical biosecurity which prevent disease-causing agents into aquaculture premises and control their spread is the bedrock of a successful industry. Aquaculture practitioners must understand this important pillar of sustainable aquaculture development. This must be reinforced by government agencies mandated to enforce regulations designed to protect the industry from disease causing agents.

The majority of sector respondents provided evidence of aquaculture and biosecurity regulations in the represented countries. However, compliance is notably low (Figure 5C). This can be attributed to policy implementing agencies not being adequately resourced to discharge their duties. Consequently, activities such as biosecurity monitoring are only conducted reactively when the need arises, compared to routine monitoring (Figure 5D). This pattern may be linked to the prevailing approach to health management in African aquaculture, which tends to be reactive than proactive in protecting the industry against disease-causing agents (FAO, 2018). This survey further revealed a high level of certainty among academic and private sector respondents, with more than 35% confirming biosecurity specific training for farmers. Nonetheless, the public sector remained uncertain, with 38% of respondents in agreement but disputed by 44% of respondents (Figure 6D). However, academia's claim of providing biosecurity training to farmers contradicts their earlier responses regarding the existence of biosecurity policies or plans and their enforcement (Figures 5A,B). In responses from academia, it emerged majority of 58% have insufficient biosecurity knowledge and confirmed the absence of a national biosecurity policy or plan. This observation is concerning and could potentially impact students' training in biosecurity if educational institutions give less preference to aquatic animal health courses. Knowledge-based institutions are expected to make education more responsive to meet industry needs (Nda and Fard, 2013; Kuna et al., 2022). Additionally, academia confirmed a lack of compliance with mandated biosecurity measures, a situation that could further complicate the essence of biosecurity measures in the education to students. Meanwhile, a bulk of the graduates are easily employed in the aquaculture industry where biosecurity measures are most needed (Figure 2E). Biosecurity training especially for students and fish farmers should be a continual process to facilitate the adoption and compliance to biosecurity measures. This must include national biosecurity policies for aquatic animals in represented countries that underpin the implementation of aquaculture biosecurity measures.

In addition, biosecurity checklists are generally lacking at the industry level compared to checklist imposed by competent authorities and based on farmer initiatives. This is not new, as most countries lack regulations to enforce disease prevention in aquaculture (Leaño, 2022; Adah et al., 2023). As a result, fish farmers' practices generally do not align with biosecurity principles. Consequently, the aquaculture industry may remain unregulated in terms of biosecurity compliance. For instance, inputs such as feed and seed delivered to fish farmers may already be compromised in terms of contamination and quality. This can have significant negative impacts on fish health at the farm level. Therefore, we propose implementing biosecurity checklists alongside biosecurity trainings. It is imperative to adopt collaborative approaches that allow regulatory authorities and private sector institutions to complement each other's expertise for shared biosecurity monitoring. Involving the private sector enables them to support and contribute to government efforts in addressing biosecurity risks in various aspects, including policy, knowledge-base, capacity building, and investments (FAO, 2015). This collaborative approach will pave way for holistic strategies in monitoring fish health and aquaculture activities in general to ensure sustainability across the participating countries.

While this study contributed to identifying the gaps in educations, research, and biosecurity, one of its limitations is the reliance on self-reported data from respondents. Although the online survey forms were distributed to many individuals, not all chose to respond, resulting in the limited number of study participants (or sample size). Self-report studies are less expensive and not time consuming, but having researchers conduct one-on-one interactions with participants can potentially increase the response rate and sample size. Nevertheless, the study provided a snapshot of the research, education, and biosecurity gaps in the represented countries.

5. Conclusion

To enhance aquatic animal health management in East and West African nations, this study identified the gaps in education, research, and biosecurity. The results suggest that aquatic animal health education should adopt practical approaches rather than focusing solely on theory. It is therefore critical to address the need for additional personnel trained in aquatic animal health management, nutrition, and genetics through practical oriented education. The disconnection among academia, private, and public sectors requires close partnerships to establish developmental goals for the aquaculture industry. These partnerships can shape educational curriculums and training programs to develop the necessary competence to meet industry goals. Moreover, the government must be intentional about providing adequate resources to support national aquaculture research institutions in their collaborative efforts with stakeholders to generate requisite knowledge for industry decision making. The respondents also recognized the need to establish a national reference laboratory for research, confirming field observations, and validating diagnostic results. Furthermore, the lack of biosecurity measures and understanding of the importance of biosecurity measures in the industry addressed through awareness creation. Creating awareness on biosecurity underpinned with national aquaculture biosecurity policies can prevent disease incidences in the industry. The outcomes of the study can guide aquaculture stakeholders in East and West Africa to foster sustainable and resilient aquaculture as they address the gaps in education, research, and biosecurity practices.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JZ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. ST: Conceptualization, Investigation, Methodology, Writing – review & editing. AS: Conceptualization, Investigation, Methodology, Writing – review & editing. SA: Conceptualization, Investigation, Methodology, Writing – review & editing. PN: Conceptualization, Investigation, Methodology, Writing – review & editing. MD: Conceptualization, Investigation, Methodology, Writing – review & editing. KN: Conceptualization, Investigation, Methodology, Writing – review & editing. EB: Conceptualization, Investigation, Methodology, Writing – review & editing. KC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was undertaken as part of the Aquatic Animal Health Africa project, "Increased Sustainability in the Aquaculture Sector in Sub-Saharan Africa, through improved Aquatic Animal Health Management" led by WorldFish and the Norwegian Veterinary Institute. The project is supported by the Norwegian Agency for Development Cooperation (NORAD) grant no. RAF-19/0051.

Acknowledgments

All stakeholders that volunteered to participate in providing information during the survey are duly acknowledged.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abarike, E. (2018). A review of Ghana's aquaculture industry. *J. Aquac. Res. Dev.* 9, 2–6. doi: 10.4172/2155-9546.1000545

Adah, D. A., Saidu, L., Oniye, S. J., and Adah, A. S. (2023). An assessment of the impacts of biosecurity measures on mortality of fish from fish farms. *Aquac. Stud.* 23:AQUAST1060. doi: 10.4194/AQUAST1060

Agyei, B. P. (2022). *Sustainability of pond and cage fish farming Systems in the Ashanti, bono, eastern and Volta regions in Ghana (unpublished master's thesis).* Norwegian University of Life Sciences, Ås, Norway.

Anon (2001). "Aquaculture development: financing and institutional support" in *Aquaculture in the third millennium. Technical proceedings of the conference on aquaculture in the third millennium, Bangkok, Thailand, 20–25 February 2000*. eds. R. P. Subasinghe, P. Bueno, M. J. Phillips, C. Hough, S. E. McGladdery and J. R. Arthur (Rome: NACA, Bangkok and FAO), 259–263.

Bondad-Reantaso, M. G., Subasinghe, R. P., Arthur, J. R., Ogawa, K., Chinabut, S., Adlard, R., et al. (2005). Disease and health management in Asian aquaculture. *Vet. Parasitol.* 132, 249–272. doi: 10.1016/j.vetpar.2005.07.005

Brugere, C., Padmakumar, K. P., Leschen, W., and Tocher, D. R. (2021). What influences the intention to adopt aquaculture innovations? Concepts and empirical assessment of fish farmers' perceptions and beliefs about Aquafeed containing non-conventional ingredients. *Aquac. Econ. Manag.* 25, 339–366. doi: 10.1080/13657305.2020.1840661

Chinabut, S. (2001). Health management for sustainable aquaculture. In L. M. B. Garcia (Ed.), Responsible aquaculture development in Southeast Asia. Proceedings of the seminar-workshop on aquaculture development in Southeast Asia organized by the aquaculture department, southeast Asian fisheries development center, 12–14 October 1999, Iloilo City, Philippines (pp.115–119). Tigbauan, Iloilo, Philippines: Aquaculture department, southeast Asian fisheries development center. Bondad

Dehaven, W., and Scarfe, A. D. (2011). Professional education and aquatic animal health: A focus on aquatic veterinarians and veterinary Para-professionals. Proceedings of the OIE global conference on AquaticAnimal health: Aquatic animal health Programmes: Their benefits for global food security.

Falconer, L., Cutajar, K., Krupandan, A., Capuzzo, E., Corner, R. A., Ellis, T., et al. (2023). Planning and licensing for marine aquaculture. *Rev. Aquac.* 15, 1374–1404. doi: 10.1111/raq.12783

FAO (2015). Side event – Biosecurity and public-private sector partnership (PPP): A shared responsibility. Eighth Session. Sub-Committee on aquaculture. Available at: https://www.fao.org/cofi/43803-058361d8762ef9d2197aa2d01c4a4175c.pdf

FAO (2018). *Development of a regional aquatic biosecurity strategy for the southern African development community (SADC).* FAO Fisheries and Aquaculture circular no. C1149. Rome. 344.

Further Africa (2023). Developing sustainable aquaculture in Africa. Farmers review Africa Available at: https://furtherafrica.com/2023/02/01/developing-sustainable-aquaculture-in-africa/. (Accessed June 12, 2023)

Georges, F., Judith Georgette, M., Alex Henri, K., Franck, K. D., Jacques, N., Julius, A. N., et al. (2023). Determining factors and Zootechnical output of biosecurity practices in fish farms in the Wouri division, Cameroon. *Vet. Med. Int.* 2023:2504280. doi: 10.1155/2023/2504280

Hansen, K. S. (2023). Investing 90 million in the aquaculture industry of the future. Available at: https://nofima.com/press-release/investing-90-million-in-the-aquaculture-industry-of-the-future/ (Accessed June 12, 2023)

Hartman, K., Yanong, R., Harms, C., and Lewbart, G. (2006). The future of training for aquatic animal health veterinarians. *J. Vet. Med. Educ.* 33, 389–393. doi: 10.3138/jvme.33.3.389

Hinrichsen, E., Walakira, J., Langi, S., Nabil, A., Tarus, V., Badmus, O., et al. (2022). *Prospects for aquaculture development in Africa: a review of past performance to assess future potential.* Center for Development Research (ZEF). doi: 10.48565/bonndoc-17

Kuna, P., Hašková, A., and Hodál, P. (2022). Tailor-made training for industrial sector employees. *Sustainability* 14:2104. doi: 10.3390/su14042104

 10.3389/fsufs.2023.1256860

Kyule-Muendo, D., Otachi, E., Awour, F., Ogello, E., Obiero, K., Abwao, J., et al. (2022). Status of fish health management and biosecurity measures in fish farms, cages and hatcheries in Western Kenya. *CABI Agri. Biosci.* 3:18. doi: 10.1186/s43170-022-00086-7

Leaño, E. M. (2022). Collection and evaluation of existing guidelines and awareness materials on aquaculture biosecurity for small-scale farms in the Asia-Pacific region. Network of Aquaculture Centres in Asia-Pacific. Available at: https://rr-asia.woah.org/wp-content/uploads/2022/07/final-report-woah-naca-aquaculture-biosecurity-project-final.pdf

Lusiastuti, A. M., Taukhid, M., Murwantoko, P. S. B., Sugiani, D., and Caruso, D. (2020). Building and improving the capacity of fish and environmental health management strategy in Indonesia. *Earth Environ.* 521:012016. doi: 10.1088/1755-1315/521/1/012016

McHugh, M. L. (2013). The Chi-square test of independence. *Biochem Med (Zagreb)* 23:143. doi: 10.11613/BM.2013.018

Ministry of Marine Affairs and Fisheries (MMAF) (2022). Indonesia: infrastructure improvement for shrimp aquaculture project. Project Number: 55020–55001. Available at: https://www.adb.org/sites/default/files/project-documents/55020/55020-001-rrp-en.pdf

Natsios, A. S. (2005). Five debates on international development: the US perspective. *Dev. Policy Rev.* 24, 131–139. doi: 10.1111/j.1467-7679.2006.00318.x

Nda, M. M., and Fard, R. Y. (2013). *The impact of employee training and development on employee productivity*, The Global Journal of Commerce and Management Perspective. vol. 2, 91–93.

Oidtmann, B. C., Thrush, M. A., Denham, K. L., and Peeler, E. J. (2011). International and national biosecurity strategies in aquatic animal health. *Aquaculture* 320, 22–33. doi: 10.1016/j.aquaculture.2011.07.032

Olapade, J. O. (2020). The role of international donors in aquaculture development in Africa. *IntechOpen*. doi: 10.5772/intechopen.86569

Oliva-Teles, A. (2012). Nutrition and health of aquaculture fish. *J. Fish Dis.* 35, 83–108. doi: 10.1111/j.1365-2761.2011.01333.x

Opiyo, M., Marijani, E., Muendo, P. N., Odede, R., Leschen, W., and Karisa, H. C. (2018). A review of aquaculture production and health management practices of farmed fish in Kenya. *Int. J. Vet. Sci. Med.* 6, 141–148. doi: 10.1016/j.ijvsm.2018.07.001

Osborn, A., and Henry, J. (2019). The role of aquaculture farm biosecurity in global food security. *Rev. Sci. Tech.* 38, 571–587. doi: 10.20506/rst.38.2.3005

Peeler, E. J., and Ernst, I. (2019). Introduction: improved aquatic animal health management is vital to aquaculture's role in global food security. *Rev. Sci. Tech.* 38, 361–383. doi: 10.20506/rst.38.2.2992

Peeler, E. J., Murray, A. G., Thebault, A., Brun, E., Giovaninni, A., and Thrush, M. A. (2007). The application of risk analysis in aquatic animal health management. *Prev. Vet. Med.* 81, 3–20. doi: 10.1016/j.prevetmed.2007.04.012

Peeler, E. J., and Taylor, N. G. (2011). The application of epidemiology in aquatic animal health -opportunities and challenges. *Vet. Res.* 42:94. doi: 10.1186/1297-9716-42-94

Prabu, E., Felix, S., Felix, N., Ahilan, B., and Ruby, P. (2017). An overview on significance of fish nutrition in aquaculture industry. *Int. J. Fish. Aqua. Stud.* 5, 349–355.

Ragasa, C., Charo-Karisa, H., Rurangwa, E., Tran, N., and Shikuku, K. M. (2022). Sustainable aquaculture development in sub-Saharan Africa. *Nat. Food* 3, 92–94. doi: 10.1038/s43016-022-00467-1

Scarfe, D., Padrós, F., Iatridou, D., Bravo, A., Palić, D., and Fabris, A. (2021). Workshop report: aquatic animal health education. *Bull. Europ. Ass. Fish Patholo.* 41, 225–232. doi: 10.48045/001c.36867

Scarfe, D., and Palić, D. (2020). Aquaculture biosecurity: Practical approach to prevent,control, and eradicate diseases. *Aquaculture Health Management*. 75–116. doi: 10.1016/b978-0-12-813359-0.00003-8

Scutt, K., and Ernst, I. (2019). Sharing responsibility between public and private sectors for the management of aquatic emergency animal diseases. *Rev. Sci. Tech.* 38, 533–570. doi: 10.20506/rst.38.2.3004

Short, M., Goetzel, R., Pei, X., Tabrizi, M., Ozminkowski, R., DeJoy, D., et al. (2009). How accurate are self-reports? Analysis of self-reported health care utilization and absence when compared with administrative data. *J. Occup. Environ. Med.* 51, 786–796. doi: 10.1097/JOM.0b013e3181a86671

Subasinghe, R. P., Bondad-Reantaso, M. G., and McGladdery, S. E. (2001). Aquaculture development, health and wealth. In: Subasinghe, R. P., Bueno, P., Phillips, M. J., Hough, C., McGladdery, S. E., Arthur, J. R. (Eds.). Aquaculture in the third Millenium. Technical proceedings of the conference on aquaculture in the third Millenium, Bangkok, Thailand. Available at: http://www.fao.org/DOCREP/003/AB412E/ab412e09.htm

Tonje, C., Osmundsen, P. A., and Ragnar, T. (2017). Fish farmers and regulators coping with the wickedness of aquaculture. *Aqua. Econ. Manag.* 21, 163–183. doi: 10.1080/13657305.2017.1262476

United Nations (2007) −−*World population prospects: the 2006 revision, vol. I, Comprehensive Tables* (United Nations publication, ST/ESA/SER.A/261/ES, ISBN 978-92-1-151429-2).

Weber, E. S., Blanc, G., and Hedrick, R. P. (2009). Essential veterinary education in fish health and disease: a global perspective. *Rev. Sci. Tech.* 28, 551–558. doi: 10.20506/rst.28.2.1893

World Organization for Animal Health (WOAH) (2019) Aquatic animal health code. Available at: https://www.oie.int/index.php?id=171&L=0&htmfile=glossaire.htm. (Accessed May 24, 2023).

WorldFish (2021). *Increased sustainability in the aquaculture sector in sub-Saharan Africa, through improved aquatic animal health management*. Penang, Malaysia: WorldFish. Fact Sheet: 2021-10

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 23 November 2023
DOI 10.3389/fsufs.2023.1296265

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OPEN ACCESS

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RECEIVED 18 September 2023
ACCEPTED 30 October 2023
PUBLISHED 23 November 2023

CITATION
Barros D, Nova P, Cunha S, Monteiro V, Fernandes É, Pereira-Pinto R, Barbosa C, Pintado M, Gomes A and Vaz-Velho M (2023) Enhancing storage stability of smoke-flavored horse mackerel filets using natural extracts as preservatives.
Front. Sustain. Food Syst. 7:1296265.
doi: 10.3389/fsufs.2023.1296265

Enhancing storage stability of smoke-flavored horse mackerel filets using natural extracts as preservatives

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The Atlantic horse mackerel (*Trachurus trachurus*) is a globally favored fish due to its abundance, nutritional value, and affordability, but it faces quality preservation challenges. To address this, this study aimed to enhance its value by creating low-salt smoked products with natural bioactive compounds from seafood and forest sources. The fish filets were divided into four groups: one as a control, and the others were treated with various bioactive extract solutions, specifically pine bark, mussels, and microalgae. After 15 days of storage at 4°C, significant differences in properties were observed. Moisture and salt had an inverse relationship, with decreasing moisture and pH over time. Oxidation levels remained acceptable, although sensory quality was affected by storage. Microbiological analysis uncovered high contamination levels in certain samples at specific points in time, although no pathogens such as *Salmonella* spp. or *Listeria monocytogenes* were detected. While microalgae extract was the most powerful antioxidant, its performance was hampered by the poor sensory scores. On the other hand, pine bark extract was the most acceptable from a sensory point of view and revealed some antimicrobial inhibition. Using natural antioxidants provides an appealing solution for consumers seeking products with clean labels.

KEYWORDS

bioactive extracts, salt reduction, smoked fish, pine bark extract, mussel extract, microalgae extract

1 Introduction

Fisheries and aquaculture products play a vital role in human food, and it is estimated that about 15% of the world's ingested animal protein comes from fish (FAO, 2012, 2017). Portugal is one of the largest consumers of fish in the world (first consumer of fish in European Union and third worldwide), with abundant fish species on its coast, but little valued both commercially and by the final consumer, leading to the need for simultaneous import of significant volumes of other species (Almeida et al., 2015; Silva et al., 2020). Fish is greatly perishable but an essential foodstuff due to its protein and unsaturated fatty matter contents. Horse mackerel (*Trachurus trachurus*), a medium-fat species abundant in the northeast Atlantic (Adeyemi et al., 2013), plays a significant role in the world's marine fisheries (Karoui and Hassoun, 2017).

Currently, the food industry's quest for extended shelf life, in conjunction with consumers' preferences for healthy, safe, and convenient food options, has spurred the exploration of innovative preservation methods. Within the food sector, the employment of antioxidants ranks among the frequently employed means to manage lipid oxidation. Various traditional techniques for delivering antioxidants have been utilized for this objective, including direct mixing for minced products and methods such as spraying, glazing, or injection for whole muscle pieces, as discussed in a study (Baptista et al., 2020). Antioxidants, whether natural or synthetic, play a crucial role in slowing down or preventing the oxidative breakdown of substances, especially unsaturated fatty acids, during processing and storage. These antioxidants need to efficiently hinder oxidation at lower concentrations, maintain stability throughout processing and storage, and should be free from any undesirable odors, tastes, or toxicity. Additionally, antioxidants contribute to prolonging shelf life without adversely affecting sensory attributes or nutritional content (Rathod et al., 2021).

Numerous plant extracts have been used for food applications (Pazos et al., 2006; Khan et al., 2009; Ucak et al., 2011). Recent efforts focus on the positive role of antioxidant molecules in plant extracts. Thus, successful applications have widely been carried out on marine oils (Thorisson et al., 1992; Hamilton et al., 1998), minced fish (Ramanathan and Das, 1992; Boyd et al., 1993) and filets (He and Shahidi, 1997; Khalil and Mansour, 1998). In works published so far, bark extracts are a good source of phenolic compounds (Jerez et al., 2007; Aspé and Fernández, 2011) with different extraction processes using various solvents, affecting the composition and biological activity of the extracts (Tümen et al., 2018). Bark extracts of *Pinus pinaster* have a mixture of many substances used to treat a wide range of degenerative diseases through their antioxidative, anti-inflammatory, antitumor, antiatherogenic, antiviral, and antimicrobial properties. They have cardiovascular and cholesterol-lowering benefits and increase microcirculation by increasing capillary permeability (Tümen et al., 2018). Nowadays, there is great interest centered on the potential benefits of adding bioactive compounds to food products due to their known antioxidant and antimicrobial activities, arousing scientific interest mainly due to the high number of microorganisms resistant to emerging antibiotics (Balasundram et al., 2006; Jerez et al., 2007; Seabra et al., 2012; Chupin et al., 2015), and Atlantic pine bark extracts becoming in some way interesting for the pharmaceutical and food industries, mainly by patenting them as a source of procyanidins under the trade names of Pycnogenol®, Oligopin® as well as Flavangenol®, Mármol et al. (2019), Dziedziński et al. (2021), and Alonso-Esteban et al. (2022). Some studies published on using Pycnogenol in meat products (Ahn et al., 2004, 2007; Hameş-Kocabaş et al., 2008) reported a reduction of *Staphylococcus aureus*, *Escherichia coli* O157:H7 and *Salmonella typhimurium* and delayed growth of *Listeria monocytogenes* and *Aeromonas hydrophila*. In studies carried out by Iglesias et al. (2010), adding maritime pine bark extracts to fish muscle reduced the formation of lipid oxidation products.

Regarding seaweeds, highly productive photosynthetic organisms, their great metabolic and physiological diversity makes them a sustainable source of various products with commercial interest. In recent years, much interest has been focused on the biotechnological potential of macro and microalgae. As a natural source of bioactive compounds, algae have a wide range of biological activities, including antimicrobial, antioxidant, antitumor, antiviral, and anti-inflammatory, besides other health benefits (Mendes et al., 2013; Fleita et al., 2015; Michalak and Chojnacka, 2015; Pane et al., 2015; Sousa et al., 2016). Until now, the antimicrobial potential of algae has generally been tested *in vitro*, providing reliable quantitative estimates of minimum inhibitory concentration (MIC) values for many samples (Pina-Pérez et al., 2017). Compounds reported as present in algae include phlorotannins, terpenoids, phenolic compounds, acrylic acid, steroids, cyclic polysulfides, ketones and halogenated alkanes, and also fatty acids that act as bactericidal agents (Watson and Cruz-Rivera, 2003). *Tetraselmis* species are sources of polyunsaturated fatty acid (PUFAs), vitamin E, carotenoids, chlorophyll, tocopherols, and polyphenols (Pérez-López et al., 2014). Several algae species are commercially cultivated in some countries. The biomass produced is used as a source of products for application in the food, pharmaceutical, medical, nutraceutical, cosmetic and aquaculture industries. Its balanced nutritional composition (source of carbohydrates, proteins of high biological value, fatty acid profile, vitamins, and minerals) and the presence of minor bioactive compounds (antioxidant pigments such as beta-carotene, chlorophyll, lutein, zeaxanthin, fucoxanthin or astaxanthin) are important characteristics to be explored in the development of new foods with added value (Sousa et al., 2008; Nova et al., 2020). Seaweeds and microalgae are excellent sustainable marine resources for developing innovative food products that privilege health, nutrition, and environmental sustainability (Nova et al., 2020). In addition, as the marine environment contains about half of the global biodiversity and abundant waste related to its exploration, using marine species to produce bioactive peptides may contribute to sustainable development. It may also represent economic gains (Cunha and Pintado, 2022).

Peptides with antimicrobial activity have aroused scientific interest mainly due to the high number of microorganisms resistant to emerging antibiotics (Bahar and Ren, 2013). Therefore, marine species have often been described as a source of bioactive peptides. The mussels belong to this group with their peptides associated with bioactive properties, including antioxidant, anti-hypertensive, antimicrobial, anticancer, anti-inflammatory, anticoagulant, antidiabetic, and antiviral properties (Je et al., 2005; Jung et al., 2007; Jung and Kim, 2009; Balseiro et al., 2011; Kim et al., 2012; Neves et al., 2016; Cunha et al., 2021). Beyond this, other peptides have been isolated from the *Mytilus* sp. with broad-spectrum activity against Gram-positive (*S. aureus*) and Gram-negative (*E. coli*) bacteria (Grienke et al., 2014). In the work by Cunha et al. (2021), a more efficient hydrolysate was produced from the mussel *Mytilus galloprovincialis*, with higher protein/peptide levels and increased antioxidant and antihypertensive activity. It should also be noted that the discarded mussels used to produce functional ingredients for the food, cosmetic and pharmaceutical industries can contribute to the valorisation of world waste in a circular economy context (Cunha et al., 2021). The aim of this study was the valorisation of low commercial value and abundant fish species on the Portuguese coast, such as Atlantic horse mackerel (*T. trachurus*), by developing smoked-flavored products with reduced salt content and fortified with natural bioactive compounds extracted from forest by-products (pine bark extract (*P. pinaster* Aiton subsp. *atlantica*) and seafood (mussel extract, *M. galloprovincialis*, with peptides <3 kDa and microalgae extract, *Tetraselmis* sp. with peptides <3 kDa).

2 Materials and methods

2.1 Extraction of phenolic compounds

Phenolic compounds were extracted from three distinct sources: pine bark, mussels, and microalgae. Due to the unique characteristics of each of these materials, specific extraction techniques were employed, which are detailed in the subsequent sections.

2.1.1 Pine bark

Pine bark was collected from *P. pinaster* Aiton subsp. *atlantica* trees in the northern region of Portugal (Vila Nova de Cerveira, Viana do Castelo, Portugal) was collected from trees ∼22–25 years old. The collection process involved making a circular cut in a specific area of the main trunk of freshly cut trees, ∼1.30 cm above ground level. To prepare the extract, the pine bark samples underwent a thorough cleaning process, which included multiple washes with distilled water to remove impurities such as dirt, lichens, and resin. Subsequently, the cleaned samples were dried at 40°C for 48 h. The resulting dried material was then finely ground and sieved with an amplitude of 0.2 for 1 min using the Analysette 3 PRO machine (Fritsch, Germany) to select particles within the diameter range of 200–850 μm. These samples were stored in airtight bags in a cool, dry, and dark environment until further use. The pine bark extract was obtained through microwave-assisted extraction, utilizing the ETHOS X microwave extraction system with the SK-12 medium-pressure rotor (Milestone, Italy). The extraction process was conducted for 30 min, employing microwave irradiation at a power of 1,600 W and a temperature of 110°C. A sample of 2.5 g of pine bark sample was placed into an extraction vessel within the equipment. Subsequently, 50 ml of a solvent mixture [water: ethanol (50:50)] was added to the vessel, resulting in a solid-to-liquid ratio of 1:20 (w:v). Upon completion of the extraction, the resulting extract was cooled and diluted to a final volume of 200 ml using the extraction solvent. It was then frozen at −80°C and subjected to lyophilisation using the Alpha 1-2 LDplus lyophiliser (Christ, Germany) under vacuum conditions for 48 h. The lyophilised extract was subsequently dissolved in water to achieve the desired concentration.

2.1.2 Mussel

The extraction of mussel peptides was performed according to Cunha et al. (2021) procedure. First, mussel biomass was mixed with ultrapure water in a ratio of mussel:water of 1:2 (w:v) and pH was adjusted to 7.5. Then, 2.7% (v/w) of subtilisin (New Cell Supreme 4000L, was supplied by NewEnzymes) was added, and the mixture was incubated at 40°C for 3 h in an orbital shaker (Thermo Scientific™ MaxQ™ 6000). The pH was verified and adjusted to 7.5 every 15 min. To stop the hydrolysis reaction, the samples were incubated at 90°C for 10 min to inactivate the enzymes. Samples were centrifuged (30 min, 5,000×g), and the supernatant was collected.

2.1.3 Microalgae

The *Tetraselmis* hydrolysate was prepared following a method previously described for the microalgae *Nannochloropsis oceanica* (Cunha et al., 2023). Briefly, the microalga (spray-dried) was mixed with deionised water in a 1:10 (w/v) ratio and hydrolysed with 4.7% cellulase (New Pro 16L, was supplied by NewEnzymes) for 2 h at 50°C. Then, 5% subtilisin (New Cell Supreme 4000L, was supplied by NewEnzymes) was added, and the hydrolysis proceeded at 40°C for 2 h. All the hydrolysis steps occurred with a controlled pH of 7.5 and an agitation of 125 rpm. The enzymatic reaction was stopped by increasing the temperature to 90°C for 10 min. The water-soluble extract (supernatant) was then separated by centrifugation (20 min, 5,000×g).

2.1.4 Filtration

The water-soluble hydrolysates produced from the microalgae and the mussels were submitted to an ultrafiltration (UF) process on a tangential flow filtration system (Cogent® μScale; Merckmillipore) recurring to a cut-off membrane threshold of 3 kDa. The <3 kDa fraction was then frozen for further application.

2.2 Sample preparation/fish processing

About 180 whole Atlantic horse mackerel (*T. trachurus*), size T3 (200–400 g), were donated by the local company Docapesca—Portos e Lotas, SA (Matosinhos, Portugal) and transported to Viana do Castelo research laboratory in refrigeration boxes. The same day, fishes were beheaded, eviscerated, fileted manually without removing the skin layer, and immediately washed with tap water. Two filets were obtained from each fish, and all filets were immersed in a brine of salt (2%) and liquid smoke (5%, RudinSmoke Euro 100, Ruitenberg) and kept for 16 h at 4°C. A filet:brine ratio of 1:1 (w/v) was used. Then, they were removed and drained for 10 min, followed by drying in a mechanical smoker (Maxi AFOS MK, England), without smoke production, at 70°C for 4 h with a final thermal shock of 90°C for 1 h. Smoke-flavored filets were divided into four groups with distinct treatments: sprayed (13 $\mu l/cm^3$) bioactive extract solutions (100 mg/ml), mussel extract solution (sample code MuE), *M. galloprovincialis*, with peptides <3 kDa; microalgae extract solution (sample code MiE), *Tetraselmis* sp. with peptides <3 KDa; and pine bark extract solution (*P. pinaster* Aiton subsp. *Atlantica*; sample code PBE), and one without any further spraying after processing, acting as a control sample (sample code C). The smoke-flavored fish were cooled in a blast chiller (Mercatus, Italy) until 3°C, vacuum-packed (thickness 90 μm; Permeability: O_2−50 cm^3/m^3 dbar; CO_2−150 cm^3/m^2 dbar; N_2−10 cm^3/m^2 dbar; Water vapor transmission−−2.8 g/m^2 d) and stored at 4–5°C for 15 days. Quality changes were studied by monitoring the physicochemical, microbiological and sensory properties weekly. Antioxidant and anti-hypertensive activities were determined at day 0. Each sample was composed of three filets homogenized for the analytical determinations. Triplicate measurements were conducted for each parameter.

2.3 Physicochemical analysis

Moisture content was assessed through a drying process in a vacuum oven (Memmert UFP 600, Schwabach, Germany) at a temperature of 103°C until a constant weight was obtained according to the AOAC procedures 925.40 (AOAC, 1995). Water activity was measured using a water-activity meter (LabTouch-aw meter Novasina, Switzerland). The pH values were measured using in the fish muscle a pH meter (CRISON pH 25+) with a glass probe. The sodium chloride (NaCl) content was determined following the guidelines outlined in AOAC method 937.09 (AOAC, 1995), which employs Volhard's method. This method involves back titration using potassium thiocyanate. Before titration, an excess volume of silver nitrate solution was added to the solution containing chloride ions (specifically fish chlorides), forming a silver chloride precipitate. The excess silver ions were then titrated with potassium thiocyanate in the presence of ammonium iron (III) sulfate. The peroxide values (PV) were determined in 25 g of the blended sample using the iodometric method with visual endpoint detection, as described in ISO 3960:2017. Additionally, the thiobarbituric acid reactive substances (TBARs) were determined in a 15 g portion of the sample through the spectrophotometric method specified in Ke et al. (1984). Each sample was composed of three filets homogenized for performing the analytical determinations. Triplicate measurements were conducted for each parameter.

2.4 Antioxidant and anti-hypertensive activity

The Oxygen radical absorbance capacity (ORAC) assay for measuring the antioxidant activity was performed in a black 96-well microplate (Nunc, Denmark), and the fluorescence was evaluated for 80 min in a multi-detection plate reader (Synergy H1; Biotek Instruments, Winooski VT, USA) as previously described by Cunha et al. (2021). The ORAC activity was expressed as μmol TE (Trolox equivalent)/g. ABTS scavenging assay was performed as described previously by Cunha et al. (2021). The reaction was executed in a 96-well microplate, and the absorbance was measured at 734 nm in a multi-detection microplate reader (Synergy H1; Biotek Instruments, Winooski VT, USA) controlled by Gen5 Biotek software (version 3.04). The results were expressed as μmol TE (Trolox equivalent)/g. The antihypertensive potential was evaluated by the capacity of inhibiting the angiotensin-converting enzyme (ACE). The assay was performed as described before by Cunha et al. (2021) in a black 96-well microplate (Nunc, Denmark) with a multi-detection microplate reader (Synergy H1; Biotek Instruments, Winooski VT, USA) controlled by Gen5 Biotek software (version 3.04). The results were expressed as the extracts' inhibitory% of ACE enzyme (iACE) at a 50 mg/ml concentration.

2.5 Microbiological analysis

A fish package was opened weekly for microbiological analysis, and a 30 g sample of smoke-flavored fish was aseptically taken from different filet parts, homogenized for 90 s in a stomacher and decimally diluted. Total Viable Counts were performed on pour plates according to EN ISO 4833-1:2013; Psychrotrophic microorganisms according to ISO 17410:2001; Enterobacteriaceae counts according to ISO 21528-2:2017 and Yeasts and Molds according to NP 3277-1:1987. *Salmonella* and *L. monocytogenes* were detected according to ISO 6579-1: 2017 and ISO 11290-1:2017, respectively.

2.6 Sensorial evaluation

The set of three smoke-flavored samples with added extract (100 mg/ml—MuE, MiE and PBE) and one control sample (C) without added extract was submitted to the sensory assessment performed in a test room (ISO 8589:2007 ISO, 2007) using a quantitative descriptive analysis—QDA® (Meilgaard et al., 2016). A portion of fish filet of each treatment was placed on coded white plates and presented to the panelists at room temperature (20°C). A panel of seven semi-trained members was selected among the ESTG-IPVC collaborators with experience in fish/seafood sensory analysis. Previously to the smoked fish sensory evaluation, judges received extra training on salty and bitter taste, as well as on smoked odors and off-flavors and defined the main attributes, scales and verbal anchors. The defined attributes, such as characteristic brightness, color, smoke, fish odor, cohesiveness, oiliness, dryness, salty taste, acid flavor, bitter taste, and smoke flavor, were rated on a 9-point intensity scale. A final question was added to the score sheet to assess global appreciation of the product, using a scale from 1 to 5, in which the values 5 and 4 corresponded to samples without defects, being the product acceptable, and the values 3, 2, and 1 to defective samples and therefore an unacceptable product. Sensory analysis was performed at 0, 7, and 15 days of storage.

2.7 Statistical analysis

The mean and standard deviation were calculated to perform a data analysis for all physicochemical analysis results. A variance analysis (ANOVA) was performed to detect any significant differences ($p < 0.05$) between treatments and over the storage period, if $p < 0.05$, a Tukey's HSD *posthoc* test was used. A Principal Component Analysis (PCA) was performed using sensory data, assessing which organoleptic properties were the most significant to explain the effect of treatments and storage. PCA is a technique for reducing the dimensionality of datasets increasing interpretability while minimizing information loss through variables and samples correlation with principal component axes (Jolliffe and Cadima, 2016). This allows better visualization of the identified groups, thus improving the interpretation of the relative variations of the different formulations and the similarities or differences between the samples. Statistics were analyzed using TIBCO Statistica Ultimate Academic 14.0.0 for Windows (TIBCO Software Inc., California, USA). Data mining was carried out with principal component analysis (PCA) to investigate differences between treatments and to correlate the main characteristics and their changes along storage time. PCA was performed using the Autobiplot.PCA function was built in R language by Alves (2012).

3 Results and discussion

3.1 Physicochemical characterization and changes during storage

Results of analytical determination of moisture content, water activity (a_w) and NaCl content carried out on the different samples/treatments are shown in Table 1. Given the high heterogeneity of the fish filet samples, these parameters were determined with a reasonable sample size ($n = 9$ for each condition) and carried out when opening the packages for further analysis. Significant differences ($p < 0.05$) were observed in all parameters when comparing with control samples with MuE, MiE, and PBE: the control sample showed lower moisture content and water activity and higher NaCl concentration. The application of the extract by spraying it onto the surface of the filets likely led to an increase in the moisture content of the treated samples when compared to the control group, as expected. This is because moisture content, water activity, and salt content are closely interconnected parameters. Moisture content represents the quantity of water present in food and its constituents. In contrast, the water activity parameter signifies the amount of water in foods available to engage in degradation processes, such as microbial spoilage. Higher water activity values tend to elevate the likelihood of accelerated microorganism growth, as documented by St. Angelo et al. (1996). Concerning moisture levels, Cardinal et al. (2001) suggested maintaining a content below 65% for smoked fish. In this investigation, all moisture values remained below this recommended threshold, with the highest recorded moisture content being 57.97% in samples treated with PBE. Kolodziejska et al. (2002) and Goulas and Kontominas (2005) also reported similar observations of notably lower moisture levels in various mackerel samples.

Regarding salt content, it's worth noting that the control sample displayed higher values, approximately double those of the other samples. This disparity can be explained by the fact that the control sample did not undergo the spraying process with solutions containing bioactive compounds. Furthermore, when evaluating the ratio of NaCl to water, it becomes evident that the control sample exhibits significantly higher values due to the absence of extract spraying. This variation can also be attributed to the substantial variability within the filets, leading to differences in the absorption of NaCl within the brine. This variability is further underscored by the notable standard deviation values observed among the samples. Reducing the salt content in food products is a global objective. Many individuals following a sodium-restricted or health-conscious diet tend to avoid consuming smoked fish due to its high sodium content. As highlighted in the study by Rybicka et al. (2022), which investigated the production of smoked mackerel filets with reduced sodium chloride (NaCl) content, the sodium chloride values reported in their research were similar to those obtained in this study, albeit with higher moisture content.

Figure 1 illustrates the pH values of the samples during their refrigerated storage. On the first day of storage, the pH of the samples fell within the range of 6.39–6.76, with PBE samples displaying the higher values and the control samples having the lower ones. Notably, at this initial sampling point, there were no significant differences ($p > 0.05$) between the MuE samples (6.57 $\pm$ 0.02) and MiE samples (6.55 $\pm$ 0.02). However, the pH of all treated samples decreased after 7 days of storage, with the MuE sample presenting the lowest pH value (6.20 $\pm$ 0.03), which was statistically distinct from the other samples. In contrast, the pH of the control samples increased on the same day. The pH value of the PBE sample did not differ significantly from that of the control sample at this stage. By day 15, the pH of the samples continued to decline, except for the MuE samples. At this juncture, the PBE sample exhibited the highest pH value (6.38 $\pm$ 0.03), demonstrating significant differences ($p < 0.05$) when compared to the Control and MiE samples. This decline in pH values observed in all samples after 15 days of storage ($p < 0.05$) is likely attributed to the expected increase in activity of lactic acid bacteria, which typically exert a buffering effect on the food substance, as noted by Iacumin et al. (2017).

Eyo (2001) emphasized that pH indicates the degree of microbial spoilage in fish, noting that some proteolytic microbes produce acid from carbohydrate decomposition, thereby elevating the acidity of the medium. In our study, total viable counts (TVC) were higher at the 15-day mark in the control and MiE samples, exhibiting the lowest pH values (Figure 1). Moreover, it's important to note that the decline in pH values could also be attributed to the increased presence of free fatty acids resulting from lipolysis. This biochemical reaction has the potential to adversely affect the taste, flavor, odor, color, texture, and appearance of food products, along with diminishing their nutritional value, as described by Gotoh and Wada (2006).

To assess the impact of the treatments on the oxidative stability of the smoke-flavored fish samples during refrigerated storage, peroxide value (PV) and thiobarbituric acid reactive substances (TBARs) were evaluated, as detailed in Table 2. These two methods operate on different principles: PV assesses the formation of hydroperoxides as a result of fat and oil oxidation, and TBARs evaluate the products generated due to the oxidation of unsaturated fatty acids in fat and oil, as well as other thiobarbituric acid reactive substances, effectively gauging the secondary breakdown products of lipid peroxidation, as reported by Gotoh and Wada (2006). PV serves as an indicator of the initial oxidation stage in fish muscle, and it plays a crucial role in fish spoilage during storage. Peroxides, the primary products in the early stages of lipid oxidation, are unstable and eventually break down into volatile low molecular weight compounds such as ketones, acids, aldehydes, and alcohol. These breakdown products can impart an unusual taste and odor to food products, as Ucak et al. (2011) documented. As indicated in Table 2, the peroxide value (PV) levels initially exhibited an increase

TABLE 1 Physicochemical quality parameters (Moisture, a_w and NaCl and NaCl:Water ratio) of the smoke-flavored horse mackerel filets: C, control sample; MuE, mussel extract; MiE, microalgae extract; PBE, pine bark extract.

Sample	Moisture content (g/100 g)	a_w	NaCl (g/100 g)	NaCl:Water ratio (g/kg)
C	48.88 ± 1.34^c	0.930 ± 0.017^c	2.75 ± 0.30^a	56.26 ± 6.38^a
MuE	54.59 ± 0.97^b	0.946 ± 0.010^b	1.33 ± 0.68^b	24.36 ± 14.68^b
MiE	53.10 ± 2.96^b	$0.954 \pm 0.006^{b,a}$	$1.27 \pm 0.29^{b,c}$	23.92 ± 6.52^b
PBE	57.97 ± 2.75^a	0.961 ± 0.007^a	0.76 ± 0.16^c	13.11 ± 3.27^b

^{a,b,c}Items in the same column with different superscripts are significantly different ($p < 0.05$).

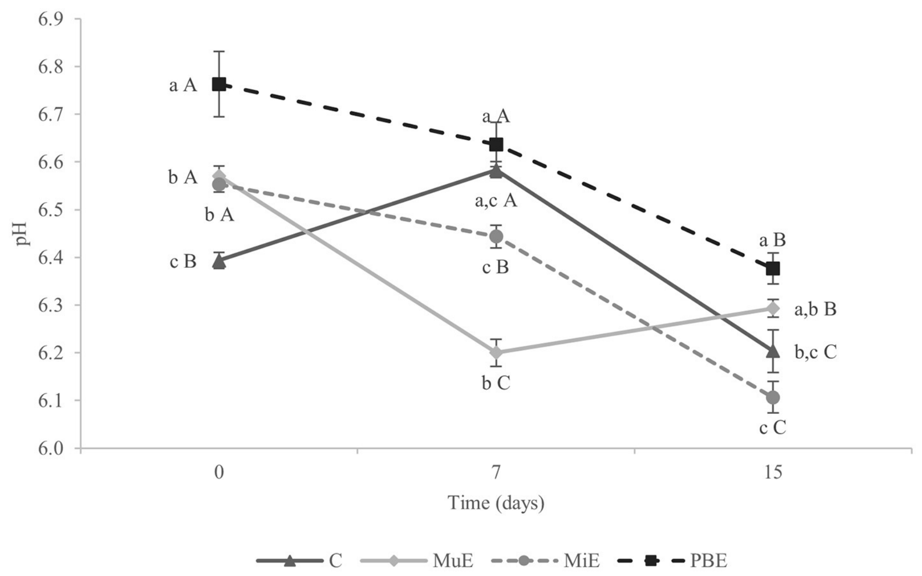

FIGURE 1
pH values of smoke-flavored horse mackerel filets during 15 days of storage: C, control sample; MuE, mussel extract; MiE, microalgae extract; PBE, pine bark extract. a,b,c—Items in the same storage time with different superscripts are significantly different ($p < 0.05$); A, B, C—Items in the same sample along the time with different superscripts are significantly different ($p < 0.05$).

and then subsequently decreased over time, with the exception of the MiE sample. These patterns align with findings reported in previous studies by Nair et al. (1976), Ke et al. (1977), and Al-Bulushi et al. (2005). The initial increase in PV observed in the samples during the first 7 days can be attributed to lipid oxidation processes. The subsequent decrease in PV may be attributed to the decomposition of hydroperoxides, which are primary products of oxidation, into secondary lipid oxidation products, as well as their interaction with proteins, as noted by Boselli et al. (2005) and Ozogul et al. (2017). Notably, samples that had extract added showed consistently lower PV values throughout the entire study period compared to the control group, and these differences were statistically significant ($p < 0.05$), except for the 15-day time point for the MiE sample. In the case of the PBE sample, a significant decline in PV was observed after it reached its peak values, suggesting the instability of peroxides and their susceptibility to forming secondary products, in line with the observations made by Danowska-Oziewicz and Karpińska-Tymoszczyk (2005). These results are consistent with findings from other studies (Alçiçek, 2011; Kumolu-Joh and Ndimele, 2011; Tenyang et al., 2020), where extracts of plant origin were applied to smoked fish products. According to Raeisi et al. (2016), the maximum acceptable limit for peroxide value (PV) in food products is typically set between 10 and 20 mEq O_2/kg of fat. In this study, all samples maintained peroxide content within the acceptable range for human consumption, with the maximum value for the control sample being 15.97 ± 0.06 mEq O_2/kg fat. Furthermore, the samples with the addition of extract remained well within the recommended limit of 15 mEq O_2/kg of fat as advised by the Codex Alimentarius Commission (FAO/WHO, 2001).

In the case of thiobarbituric acid reactive substances (TBARs) values, there was an initial decrease followed by an increase over time, except for the PBE sample, which exhibited a consistent decline throughout the entire storage period. Malondialdehyde, a compound that reacts with TBA to form TBARs, can create amidine bonds by crosslinking amino acids and interact with various components in fish, including nucleosides, nucleic acids, phospholipid amino acids, and other aldehydes produced during lipid oxidation. The extent of this interaction can vary depending on the fish species, as noted by Nair et al. (1986). This interaction could explain the initial decrease in TBARs levels from 0 to 7 days. As storage progresses, the rate of consumption of hydroperoxides may exceed the rate of their formation (Undeland et al., 1999), leading to the formation of other oxidation products detectable as

TABLE 2 Biochemical parameters (TBARs and PV) of smoke-flavored horse mackerel filets during 15 days of storage: C, control sample; MuE, mussel extract; MiE, microalgae extract; PBE, pine bark extract.

	Time (days)		
	0	7	15
PV (mEq.O_2/Kg fat)			
C	2.76 ± 0.17^{aC}	15.97 ± 0.06^{bA}	14.27 ± 0.07^{aB}
MuE	1.98 ± 0.01^{bA}	5.89 ± 0.36^{cB}	5.06 ± 0.27^{cB}
MiE	1.53 ± 0.01^{cB}	13.15 ± 0.04^{aA}	13.57 ± 0.38^{aA}
PBE	0.51 ± 0.02^{dC}	13.73 ± 0.60^{aA}	10.73 ± 0.23^{bB}
TBARs (mg malondialdehyde/kg sample)			
C	7.89 ± 0.10^{bA}	3.40 ± 0.05^{bC}	6.19 ± 0.04^{bB}
MuE	5.83 ± 0.10^{cA}	1.13 ± 0.02^{dC}	2.22 ± 0.01^{cB}
MiE	10.90 ± 0.85^{aA}	2.47 ± 0.03^{cC}	7.14 ± 0.02^{aB}
PBE	7.36 ± 0.24^{bA}	5.99 ± 0.08^{aB}	1.50 ± 0.01^{dC}

a,b,c,d—Items in the same column with different superscripts are significantly different ($p < 0.05$).
A, B, C—Items in the same row with different superscripts are significantly different ($p < 0.05$).

TBARs. This phenomenon may account for the observed results in the samples, except for the PBE sample. Since TBARs can also react and degrade over time, their levels may not consistently increase, which could explain the decrease observed in the samples. Throughout the entire storage period, the peroxide value exhibited an increase from the initial value, and this increase was statistically significant ($p < 0.05$) for all samples. In contrast, TBARs values displayed an inverse trend, with a significant decrease ($p < 0.05$) observed between the beginning and end of the storage period. Additionally, it was noted that at 0 and 15 days, the TBARs values of the samples containing extracts were lower than those of the control samples, except for the MiE sample. Among the extracts tested, the PBE extract appears to have had the most effective prevention against lipid oxidation, with decreasing values of TBARs over the 15 days. In contrast, the results presented by MiE and MuE extracts seem to indicate that their ability to prevent lipid oxidation decreased after 7 days of storage. This study also investigated the effectiveness of natural extracts in slowing down lipid oxidation during the shelf life of hot-smoked catfish, and the results were promising, as reported by Kumolu-Joh and Ndimele in 2011. According to the statistical analysis of variance, significant differences were observed at all sampling points and among various sample treatments ($p < 0.05$). It's important to note that the formation of aldehydes in fish is typically attributed to enzymatic reactions. However, in the context of hot smoking, their generation primarily results from processes such as thermal degradation, Maillard reactions, and modifications in lipid composition. These reactions occur when fish are subjected to thermal treatments like heating, baking, or smoking, as described by Bienkiewicz et al. (2022).

Moreover, the intricate nature and composition of fish fats, liquid smoke, and the extracts themselves can contribute to the absence of clear patterns in lipid oxidation, as measured by parameters such as peroxide value (PV) and thiobarbituric acid reactive substances (TBARs), in processed foods. While PV and TBARs serve as valuable biochemical indicators of spoilage, additional research is needed to establish their correlations with sensory attributes and microbiological aspects.

The combination of antioxidant extracts, salting, drying techniques, and vacuum packaging (thus minimizing oxygen exposure) has shown a significant reduction in primary lipid oxidation. For instance, Swastawati et al. (2020) examined the application of liquid smoke nanocapsules to catfish filets roasted at 90°C for 4 h. They discovered that using nanocapsules could effectively inhibit oxidation during storage, as PV and TBA results remained below the established thresholds for up to 10 days of storage.

In another study conducted by Fellenberg et al. (2020), the objective was to determine the antioxidant effects of natural extracts on the oxidative quality and color changes in marinated rainbow trout filets during storage at 4°C. The findings suggested that natural antioxidants could offer an alternative approach to extending the shelf life of trout filets, particularly during the initial 6 days of storage at 4°C.

3.2 Antioxidant and anti-hypertensive activity of smoke-flavored horse mackerel filets

The results of antioxidant activity determined by ORAC and ABTS methods are presented in Table 3. Among the filets, the one treated with microalgae extract (MiE) demonstrated the most favorable outcomes in terms of antioxidant activity, as determined by the ORAC and ABTS methods, with values of 45.20 ± 1.84 and 12.90 ± 0.64 µM TE/g initial sample, respectively. In comparing the MiE sample with the other samples, statistically significant differences in the results of the ABTS method were observed. However, there were no significant differences in the results obtained from the ORAC method between the MiE and MuE samples, with values of 45.20 ± 1.84 and 37.65 ± 2.64 µM TE/g, respectively. Additionally, the smoked-flavored horse mackerel filet exhibited an interesting antihypertensive profile, with an ACE (angiotensin-converting enzyme) inhibition of 14.41 ± 0.8 at a 50 mg/ml concentration. Nonetheless, the tested extracts notably enhanced their biological potential, with the microalgae extract achieving the most significant anti-hypertensive profile at 64.43 ± 4.3 iACE inhibition (50 mg/ml). These results suggest that the studied extracts hold substantial potential for developing innovative food products that emphasize functionality, convenience, nutrition, and health benefits.

3.3 Microbiological quality of smoke-flavored horse mackerel filets during storage

The microbiological values of studied samples at 0, 7, and 15th day of storage are shown in Figure 2. The initial bacterial counts for Total Viable Bacteria (TVC) and Psychrotrophic bacteria (Figures 2A, B) in the control sample were 3.9×10^2 and 1

TABLE 3 Results obtained for the Anti-hypertensive and Antioxidant activity in smoke-flavored horse mackerel filets.

	iACE inhibition (50 mg/ml)	ORAC (μM TE/g initial sample)	ABTS (μM TE/g initial sample)
C	14.41 ± 0.8[a]	15.20 ± 6.36[a]	6.57 ± 0.28[a]
MuE	18.61 ± 0.6[a]	37.65 ± 2.64[b]	8.52 ± 0.18[a,c]
MiE	64.43 ± 4.3[b]	45.20 ± 1.84[b]	12.90 ± 0.64[b]
PBE	16.55 ± 1.7[a]	12.34 ± 3.60[a]	9.56 ± 1.02[c]

[a,b,c]Items in the same column with different superscripts are significantly different ($p<0.05$).

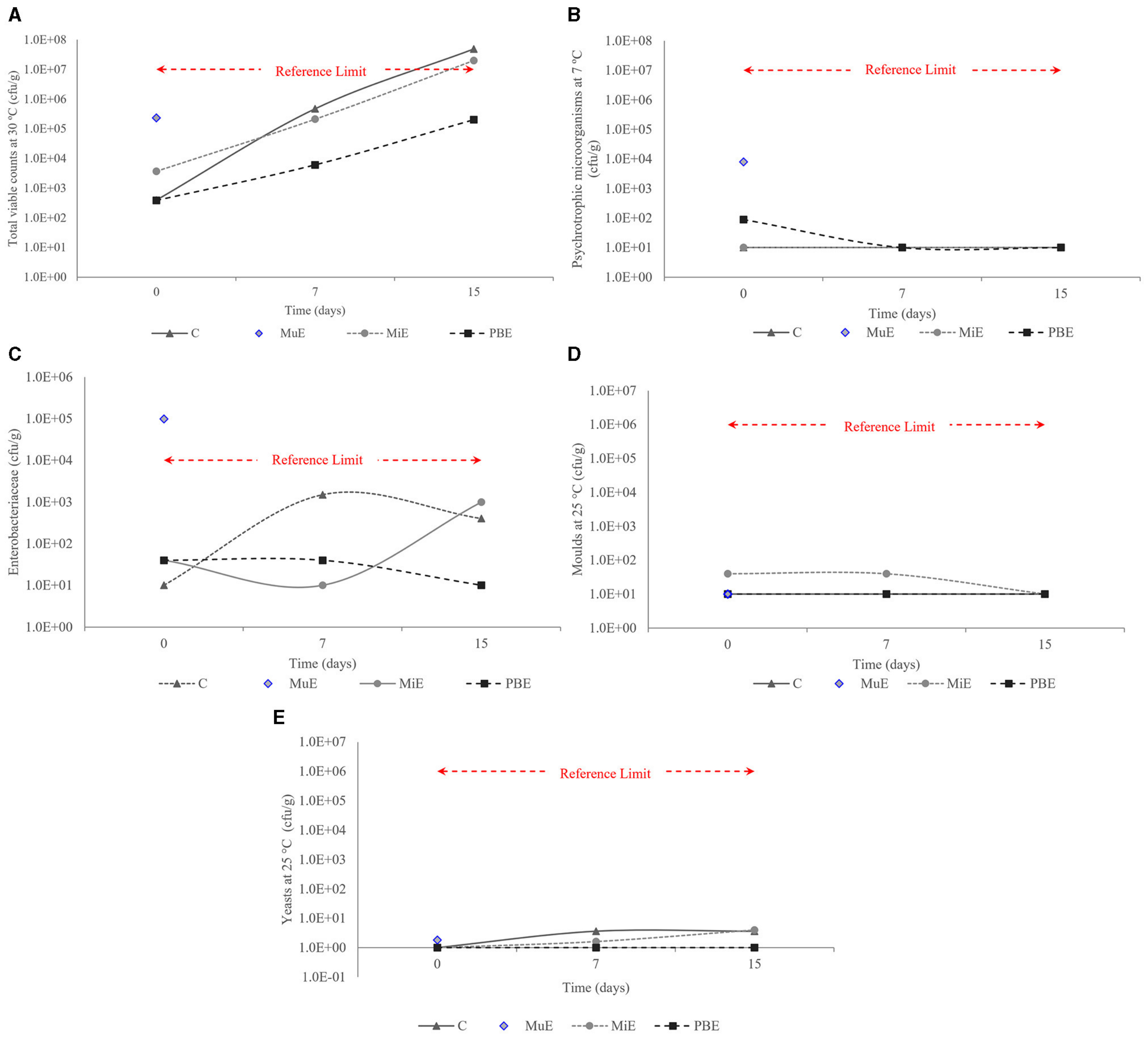

FIGURE 2
(A) Total viable counts; **(B)** Psychrotrophic bacteria at 7°C; **(C)** Enterobacteriaceae counts; **(D)** Molds counts at 25°C; and **(E)** Yeast counts at 25°C at 30°C during storage.

$\times$ 10^1 cfu/g, respectively. In the MuE sample, the counts were 2.3 $\times$ 10^5 for TVC and 8 $\times$ 10^3 cfu/g for Psychrotrophic bacteria. The MiE sample had counts of 3.7 $\times$ 10^3 for TVC and 1 $\times$ 10^1 cfu/g for Psychrotrophic bacteria, while the PBE sample had counts of 3.8 $\times$ 10^2 for TVC and 9 $\times$ 10^1 cfu/g for Psychrotrophic bacteria. For ready-to-eat products, the recommended limit value for Total Viable Bacteria is typically $<10^7$ cfu/g (HPA, 2009; INSA, 2019). Considering that the TVC counts in the Control and MiE samples, after 15 days of storage, as well as the numbers of Enterobacteriaceae (Figure 2C) in the

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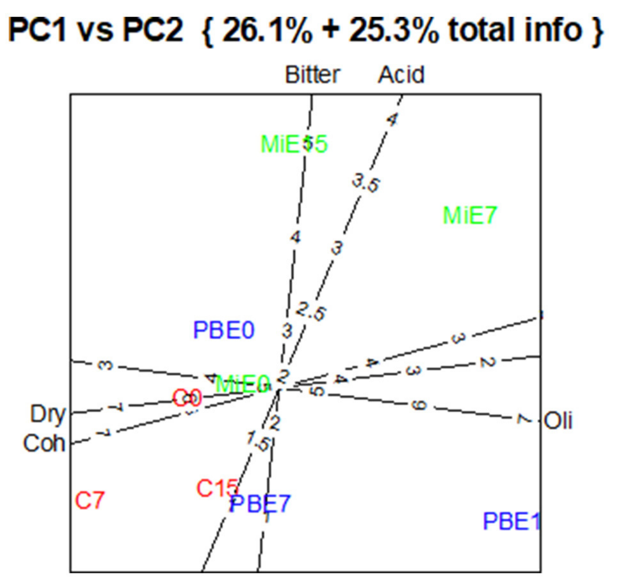

FIGURE 3
Principal component analysis of sensory data (PC1 vs. PC2) were C is control formulation; MiE—formulation with the application of seaweed extract; PBE—formulation with the application of pine bark extract, for sampling times 0, 7, and 15 days.

MuE samples at day 0 (initial time), exceeded the recommended limit value for ready-to-eat products, the decision was made to discontinue the study at this sampling point. Additionally, since the numbers of Enterobacteriaceae in the MuE samples exceeded the recommended limit value for ready-to-eat products, no further microbiological assays were conducted beyond this point. In all samples, a notable increase in bacterial populations was observed over time, except in the case of the PBE sample. Specifically, between day 0 and day 7 of shelf life, the population increased by 1.47 logarithms (approximately 15 times the initial population) when PBE was used. In contrast, in the control sample (C), the observed increase was 2.2 logarithms (equivalent to 22 times the initial population). This suggests that the use of PBE had a partial to moderate bacteriostatic effect on the growth of mesophilic bacteria, potentially extending the product's shelf life compared to the other samples. Some studies have suggested that compounds found in pine bark, such as tannins and flavonoids, can inhibit the growth of both gram-positive and gram-negative bacteria, including mesophiles (Torras et al., 2005). These extracts also contain various phenolic compounds like catechins, taxifolin, and phenolic acids, which have been demonstrated to possess antimicrobial activity (Iravani and Zolfaghari, 2014). The increase in Psychrotrophic bacteria counts from 0 to 7°C is associated with issues related to the preservation of cold-stored foods (Erkmen and Bozoglu, 2016). When a significant number of psychrotrophic bacteria are detected, it indicates shortcomings in the preservation process (González-Fandos et al., 2004).

In the present study, there was no observed increase in the psychrotrophic bacterial population over time in any of the samples, and relatively low and stable levels were maintained, well below the maximum reference value of 10^7 cfu/g. Based on these findings, there was no significant effect from any compound on the psychrotrophic bacteria. However, it's important to note that no definitive conclusions can be drawn due to the low quantities of psychrotrophic bacteria detected. The Enterobacteriaceae counts exhibited an abnormal variation in population over time. The distribution of these bacteria did not follow a normal (uniform) distribution but rather a sporadic distribution, where each spot corresponds to establishing a bacterium that has developed into a colony. This development could have occurred due to exposure or cross-contamination, typically at the surface of the fish filet samples processed in this study. Another possible explanation for the results obtained could be sampling variability, which refers to variations in the preparation of the mother suspension despite taking precautions to obtain a sample that was as representative as possible (including parts with more or fewer stains) and batch variability, as the samples originated from different fish with potentially different and variable flora depending on exposure and handling.

The decrease in Enterobacteria numbers in PBE samples may be attributed to various hurdle factors, such as pH reduction, in combination with the bactericidal and antioxidant properties of phenolic compounds present in the smoke, as suggested by Zaki et al. (2021). The results indicate the presence of Enterobacteriaceae in the samples but do not provide a comprehensive assessment of their evolution over time. The recommended limit for Enterobacteriaceae in ready-to-eat products is typically $<10^4$ cfu/g (HPA, 2009; INSA, 2019). The yeast and mold counts (Figures 2D, E) observed in this study did not exceed the recommended value of $<10^6$ cfu/g (HPA, 2009) throughout the storage period for all samples. The increase in yeast counts may have been influenced by the vacuum packaging of the samples, as the absence of oxygen prevents the proliferation of yeasts and molds. It's noteworthy that *Salmonella* and *Listeria* were not detected during storage. These results suggest a correlation between sensory analysis and the microbiological analysis of the horse mackerel filets, supporting the overall safety and quality of the products.

3.4 Sensory quality of smoke-flavored horse mackerel filet

Sensory analysis is widely recognized as a crucial tool for evaluating fish quality within the industry (Warm et al., 2001; Loutfi et al., 2015). The sensory attributes of fish quality are closely intertwined with the chemical and biochemical composition of the fish and how they evolve during storage (Du et al., 2001; Gómez-Guillén et al., 2009; Messina et al., 2016). Therefore, sensory analysis plays a significant role in estimating the shelf life of fish products (Leroi and Joffraud, 2000; Martinez et al., 2007). In Figure 3, the Principal Component Analysis (PCA) output represents the sensory analysis results provided by the panel of evaluators, capturing 51.4% of the total information. It's important to note that sensory analysis was not concluded for MuE samples due to the presence of off-odors reported by the panelists. Additionally, in accordance with microbiological determinations, MuE samples exhibited a higher level of contamination by Enterobacteriaceae on day 0, exceeding

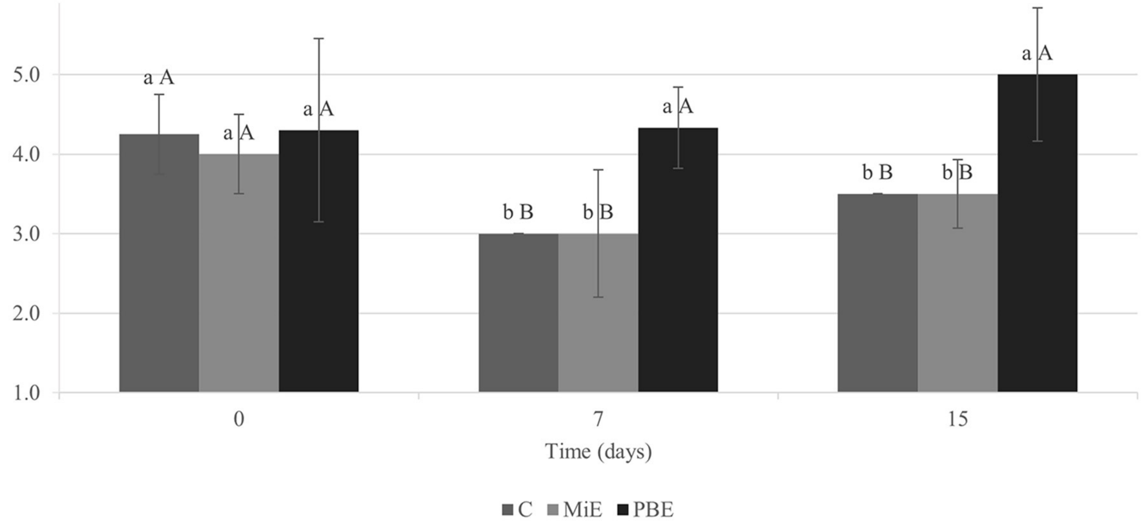

FIGURE 4
Global acceptance. C, control formulation; MiE, formulation with the application of seaweed extract; PBE, formulation with the application of pine bark extract, for sampling times 0, 7, and 15 days. a,b Items in the same study time with different superscripts are significantly different ($p < 0.05$). A, B Items in the same sample with different superscripts are significantly different ($p < 0.05$).

the recommended limit value established by the Guidelines for Assessing the Microbiological Safety of Ready-to-Eat Foods Placed on the Market (HPA, 2009) by more than 1 log.

The sensory data analysis employed the "Autobiplot.PCA" function, which applies a biplot to PCA displays. In Figure 3, the biplot is depicted on the plane of principal components 1 and 2, summarizing nearly 58% of the total information contained in the sensory data. These results shed light on which sensory attributes played a crucial role in discriminating between samples, with bitterness, acidity taste, and attributes related to texture such as dryness, cohesiveness, and oiliness standing out.

The biplot can be interpreted by drawing a perpendicular line from a specific variable axis to the sample position, allowing for multiple variable readings to be made within a single orthogonal plane. For instance, if we take samples C0, MiE0, and PBE0, they project orthogonally to attributes such as oily (≈4.0), acidity (≈2.4), and bitterness (≈3). This type of PCA analysis facilitates the interpretation of results in terms of the original sensory attributes and sample values, thus avoiding the complexities associated with interpretations in terms of latent variables and relative values.

The PCA plot in Figure 3 also reveals a grouping of samples based on storage time. Samples MiE7 and MiE15 are discriminated and projected toward the upper side of the plot. This separation is attributed to higher scores in attributes related to bitterness and acidity taste, which increase over the storage period. In contrast, samples treated with PBE for 7 and 15 days were characterized by the panelists as more oily and less dry or cohesive than the control (C). Among them, PBE15 and MiE7 were considered significantly oilier than the others. The control samples were generally perceived as drier, with higher cohesiveness and a saltier taste (Supplementary Table 1). This observation aligns with expectations, as these attributes tend to be highly correlated.

Figure 4 illustrates the overall appreciation of the products using a 5-point scale, where panelists were asked to assess the overall suitability of the products. In this scale, scores equal to or <3 points were considered indicative of the existence of a defect, while values of 4 and 5 indicated that the product met quality requirements. The threshold between the presence or absence of a defect, when considering average values, was set at 3.5. The results indicate that there were no statistically significant differences ($p > 0.05$) among the samples collected at the first sampling point (C0, MiE0, and PBE0). The average score for these samples was approximately 4, suggesting that the products were considered satisfactory or good. At the second sampling point (7 days of storage), panelists noted significant differences ($p < 0.05$), primarily between the control (C) and MiE samples. However, PBE-treated samples were consistently rated as good or satisfactory across all sampling points. Samples with 15 days of storage exhibited a similar pattern in panelist evaluations. Therefore, it can be inferred that the PBE treatment was more suitable for this product, as the samples treated with PBE appeared to be more stable over the duration of the study.

4 Conclusions

Consumers are increasingly demanding safe and natural products, and reducing salt in foods is a global objective. This drive has led to the exploration of new preservation techniques that enhance microbial quality and safety while minimizing the impact on nutritional and sensory qualities. In this context, natural compounds have garnered significant attention from both research and industry due to their potential to offer quality and safety benefits with minimal health implications. Additionally, the use of natural ingredients aligns with the principles of food sustainability. However, salt remains a crucial component for ensuring microbial stability in products like smoked-flavored fish. This study has demonstrated that natural extracts possess antioxidative and antimicrobial properties that can delay oxidative rancidity, thereby extending the shelf life of smoked-flavored fish. At the outset, MiE samples exhibited the highest antioxidant activity as determined by the ORAC and ABTS methods. However, an increase in total viable counts was observed in these samples by the end of the 15-day storage period, although it remained below the recommended limit levels at days 0 and 7. MuE samples demonstrated the lowest PV value at day 15, but these extracts were associated with off-odors detected by sensory panelists. After 15 days of storage, the only acceptable samples in both microbiological and sensorial analysis were those with the application of PBE extract, with this result seeming to indicate that this extract was more effective, resulting in a product with a longer shelf life, that is, of at least 15 days. While TBARs and PV remained below detection levels throughout the study, it is essential to acknowledge that extended storage can potentially lead to rancidity, which can adversely impact the sensory attributes of the samples.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

DB: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing. PN: Investigation, Methodology, Project administration, Writing – review & editing. SC: Investigation, Methodology, Project administration, Writing – review & editing. VM: Formal analysis, Writing – review & editing. ÉF: Investigation, Validation, Writing – original draft, Writing – review & editing. RP-P: Formal analysis, Investigation, Validation, Writing – original draft, Writing – review & editing. CB: Formal analysis, Investigation, Writing – original draft. MP: Formal analysis, Supervision, Writing – review & editing. AG: Conceptualization, Data curation, Supervision, Writing – review & editing. MV-V: Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article, through FCT-SFRH/BD/146720/2019 PhD scholarship, co-financed by Fundo Social Europeu (FSE) through the Programa Operacional Regional Norte 2020 and also through the Foundation for Science and Technology (FCT, Portugal) FCT/MCTES, funding CISAS (UIDB/05937/2020 and UIDP/05937/2020).

Acknowledgments

To VALORMAR—Valorização integral dos recursos marinhos: potencial, inovação tecnológica e novas aplicações, PPS1 Novos produtos de mar, tecnologias e processos para a indústria e mercado financed by Sistema de Incentivos à Investigação e Desenvolvimento Tecnológico (SI I&DT)/Programas Mobilizadores, POCI-01-0247-FEDER-024517_024517; To DOCAPESCA—PORTOS E LOTAS, SA for the donation of Horse mackerel (*Trachurus trachurus*) for the preparation of this study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1296265/full#supplementary-material

References

Adeyemi, O. T., Osilesi, O. O., Onajobi, F., Adebawo, O., and Afolayan, A. J. (2013). Stability study of smoked fish, and horse mackerel (*Trachurus trachurus*) by different methods and storage at room temperature. *Afr. J. Biochem. Res.* 7, 98–106.

Ahn, J., Grün, I. U., and Mustapha, A. (2004). Antimicrobial and antioxidant activities of natural extracts in vitro and ground beef. *J. Food Prot.* 67, 148–155. doi: 10.4315/0362-028X-67.1.148

Ahn, J., Grün, I. U., and Mustapha, A. (2007). Effects of plant extracts on microbial growth, colour change, and lipid oxidation in cooked beef. *Food Microbiol.* 24, 7–14. doi: 10.1016/j.fm.2006.04.006

Al-Bulushi, I. M., Kasapis, S., Al-Oufi, H., and Al-Mamari, S. (2005). Evaluating the quality and storage stability of fish burgers during frozen storage. *Fish. Sci.* 71, 648–654. doi: 10.1111/j.1444-2906.2005.01011.x

Alçiçek, Z. (2011). The effects of thyme (Thymus vulgaris L.) oil concentration on liquid-smoked vacuum-packed rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792) fillets during chilled storage. *Food Chem.* 128, 683–688. doi: 10.1016/j.foodchem.2011.03.087

Almeida, C., Karadzic, V., and Vaz, S. (2015). The seafood market in portugal: driving forces and consequences. *Mar. Policy* 61, 87–94. doi: 10.1016/j.marpol.2015.07.012

Alonso-Esteban, J. I., Carocho, M., Barros, D., Velho, M. V., Heleno, S., Barros, L., et al. (2022). Chemical composition and industrial applications of Maritime pine (Pinus pinaster Ait.) bark and other non-wood parts. *Rev. Environ. Sci. Biotechnol.* 21, 1–51. doi: 10.1007/s11157-022-09624-1

Alves, M. R. (2012). Evaluation of the predictive power of biplot axes to automate the construction and layout of biplots based on the accuracy of direct readings from common outputs of multivariate analyses: 1. Application to principal component analysis. *J. Chemom.* 26, 180–190. doi: 10.1002/cem.2433

AOAC (1995). *Official Methods of Analysis,* 15th ed. Washington, DC: Association of official analytical chemists.

Aspé, E., and Fernández, K. (2011). The effect of different extraction techniques on extraction yield, total phenolic, and anti-radical capacity of extracts from *Pinus radiata* Bark. *Ind. Crops Prod.* 34, 838–844. doi: 10.1016/j.indcrop.2011.02.002

Bahar, A. A., and Ren, D. (2013). Antimicrobial peptides. *Pharmaceuticals* 6, 1543–1575. doi: 10.3390/ph6121543

Balasundram, N., Sundram, K., and Samman, S. (2006). Phenolic compounds in plants and agri-industrial by-products: antioxidant activity, occurrence, and potential uses. *Food Chem.* 99, 191–203. doi: 10.1016/j.foodchem.2005.07.042

Balseiro, P., Falcó, A., Romero, A., Dios, S., Martínez-López, A., Figueras, A., et al. (2011). *Mytilus galloprovincialis* Myticin C: a chemotactic molecule with antiviral activity and immunoregulatory properties. *PLoS ONE* 6, e23140. doi: 10.1371/journal.pone.0023140

Baptista, R. C., Horita, C. N., and Sant'Ana, A. S. (2020). Natural products with preservative properties for enhancing the microbiological safety and extending the shelf-life of seafood: a review. *Food Res. Int.* 127, 108762. doi: 10.1016/j.foodres.2019.108762

Bienkiewicz, G., Tokarczyk, G., and Biernacka, P. (2022). Influence of storage time and method of smoking on the content of EPA and DHA acids and lipid quality of Atlantic Salmon (*Salmo salar*) meat. *Int. J. Food Sci.* 2022, 1218347. doi: 10.1155/2022/1218347

Boselli, E., Caboni, M. F., Rodriguez-Estrada, M. T., Toschi, T. G., Daniel, M., Lercker, G., et al. (2005). Photoxidation of cholesterol and lipids of turkey meat during storage under commercial retail conditions. *Food Chem.* 91, 705–713. doi: 10.1016/j.foodchem.2004.06.043

Boyd, L. C., Green, D. P., Giesbrecht, F. B., and King, M. F. (1993). Inhibition of oxidative rancidity in frozen cooked fish flakes by tert-butylhydroquinone and rosemary extract. *J. Sci. Food Agric.* 61, 87–93. doi: 10.1002/jsfa.2740610114

Cardinal, M., Knockaert, C., Torrissen, O., Sigurgisladottir, S., Mørkøre, T., Thomassen, M., et al. (2001). Relation of smoking parameters to the yield, colour and sensory quality of smoked Atlantic salmon (*Salmo salar*). *Food Res. Int.* 34, 537–550. doi: 10.1016/S0963-9969(01)00069-2

Chupin, L., Maunu, S. L., Reynaud, S., Pizzi, A., Charrier, B., Charrier-El Bouhtoury, F., et al. (2015). Microwave assisted extraction of maritime pine (*Pinus pinaster*) bark: Impact of particle size and characterization. *Ind. Crops Prod.* 65, 142–149. doi: 10.1016/j.indcrop.2014.11.052

Cunha, S. A., Coscueta, E. R., Alexandre, A. M. R. C., Partidário, A. M. C., Fernández, N., Paiva, A., et al. (2023). Integral valorization of Nannochloropsis oceanica via enzymatic hydrolysis to obtain bioactive peptide extracts and eicosapentaenoic acid enriched fraction. *Food Funct.*

Cunha, S. A., de Castro, R., Coscueta, E. R, and Pintado, M. (2021). Hydrolysate from mussel *Mytilus galloprovincialis* meat: enzymatic hydrolysis, optimization and bioactive properties. *Molecules* 26, 5228. doi: 10.3390/molecules26175228

Cunha, S. A., and Pintado, M. E. (2022). Bioactive peptides derived from marine sources: Biological and functional properties. *Trends Food Sci. Technol.* 119, 348–370. doi: 10.1016/j.tifs.2021.08.017

Danowska-Oziewicz, M., and Karpińska-Tymoszczyk, M. (2005). Quality changes in selected frying fats during heating in a model system. *J. Food Lipids* 12, 159–168. doi: 10.1111/j.1745-4522.2005.00014.x

Du, W. X., Huang, T., Kim, J., Marshall, M. R., and Wei, C. (2001). Chemical, microbiological, and AromaScan evaluation of mahi-mahi fillets under various storage conditions. *J. Agric. Food Chem.* 49, 527–534. doi: 10.1021/jf0011135

Dziedziński, M., Kobus-Cisowska, J., and Stachowiak, B. (2021). Pinus species as prospective reserves of bioactive compounds with potential use in functional food—current state of knowledge. *Plants* 10, 1306. doi: 10.3390/plants10071306

Erkmen, O., and Bozoglu, T. F. (2016). "Food preservation by low temperatures," in *Food Microbiol.: Principles into Practice*, eds O. Erkmen, and T. Faruk Bozoglu (Hoboken, NJ: Wiley), 34–43. doi: 10.1002/9781119237860.ch29

Eyo, A. A. (2001). *Fish Processing Technology in the Tropics*. Niger: National Institute for Freshwater Fisheries Research (NIFFR).

FAO (2012). *The State of World Fisheries and Aquaculture*. Available online at: https://www.fao.org/3/i2727e/i2727e.pdf (accessed July 19, 2022).

FAO (2017). *Fishery and Aquaculture Country Profiles.* Portugal. Available online at: https://www.fao.org/fishery/en/facp/prt?lang=en (accessed July 23, 2022).

FAO/WHO (2001). *Codex alimentarius, Volume 8: Fats, Oils and Related Products*, 2nd ed. Rome: Food and Agriculture Organization of the United Nations (FAO).

Fellenberg, A., Carlos, F., Peña, I., Ibáñez, R., and Vargas-Bello-Pérez, E. (2020). Oxidative quality and color variation during refrigeration (4 °C) of rainbow trout fillets marinated with different natural antioxidants from oregano, quillaia and rosemary. *Agric. Food Sci.* 29, 42–44. doi: 10.23986/afsci.87078

Fleita, D., El-Sayed, M., and Rifaat, D. (2015). Evaluation of the antioxidant activity of enzymatically-hydrolyzed sulfated polysaccharides extracted from red algae; *Pterocladia capillacea. LWT - Food Sci.* 63, 1236–1244. doi: 10.1016/j.lwt.2015.04.024

Gómez-Guillén, M., Gómez-Estaca, J., Gimenez, B., Montero, P. (2009). Alternative fish species for cold-smoking process. *Int. J. Food Sci. Technol.* 44, 1525–1535. doi: 10.1111/j.1365-2621.2008.01762.x

González-Fandos, E. Garcia-Linares, M. C., Villarino-Rodriguez, A., Garcia-Arias, M. T., Garcia-Fernández, M. C. (2004). Evaluation of the microbiological safety and sensory quality of rainbow trout (Oncorhynchus mykiss) processed by the sous vide method. *Food Microbiol.* 21, 193–201. doi: 10.1016/S0740-0020(03)00053-4

Gotoh, N., and Wada, S. (2006). The importance of peroxide value in assessing food quality and food safety. *J. Am. Oil Chem. Soc.* 83, 473–474. doi: 10.1007/s11746-006-1229-4

Goulas, A., and Kontominas, M. (2005). Effect of salting and smoking-method on the keeping quality of chub mackerel (*Scomber japonicus*): biochemical and sensory attributes. *Food Chem.* 93, 511–520. doi: 10.1016/j.foodchem.2004.09.040

Grienke, U., Silke, J., and Tasdemir, D. (2014). Bioactive compounds from marine mussels and their effects on human health. *Food Chem.* 142, 48–60. doi: 10.1016/j.foodchem.2013.07.027

Hameş-Kocabaş, E. E., Yeşil-Çeliktaş, Ö., Işleten, M., and Vardar-Sukan, F. (2008). Antimicrobial activities of pine bark extract and assessment of potential application in cooked red meat. *J. Geogr. Inf. Syst.* 33, 123–127.

Hamilton, R. J., Kalu, C., McNeill, G. P., Padley, F. B., and Pierce, J. H. (1998). Effects of tocopherols, ascorbyl palmitate, and lecithin on autoxidation of fish oil. *J. Am. Oil Chem. Soc.* 75, 813–822. doi: 10.1007/s11746-998-0231-4

He, Y., and Shahidi, F. (1997). Antioxidant activity of green tea and its catechins in a fish meat model system. *J. Agric. Food Chem.* 45, 4262–4266. doi: 10.1021/jf9706134

HPA (2009). *Guidelines for Assessing the Microbiological Safety of Ready-to-Eat Foods Placed on the Market*. Health Protection Agency. Available online at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/363146/Guidelines_for_assessing_the_microbiological_safety_of_ready-to-eat_foods_on_the_market.pdf (accessed July 19, 2021).

Iacumin, L., Tirloni, E., Manzano, M., and Comi, G. (2017). Shelf-life evaluation of sliced cold-smoked rainbow trout (*Oncorhynchus mykiss*) under vacuum (Pv) and modified atmosphere packaging (MAP). *J. Fish. Aquat. Sci.* 17. doi: 10.4194/1303-2712-v17_6_21

Iglesias, J., Pazos, M., Lois, S., and Medina, I. (2010). Contribution of galloylation and polymerization to the antioxidant activity of polyphenols in fish lipid systems. *J. Agric. Food Chem.* 58, 7423–7431. doi: 10.1021/jf100832z

INSA (2019). *Interpretação de Resultados de Ensaios Microbiológicos em Alimentos Prontos para Consumo e em Superfícies do Ambiente de Preparação e Distribuição Alimentar: Valores-guia*. INSA. Available online at: https://www.insa.min-saude.pt/wp-content/uploads/2019/12/INSA_Valores-guia.pdf (accessed July 21, 2021).

Iravani, S., and Zolfaghari, B. (2014). Phytochemical analysis of *Pinus eldarica* bark. *Res. Pharm. Sci.* 9, 243–250.

ISO (2007). *Sensory Analysis — General Guidance for the Design of Test Rooms*. Geneva: International Organization for Standardization.

Je, J. Y., Park, P. J., Byun, H. G., Jung, W. K., and Kim, S. K. (2005). Angiotensin I converting enzyme (ACE) inhibitory peptide derived from the sauce of fermented blue mussel, *Mytilus edulis*. *Bioresour. Technol.* 96, 1624–1629. doi: 10.1016/j.biortech.2005.01.001

Jerez, M., Touriño, S., Sineiro, J., Torres, J. L., and Núñez, M. J. (2007). Procyanidins from pine bark: Relationships between structure, composition and antiradical activity. *Food Chem.* 104, 518–527. doi: 10.1016/j.foodchem.2006.11.071

Jolliffe, I. T., and Cadima, J. (2016). Principal component analysis: a review and recent developments. *Philos. Trans. Royal Soc.* 374, 20150202. doi: 10.1098/rsta.2015.0202

Jung, W.-K., and Kim, S.-K. (2009). Isolation and characterisation of an anticoagulant oligopeptide from blue mussel, *Mytilus edulis*. *Food Chem.* 117, 687–692. doi: 10.1016/j.foodchem.2009.04.077

Jung, W. K., Qian, Z. J., Lee, S. H., Choi, S. Y., Sung, N. J., Byun, H. G., et al. (2007). Free radical scavenging activity of a novel antioxidative peptide isolated from in vitro gastrointestinal digests of *Mytilus coruscus*. *J. Med. Food* 10, 197–202. doi: 10.1089/jmf.2006.101

Karoui, R., and Hassoun, A. (2017). Efficiency of rosemary and basil essential oils on the shelf-life extension of atlantic mackerel (*Scomber scombrus*) fillets stored at 2°C. *J. AOAC Int*. 100, 335–344. doi: 10.5740/jaoacint.16-0410

Ke, P. J., Ackman, R. G., Linke, B. A., and Nash, D. M. (1977). Differential lipid oxidation in various parts of frozen mackerel. *Int. J. Food Sci. Technol.* 12, 37–47. doi: 10.1111/j.1365-2621.1977.tb00083.x

Ke, P. J., Cervantes, E., and Robles-Martinez, C. (1984). Determination of thiobarbituric acid reactive substances (TBARS) in fish tissue by an improved distillation–spectrophotometric method. *J. Sci. Food Agric.* 35, 1248–1254. doi: 10.1002/jsfa.2740351117

Khalil, A. H., and Mansour, E. H. (1998). Control of lipid oxidation in cooked and uncooked refrigerated carp fillets by antioxidant and packaging combinations. *J. Agric. Food Chem.* 46, 1158–1162. doi: 10.1021/jf970601i

Khan, S., Priyamvada, S., Farooq, N., Khan, S., Khan, M. W., Yusufi, A., et al. (2009). Protective effect of green tea extract on gentamicin-induced nephrotoxicity and oxidative damage in rat kidney. *Pharmacol. Res.* 59, 254–262. doi: 10.1016/j.phrs.2008.12.009

Kim, E. K., Joung, H. J., Kim, Y. S., Hwang, J. W., Ahn, C. B., Jeon, Y. J., et al. (2012). Purification of a novel anticancer peptide from enzymatic hydrolysate of *Mytilus coruscus*. *J. Microbiol. Biotechnol.* 22, 1381–1387. doi: 10.4014/jmb.1207.07015

Kolodziejska, I., Niecikowska, C., Januszewska, E., and Sikorski, Z. E. (2002). The microbial and sensory quality of mackerel hot smoked in mild conditions. *LWT - Food Sci.* 35, 87–92. doi: 10.1006/fstl.2001.0824

Kumolu-Joh, C. A., and Ndimele, P. E. (2011). Anti-oxidative and anti-fungal effects of fresh ginger (*Zingiber officinale*) treatment on the shelf life of hot-smoked catfish (*Clarias gariepinus*, Burchell, 1822). *Asian J. Biol. Sci.* 4, 532–539. doi: 10.3923/ajbs.2011.532.539

Leroi, F., and Joffraud, J. J. (2000). Salt and smoke simultaneously affect chemical and sensory quality of cold-smoked salmon during 5 degrees C storage predicted using factorial design. *J. Food Prot.* 63, 1222–1227. doi: 10.4315/0362-028X-63.9.1222

Loutfi, A., Coradeschi, S., Mani, G. K., Shankar, P., and Rayappan, J. B. B. (2015). Electronic noses for food quality: a review. *J. Food Eng.* 144, 103–111. doi: 10.1016/j.jfoodeng.2014.07.019

Mármol, I., Quero, J., Jiménez-Moreno, N., Rodríguez-Yoldi, M. J., and Ancín-Azpilicueta, C. (2019). A systematic review of the potential uses of pine bark in food industry and health care. *Trends Food Sci. Technol.* 88, 558–566. doi: 10.1016/j.tifs.2018.07.007

Martinez, O., Salmerón, J., Guillén, M. D., and Casas, C. (2007). Sensorial and physicochemical characteristics of salmon (*Salmo salar*) treated by different smoking processes during storage. *Food Sci. Technol. Int.* 13, 477–484. doi: 10.1177/1082013207087816

Meilgaard, M. C., Civille, G., and Carr, B. (2016). *Sensory Evaluation Techniques,* Vol. II. Boca Raton, FL.

Mendes, M., Pereira, R., Pinto, I. S., Carvalho, A., and Gomes, A. (2013). Antimicrobial activity and lipid profile of seaweed extracts from the North Portuguese Coast. *Int. Food Res. J.* 20, 3337–3345.

Messina, C., Bono, G., Arena, R., Randazzo, M., Manuguerra, S., Santulli, A., et al. (2016). Polyphenols from halophytes and modified atmosphere packaging improve sensorial and biochemical markers of quality of common dolphinfish (*Coryphaena hippurus*) fillets. *Food Sci. Nutr.* 4, 723–732. doi: 10.1002/fsn3.337

Michalak, I., and Chojnacka, K. (2015). Algae as production systems of bioactive compounds. *Eng. Life Sci.* 15, 160–176. doi: 10.1002/elsc.201400191

Nair, P. V., Gopakumar, K., and Rajendranathan Nair, M. (1976). Lipid hydrolysis in mackerel (Rastrelliger kanagurta) during frozen storage. *Fish Technol.* 13, 111–114.

Nair, V., Cooper, C. S., Vietti, D. E., and Turner, G. A. (1986). The chemistry of lipid peroxidation metabolites: crosslinking reactions of malondialdehyde. *Lipids* 21, 6–10. doi: 10.1007/BF02534294

Neves, A. C., Harnedy, P. A., and FitzGerald, R. J. (2016). Angiotensin converting enzyme and dipeptidyl peptidase-iv inhibitory, and antioxidant activities of a blue mussel (*Mytilus edulis*) meat protein extract and its hydrolysates. *J. Aquat. Food Prod.* 25, 1221–1233. doi: 10.1080/10498850.2015.1051259

Nova, P., Pimenta, A., Teixeira, C., Abreu, H., Silva, J., Silva, A., et al. (2020). Foods with microalgae and seaweeds fostering consumers health: a review on scientific and market innovations. *J. Appl. Phycol.* 32, 1789–1802. doi: 10.1007/s10811-020-02129-w

Ozogul, Y., Yuvka, I., Ucar, Y., Durmus, M., Kösker, A. R., Öz, M., et al. (2017). Evaluation of effects of nanoemulsion based on herb essential oils (rosemary, laurel, thyme and sage) on sensory, chemical and microbiological quality of rainbow trout (*Oncorhynchus mykiss*) fillets during ice storage. *LWT* 75, 677–684. doi: 10.1016/j.lwt.2016.10.009

Pane, G., Cacciola, G., Giacco, E., Mariottini, G. L., and Coppo, E. (2015). Assessment of the antimicrobial activity of algae extracts on bacteria responsible of external otitis. *Mar. Drugs* 13, 6440–6452. doi: 10.3390/md13106440

Pazos, M., Alonso, A., Fernández-Bolaños, J., Torres, J. L., and Medina, I. (2006). Physicochemical properties of natural phenolics from grapes and olive oil byproducts and their antioxidant activity in frozen horse mackerel fillets. *J. Agric. Food Chem.* 54, 366–373. doi: 10.1021/jf0518296

Pérez-López, P., González-García, S., Ulloa, R. G., Sineiro, J., Feijoo, G., Moreira, M. T., et al. (2014). Life cycle assessment of the production of bioactive compounds from Tetraselmis suecica at pilot scale. *J. Clean. Prod.* 64, 323–331. doi: 10.1016/j.jclepro.2013.07.028

Pina-Pérez, M. C., Rivas, A., Martínez, A., and Rodrigo, D. (2017). Antimicrobial potential of macro and microalgae against pathogenic and spoilage microorganisms in food. *Food Chem.* 235, 34–44. doi: 10.1016/j.foodchem.2017.05.033

Raeisi, S., Quek, S. Y., Ojagh, S. M., and Alishahi, A. R. (2016). Effects of cumin (*Cuminum cyminum* L.) seed and wild mint (*Mentha longifolia* L.) leaf extracts on the shelf life and quality of rainbow trout (*Oncorhynchus mykiss*) fillets stored at 4C ± 1. *J. Food Saf.* 36, 271–281. doi: 10.1111/jfs.12240

Ramanathan, L., and Das, N. P. (1992). Studies on the control of lipid oxidation in ground fish by some polyphenolic natural products. *J. Agric. Food Chem.* 40, 17–21. doi: 10.1021/jf00013a004

Rathod, N., Ranveer, D. R., Benjakul, S., Kim, S. K., Pagarkar, A., Patange, S., et al. (2021). Recent developments of natural antimicrobials and antioxidants on fish and fishery food products. *Compr. Rev. Food Sci. Food Saf.* 20, 4182–4210. doi: 10.1111/1541-4337.12787

Rybicka, I., Silva, M., Gonçalves, A., Oliveira, H., Marques, A., Fernandes, M. J., et al. (2022). The development of smoked mackerel with reduced sodium content. *Foods* 11, 349. doi: 10.3390/foods11030349

Seabra, I. J., Dias, A. M. A., Braga, M. E. M., and de Sousa, H. C. (2012). High pressure solvent extraction of maritime pine bark: study of fractionation, solvent flow rate and solvent composition. *J. Supercrit. Fluids* 62, 135–148. doi: 10.1016/j.supflu.2011.10.016

Silva, F., Duarte, A. M., Mendes, S., Magalhães, E., Pinto, F. R., Barroso, S., et al. (2020). Seasonal sensory evaluation of low commercial value or unexploited fish species from the Portuguese coast. *Foods* 9, 1880. doi: 10.3390/foods9121880

Sousa, I., Gouveia, L., Batista, A., Raymundo, A., and Bandarra, N. (2008). "Microalgae in novel food products," in *Food Chemistry Research Developments*, ed. K. Papadoupoulos (New York, NY: Nova Science Publishers), 75–112.

Sousa, W. M., Silva, R. O., Bezerra, F. F., Bingana, R. D., Barros, F. C. N., Costa, L. E. C., et al. (2016). Sulfated polysaccharide fraction from marine algae *Solieria filiformis*: Structural characterization, gastroprotective and antioxidant effects. *Carbohydr. Polym.* 152, 140–148. doi: 10.1016/j.carbpol.2016.06.111

St. Angelo, A. J., Vercellotti, J., Jacks, T., and Legendre, M. (1996). Lipid oxidation in foods. *Crit. Rev. Food Sci. Nutr.* 36, 175–224. doi: 10.1080/10408399609527723

Swastawati, F., Al-Baarri, A., Susanto, E., and Purnamayati, L. (2020). The effect of antioxidant and antibacterial liquid smoke nanocapsules on catfish fillet (*Pangasius* sp.) during storage at room temperature and cold temperature. *Carpathian J. Food Sci. Technol.* 11, 165–175. doi: 10.34302/2019.11.4.16

Tenyang, N., Zambou, G. T., Ponka, R., and Womeni, H. M. (2020). Antioxidant effect of plants aqueous extract on lipid stability of andlt;iandgt;oreochromis niloticusandlt;/iandgt; during traditional sun and smoke drying in Far-North Cameroon. *Food Sci. Nutr.* 11, 854–871. doi: 10.4236/fns.2020.118060

Thorisson, S., Gunstone, F., and Hardy, R. (1992). The antioxidant properties of ethoxyquin and of some of its oxidation products in fish oil and meal. *J. Am. Oil Chem. Soc.* 69, 806–809. doi: 10.1007/BF02635920

Torras, M. A., Faura, C. A., Schönlau, F., and Rohdewald, P. (2005). Antimicrobial activity of pycnogenol. *Phytother. Res.* 19, 647–648. doi: 10.1002/ptr.1662

Tümen, I., Akkol, E. K., Taştan, H., Süntar, I., and Kurtca, M. (2018). Research on the antioxidant, wound healing, and anti-inflammatory activities and the phytochemical composition of maritime pine (*Pinus pinaster* Ait). *J. Ethnopharmacol.* 211, 235–246. doi: 10.1016/j.jep.2017.09.009

Ucak, I., Özogul, Y., and Durmuş, M. (2011). The effects of rosemary extract combination with vacuum packing on the changes of Atlantic mackerel fish burgers. *Int. J. Food Sci. Technol.* 46, 1157–1163. doi: 10.1111/j.1365-2621.2011.02610.x

Undeland, I., Hall, G., and Lingnert, H. (1999). Lipid oxidation in fillets of herring (*Clupea harengus*) during Ice Storage. *J. Agric. Food Chem.* 47, 524–532. doi: 10.1021/jf9807871

Warm, K., Martens, H., Nielsen, J., and Martens, M. (2001). Sensory quality criteria for five fish species predicted from near-infrared (NIR) reflectance measurement. *J. Food Qual.* 24, 389–403. doi: 10.1111/j.1745-4557.2001.tb00618.x

Watson, S. B., and Cruz-Rivera, E. (2003). Algal chemical ecology: an introduction to the special issue. *Phycologia* 42, 319–323. doi: 10.2216/i0031-8884-42-4-319.1

Zaki, H., Emara, M., and Abdallah, M. (2021). Effect of smoke duration on compositional analysis, deterioration criteria, microbial profile and sensory attributes of marine and freshwater fish: a comparative study. *Adv. Anim. Vet. Sci.* 9, 1259–1266. doi: 10.17582/journal.aavs/2021/9.8.1259.1266

TYPE Original Research
PUBLISHED 19 December 2023
DOI 10.3389/faquc.2023.1302571

OPEN ACCESS

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RECEIVED 26 September 2023
ACCEPTED 30 November 2023
PUBLISHED 19 December 2023

CITATION
Rossignoli CM, Obi C, Ali SA, Ullah N, Khalid S, Hafeez M and Shah SMH (2023) Production system and challenges of saline aquaculture in Punjab and Sindh provinces of Pakistan. *Front. Aquac.* 2:1302571. doi: 10.3389/faquc.2023.1302571

Production system and challenges of saline aquaculture in Punjab and Sindh provinces of Pakistan

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Introduction: Lack of data about saline aquaculture in Pakistan has curtailed informed policy and investment decision making resulting in undervaluation of and underinvestment in the sector. Therefore, saline aquaculture in Pakistan is today an underdeveloped sector despite its potential as an alternative livelihood for the country's rural farmers. This study represents one of the initial exploratory investigations into saline aquaculture systems in Pakistan, aiming to comprehend the existing sectoral landscape, production challenges, post-harvest constraints, and the associated capacity and investment needs.

Methods: The study employed purposive sampling to survey 121 low-income saline aquaculture farmers across five districts of Southern Punjab and Sindh provinces. The analysis was carried out using descriptive statistics.

Results: The results revealed that the saline aquaculture sector is predominantly male-centric, with agricultural land utilized for both agriculture and aquaculture purposes. Ponds, which usually serve multiple functions, focus primarily on carp production, but adherence to good management practices remains limited. Farmers face various challenges, including the high costs of feed and seeds, freshwater scarcity, inadequate technical knowledge, and marketing issues.

Discussion and conclusion: This study serves as a foundational assessment, addressing data and information gaps crucial for supporting the sustainable development of saline aquaculture in Pakistan. To facilitate such development, the study recommends initiating programs to strengthen technical skills in saline aquaculture, together with the establishment of hatcheries and breeding stations for saline-tolerant species, aiming to reduce dependence on freshwater species in saline pond environments.

KEYWORDS
Saline aquaculture, Pakistan, Production challenges, Production system, Economic analysis, Investment needs

1 Introduction

Rising salinity in Pakistan has created a difficult challenge for agricultural activities, necessitating alternative livelihoods for rural farmers. Climate change, coupled with floods and escalating salinity levels, has become a primary driver of livelihood loss for thousands of farmers in rural areas. The arid and semi-arid climate, characterized by scarce and irregular rainfall, exacerbates salinity and waterlogging, rendering vast acres unsuitable for cultivation and intensifying rural poverty and food insecurity (World Bank, 2021).

Amid these multifaceted challenges, a recent development has emerged: saline aquaculture, a land-based aquaculture utilizing saline groundwater on lands deemed unfit for crop cultivation, has emerged as a viable alternative for rural farming households. This shift is particularly pronounced in areas with brackish groundwater, such as Sindh and Punjab provinces. Saline aquaculture, at its core, involves the cultivation of aquatic organisms in waters with elevated salinity levels. In the context of Punjab and Sindh provinces, this often takes the form of land-based ponds utilizing saline groundwater. The ponds are strategically located, considering their proximity to seashores in coastal areas or constructed in the hinterland using irrigated waters connected to the sea. This unique approach allows for the utilization of lands rendered unsuitable for traditional crop cultivation due to salinity and waterlogging.

However, despite the potential of saline aquaculture, Pakistan's aquaculture sector remains underdeveloped and in need of strategic development (Patil et al., 2018). As of 2021, fisheries contributed merely 0.4% to the country's GDP, with approximately 390,000 people employed directly in fisheries and aquaculture. In contrast to neighboring countries like Bangladesh and India, aquaculture production in Pakistan lags behind, with slow growth rates of around 1.5% per year, compared to India's 8% and Bangladesh's 2.3% (FAO, 2022a). Figure 1 illustrates the significant disparities in aquaculture production among Pakistan, Bangladesh, and India.

While saline aquaculture is rapidly evolving globally, featuring prominently in countries like Israel, the USA, India, Bangladesh, and Australia with substantial government investments (Allan et al., 2009; Anufriieva, 2018; Faruque et al., 2017; Mandal et al., 2021), it remains a nascent practice in Pakistan, with limited support for farmers. Studies from India and Bangladesh highlight the positive impact of saline aquaculture on nutrition, income, employment generation, and women's empowerment in coastal regions (Belton et al., 2017; Hernandez et al., 2018; Kumar & Sharma, 2020; Mamun et al., 2021; Dam Lam et al., 2022). However, there is currently no such study or data for Pakistan. Thus, the lack of information on the saline aquaculture sector in Pakistan impedes the development of effective policies and strategies.

This study represents one of the initial exploratory investigations conducted on saline aquaculture systems in Pakistan, specifically focusing on Sindh and Punjab provinces. By delving into the current sectoral landscape, production challenges, post-harvest constraints, and capacity and investment needs, this study aims to bridge the knowledge gap and inform crucial policy decisions for the growth of saline aquaculture in the country.

2 Materials and methods

2.1 Study area

This investigation stems from an exploratory survey conducted in 2022 by the International Water Management Institute (IWMI) and WorldFish, focusing on the landscape of saline aquaculture in Pakistan. The survey specifically targeted Southern Punjab and Sindh Provinces, where soil salinity poses a growing challenge in the agriculture sector.

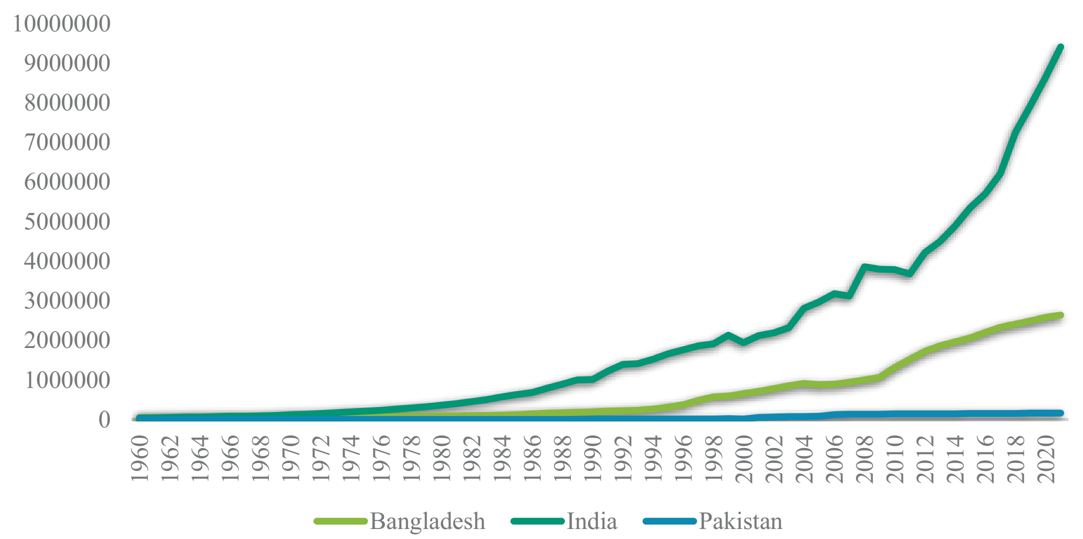

FIGURE 1
Aquaculture Production (metric tons) – Pakistan, Bangladesh and India. Source: FAOSTAT, 2023.

According to FAO estimates (FAO 2022b), aquaculture covers 121 thousand acres in Sindh and 27 thousand acres in Punjab, featuring fish farms averaging between 12 to 25 acres. Previous research indicates that in Punjab, 23% of the area contends with poor groundwater quality, while in Sindh, a substantial 78% of the groundwater is saline due to the confinement of fresh groundwater to a narrow strip along the river Indus (Qureshi, 2020). Annually, about 100 thousand acres are abandoned within the Indus Basin due to secondary salinization (Qureshi et al., 2008), rendering these areas unsuitable for traditional irrigation or field crop production.

Recognizing the potential of saline areas in Punjab and Sindh for aquaculture, provincial fisheries departments introduced fish farming techniques in earthen ponds and community reservoirs as early as the 1960s. Patil et al. (2018) highlighted the introduction of polycultures involving Indian and Chinese carps in the two provinces since the 1980s. Recent trends reveal an increasing adoption of commercially produced fish feed, including floating and sinking pellets, by fish farmers.

Punjab and Sindh were chosen for this study due to their significant potential for enhancing farmers livelihood through saline aquaculture. Moreover, these areas exhibit scalability potential across diverse regions if proven successful (Troell et al., 2009). In districts such as Thatta, Badin, and Dadu in Sindh, fish farming commonly occurs in waterlogged floodplains, with major species like carp and tilapia (Patil et al., 2018). Meanwhile, aquaculture species in districts like Sheikhpura, Gujranwala, Attock, and Muzarfagarh in Punjab include carp, tilapia, trout, shrimp, and catfish. Punjab also boasts several feed producers and fish training centers, such as the Punjab Fisheries Research and Training Centre.

2.2 The survey

The research incorporated on-site visits, surveys targeting saline aquaculture farmers, and extensive consultations with stakeholders. District selection involved consultations with stakeholders in Sindh and Punjab, identifying marginalized saline areas with potential for aquaculture improvement. The chosen districts were in South Punjab (Dera Ghazi Khan and Rahim Yar Khan) and in Sindh (Thatta and Badin). To know the universe of saline ponds population, a spatial analysis was conducted using high resolution imagery to mark ponds in the study area. At the second step, a random sampling approach was used to reach out the sample size by using the basis which produced statistically significant results and keep the cost of primary data collection within the available budget. The basis used for sample size calculation were population size of 4560 ponds, 95% confidence level and 10% margin of error.

The team collaborated with the Pakistan Council of Research on Water Resources (PCRWR) and local partners and universities in identifying eligible farmers. At the end, 121 farmers across five districts in Sindh and Punjab: Bahawalpur (n=5), Thatta (n=35), Badin (n=30), DGK/Muzaffargarh (n=30), and Rahim Yar Khan (n=21) were selected through snowball approach[1]. The selection criteria focused on low-income farmers with a) pond salinity exceeding 2 milliSiemens per centimeter (mS/cm), and b) farmers with small, medium and large ponds were interviewed to ensure a robust sample size in each district.

Data collection spanned two months, facilitated by male and female enumerators well-versed in saline aquaculture, utilizing Computer-Assisted Personal Interviews (CAPI) through Kobo Toolbox. Interviews occurred in local languages (e.g., Urdu, Siraiki, Punjabi), supported by local partners to address language barriers. Real-time data collection and online uploading were managed through daily data monitoring by the project field monitor, with daily debriefs conducted with enumerators to address challenges. The research adhered to standard research ethics, with IWMI Internal Review Board approval for the survey tool. Participants' privacy was safeguarded through de-identified data, and interviews were conducted post-informed consent.

Post data collection and preliminary analysis, two additional provincial stakeholders' consultation workshops were organized to validate survey findings and discuss recommendations. These workshops, one in Punjab and one in Sindh, engaged 35 and 36 key stakeholders respectively, representing government departments, academia, fish farmers, hatchery owners, feed millers, and experts in supply chain and value. The workshops covered four principal topics: 1) challenges and opportunities for healthy seeds and salt-tolerant breeds, 2) challenges in pond water management and disease control, 3) challenges and opportunities for quality fish feed and proper fertilizer use, and 4) opportunities and modern techniques for small-scale farmers and women to promote saline aquaculture.

3 Results

3.1 Socioeconomic profile of the respondents

Table 1 summarizes the socioeconomic profile of the respondents. It shows that saline aquaculture in the study area is dominated by men. The majority of farmers are married (nearly 90%) with an average household size of 10 persons including the farmer. Close to 80% of the farmers are the primary breadwinners of their family while close to 60% have below secondary level education. Farmers have varied years of experience in fish farming, with only 28% with more than 10 years of experience and 72% with less than 10 years of experience.

1 The initial sample size was 30 ponds per district, however, due to challenges in randomly selecting ponds using GIS data, the snowball approach was used to identify small functional fish farming ponds in each district using fish farmers' networks. In Rahim Yar Khan, many ponds had dried up due to drought conditions during the time of data collection in the summer months, resulting in a lower sample size, with the remaining sample drawn from other districts. The survey tool was piloted in district Bahawalpur, while the actual survey took place in the remaining four districts.

TABLE 1 Socioeconomic of respondents.

	Frequency	Percent	Mean
Gender			
Male	121	100.00	
Marital Status			
Married	106	87.60	
Single	15	12.40	
Primary Breadwinner of Household			
Male Relative	25	20.66	
Self	96	79.34	
Head of Household (Primary Decision-Maker)			
Male Relative	25	20.66	
Self	96	79.34	
Level of Education of Household Head			
Below Secondary	70	57.85	
At least Secondary	51	42.15	
Years of Fish Farming			
0-2 Years	14	11.57	
3-5 Years	40	33.06	
6-10 Years	32	27.27	
>10 Years	34	28.10	
Number of People in Household			
Household size			10
Number of Males			4
Number of Female			3
Number of Children less than 14 years old			3
Location			
Interviews in Sindh province	65	53.72	
Interviews in Punjab province	56	46.28	

3.2 Farm characterization

All respondents are crop or livestock farmers who have diversified their production into saline aquaculture farming. Hence, their land has multi-functional uses shared between farming and saline aquaculture. The size of farm owned by the respondents varies considerably, averaging 16.5 acres per farmer, in line with FAO (2022) estimates that the national farm size of fish farmers in Pakistan ranges from 12 to 25 acres. The land is evenly distributed between agriculture farming and saline aquaculture. Most of the ponds (65%) are owned and operated by the respondents, while a third of the respondents lease the ponds from the original owners. At the time of the survey, almost all ponds owned or leased (93%) were in use for saline aquaculture. Only 7% of the ponds were not in use, although they are saline aquaculture capable.

A typical pond size covers 4 acres of land, with an average pond depth of 7.3 feet and average water depth of 4.8 feet. Pond size varies substantially between 1 to 5 acres, with the smallest at 1 acre and the largest 25 acres. The average pond size reported by the respondents is similar to the averages reported for Bangladesh and India (Sarkar et al., 2015; Castine et al., 2017). Around 37% of the farmers have a pond measuring 1-2 acres, almost 50% owned a pond of 3-5 acre, and only 15% owning a pond larger than five acres of land. The similar pond size in the study area compared to neighboring countries reiterates the potential to scale aquaculture production in Pakistan to achieve similar levels of productivity. For the disaggregated analysis of this study, farmers with pond sizes of 1-2 acres will be referred to as small-scale, those with 3-5 acres will be referred to as medium-scale, and large-scale farmers will be those with over 5 acres.

In addition to fish farming, more than half of the fish ponds (55%) are used for multiple activities. About 7 in 10 ponds owned by the respondents are used for other household activities, but leased ponds are rarely used for other activities. Besides fish production, 32% of the ponds serve as a source of water for livestock, while close to 12% are used for agriculture and irrigation. The survey also found that some respondents use their ponds for water, sanitation, and hygiene (WASH) activities including bathing (22%), washing (10%) and cooking (4%). The usage of ponds for WASH underscores the challenge of limited fresh water supply in the study area, with possible health and hygiene implications. Further, almost 75% of ponds in Sindh district are multi-purpose compared to only 32% of ponds in Punjab districts, highlighting the different socioeconomic context of the two provinces.

3.3 Pond management practices

Most of the ponds are constructed close to seashores in coastal areas, and others are constructed in the hinterland using irrigated waters connected to the sea. The major sources of water are from brackish groundwater (43%) or irrigation canal (58%). Only 1% of the farmers source their water from rivers. As expected, pond water is saline with an average conductivity of 7.6 mS/cm, and groundwater conductivity is higher than 3 mS/cm. In contrast, the average conductivity found in most freshwater is 0 - 1.5 mS/cm. Ponds in brackish environments often have issues with water quality, as they are easily waterlogged from runoff from the sea or heavy rain. Saline sand arising from the waterlogged soil occasionally flows into the pond, increasing its salinity. In general, proper monitoring and management of water quality is extremely important to the success of saline aquaculture because poor quality of water affects fish growth and causes fish diseases.

However, only 9% of respondents monitor pond water quality (Figure 2). Pond ownership, level of experience, and pond size are major factors predicting who is likely to monitor water quality. For instance, 11.4% of farmers who own their ponds reported monitoring their pond water quality as compared to 5% of those who lease. Almost 12% of experienced farmers monitor water quality compared to 8% of less experienced farmers. Equally,

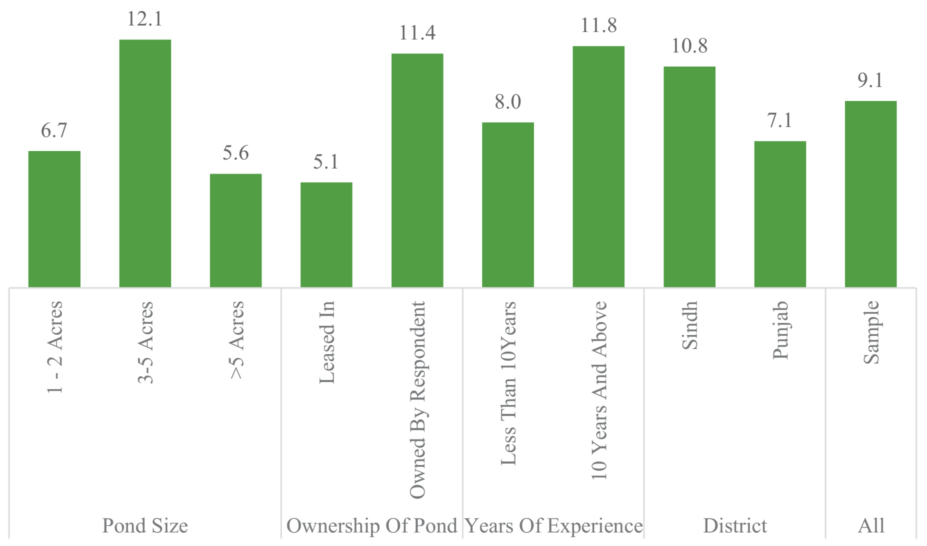

FIGURE 2
Proportion of respondents that conduct water quality monitoring.

farmers with medium pond sizes are more likely to conduct water quality checks than farmers with smaller size ponds. Major constraints reported are lack of technical knowledge and equipment to measure water quality and salinity. Due to these limitations, most of the farmers adopted rudimentary techniques in monitoring the quality of water such as tasting the pond water.

Most of the respondents do not practice better management practices which is important for the healthy growth of fish (Dickson et al., 2016). During the time of the survey, only a third of the farmers implemented some type of better management practice Figure 3. Medium-scale farmers (37.9%) and farmers who are less experienced (35.6%) are most likely to adopt management practices. Species selection is the most common management practice adopted in each season, and was followed by liming during both the pond preparation and the grow out period. Other practices, such as maintaining stock densities, testing natural food adequacy in the pond, post-harvest handling and using quality fish seeds are rarely practiced.

3.4 Pond preparation and input use

More than half (55%) of the respondents do not apply fertilizer before stocking the fish, approximately 12% do not apply fertilizer post-stocking, and about 21% do not apply any form of fertilizer (Figure 4). Among all the respondents, large-

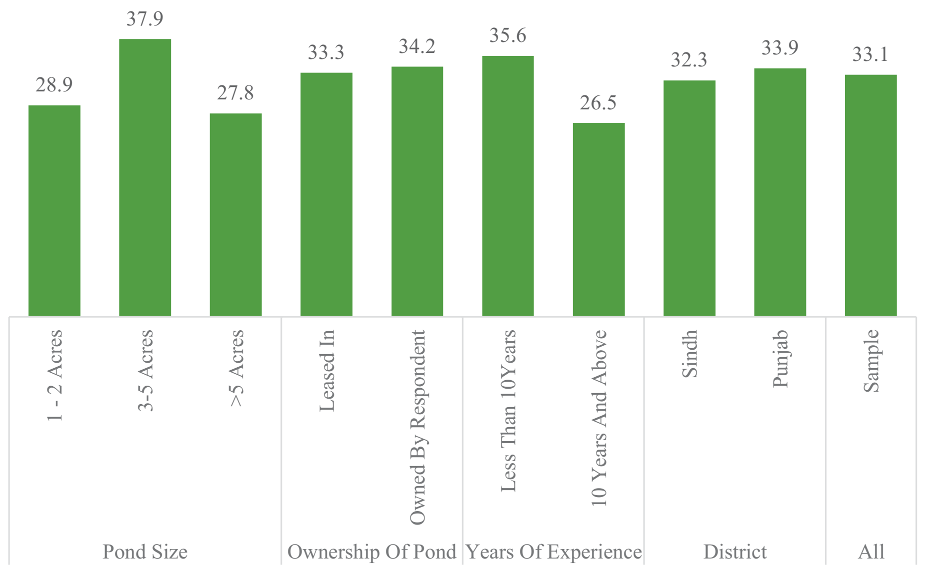

FIGURE 3
Share of farmers practicing special management practices.

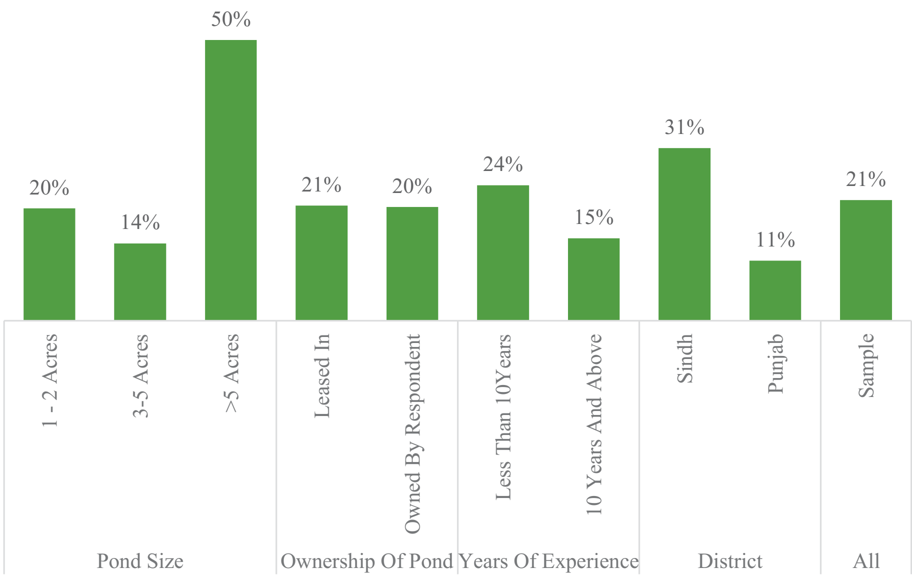

FIGURE 4
Share of respondents that applies fertilization.

scale farmers, less experienced farmers, and those living in Sindh are the least likely to apply fertilization at 50%, 24% and 31% respectively. Second, while the fertilizers applied vary considerably, inorganic fertilizers such as urea (65%), Di-ammonium Phosphate–Dap (58%), and quicklime (26%) are the most common. Cow dung is the most common form of organic fertilizer, applied by 21% of farmers (Table 2).

The high cost of fertilizer is a major problem reported by farmers which decreases their ability to practice proper pond preparation and fertilization. The survey estimates the average cost of fertilization at USD 44 per acre per year. The average total cost of fertilizer for each farmer per year is USD 123. This cost ranges from USD 102 per year for farmers with 1-2 acres, to over USD 137 per year for farmers with more than three acres. The price of fertilizers varies, with Nitrophos, DAP, and urea being the most expensive fertilizers in the study area.

3.5 Fish seed source and stocking

The farmers are dependent on external hatcheries for their seeds. Only a few farmers (1.7%) have their own fish hatchery for breeding purposes. Around 58% of farms purchase seed from private hatcheries while 29% purchase from private nurseries. Most of the respondents purchase fish fingerlings (95%) or fries (5%) from private hatcheries. Only 9% of farmers source their fish from the Department of Fisheries. Depending on the species, fish seed stocking generally occurs between January and March (68%). A majority of the farmers (97%) practice polyculture, meaning that they stock more than one fish species – about 32% of the farmers stock up to 4 fish species, 22% stock up to 5 species, and 6% stock up to 6 species. Fish are often stocked in one pond from an early stage until the grow out stage since most of the farmers (62%) do not have access to nursery ponds in addition to their production ponds.

Saline aquaculture farming in the study area is dominated by carps with a small number of farmers cultivating tilapia. At 84%, Rohu is the most prevalent species stocked by majority of the farmers in the study area (Table 3). Rohu is followed by Catla (71%), Mirgel (63%), Common Carp (55%), and Grass Carp (53%). Only 12% of farmers stock Singhari (catfish) and Tilapia and less than 7% stock other local seeds.[2] More than 90% of farmers stock carp species and fewer than 20% of farmers stock non-carps such as Catfish or Tilapia. The percentage of small and medium farms who stock carp is 93% and 100% respectively, whereas the percentage of large farms who stock carp is lower at 67%. This is mainly because medium and large scale farmers tend to stock Catfish or Tilapia. More so, farmers who lease (23%) and those with more experience (21%) stock more non-carps compared to farmers who own ponds (14%) and those with less experience (15%).

The common size of stocked fingerlings ranges from 4 to 6 inches. At 6.1 inches, Singhari (catfish) has the highest average size among fish stocked by the farmers. The common size of the carp species ranges from 4 to 5 inches, whereas the average size of tilapia fingerling is 3.6 inches. Large and medium farms, experienced farmers, and farmers in Punjab stock seed that have larger average sizes than their counterparts do. The stocking density varies according to the type of fish stocked – 800 fish/acre for carps, 220 fish/acre for Singhari, and 9,133 fish/acre for Tilapia. Average stocking density per acre is low at 2,194 fish/acre. For comparison, in India, stocking density of 10 inch carp fingerlings is at 7,500-10,000/ha (Belton et al., 2017). It is also observed from the data that small farms have higher average stocking densities than medium and large farms, 2,279 fish/acre versus 1,924 fish/acre. By

2 While ornamental fish like Moli and Shipping-King are stocked by around 3% of the farmers, these species were dropped from the analysis as it skewed the averages due to their unique sizes and purposes.

TABLE 2 Input use and cost for pond preparation.

Input (Kg)	Usage (%)	Pre-stocking period		Post-stocking period	
		Usage amount (Kgs/ml)	Total cost (USD)	Usage amount (Kgs/ml)	Total cost (USD)
Cow dung	21%	712.0	23.3	828.0	16.8
Poultry droppings	4%	65.0	7.1	267.3	91.4
Compost	1%		0.0	50.0	0.0
Urea	65%	94.8	16.2	326.6	37.4
MoP	1%	50.0	21.4		0.0
Quick lime	26%	163.9	8.5	225.8	13.3
Limestone	2%	400.0	21.4	80.0	3.6
Gypsum	7%	1333.3	18.5	1810.0	28.7
Nitrophos	2%	37.5	13.8	187.5	73.2
DAP	58%	166.2	36.6	243.8	93.1
Cypermethrine	15%			816.7	3.6

1 USD = PKR 280.

increasing stocking densities, small farms focus on maximizing production per unit volume, and potentially increasing their overall production and profitability.

Seed of Singhari fish species are more expensive on average USD 0.10 per piece than other fish seed in the study area. The average cost of carp fingerlings ranges from USD 0.05 to 0.08 per piece. Among the carps, Catla and Rohu species are the most expensive, averaging USD 0.08 per piece. The cost of Tilapia fingerlings average at USD 0.05 per piece. The average cost of stocking for each farmer is USD 37.9 per farmer. The average outlay stocking cost per acre is USD 12.25 per acre per acre. The average stocking costs of small farms per acre were relatively higher than those of medium and larger farms. This may be in relation to the higher stocking densities of small farmers. Small farmers with less than two acres have a stocking cost of USD 14 per acre, medium farms with 3–5 acres have a stocking cost of USD 11.8 per acre and large farms over five acres have a stocking cost of USD 8.4 per acre.

3.6 Fish feed and feeding routine

Fish feed constitutes a major cost in the saline aquaculture production system in the study area, comprising over 65% of total input cost. Feed cost is total amount spent by the farmer in the purchase of feed for all the fishes cultured per production cycle. Unconditional to the species cultivated, the average cost of fish feed reported by the saline aquaculture farmers during the time of the study is USD 280 per acre. For small-scale ponds, feed cost per acre is USD 246 per acre, for medium-scale farmers USD 337 per acre, and USD 159 per acre for large-scale farmers. In total, saline aquaculture farmers spent approximately USD 90.5 on fish feed per production cycle.

Farmers use a combination of fish feed including rice polish, poultry feed, grass, choker, and gluten meal. Around 34% of the farmers use rice polish, 23% poultry feed, 15% grass, 14% choker, and 14% gluten. The fish feed adopted by the farmers can be divided

TABLE 3 Stocking rate and cost of fish fingerling.

Seed species	Share of respondents that stock (%)	Total number of fish seed stocked	Stocking density	Average fish seed size (Inch)	Cost per fish piece (USD)
Singhari	12%	43.1	220	6.1	0.10
Grass carp	53%	2333.0	1360	4.8	0.06
Rohu	84%	3467.4	2368	4.9	0.08
Mirgel	63%	5276.5	275	4.4	0.06
Tilapia	12%	3865.0	9133	3.6	0.05
Catla	71%	2595.2	264	5.2	0.08
Common carp	55%	8574.8	275	4.3	0.05

1 USD = PKR 280.

into two categories: agro-processing byproducts and the more expensive commercially produced pellets. Because of the cost, most farmers use agro-processing byproducts like rice, poultry feed, and grass feed rather than commercial pellets. However, commercial pellets are often more desirable and of higher quality. Compared to other farms, medium scale farms of 3-5 acres are more likely to use commercially manufactured pelleted feeds. The number of farmers using pellets is considerably lower than observed in neighboring countries. For instance, in Bangladesh, Hernandez et al. (2018) reported that 38% of saline aquaculture farmers use pelleted feeds. In Andhra Pradesh, India more than 15% of carp farmers have adopted pelleted feed, and the switch to pelleted feed was attributed as one factor that contributed to the superior growth performance of fish (Belton et al., 2017).

Feeding routines depend on the type of fish and type of the farm. Farmers stocking Rohu, Catla and Grass Carp are more likely to feed twice a day, whereas farmers who stock non-carps like Singhari and Tilapia are more likely to feed once a day. Large-scale farmers often feed once, but small and medium-scale farmers feed their fish, on average, twice a day. Lease farmers feed their fish on average once a day, in contrast to farmers who own their pond, who feed at least twice a day. Farmers with large ponds who stock mostly non-carp fish like Tilapia seem to have bigger challenges in providing adequate feed, possibly because these species may require higher feeding regimes under those farming conditions. This finding confirms that there is a difference in the production intensity among the farmers.

The feeding quantity varied according to the fish stocked, ranging from 2.5 kg/ha to 15 kg/ha. Among the carps, farmers stocking Rohu have the highest amount of feeding quantity, with 8.2 kg/ha per feeding session. Again, this may be related to the high stocking density of Rohu compared to other carps. Farmers with non-carps like Tilapia and Singhari have a feeding quantity of 2.5 kg/ha per session, which is equivalent to the average recorded in farms with other non-Rohu carps.

Majority of respondents purchase their feed from feed fish outlets, with a small share of the farmers producing the feed themselves. 91% of the respondents purchase their fish feed, whereas the remaining 9% produce it or already have it at home. Medium scale farmers, owners of ponds, and farmers in Sindh are most likely to produce their fish feed compared to others. Unlike in Punjab where there are several feed producers where farmers can purchase from, in Sindh province, many farmers do not have sufficient access to feed producing centers and thus have to prepare fish feed themselves.

Feed trading is a major source of fish feed for more than half of the respondents (55%). Feed rice millers are also an important source of fish feed among the respondents, with about 8% of farmers purchasing fish feed from them. In addition, many farmers (40%) have alternative sources of feed, including self-production. Small (64%) and medium-scale (55%) farmers are most likely to purchase feed directly from fish traders, in contrast to large-scale farmers (28%). Additionally, farmers in Sindh districts are more likely to produce fish feed themselves (52%) or purchase from feed mills (14%), in contrast to farmers in Punjab who purchase from feed traders (71%). This may indicate lack of feed mills in Sindh or low accessibility to farmers as compared to those in Punjab.

3.7 Production, harvest and exchange

Around 50% of farmers harvest their fish between January and March, 35% harvest between October and December, and 15% harvest between April and September. The average culture period of the fish is between 10 and 12 months (Table 4). In line with expectation, Carp are the most harvested fish. Most of the farmers (98%) use gillnets for harvesting, while 7% use portable fishing nets and 2% use cast fishing nets. Large-scale farmers are the least likely to use gillnets (89%) in contrast to nearly 100% of small- and medium- scale farmers. A large majority (88%) of farmers expressed satisfaction with the growth parameters of their fish.

Rohu is the most common harvested species, with 84% of the farmers harvesting Rohu species. Around 70% of the farmers harvested Catla (70%), Mirgel (65%) and Common Carp (55%). Around one-tenth (12%) of farmers harvest species other than Carp, like Tilapia or Singhari (catfish). When analyzed as a share of the total quantity of fish produced, Carps account for over 80% of the volume of the fish produced in the study area. Among the Carps, Rohu leads with 35% of the volume of fish produced. Surprisingly, Tilapia was the second largest share of fish per volume in the study area after Rohu, accounting for 18% of the total volume of fish produced.

Around 39% of large-scale farms produce Tilapia, in contrast to 4% and 9% of small- and medium-scale farms. This might be because the cost of tilapia farming is higher, as it requires more seed and feed than carps. The average size of harvested fish ranges from 0.1 to 2.3 kg. depending on the fish species. Average sizes are 2.3 kg per fish for Singhari, 2.2 kg for Silver Carp and Grass Carp, 1.9 kg for Catla, and 1.8 kg for Common Carp. Rohu fish attained an average size of 1.5 kg, and Tilapia averaged 0.3 kg per fish.

On average, farmers harvest about 3,747 kg of fish per farm (Table 5). Large farms harvest 6,225 kg, medium farms 4,749 kg, and small farms a total of 1,466 kg. Leased-pond farmers harvest an average of 6,976 kg, which is three times more than the average harvest of owned farms (2,191 kg). Farms in Punjab harvest on average twice the number in Sindh, 4,846 kg per farm compared to 2,800 kg per farm. Less experienced farmers produce less volume of fish (3,421 kg) compared to more experienced farmers (4,583 kg). In terms of kg per acre, smaller farms tend to outperform larger farms. Medium-scale farmers achieve the highest productivity at 1,214 kg per acre, while small-scale farmers tend to outperform (867 kg per acre) large-scale farmers (620 kg per acre). Leased farms outperformed owned farms both in total volume and in volume per acre. This finding is in line with Patil et al. (2018) who wrote that yields in Pakistan are often between 969 kg per acre to 1215 kg per acre per year. It is, however, lower than the average reported in Bangladesh (1862 kg per acre per year).

Upon harvest, farmers transport their fish to the market for sale. Most of farmers (84%) sell to wholesalers while 24% sell directly to consumers. Around 98 percent of fish sold are raw (fresh), whereas

TABLE 4 Production performance of fish species.

	Average Culture Period (Months)	Total Fish Harvested per farm (kg)	Selling Price (USD per Kg)
Catla	11.1	420.4	0.96
Common Carp	10.6	488.0	1.11
Grass Carp	10.9	436.0	0.81
Mirgel	10.9	722.6	0.72
Rohu	10.9	1621.9	0.87
Silver Carp	11.3	1052.0	0.49
Singhari	10.3	115.8	0.98
Tilapia	10.2	5726.4	0.25

1 USD = PKR 280.

2% are processed. Large-scale farmers are most likely to sell processed fish compared to small-scale farmers. Farmers reported that all fish buyers are male, and that fish is often priced low. The average price of fish in the study is USD 0.79 per kg. The price of Tilapia was very low, averaging only USD 0.25 per kg. Summing all the production and sales in each farm, a typical farm could sell 3,698 kg of raw fish in one production cycle (irrespective of species), earning a revenue of around USD 2,627. Medium-scale farmers, farmers who lease their ponds, experienced farmers, and farmers in Punjab tend to earn higher revenue than their counterparts. These farmers were found to be more likely to regularly check the water quality of their ponds.

Almost all farmers (91%) consume some of the fish they produce, and 90% gift fish to other households. On average, each household consumes around 46 kg of fish per year, about 5 kg per person per year, which although higher than the national average of 1.9 kg per year, is still significantly lower than the FAO recommended minimum requirement of 18 kg per year.

3.8 Economic analysis

The economic analysis provides an aggregated economic performance of the saline ponds, calculated by summing all the sales of different fishes cultured by the farmer. The input cost is simply the total cost of seeds, feeds, and fertilizer used by the farmer per production cycle. Due to their unavailability, data on labor and land costs were not included in the analysis. Revenue is the total amount received from the sales of fishes. Gross profit is calculated by deducting the total cost of inputs from the total revenue. In general, the average total input cost is USD 1065.7 per production cycle, while the average revenue is USD 2627 per production cycle (Table 6). Thus, in terms of the economic performance of saline aquaculture, farmers achieve an average gross profit of USD 1561 per farmer per production cycler.

Gross profit per farmer demonstrates an upward trend with increasing pond size, rising from USD 764 per year for small farms (1-2 acres) to USD 1841 for larger farms exceeding 5 acres. Notably, gross profit in Sindh surpasses that in Punjab, attributed to lower costs in Sindh. When considering gross profit per acre, the average stands at USD 448 per acre. The highest is observed among medium-sized farms (3-5 acres) at USD 518 per acre, while farms

TABLE 5 Fish production, harvest and exchange.

	All	Pond Size			Province	
	Sample	1-2 Acres	3-5 Acres	>5 Acres	Sindh	Punjab
Per farm						
Total amount of fish harvested	3747	1466	4749	6225	2800	4846
Total amount of fish sold raw	3698	1461	4730	5965	2809	4730
Total amount of fish sold processed	3	0	5	1	5	0
Total amount of money received from sales (USD)	2,627	1,318	3,546	2,941	2,060	3,286
Total amount of fish consumed	46	30	33	126	30	65
Total amount of fish gifted	44	34	35	96	28	61
Per acre						
Total amount of fish harvested	997	867	1214	620	776	1253
Total amount of fish sold raw	986	865	1207	576	776	1229
Total amount of fish sold processed	1	0	2	0	2	0
Total amount of money received from sales (USD)	785	780	903	416	575	1,028
Total amount of fish consumed	13	21	9	9	10	17
Total amount of fish gifted	14	23	10	8	10	20

1 USD = PKR 280.

TABLE 6 Economic performance of the farmers.

	Total	Pond Size			District	
		1 - 2 Acres	3-5 Acres	>5 Acres	Sindh	Punjab
Per farm						
Seed cost	37.8	24.4	44.4	50.7	21.6	56.4
Feed cost	904.9	426.5	1294.2	929.7	168.2	1626.3
Fertilizer cost	123.0	102.2	138.5	119.5	85.6	156.6
Total input cost	1065.7	553.1	1477.1	1100.0	275.4	1839.3
Revenue	2627.0	1317.8	3545.6	2940.5	2059.5	3285.8
Gross profit	1561.3	764.6	2068.4	1840.6	1784.1	1446.5
Per acre						
Seed cost	12.3	14.1	11.8	8.4	7.2	18.0
Feed cost	280.0	246.0	337.0	158.9	64.5	490.9
Fertilizer cost	44.3	61.0	36.7	19.3	32.1	55.3
Total input cost	336.5	321.0	385.5	186.6	103.9	564.1
Revenue	784.9	779.6	903.4	416.2	575.2	1028.3
Gross profit	448.4	458.6	517.8	229.6	471.3	464.2

1 USD = PKR 280.

with over 5 acres yield the lowest at USD 230 per acre. Similarly, gross profit per acre is slightly higher in Sindh (USD 471 per acre) compared to Punjab (USD 464 per acre).

Despite these positive indicators, it is crucial to note that the data lacks information on labor and land costs. This omission poses a challenge in providing a comprehensive assessment of the economic viability of saline aquaculture. Labor and land costs are substantial components influencing overall profitability, and their exclusion may result in an underestimation of the true economic implications. Nonetheless, considering the positive trends in gross profit and regional disparities, coupled with the potential for local market demand, saline aquaculture holds promise as a good investment. However, a more comprehensive analysis incorporating labor and land costs, detailed market research, and an assessment of environmental sustainability would provide a more accurate picture.

3.9 Key challenges facing the saline aquaculture farmers

Access to quality water and fish diseases are major problems identified by respondents (Figure 5). About 27.3% of farmers cite lack of quality water, while 22.4% cite diseases and pest as the major challenges they face. Fish disease and pests are contributing to low volume of fish production in the area. More than half of the respondents have observed disease in their farms. Lernaea pest is commonly seen, reported by 52% of farmers. Other diseases and pests include abdominal dropsy, fungus, and fin rot. In addition to facing fish disease, most of the ponds (96%) also face attacks by animals including otters, rodents, and birds. Around 28% of farmers worry about disease outbreak. Stakeholder consultation noted that the districts have limited disease diagnostic facilities, and there is a lack of facilities for disease diagnosis at a large-scale level. Due to the lack of quarantine and quality check facilities, farmers' ability to properly control and manage diseases is constrained.

Almost 15% of the farmers mentioned quality, cost, and access to fish seed as another major constraint to their production. As found in the survey, private hatcheries and hatcheries are the primary source of seeds for farmers, while only 9% of farmers purchase seeds from the provincial Department of Fisheries. Although carp seeds are readily available from private hatcheries, many farmers are still concerned about the fish survival rate and growth potential.

Cost of and access to quality feed is another issue raised by farmers. Few farmers are using the highly recommended commercially manufactured concentrated feed pellets. Tilapia fish farmers in the study area complain that the high cost of feed is an impediment to grow Tilapia to a proper size. The high cost of feed poses a significant issue, as it constitutes 65% of the total production cost, which is a challenge for farmers with low purchasing power.

Inadequate technical and management knowledge is another challenge affecting farmers. Only a third of the farmers implement any special management practice in their pond. Almost all the farmers do not know how to properly test the salinity of the water and thus have adopted some rudimentary practices. More than a tenth of the farmers do not know of any improved pond management technology or practice. There is clearly a need for training in better management practices and the use of modern technology. For instance, there is a potential for integrated saline aquaculture in the provinces, considering

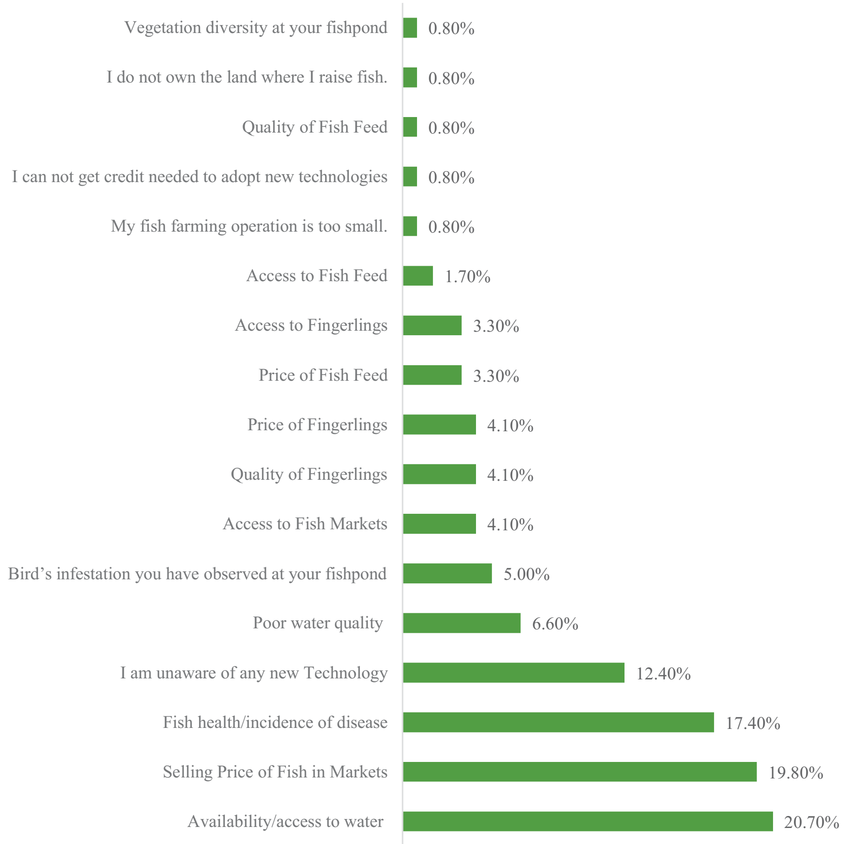

FIGURE 5
Major challenges reported by the respondents.

that most of the ponds are already multi-use ponds. There are practices that have very low cost of adoption while others may be see their adoption influenced by production and productivity.

A majority of farmers are worried about the limited value-added and poor marketing of their product. Around 24% of the respondents identified the selling price of fish and access to fish markets as their major challenges. Due to lack of processing facilities, fish need to be sold fresh in the local market once they attain majority. Farmers complain of bad roads and the high cost of transportation to the market. Only 17% of the farmers have access to vehicles to carry products to market. Hence, a majority are left at the mercy of the local transport companies who charge exorbitant prices. More so, almost all the farmers sell to intermediaries at a cheaper rate, considering the fish need to be sold once they are brought to the market. Currently, less than 5% of the farmers are processing their fish.

In addition, there is limited participation of women in saline aquaculture. The respondents surveyed are all men, and the study highlights that saline aquaculture in the study area is entirely dominated by men. Close to 80% of respondents said that women do not have equal access to saline aquaculture farming as men, and around 59% of the farmers said that it is better for women to not work in the sector. There may be a cultural barrier preventing women from engaging in fish farming which needs to be tackled. Capturing fish is considered a difficult task for women, and certain activities are deemed men's jobs, such as the preparation of ponds and catching fish by net. The distance between the farmers' homes and the pond is another major problem for women to work at fish farms, as they face security threats and harassment when working alone. Currently, women typically decide on how income from fish farming is used and how many fish to take home for consumption or sale.

4 Summary and discussion

Overall, the study provides insights into the demographic characteristics of the farmers involved in saline aquaculture in Punjab and Sindh provinces of Pakistan. All the respondents are primarily male farmers who have diversified into saline aquaculture farming, indicating that saline aquaculture is an additional income-generating activity for these farmers, and their land is utilized for both agriculture and saline aquaculture purposes. The majority of the farmers have less than 10 years of experience, which is an evidence that saline aquaculture is a relatively newer venture for a significant portion of the farmers. There is also a lower level of

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formal education within the farming community, suggesting that there may be a need for targeted training and capacity-building programs to enhance the technical knowledge and skills of these farmers in saline aquaculture practices.

Men are more actively engaged in this sector compared to women. The reasons behind this gender disparity is attributed to cultural norms, traditional roles, and gender-specific divisions of labor in the region. Enabling women to fully engage in saline aquaculture can boost production and improve nutrition. Women's Saline Aquaculture Groups can be formed to provide a platform for women to share knowledge and support each other in the saline aquaculture business. Experiences from Bangladesh and India could be tested in Pakistan also.

Generally, there is a different level of production intensity across the small, medium and large scale farmers. Hence, any intervention suggested must consider these differences. It is clear that medium farm have higher productivity and profitability, they may be more open to innovation and adoption of these new technologies.

The dominance of Carp species, particularly Rohu, highlights their economic significance in the region and lack of species diversification, especially in consideration of low saline tolerance of some of the key species of carp. This presents an investment need to provide healthy seeds and salt tolerant breeds that can contribute to species diversification.

The study emphasizes the significance of fish feed as a major cost component in saline aquaculture production. Additionally, the variations in feeding routines, sources of feed, and associated costs provide insights into the practices and challenges faced by farmers in accessing and utilizing fish feed in the study area. The lower size of Tilapia for example and the challenges associated with the cost of feed for Tilapia farming indicate potential areas for improvement. Enhancing feed affordability can lead to further growth and development of the saline aquaculture sector. The utilization of different feed types and the relatively lower adoption of pelleted feeds highlight the need to explore cost-effective feed options.

There are challenges related to water quality monitoring and the limited adoption of better management practices in saline aquaculture systems. Encouraging farmers to monitor water quality accurately and providing technical support, knowledge, and resources for implementing effective management practices can contribute to improving fish growth, disease prevention, and overall sustainability of saline aquaculture operations.

A significant proportion of farmers do not apply fertilizers or face difficulties due to the high cost of fertilization. This can affect the availability of nutrients, the growth of planktonic algae, and overall fish production. Addressing the cost constraints and promoting the use of appropriate fertilizers, including both organic and inorganic options, can contribute to improved pond preparation, nutrient availability, and productivity in saline aquaculture systems.

The study also highlights the market dynamics, pricing, revenue generation, and consumption patterns in the saline aquaculture sector. The dominance of wholesalers as buyers, coupled with low pricing, indicates challenges in the value chain and the need to explore strategies for improving market access and profitability for farmers. Additionally, the low average consumption of fish per person underscores the potential for increased fish consumption to meet nutritional needs. Efforts to promote awareness of the nutritional benefits of fish and improve accessibility to fish products can contribute to improved food security and health outcomes in the region.

5 Conclusion and recommendation

In conclusion, this study provided valuable insights into the demographic characteristics, farming practices, and challenges faced by farmers engaged in saline aquaculture in the Punjab and Sindh provinces of Pakistan. The findings reveal that saline aquaculture serves as an additional income source for predominantly male farmers who have diversified into this sector. With the majority of farmers having less than 10 years of experience and lower formal education levels, there is a clear need for targeted training and capacity-building initiatives to enhance technical knowledge and skills in saline aquaculture practices.

The study underscores the importance of considering production intensity differences among small, medium, and large-scale farmers in designing interventions, with medium-scale farms showing higher productivity and profitability. Gender disparities, attributed to cultural norms, requires serious attention. Addressing challenges such as feed affordability, water quality monitoring, and limited fertilizer application is crucial for the sector's sustainable development. Strategies to improve market access, pricing, and awareness for increased fish consumption can contribute to enhanced food security and health outcomes in the region. Overall, this study serves as a foundation for informed policy decisions and targeted interventions to foster the growth and sustainability of the saline aquaculture sector in Pakistan.

The following recommendations are provided:

1. There is a crucial need for heightened awareness and knowledge regarding saline aquaculture management. Additionally, there is a necessity to develop and implement capacity-building programs for technical knowledge in saline aquaculture.
2. There is a requirement to establish hatcheries and breeding facilities for saline-tolerant species, aiming to reduce reliance on freshwater species in saline ponds.
3. In terms of social norms and gender equality, there is a need to conduct awareness-raising campaigns to address societal norms hindering women's participation in the saline aquaculture sector. Simultaneously, policies and programs must be developed to rectify gender inequalities within the sector and enhance the participation of women in saline aquaculture.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was provided by the participants.

Author contributions

CR: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing. CO: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. SA: Conceptualization, Formal analysis, Resources, Supervision, Writing – review & editing. NU: Project administration, Methodology, Supervision, Resources, Writing – review & editing. SK: Data curation, Investigation, Resources, Supervision, Project administration, Validation, Writing – review & editing. MH: Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Validation, Writing – review & editing. SS: Data curation, Methodology, Resources, Validation, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. Funding for this research study came from the Australian Centre for International Agricultural Research (ACIAR) to the International Water Management Institute and WorldFish. This work was undertaken as part of the CGIAR Research Initiative on Resilient Aquatic Food Systems for Healthy People and Planet led by WorldFish and funded by CGIAR Trust Fund donors.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Allan, G. L., Fielder, D. S., Fitzsimmons, K. M., Applebaum, S. L., and Raizada, S. (2009). "Inland saline aquaculture," in *New Technologies in Aquaculture: Improving Production Efficiency, Quality and Environmental Management* (Woodhead Publishing Limited, Cambridge). doi: 10.1533/9781845696474.6.1119

Anufriieva, E. V. (2018). How can saline and hypersaline lakes contribute to aquaculture development? A review. *J. Oceanol. Limnol.* 36 (6), 2002–2009. doi: 10.1007/s00343-018-7306-3

Belton, B., Padiyar, A., Ravibabu, G., and Gopal Rao, K. (2017). Boom and bust in Andhra Pradesh: Development and transformation in India's domestic aquaculture value chain. *Aquaculture* 470, 196–206. doi: 10.1016/j.aquaculture.2016.12.019

Castine, S. A., Bogard, J. R., Barman, B. K., Karim, M., Mokarrom Hossain, M., Kunda, M., et al. (2017). Homestead pond polyculture can improve access to nutritious small fish. *Food Secur.* 9 (4), 785–801. doi: 10.1007/s12571-017-0699-6

Dam Lam, R., Barman, B. K., Lozano Lazo, D. P., Khatun, Z., Parvin, L., Choudhury, A., et al. (2022). Sustainability impacts of ecosystem approaches to small-scale aquaculture in Bangladesh. *Sustainability Sci.* 17 (1), 295–313. doi: 10.1007/s11625-021-01076-w

Dickson, M., Nasr-Allah, A., Kenawy, D., and Kruijssen, F. (2016). Increasing fish farm profitability through aquaculture best management practice training in Egypt. *Aquaculture* 465, 172–178. doi: 10.1016/j.aquaculture.2016.09.015

FAO (2022a) *Pakistan. Text by Hayat, M. Fisheries and Aquaculture Division.* Available at: https://www.fao.org/fishery/en/countrysector/pk/en?lang=en.

FAO (2022b). *The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation* (Rome: FAO). doi: 10.4060/cc0461en.

FAOSTAT. (2023) *Food and Agriculture Organization of the United Nations.* (Rome). Retrieved 05,07,2023. Available at: https://www.fao.org/faostat/en/#data/QV.

Faruque, G., Sarwer, R. H., Karim, M., Phillips, M., Collis, W. J., Belton, B., et al. (2017). The evolution of aquatic agricultural systems in Southwest Bangladesh in response to salinity and other drivers of change. *Int. J. Agric. Sustainability* 15 (2), 185–207. doi: 10.1080/14735903.2016.1193424

Hernandez, R., Belton, B., Reardon, T., Hu, C., Zhang, X., and Ahmed, A. (2018). The "quiet revolution" in the aquaculture value chain in Bangladesh. *Aquaculture* 493 (May 2017), 456–468. doi: 10.1016/j.aquaculture.2017.06.006

Kumar, P., and Sharma, P. K. (2020). Soil salinity and food security in India. *Front. Sustain. Food Syst.* 4 (October). doi: 10.3389/fsufs.2020.533781

Mamun, A.-A., Murray, F. J., Sprague, M., McAdam, B. J., Roos, N., de Roos, B., et al. (2021). Export-driven, extensive coastal aquaculture can benefit nutritionally vulnerable people. *Front. Sustain. Food Syst.* 5 (November). doi: 10.3389/fsufs.2021.713140

Mandal, B. K., Islam, A., Sarkar, B., and Rahman, A. (2021). Evaluating the spatio-temporal development of coastal aquaculture: An example from the coastal plains of West Bengal, India. *Ocean Coast. Manage.* 214, 105922. doi: 10.1016/j.ocecoaman.2021.105922

Patil, P., Kaczan, D., Roberts, J., Jabeen, R., Roberts, B., Barbosa, J., et al. (2018). *Revitalizing Pakistan's Fisheries: Options for Sustainable Development* (Washington, DC: The World Bank Group and L'Agence Française de Développement). doi: 10.1596/30156

Qureshi, A. S. (2020). Groundwater governance in Pakistan: from colossal development to neglected management. *Water* 12 (11), 3017. doi: 10.3390/w12113017

Qureshi, A. S., McCornick, P. G., Qadir, M., and Aslam, Z. (2008). Managing salinity and waterlogging in the Indus Basin of Pakistan. *Agric. Water Manage.* 95 (1), 1–10. doi: 10.1016/j.agwat.2007.09.014

Sarkar, S., Kumar, A., Kumar, D., Sethi, L. N., Hazarika, M. M., and Das, G. (2015). Optimal size of fish pond for socio-economical development of Cachar (Assam). *Int. J. Agric. Environ. Biotechnol.* 8 (2), 405. doi: 10.5958/2230-732x.2015.00048.0

Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A. H., and Fang, J. G. (2009). Ecological engineering in aquaculture - Potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture* 297 (1), 1–9. doi: 10.1016/j.aquaculture.2009.09.010

World Bank (2021) *Poverty & Equity Brief: Pakistan. Poverty & Equity Brief: South Asia*. Available at: https://databank.worldbank.org/data/download/poverty/987B9C90-CB9F-4D93-AE8C-750588BF00QA/SM2020/Global_POVEQ_GEO.pdf.

frontiers | Frontiers in Sustainable Food Systems

TYPE Review
PUBLISHED 04 January 2024
DOI 10.3389/fsufs.2023.1287034

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RECEIVED 01 September 2023
ACCEPTED 11 December 2023
PUBLISHED 04 January 2024

CITATION
N'Souvi K, Sun C, Che B and
Vodounon A (2024) Shrimp industry in China: overview of the trends in the production, imports and exports during the last two decades, challenges, and outlook.
Front. Sustain. Food Syst. 7:1287034.
doi: 10.3389/fsufs.2023.1287034

Shrimp industry in China: overview of the trends in the production, imports and exports during the last two decades, challenges, and outlook

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China's shrimp farming industry has experienced significant growth in recent years. With such a development, some major constraints linked to the industry's sustainable development have emerged. This paper aims to present an overview of China's shrimp industry over the last two decades, with special attention to farm-raised shrimp both in marine and inland waters. Documentary research on its recent evolution was carried out based on data collected from China Fishery Statistics Yearbooks 2003 to 2022 coupled with data from FAO. Findings indicated that there has been an upward trend in China's total shrimp production over the last 20 years, with a growth rate of 120%, representing an average annual growth rate of 4.3%. The observed higher shrimp production was driven by expanded shrimp aquaculture production, with major species dominated by the Pacific whiteleg shrimp (*litopenaeus vannamei*), the black tiger shrimp (*Penaeus monodon*), the Chinese shrimp (*Penaeus chinensis*), and the Japanese prawn (*Penaeus japonicus*). Challenges associated with the intensification of the production and the driven environmental deterioration need to be properly addressed. First, the shrimp farming industry should be practiced while considering both environment and ecosystem protection. Applying such an organic farming principle presupposes some practices for addressing the existing issues threatening the sustainable growth of the industry. To that end, there is a need for innovative techniques that should be strengthened. Second, possible solutions to shrimp disease problems, namely prevention, early diagnosis, and various control techniques, should also be developed and improved, with an emphasis on the former. In addition, encouraging the use of good-quality feed in appropriate quantity and form is also of paramount importance. It is thus worth noting that further policies need to focus on promoting a large range of ecological shrimp aquaculture technologies that should be encouraged among farmers.

KEYWORDS

shrimp aquaculture industry, challenges, outlook, ecological farming, sustainability, China

1 Introduction

Aquaculture has become a flourishing industry by undergoing a particular intensification process in recent years (Dong and Raghavan, 2022). Shrimp aquaculture industry has enjoyed phenomenal growth during the 1980s and has become the leading contributor to the world's fishery production in recent years (FAO, 2021; Yu et al., 2023). The latter was reported to be the second largest seafood traded worldwide after salmon fisheries (FAO, 2019). In today's world, there is a high demand for seafood products, but the supply from wild-stock fisheries is not enough to meet this demand. As such, the aquaculture industry as a whole and shrimp aquaculture in particular can be an alternative food source to compensate for the shortages. This can help address the increasing food scarcity and reduce the pressure on wild fisheries (Mansour et al., 2022).

Asian countries led by China, were the main fisheries and aquaculture producing countries, representing 70% of the global production in 2020 (FAO, 2022). Since 1991, China has remained the top producer of farmed aquatic animals and algae in the world, with its shares being 56.7% and 59.5%, respectively, in 2020. Indeed, aquaculture industry exists in almost every province in China, with its major areas located in the southeast coastal watershed and the middle and lower reaches along the Yangtze River (Chao et al., 2017). Precisely, pond and freshwater aquaculture production in China are mainly concentrated in Guangdong, Hunan, Hubei, Jiangxi, Anhui, Jiangsu, Shandong, and Sichuan (Hu et al., 2021).

The People's Republic of China has been one of the world's leading shrimp producing countries since the late 1980s (Biao and Kaijin, 2007). China's shrimp industry faces potential long-term challenges despite short-term yield success (Dong and Raghavan, 2022). Although the shrimp industry is widely researched, with many studies reporting on breeding, growth performance, genetics or genomic aspects and experimental conditions and/or observations (e.g., Li et al., 2021; Abdel-Latif et al., 2022; Liu et al., 2023; Huang et al., 2024), little is known on the current status, evolution and prospective of China's shrimp industry. Regarding both its marine and freshwater shrimp aquaculture, no abundant information was found that reviewed the trends in shrimp production over the last two decades. As such, there is insufficient scientific information available on these particular aspects. The available recent studies on similar matter were found performed on the tendencies and dynamics of aquaculture ponds at provincial levels (e.g., Duan et al., 2021; Fu et al., 2021). However, given the importance of shrimp as one of the major aquatic products in China, presenting an overview of key features of the industry is crucial for understanding the drivers of its aquaculture development and dynamics. This could also help overcome issues that challenge the industry and thus plan consistently what should be the way ahead. To that end, there is a need to review the trends in its shrimp aquaculture production, imports into China and exports from China in recent years and thereafter make policy recommendations, whose implementation could help the country maintain its leading position in the global shrimp industry.

Therefore, this paper presents an overview of the current state of the Chinese shrimp industry. This review helps understand the trends in China's shrimp production, imports and exports during the last two decades, and challenges that have emerged.

The remainder of the paper is organized as follows: Section 2 describes the methodological approach and the data sources. Section 3 presents the results of the overview of the current state of the Chinese shrimp industry, by considering both wild-caught and aquaculture species, both freshwater and marine shrimp species. Then, the discussions are presented in Section 4, in particular by focusing on the progress in shrimp aquaculture modes and technologies in China. Besides, the needs to keep on improving the quality of the fries, combating water pollution and thus developing ecological and healthier shrimp aquaculture are also discussed. Finally, the paper concludes with Section 5, which includes remarks, implications and outlook.

2 Methodological approach

This study was mainly conducted through desk research from April 16, 2023, to August 30, 2023. As a first step, we carried out a systematic review to map relevant literature. This consisted of (1) identifying relevant studies, (2) screening and selecting relevant publications, (3) charting the data and information, and then (4) summarizing the results (see Figure 1). To this end, we used a group or set of keywords (related to China's shrimp industry, ecological shrimp aquaculture, trends in China's shrimp imports and exports, challenges, and outlook) to search in two scientific databases. The first was *Scopus*, and the second one was Clarivate Analytics Web of Science (*WoS*), which were both used as research tools to obtain reliable and relevant results. We particularly opted for the WoS given it is a widely accepted and comprehensive bibliometric database (Zhu and Liu, 2020). For this present review, a checklist of criteria was used to determine which publications to include. Particularly, the selected publications were required to meet the following criteria: (i) They should be focused on shrimp aquaculture or capture and be topically relevant, (ii) They should meet academic quality standards, which means only scientific, technical, and academic documents will be considered, (iii) They should have been published in the last 15 years (between 2008 and 2023), (iv) They should be written in English, and (v) They should focus on the geographic location of China. As such, relevant terms were combined with shrimp industry and/or china and other concepts. The syntax were, among other, "Shrimp industry" AND "China" AND "last two decades," "Shrimp aquaculture" AND "China" AND "last two decades," "Shrimp production*" AND "exports OR imports "AND "China" AND "last two decades," "Shrimp industry*" AND "marine AND freshwater" AND "exports OR imports "AND "China*" AND "last two decades," "Shrimp industry*" AND "wild caught AND aquaculture" AND "marine AND freshwater" AND "exports OR imports "AND "China*" AND "last two decades," etc. This helped us locate various types of published materials such as research articles, review papers, books, and technical reports.

In other words, the review of possible available information regarding China's shrimp aquaculture industry has been conducted using key published reports and official databases. Overall, the search approach yielded 150 publications. Thereafter, we eliminated duplicates and 105 publications remained. After screening the articles 'titles and abstracts, 75 potentially relevant publications were considered. After evaluating and reading the full-text articles, 40 papers were found to meet the inclusion criteria for this review. In addition, this review contained twelve (12) records that were identified through a two-step iterative search process. This process consisted of

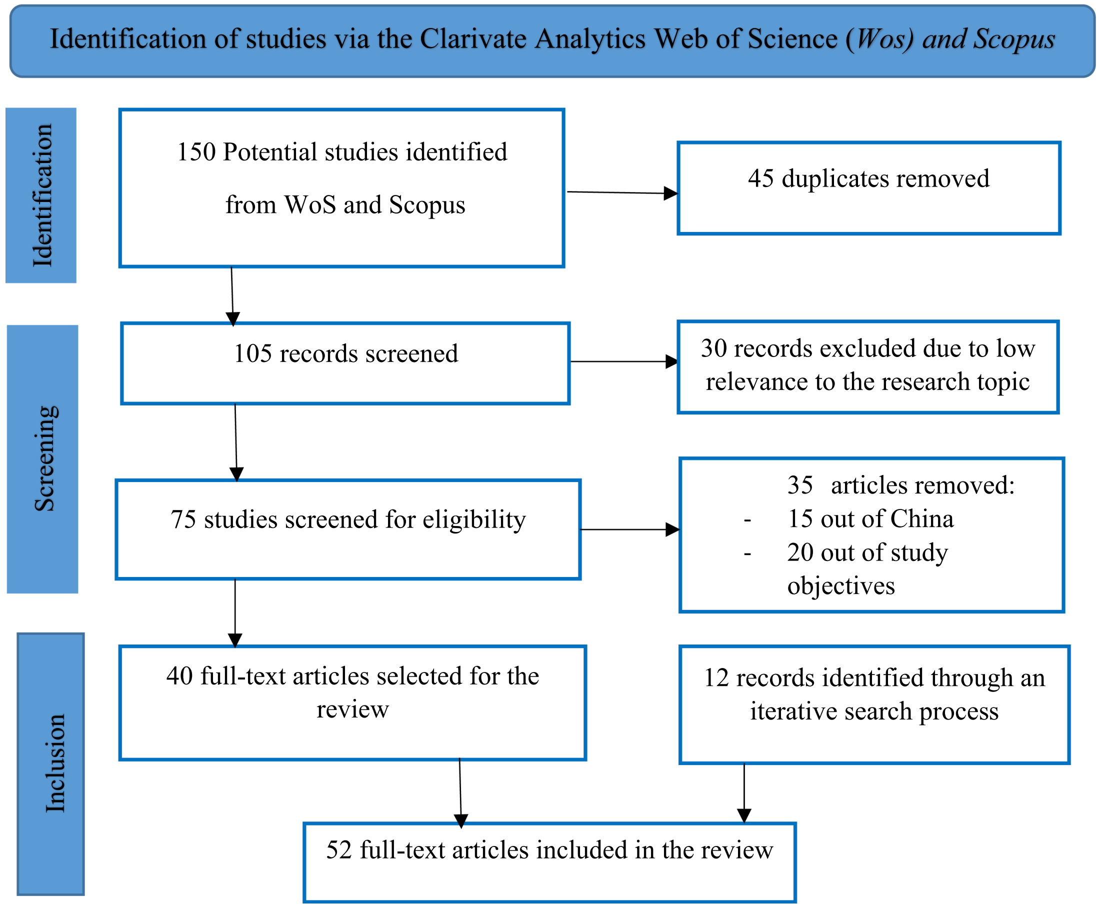

FIGURE 1
Flow chart of the selection process of studies examining shrimp industry in China and trends in production, imports and exports over the last two decades.

reviewing available literature, choosing pertinent papers for inclusion, checking the presented information, and evaluating whether it fitted properly the objectives of this study.

We then addressed the objectives of our study, which, were to: (1) present an overview of and develop a better understanding of the industry, and (2) identify challenges and/or issues currently faced by the shrimp industry in China by collecting secondary data from China Fishery Statistical Yearbooks, spanning from 2003 to 2022. In addition, data on trends in shrimp production for the world's top ten shrimp producers (2002–2021), imports and exports (2018–2022) were provided by FAO.

3 Results

3.1 Development history of shrimp aquaculture in China

Fish farming in ponds is a long-standing practice. Early farmers probably developed it as one of their initial farming systems for household food security and income generation. The earliest recorded instances of fish farming in ponds were found in China, about 4,000 years ago, and in Mesopotamia, around 3,500 years ago (FAO, 2000). The historical evolution of China 'shrimp industry can be categorized into three development phases, namely the start-up phase, new phase, and the rapid development phase (Table 1).

3.1.1 The start-up: 1949–1992

Shrimp farming in China started in 1950s but its extensive farming inception began in the late 1970s, along the eastern coast (Wang et al., 2022). In the introductory phase of shrimp farming, the yield was low; the shrimps were primarily farmed for family consumption and gradually sold in the local market. In 1978, a panel of scientists was established by the government to develop technologies for the country's shrimp farming intensification. This involved high density shrimp farming with hatchery-bred shrimp, processed feed, regular water exchange, and mechanization using many techniques and tools. Indeed, China implemented reform and open-up policies in 1978 (Zhang, 2007), which, among others, helped bolster a rapid expansion of its fisheries in order to meet the increasing demand for fish and fishery products by its growing population (Li et al., 2011). A general plan, which was drawn up for fisheries and aquaculture development in China, contained the following goals:

- To promote the transformation of the fishery economic system, including its expansion, based mainly on the socialist market economy principles;

TABLE 1 Historical phases of shrimp aquaculture development in China.

Periods	Phases	Descriptions of the evolution
1949–1992	Introductory phase	Start of wild juvenile shrimp farming in China in the early 1950s. In 1980s, development of shrimp aquaculture at large-scale in China. Constant enhancement and innovation, going from extensive culture to semi-intensive culture. Development of a systematic culture technology system since the mid-1990s.
1993–2003	Emergence of disease outbreaks	China's shrimp industry story takes a negative turn in 1993 and 2003, when, with the arrival of the white tail disease (WTD) and other pathogens, the industry suffered a contraction. Land-based Pond culture, intensive and super-intensive.
2004–2009	Rapid development phase	The multi-trophic integrated system, which is an ecosystem-based farming mode has emerged. Such an integrated culture evolves shrimp co-culture with fish, shellfish, crabs, seaweed or other species with the aim of gaining economic, and socio-environmental benefits.
2010s–Present	Prospects for developing new technologies toward the industry's sustainability	Development of new technologies such Biofloc technology, shrimp aquaponics including the recirculating aquaculture systems (RAS), the Polyculture system…

- To promote fisheries and aquaculture through education, science and technology, and new strategies implementation;
- To achieve optimal fisheries production, the industrialization of production system, farming of high-value species, pond-culture operations, etc., should be intensified;
- To prioritize seed production as the foundation and emphasize sustainable fisheries, and quality of aquatic products, and;
- To industrialize fisheries and aquaculture in a coordinated way, which will help improve agriculture, rural economy, and rural population livelihoods.

Thus, considerable efforts in terms of on-farm technical supports and extension services were undertaken by fishery research institutes and technology promotion departments at different levels towards the farmers. At the same time, the government invested considerable funds in the country's aquaculture development. Such projects were funded through loans from the World Bank, local government investments, and labor contributions. Besides, to ensure the successful execution of the fisheries promotion through science and technology, the central and local governments have invested significant funds in establishing a national aquaculture technical training and extension networks. They were set at different administrative levels in the country and the stations included at provincial, prefecture, county, and village levels, were 37, 206, 116 and 1,155, respectively. Every station was furnished with suitable equipment and training facilities. Furthermore, a system that comprised fishery administration, 25 specialized farms, and environmental protection, etc., has been established to promote high-value species (Wang, 2001).

Between 1980 and 1988, shrimp production grew by an average of 75% annually. Indeed, by 1980, shrimp farms in China spanned across 9,342 hectares and produced around 2,549 metric tons. However, in 1988, the farms expanded to cover 162,960 hectares and yielded roughly 200,000 metric tons of shrimp (Wang, 2001). Such expansion led China to become the largest shrimp producer worldwide. The country's shrimp production was mainly dominated by *Penaeus orientalis* (ADB/NACA, 1996).

3.1.2 Emergence and spread of diseases: 1993–2003

Like Taiwan province, whose shrimp industry collapsed in 1987, shrimp aquaculture industry in mainland China was exposed to some diseases in 1990 and 1993 (Wang et al., 2022). China's farm-raised shrimp production increased to 200,000 metric tons per year from 1988 to 1992. However, the country faced new challenges starting from 1993. Between 1993 and 1994, its shrimp production crashed to about 50,000 metric tons. The first disease occurrence in the shrimp industry was due to factors including the misuse of antibiotics, overstocking, inappropriately processed food, and over-exploitation of groundwater (Kautsky et al., 2000). Again, a virus, which appeared coupled with industrial and domestic pollution around the Gulf of Bohai Sea, hit the industry. In addition, China's fish (shrimp) ponds are basically located in low-lying areas. This makes it difficult to clean up bottoms in terms of pond management between harvests. But very quickly, China's brackish water shrimp breading demonstrated evidence of recovery between 1994 and 2000. In addition, given the ever-increasing demand for shrimp on the international market, the potential and real profit as well as the improvement in technologies used have led to the growth trends of the industry. As such, shrimp output increased on average by 23% per year from a low of 64,000 metric tons in 1994 to reach 218,000 in the early 2000s.

3.1.3 Rapid development phase: 2004–2009/2010

Shrimp farming in China had another period of rapid development from 2004 to 2010. The production of cultured freshwater prawns increased rapidly with the implementation of more intensive farming and improved culture techniques. The production area increased quickly during this period before a serious disease outbreak of acute hepatopancreatic necrosis disease (*AHPND*) also known as early mortality syndrome (*EMS*) of shrimp in China in 2009 (Thitamadee et al., 2016), which caused high shrimp mortalities of *L. vannamei* and *P. monodon* in southern China (Thitamadee et al., 2016) and spread sequentially to Vietnam (2010), Malaysia (2011), Thailand (2012) (Joshi et al., 2014). The *AHPND* caused significant economic losses among shrimp producers in China, estimated to USD 11.0 billion from 2009 to 2016 (Shinn et al., 2018; Estrada-Perez et al., 2020). The spectacular new recovery of the country's shrimp production resulted from increases in the production area and stocking density and technological improvements.

In terms of cultured species, the farming of pioneer shrimp species in China, started in the 1950s. Some years later, the Institute of Oceanology of the Chinese Academy of Sciences introduced

Litopenaeus Vannamei, the Pacific white shrimp, to China in 1988. Since 1992, the nursery barrier has been broken and the *Vannamei* farming has developed throughout China. Meanwhile, Chinese shrimp (*Penaeus chinensis*) remained the major farmed shrimp species in China until 1995, and its farming was primarily concentrated in the provinces along the coast of the Yellow Sea (Meng et al., 2015). At present, Guangdong, Guangxi, Fujian, Hainan, Zhejiang, Shandong and Hebei have gradually promoted their farming along with that of many other species.

3.2 Overview of the current status of shrimp industry in China (2010–present)

China is the main producer of aquatic food in East Asia, which contributed 77% to global aquaculture production in 2017 (MacLeod et al., 2020). Shrimps have become of increasing economic importance in China. The past two decades have witnessed a significant increase in China's total shrimp production (both wild-caught and aquaculture) by around 120%, from 3.2 million MT in 2003 to 7.07 million MT in 2022 (Figure 2). This represents an average annual growth rate of 4.3%. With such an upward trend and rapid growth, China overtook the leading suppliers and became the world's top shrimp producer. Meanwhile, there was a slight decrease in China's shrimp output in 2008 and 2016 as compared to their previous year, of 1 and 1.8%, respectively.

During the study period, seafood products consumption *per capita* in China and the global price of shrimp also exhibit upward trends. With Chinese consumers increasing their spending on high quality, value-added fish and seafood products (Wang et al., 2021), *per capita* consumption of fish and seafood in China jumped more than one-half from 25.77 kg/capita in 2003 to 40.33 kg/capita in 2020 (FAOSTAT, 2023). In recent years, the volume of seafood, including shrimp consumed by person in the country had increased slightly. At the same time, the global price of shrimp also had been fluctuating, wherein values varied from 7.05 USD/kg in 2003 to 8.04 USD/kg in 2022, and had reached the highest of 10.1 USD/kg in 2014 (IMF, 2023), as observed in Figure 2.

In a comparative view, it can be seen in Figure 3 that China's aquaculture shrimp was particularly higher and had outweighed that of other shrimp producing countries over the last two decades (Fu-Chi, 2023). Indeed, aquaculture shrimp in China has increased by around 194% from 1.11 million MT to 3.27million MT, from 2003 to 2022 (e.g., Wang et al., 2022). In contrast, aquaculture shrimp has decreased by 6% in the United States over the same period. Similarly to China, aquaculture shrimp has almost tripled in India (Kumar, 2022). Again, farmed shrimp has also almost tripled in Indonesia while it has quadrupled in Viet Nam (3.14%) and Argentina (3.33%) in the recent two decades. Ecuador is the country that witnessed the fastest growth rate (12.69%) for farmed shrimp over the same period (Van der Pijl, 2023), which is evident from the perspective of many policies and interventions toward fisheries development, with particular emphasis on shrimp aquaculture (Boyd and McNevin, 2018). The development of local technicians' capabilities enabled by improved environmental stewardship also contributed to this. It is worth noting that within the first half of the period under investigation, Thailand shrimp production had slightly increased and thereafter, there was a considerable decrease in the country's shrimp production between 2012 and 2014. The years after, although an observable steady increase, the volume of its shrimp production was remained smaller than that of the 2000s. Overall, as, it can be seen in Figure 3, there was an upward trend in China's aquaculture shrimp production over time.

3.3 Shrimp species farmed and caught in China

The diversity of the shrimp species is such that it is not possible to discuss them all in detail in this report. If we arbitrarily consider

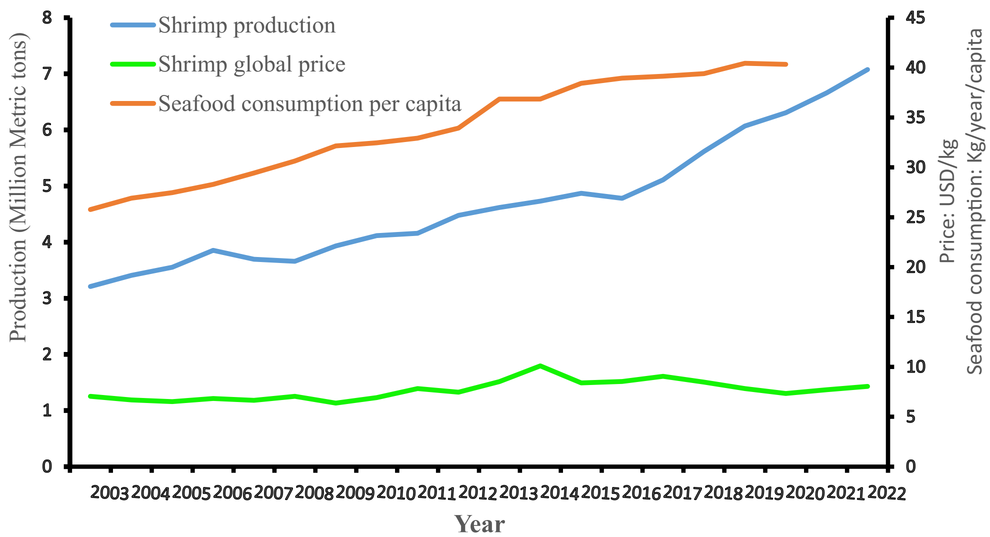

FIGURE 2
China's total shrimp production over the last two decades, 2003–2022. Source: Authors, based on data from China Fishery Statistical Yearbooks, 2003–2022, FAOSTAT (2023) and IMF (2023).

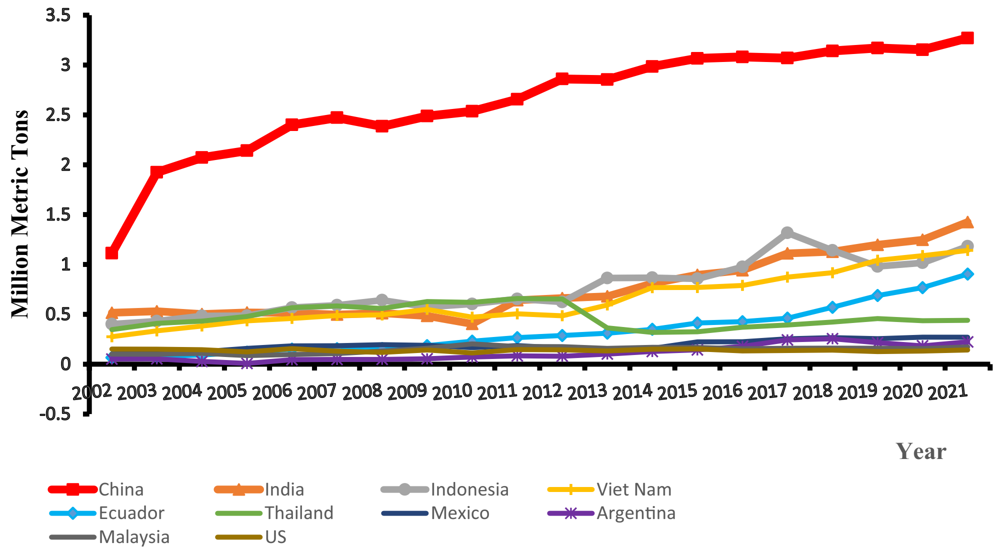

FIGURE 3
Trends in shrimp production for the world top ten shrimp producers, 2002–2021. Source: Authors, based on data from FAO database 2023.

species to whose annual volume production represents individually more than 5% of national shrimp production, five species stand out. First, white-leg shrimp, *litopenaeus vannamei*. Second, the giant freshwater prawn *Macrobrchium_Rosenbergii*. To this group should be added the giant tiger shrimp, *Penaeus monodon* and a key species of freshwater shrimp in China, the so-called, *Macrobrachium nipponensis,* the Chinese white shrimp, *Penaeus chinensis*. Likewise, globally, *L. vannamei* is the most important species in China, with the main proportion of its production coming from aquaculture.

3.3.1 Marine shrimp aquaculture

Marine shrimp aquaculture has been one of the most important industries in the field of marine economy development in China. The main species cultured are Chinese shrimp (*Penaeus chinensis*); Pacific white shrimp (*litopenaeus vannamei*); black tiger shrimp (*Penaeus monodon*); and Kuruma shrimp (*Marsupenaeus japonicus*). *P. chinensis,* whose farming in China, started in the 1950s was the major farmed shrimp species in China until 1995, particularly in the provinces comprising its natural distribution along the coast of the Yellow Sea (Meng et al., 2015; Deng et al., 2023). However, since 1995 and over the last two decades, shrimp output increases in China, have mostly come from *L. vannamei* (Figure 4). For example, in 2022, China harvested more than 1.5 million metric tons of shrimp from marine aquaculture, with *L. vannamei* accounting for 1,340 280 tons, or more than 80% of the total. The production of *P. chinensis* (30,929 tons), Spot shrimp (114,360 tons) and *M. japonicus* (46,199 tons) also contributed relatively small shares.

3.3.2 Major shrimp aquaculture species in Chinese inland waters

The development of aquaculture production in China has enabled the country to reduce its dependence on food fish supplies from a hunted to a farmed origin. Inland aquaculture has been fundamental to aquaculture growth in China, with particular attention given to some traditional species (Newton et al., 2021). In the shrimp industry, the available data show that freshwater culture was dominated by the western some imported species until recent years (e.g., Han et al., 2021). From 2016 onwards, the farming of crayfish (*Procambarus clarkia*) was reported as freshwater crustaceans that has been rapidly developed and has become an economically viable, promising and a companion of the main freshwater shrimp species in China. Indeed, it was reported as the second most cultured crustacean species in china in 2018 (Jin et al., 2019; FAO, 2020), and its production was estimated to be around 2.6336 million tons, an increase of 10.02% year-on-year, and continues to maintain rapid growth (Figure 5).

With their significant respective roles, wild-caught shrimp both in marine and freshwater showed a downward trend, while shrimp aquaculture production displayed an upward trend over the past 20 years (Figure 6). This demonstrates the steady efforts of the government to develop aquaculture and the whole fisheries sector in China. Aquaculture facilities in China have been upgraded, and the investment in capital, infrastructure, science and technology has been increased (Ren, 2021). For example, two major state-funded Basic Research programs in China (with 973 programs) that integrated many research teams from the Institute of Oceanology, Chinese Academy of Sciences, Third Institute of Oceanology, State Oceanic Administration, Zhejiang University, SUN YAT-SEN University and Shandong University were established in the 2000s to focus on shrimp immunology and disease control (Li and Xiang, 2013). In addition, advances in science and technology have played a vital role in intensifying production systems and species diversification in aquaculture. It is worth noting that the relaxation policies towards aquaculture development implemented in 1980s, with more focus on aquaculture as compared to fisheries in a global context of increasing overexploitation of fishery resources, has accelerated shrimp aquaculture in China. Thus, these efforts and investments have been productive and increased the share of shrimp aquaculture production in the country.

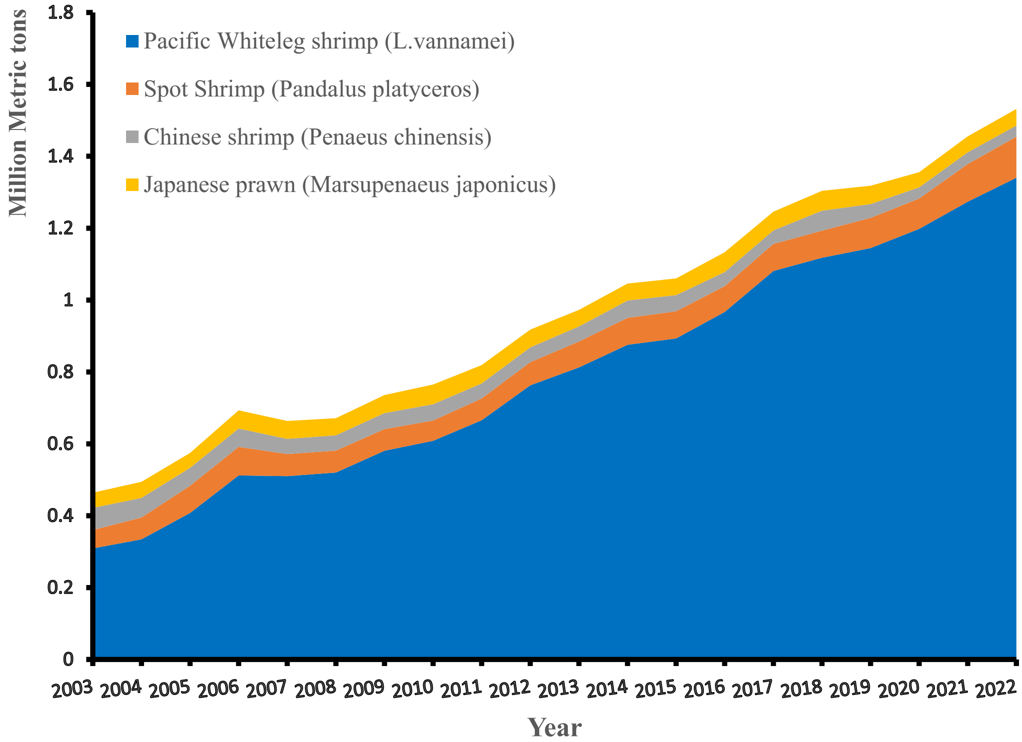

FIGURE 4
Trends in China's shrimp marine aquaculture by major species. Source: Authors, based on data from China Fishery Statistical Yearbooks, 2003–2022.

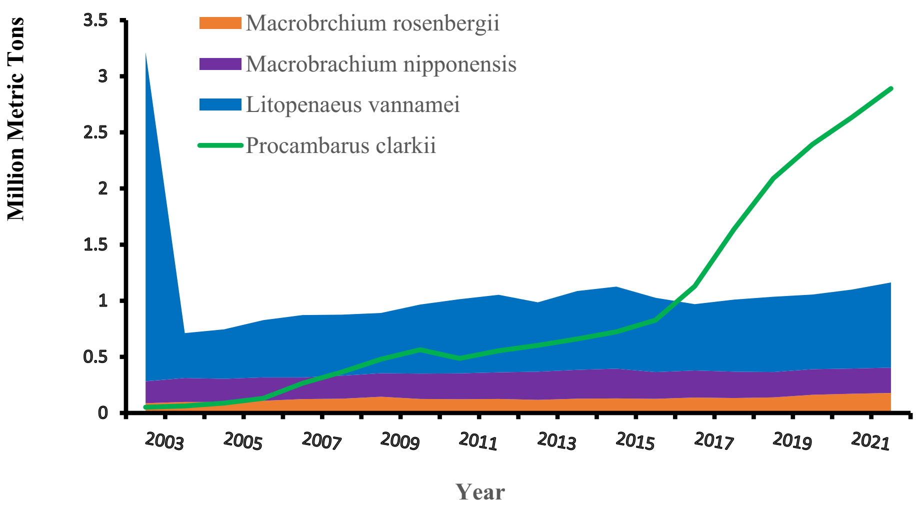

FIGURE 5
China's freshwater shrimp aquaculture production by major species. Source: Authors, based on data from China Fishery Statistical Yearbooks, 2003–2022.

3.4 China's imports and exports of shrimp over the last decades

Since the late 1990s, consumer demand for shrimp and shrimp products has been strong in the Chinese market. At the same time, supply gaps are increasingly met through imports (FAO, 2023). In 2022, a large part of the increase in seafood imports to China were accounted for by shrimp. Indeed, imports of shrimp increased by 25.8% to 370,123 metric tons during the first half of 2022. They were mainly from Ecuador, India, Viet Nam, Canada, and Greenland, accounting for 60%, 12.5%, 6%, 3.6% and 3%, respectively. By the third quarter of the same year, cumulative imports rose in the market by 51.6% to 661,822 metric tons, which made China the world's largest shrimp importer (Figures 7 A–E).

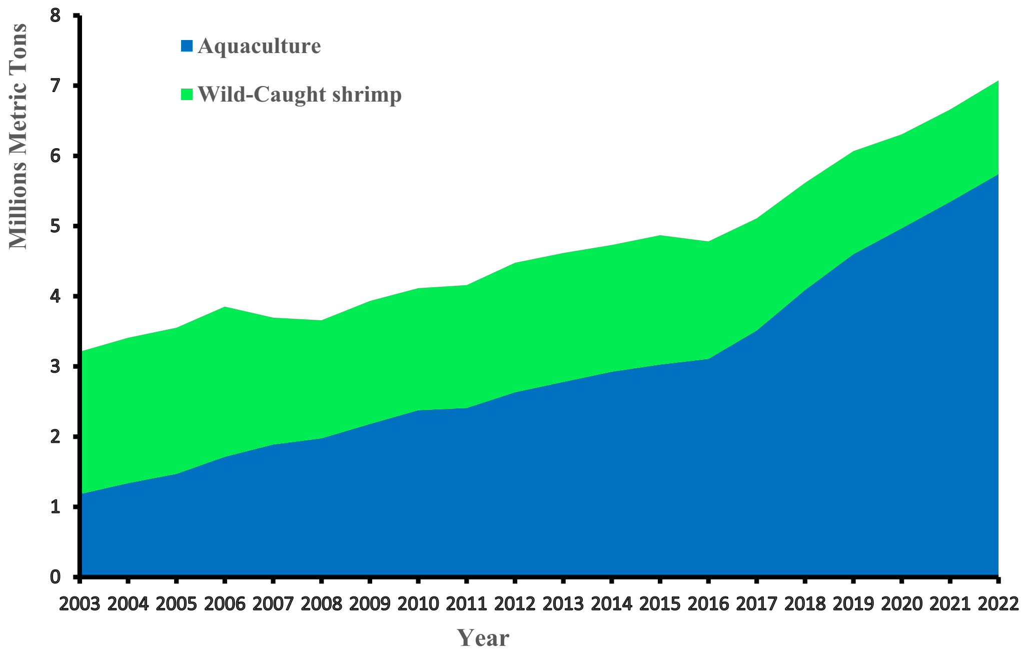

FIGURE 6
Trends in shrimp wild-caught and aquaculture production in China, 2003–2022. Source: Authors, based on data from China Fishery Statistical Yearbooks, 2003–2022.

Such a comparison with other top shrimp importers shows that China moved from the third rank in 2018 to be consecutively the second largest shrimp importer in the world for 4 years, from 2019 to 2022. In other words, except for 2018 where China ranked third for shrimp imports globally, China ranked the world's second-largest shrimp importer behind the United States for four consecutive years, from 2019 to 2022 (see Figures 7A–E). Additionally, the overall trends in shrimp imports into China exhibited a sharp upward trend, wherein values increased from 1.81 billion USD in 2018 to 6.29 billion USD in 2022, which represents, on average, approximately 4 billion USD per year, during the last four years (Figure 7F). The observable slight decrease in shrimp imports into China between late 2019 and early 2020, might due to the deterioration of the international economic environment following the global health crisis and the lockdown restrictions related to it.

From an export perspective, since ever the theory of export-led growth had been the subject of significant academic research, shrimp is a fast-growing world export market. Indeed, the export-led growth hypothesis postulates that export expansion is one of the main determinants of growth. It is believed that a country's economic growth can be achieved through an increase in labor and capital, coupled with an expansion of exports (Smith, 1776; Ricardo, 1817; Marshall, 1890; Balassa, 1978; Feder, 1983; Ram, 1987). This said, the Asian countries account for about 55% of total world shrimp exports (Khan et al., 2022). The top six shrimp exporters in Asia are India, Vietnam, Indonesia, Thailand, Bangladesh, and China, respectively, and all together account for more than 90% of the shrimp exports from Asia (OEC, 2021).

Figure 8 shows the top ten shrimp exporting countries in the world from 2018 to 2022. Similarly to the case with the imports, China is among the main exporters of shrimp in the world despite the high domestic demand and consumption that are likely to reduce the country's capacity to export to other destinations. This is particularly possible thanks to the country's considerable national production. It is worth noting that China only occupied a relative low rank among the top exporters, shifting from fourth in 2018 and 2019 to the world's fifth largest shrimp exporter for the following 3 years. Indeed, in the past 4 years, shrimp exports from China have experienced an apparent decrease. As shown in Figure 8F, the country's shrimp exports decreased from 2.4 billion USD in 2018 to 1.9 billion USD in 2022 and had reached the lowest of 1.6 billion USD in 2020. Similarly, the difference between exports and imports (hereinafter referred to as the net exports) from China, has an evident downward trend, with values declining from 0.6 billion to negative 4.3 billion USD in 2022 (Figure 9). This illustrates the importance of the domestic demand and consumption, which continue to drive both national production and imports. Apart from the fact that, globally, the United States (US) and China are the largest countries in terms of shrimp consumption globally (OEC, 2021), another reason for the huge shrimp imported into China might be that they are mostly processed and re-exported to other countries. Besides, despite China being a significant exporter of farmed and sea-caught shrimp, shrimp imports to the country are significantly higher in volume than exports. This outlines the large size of the country's internal market (Asche et al., 2022).

3.5 Progress in shrimp aquaculture modes and technologies in China

Since the inception of wild juvenile shrimp farming following the establishment of the People's Republic of China in 1949, considerable

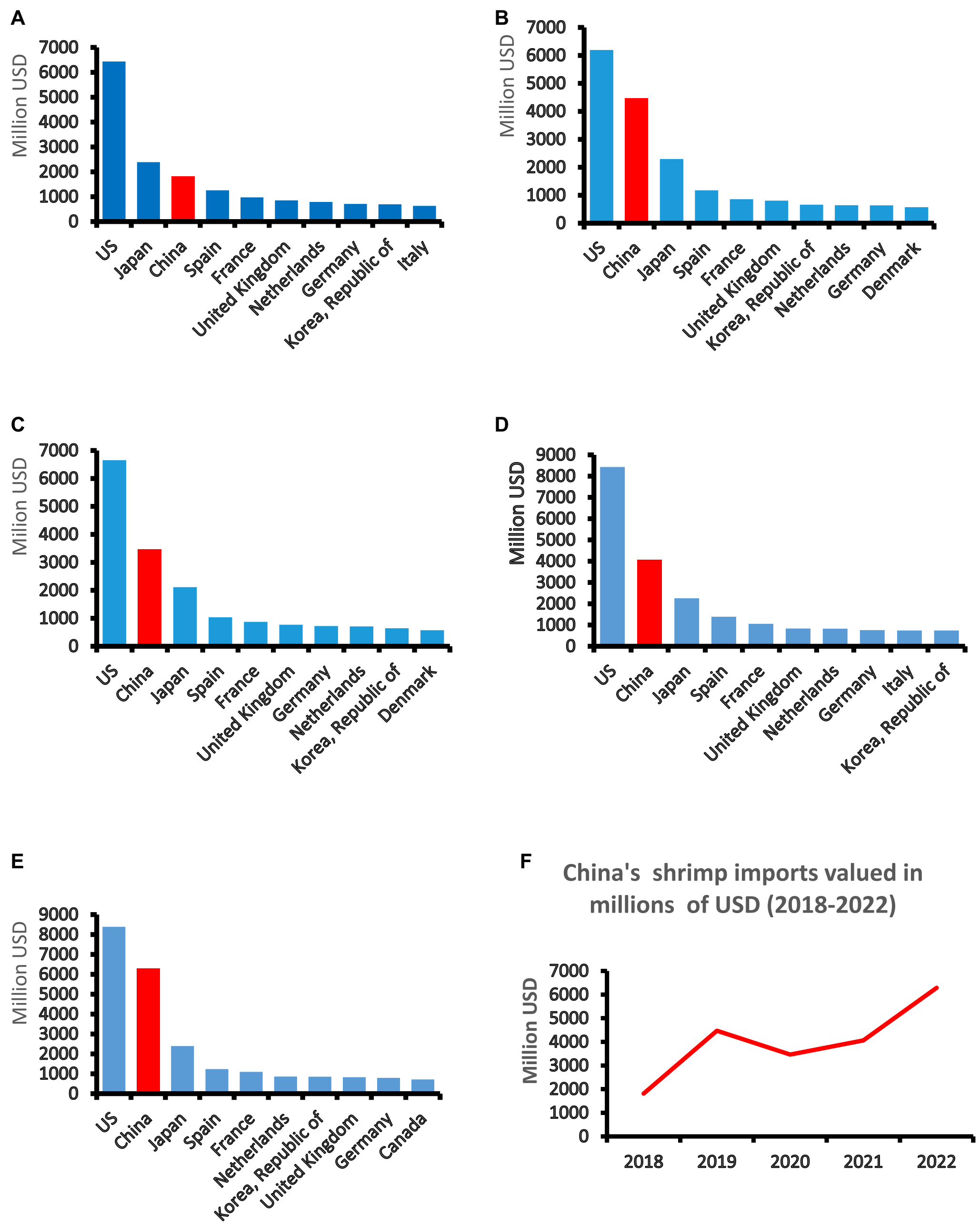

FIGURE 7
China's shrimp imports among the world's top ten shrimp importers, in 2018–2022 as shown in **(A–E)**, respectively. **(F)** Trends in China's shrimp imports valued in millions of USD (2018–2022). Source: Authors, based on FAO database, 2023.

attention has been given to researching and promoting aquaculture modes and technologies. Efforts and projects in that regard aimed at improving yields, controlling costs, and increasing farmers' benefits. Shrimp farming thus expanded from early extensive culture systems to intensive culture and, in between, the semi-intensive modes.

Shrimp aquaculture at large-scale in China can be traced back to the 1980s and, at the same time, implies the development of various farming systems and technology use since the mid-1990s. Thus, farming modes also witnessed constant enhancement and innovation, going from extensive culture to semi-intensive culture, and thereafter to land-based pond culture and greenhouse culture in the 1960s–1980s, 1980s–1990s, and in the early 2000s, respectively. For example, Artificial breeding and feeding techniques played a crucial role in the rapid expansion of shrimp farming in the early 1990s, allowing an annual production of over 200,000 MT. Similarly, these methods also helped scallops to become a more readily available product instead of being a high-value one (Wang, 2001).

Further, technological improvements namely in genetic, better pond management, vertical integration, and development of more environmentally sustainable production practices resulted globally in 9% annual growth from 1998 to 2001, with top shrimp producers, including China that contributed to such a growth (Kumar and Engle,

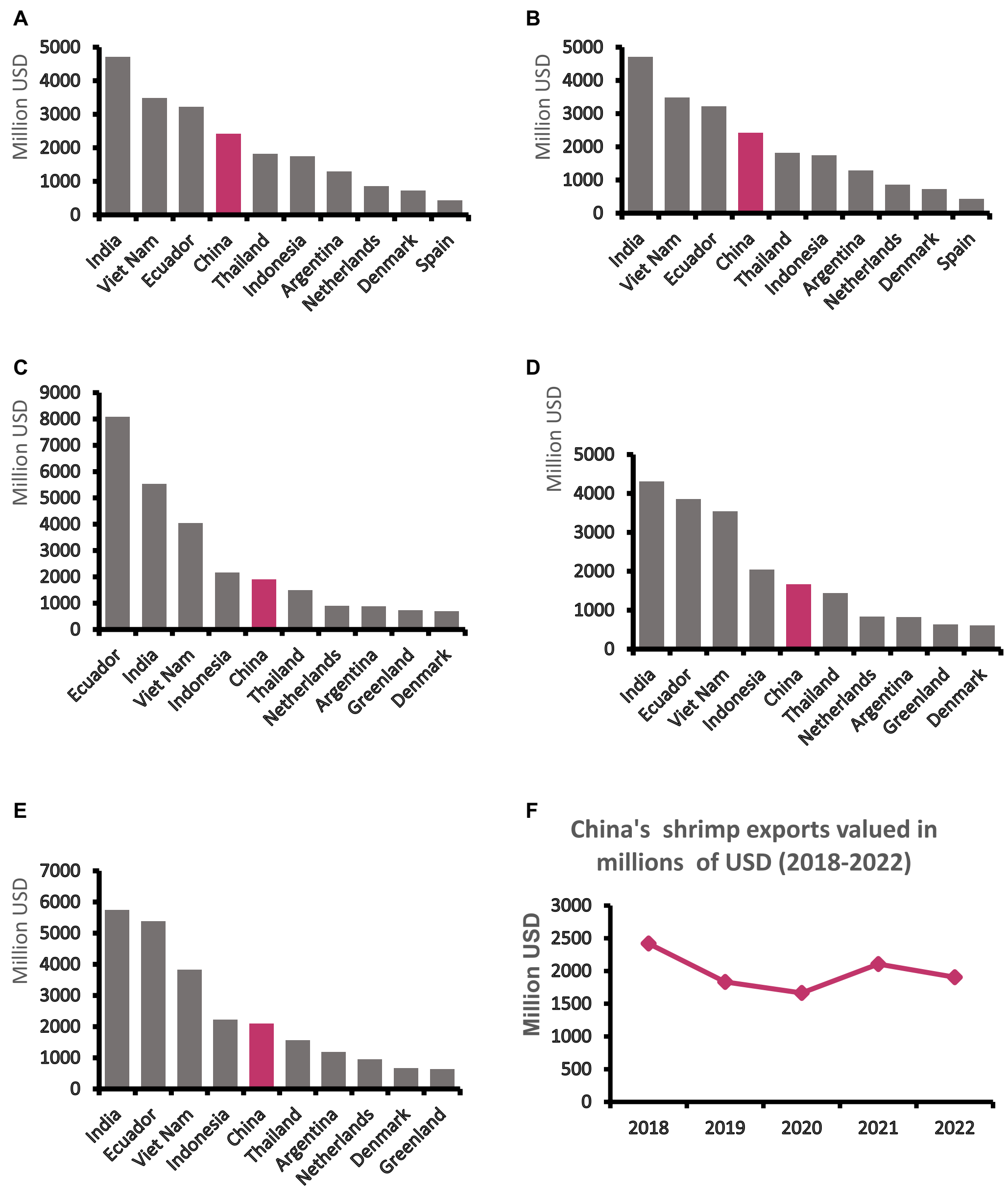

FIGURE 8
China's shrimp exports among the world's top ten shrimp exporting countries, in 2018–2022 as shown in **(A–E)**, respectively. **(F)** Trends in China's shrimp exports valued in millions of USD (2018–2022). Source: Authors, based on FAO database, 2023.

2016). Such technological advances of this time period set the stage for subsequent rapid expansion of shrimp aquaculture.

In addition, thanks to the government's continuous improvements in infrastructure, technology, production facilities, China's aquaculture capacity has been rising continuously. As a result, science and technology have played a significant role in improving the skills of workers in the aquaculture, especially in the shrimp sub-sector. Through technological research, demonstrations, training courses, and extension services, workers in the sector have been equipped with the scientific approach to shrimp farming (Wang, 2001). Hence, scientific and technological advancements were responsible for almost half of the increase in aquaculture production, leading to high returns on investment, particularly in shrimp farming, continues to have good prospects (N'Souvi et al., 2021).

Furthermore, the multi-trophic integrated system, which is an ecosystem-based farming mode, has emerged. Such an integrated culture evolves shrimp co-culture with fish, shellfish, crabs, seaweed or other species with the aim of gaining economic and socio-environmental benefits. These may include good harvests with larger fish products sizes, higher quality and market value, and being more environment-friendly. Thus, in China as elsewhere, a new pond-farming technique referred to as Biofloc technology has been considerably adopted by shrimp farmers in recent years (Cao et al., 2020; Abakari et al., 2022). It helps produce additional food sources (e.g., microbial biomass) to be used by the shrimps in addition to removing unutilized nutrients. Biofloc techniques also play a crucial role in the adjustments of dissolved-oxygen levels and in bio-control against diseases (El-Sayed, 2020; Khanjani and Sharifinia, 2022).

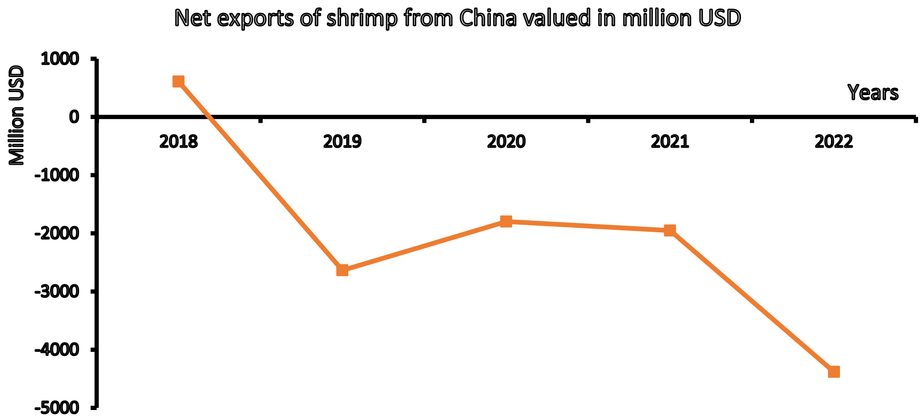

FIGURE 9
Trends in net exports of shrimp from China, valued in millions of USD (2018–2022). Source: Authors, based on FAO database, 2023.

4 Discussion

Shrimp aquaculture has many socioeconomic and other benefits (N'Souvi et al., 2021; Xuan et al., 2021). Like the global shrimp industry, China's shrimp industry has experienced rapid growth since the 1980s, thanks to technological breakthroughs and high demand for shrimp, leading to high prices and profits of its farming. Though many studies on shrimp farming in China have focused on different aspects, a very few of them have discussed the trends of its evolution in recent years and the challenges associated with such a rapid expansion. In the present study, it has been tried to present and discuss how the production of both wild-caught and aquaculture species, both freshwater and marine shrimp species has expanded in the last two decades, and the progress in shrimp aquaculture technology use, as well.

The results reveal that the aims of policies that have been implemented and concerns of shrimp farmers and other stakeholders in the sector have evolved over time. In the introductory phase of the Chinese shrimp industry, farmers, government and scientific teams had worked on the feasibility of domestication, especially of imported species. Then, thereafter this relatively long and perilous period, the general trend was profitability and marketing, which have required large-scale production. Despite its current profitability, which is overall satisfactory, the Chinese shrimp industry has seen the emergence of a number of challenges that have arisen from time to time. Indeed, the intensification of high-density shrimp farming has led to substantial environmental repercussions, including aquatic ecosystem degradation and material degradation. Its sustainability is supposed to give overall consideration to various aspects, including the population, market, quality, resources available, and environment, in order to ensure the supply of aquatic products to the generations to come based on the ecosystem carrying capacity (Wurts, 2000; Frankic and Hershner, 2003).

Besides, there has been a surge in bacterial and viral diseases (Febryano et al., 2017; Joffre et al., 2018). The environmental challenges with shrimp both wild-caught and aquaculture production in China as elsewhere in the world is likely to continue for the foreseeable future. In a word, the industry' current situation is promising but with the ever increasing and alarming effects of climate change, microplastics, water pollution, continued efforts (investment, R&D, Science and technology, etc.,) are needed to ensure sustainable development of the industry.

The present review also indicates that adoption of *Biofloc technology*, among others, could be one of the alternatives and thus, help reduce the environmental impacts that derived from the conventional shrimp farming practices. The results presented in this paper provide some implications for a more sustainable development of shrimp aquaculture in China. Any policy for promoting the sector needs to take into account the perspective of environmental change. This information is very helpful to improve the current state of the country's shrimp industry. That said, the challenges associated with the rapid expansion of shrimp aquaculture in developing countries, especially in rural poor areas should focus more on environmentally sustainable production.

4.1 Necessity to deal with disease occurrences

The first cases of disease were the serious outbreaks of shrimp diseases that have been reported in most of the largest shrimp-producing countries, including China (Villarreal, 2023). Acute problems of disease have emerged with the development, coupled with the intensification of farming practices and sales of shrimp on the international market, as well. In the early 2000s, various diseases were identified in cultured aquatic species, including shrimp and prawn culture in China (Wei et al., 2004).

Diseases have been one of the major constraints to shrimp farming sustainability in recent years (Yu et al., 2023). Severe shrimp outbreaks have taken place in many shrimp-producing areas. For example, the foremost among these are shrimp viral diseases that have affected production. Such diseases are most of the time linked to environmental issues related to the intensification of production. In order to make the maximum profit that helps cover the increasing production costs, especially the coastal land price, shrimp farmers tend to adopt more and more intensive practices. This includes an increased shrimp stock densities in the pond area, more feed, and other inputs per unit of pond area. This also results in increased effluents waste and a high risk of disease occurrence, which should be avoided at all costs.

4.2 The need for keep working on good quality of the fries and reasonable structure of shrimp aquaculture

In the past, the quality of shrimp fry was a serious issue that affected China's shrimp (Weimin, 2005). The use of poor and medium qualities, mixed with inappropriate medicine has sometimes led to shrimp quality, which is not always high enough. Besides, some breeding techniques and the repeated use of broodstock by the hatchery stakeholders also result in a deterioration of the quality of shrimp fry, presenting another challenge for the industry today. Thus, all these issues could slow down the growth rate, and thus considerably add to the production cycle and increase the risks of disease occurrence as well. Farmers own efforts combined with government support could help the former to use more advanced technologies in order to lower their environmental footprint while increasing their economic productivity (Clapano et al., 2022). With government support, shrimp farmers can continue effectively dealing with issues including overuse of chemicals, poor or medium quality feed, since feed is a crucial component of any aquaculture production system as a means to improve the final output quality (Glencross et al., 2019). The increase in broodstock imports also could be part of an effort to improve more the quality and sustainability.

In addition, seasonal markets and the rapid expansion of shrimp production affect the economic returns of the farmers due to the fact that the price sometimes is too low in the domestic market. In some cases, shrimp farmers lack frequent extension services and appropriate market orientation. This may be rendering fragile certain shrimp farmers for the market competitiveness. In the international market, China's shrimp export is facing strong pressure from non-tariff trade barrier policies implemented by other shrimp importing countries. This is another problem, a market issue that China's shrimp industry might continue to address with a great deal of interest in the short to medium-term.

4.3 The need for minimizing water pollution and other environmental impacts

While fulfilling the global demand for seafood, aquaculture expansion raises among others, concerns about its impacts on biodiversity, environment and the emergence of pathogens (Abdel-Latif et al., 2022). To ensure its sustainability, the environmental impact must be assessed and science-based management measures be implemented (Hall et al., 2011).

Like the whole aquaculture industry, shrimp aquaculture industry generates considerable amounts of wastewater as effluents. Indeed, shrimp aquaculture damages the ecosystem of mangrove areas through converting mangrove wetlands to ponds for shrimp farming. Given water exchange in the ponds is needed during shrimp production, polluted effluents are often discharged into waterways, resulting not only into land and soil fertility diminution but also into hazarded human health (Rahman et al., 2013; Hossain and Hasan, 2017). Such untreated effluent released from shrimp aquaculture can cause serious environmental issues in the future and could affect the shrimp farming industry. Only a few farmers presently treat the effluents that derive from their shrimp ponds before releasing them to the natural environment. Very often, spoiled bait, shrimp excreta, wastes from medicines for shrimp and other biological waste products in water cause nitrogen, phosphorus and other organic wastes, which result in water pollution. For example, the economic loss caused by pollution from aquaculture in China was estimated to be more than three billion yuan in 2019 (Zhang et al., 2019). Only remedial treatments of effluents that derive from the whole food industry can alleviate the environmental hazards (Venugopal and Sasidharan, 2020).

Regarding other impacts on local environments and livelihoods, shrimp cultivation is increasing salinity by constructing canals. Such effects are not only observable in soil salinity of the lands in the farm where ponds are located but also that of the surrounding areas and lands (Alam et al., 2017). As such, soil fertility declines and vegetables or other crops production decreases. This said, the driven salinity intrusion in areas surrounding shrimp farms may reduce farmers and communities' other livelihood production options (Islam and Tabeta, 2019). Furthermore, shrimp feed production affects climate change through an increase in the greenhouse gases in addition its effects on the ecosystem quality (Ramesh et al., 2023). The induced changes in the climate need to be minimized through appropriate ways and less emissions for a sustainable global shrimp aquaculture industry (Al Eissa et al., 2022).

4.4 The need for developing ecological and more healthier shrimp aquaculture

Ecological and healthy shrimp farming effectively improves the quality and safety of shrimp and shrimp products. It is also a crucial means to minimize factors that challenge the enhancement of the shrimp aquaculture industry (Sun et al., 2023). Developing ecological-friendly shrimp farming can be promoted in different ways.

First, promoting planting and breeding technologies for shrimp through the shrimp-vegetable technology enhancement. In addition, the *Biofloc* system is another farming technique that needs to be encouraged and promoted among shrimp farmers in China. This system, which consists of a modern practice for initial shrimp monoculture systems toward a more sustainability, has been used in shrimp culture by a few framers. It helps in reducing water usage by up to 90% as compared to traditional methods by maintaining water quality more effectively. Besides, *Biofloc* technique also enables culture at high stocking densities, manages land use waste, and optimizes the use of artificial food (Wasielesky et al., 2013; Krummenauer et al., 2014; Liu et al., 2017; Kumar et al., 2018). Furthermore, an integrated system of raising, for example, shrimp and tilapia, known as an integrated multi-trophic culture, could help minimize total suspended solids in the *biofloc* system. Adopting this kind of technology could allow farmers to use residues from one species to cultivate others.

5 Concluding remarks, and outlook

China's shrimp industry has developed rapidly over the last two decades. Higher shrimp production is driven by expanded shrimp aquaculture production, with major species dominated by *litopenaeus vannamei* referred to as *Penaeus monodon*, *Penaeus chinensis*, and *Penaeus japonicus*. China has remained among the world top shrimp producers over the last two decades. However, some constraints and challenges threatening the industry have emerged. A growing number of diseases and other issues that have appeared in the shrimp industry in recent years may be associated with the speedy development of the industry. A better grasp of trends in the production, exports, and imports might help predict or avoid the occurrence of disease, and other challenges. Therefore, the development of innovative shrimp industry management approaches is of critical importance in any effort toward the industry's sustainability.

First, the shrimp aquaculture industry should be farmed in a way that promotes the protection of the ecosystem and environment. Applying such an organic farming principle presupposes some practices or techniques for addressing the current issues threatening the sustainable growth of the industry. To that end, innovative techniques such as shrimp-vegetables technology, the *Biofloc* system and, integrated multitrophic culture of shrimp and other fish species should be more strengthened or encouraged. Second, appropriate techniques for diseases' prevention, their early diagnosis, and their frequent control as well, should also be developed and improved. In addition, encouraging the use of good-quality feed in an appropriate quantity and form is also crucial. To that end, the government could continue helping shrimp farmers achieve the sustainable shrimp aquaculture through more ecological technology adoptions.

Furthermore, sustainably providing sufficient and healthier shrimp seafood for both domestic and international market is going to require more effort, given the global climate change influence in the evolution of the world, and which may continue over the coming decades with associated socioeconomic and environmental implications. While the present state of the shrimp aquaculture industry in China is somewhat sustainable, continuous effort and follow up need to be kept and improved. In summary, the following points should be addressed going forward:

- Future studies to explore an overall sustainability picture of the Chinese shrimp industry. For example, an "Economic analysis of the main drivers of shrimp aquaculture expansion in China over the years: Do international market price and shrimp consumption *per capita* in China matter?".
- Further investigations are needed to better understand the socio-ecological dynamics of adopting shrimp-based systems in China as elsewhere in the world. For example, an "Analysis of externalities of shrimp aquaculture from economic and environmental viewpoints: Evidence from land use change in China".
- Other outstanding questions need to be addressed, such as shrimp aquaculture farmers' willingness to adopt ecological technologies, for example the Biofloc technology.

Author contributions

KN': Conceptualization, Data curation, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. CS: Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – review & editing. BC: Formal analysis, Resources, Writing – review & editing. AV: Formal analysis, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was supported by the Ministry of Agriculture and Rural Affairs of the People's Republic of China through the China's Agricultural Research System (Grant No CARS-48).

Acknowledgments

We wish to thank the reviewers for their valuable comments on previous versions of this manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abakari, G., Wu, X., He, X., Fan, L., and Luo, G. (2022). Bacteria in biofloc technology aquaculture systems: roles and mediating factors. *Rev. Aquac.* 14, 1260–1284. doi: 10.1111/raq.12649

Abdel-Latif, H. M. R., Yilmaz, E., Dawood, M. A. O., Ringø, E., Ahmadifar, E., and Yilmaz, S. (2022). Shrimp vibriosis and possible control measures using probiotics, postbiotics, prebiotics, and synbiotics: a review. *Aquaculture* 551:737951. doi: 10.1016/j.aquaculture.2022.737951

ADB/NACA. (1996). Aquaculture sustainability and the environment. Report on a regional study and workshop on aquaculture sustainability and the environment. Asian Development Bank and Network of Aquaculture Centres in Asia-Pacific, Bangkok, Thailand.

Al Eissa, A., Chen, P., Brown, P. B., and Huang, J. H. (2022). Effects of feed formula and farming system on the environmental performance of shrimp production chain from a life cycle perspective. *J. Ind. Ecol.* 26, 2006–2019. doi: 10.1111/jiec.13370

Alam, M. Z., Carpenter-Boggs, L., Mitra, S., Haque, M. M., Halsey, J., Rokonuzzaman, M., et al. (2017). Effect of salinity intrusion on food crops, livestock, and fish species at Kalapara Coastal Belt in Bangladesh. *J. Food Qual.* 2017, 1–23. doi: 10.1155/2017/2045157

Asche, F., Yang, B., Gephart, J. A., Smith, M. D., Anderson, J. L., Camp, E. V., et al. (2022). China's seafood imports-not for domestic consumption? *Science* 375, 386–388. doi: 10.1126/science.abl4756

Balassa, B. (1978). Exports and growth: further evidence. *J. Dev. Econ.* 5, 181–189.

Biao, X., and Kaijin, Y. (2007). Shrimp farming in China: operating characteristics, environmental impact and perspectives. *Ocean Coast. Manag.* 50, 538–550. doi: 10.1016/j.ocecoaman.2007.02.006

Boyd, C. E., and McNevin, A. A. (2018). Land use in shrimp aquaculture. *World Aquac.* 49, 28–34.

Cao, B. X., Abakari, G., Luo, G. Z., Tan, H., and Xia, W. (2020). Comparative analysis of nitrogen and phosphorus budgets in a bioflocs aquaculture system and recirculation aquaculture system during over-wintering of tilapia (GIFT, *Oreochromis niloticus*). *Aquac. Eng.* 89:102026. doi: 10.1016/j.aquaeng.2019.102026

Chao, L., Xiang, W., and Guo-feng, S. (2017). Spatio-temporal characteristics and changing trend of freshwater aquaculture production distribution in China. *Jiangsu Agric. Sci.* 45, 301–305. doi: 10.15889/j.issn.1002-1302.2017.15.076

Clapano, M. B., Diuyan, J. M. T., Rapiz, F. G. B., and Macusi, E. D. (2022). Typology of smallholder and commercial shrimp (*Penaeus vannamei*) farms, including threats and challenges in Davao region, Philippines. *Sustainability* 14:5713. doi: 10.3390/su14095713

Deng, Z., Zhang, Z., Zhao, R., Sun, J., Hao, P., Zhang, L., et al. (2023). Effects of high-salinity on the expression of aquaporins and ion transport-related genes in Chinese shrimp (*Fenneropenaeus chinensis*). *Aquac. Rep.* 30:101577. doi: 10.1016/j.aqrep.2023.101577

Dong, X., and Raghavan, V. (2022). Recent advances of selected novel processing techniques on shrimp allergenicity: a review. *Trends Food Sci. Technol.* 124, 334–344. doi: 10.1016/j.tifs.2022.04.024

Duan, Y., Tian, B., Li, X., Liu, D., Sengupta, D., Wang, Y., et al. (2021). Tracking changes in aquaculture ponds on the China coast using 30 years of Landsat images. *Int. J. Appl. Earth Obs. Geoinf.* 102:102383. doi: 10.1016/j.jag.2021.102383

El-Sayed, A. M. (2020). Use of biofloc technology in shrimp aquaculture: a comprehensive review, with emphasis on the last decade. *Rev. Aquac.* 13, 676–705. doi: 10.1111/raq.12494

Estrada-Perez, N., Ruiz-Velazco, J. M. J., and Hernández-Llamas, A. (2020). Economic risk scenarios for semi-intensive production of Litopenaeus (Penaeus) vannamei shrimp affected by acute hepatopancreatic necrosis disease. *Aquac. Rep.* 18:100442. doi: 10.1016/j.aqrep.2020.100442

FAO. (2000). Small ponds make a big difference. Available at: https://www.fao.org/3/x7156e/x7156e00.htm (Accessed August 17, 2023).

FAO. (2019). FAO yearbook. Fishery and Aquaculture Statistics 2017/FAO.

FAO. (2020). FishStatJ (Rome: FAO). Available at: www.fao.org/fishery/en/statistics/software/fishstatj/en (Accessed October 27, 2023).

FAO. (2021). Food and Agricultural Organization of the United Nations. Available at. http://www.fao.org (Accessed July 15, 2023).

FAO. (2022). *The state of world fisheries and aquaculture 2022. Towards blue transformation*. Rome, FAO.

FAO. (2023). Available at: https://www.fao.org/in-action/globefish/market-reports/resource-detail/en/c/1633618/ (Accessed July 19, 2023).

FAOSTAT (2023). Available at: http://www.fao.org/faostat/en/#data/FBS (Accessed November 5, 2023).

Febryano, I. G., Sinurat, J., and Salampessy, M. L. (2017). Social relation between businessman and community in management of intensive shrimp pond, 2nd International Conference on Tropical and Coastal Region Eco Development 2016, 55, 012042.

Feder, G. (1983). On exports and economic growth. *J. Dev. Econ.* 12, 59–73. doi: 10.1016/0304-3878(83)90031-7

Frankic, A., and Hershner, C. (2003). Sustainable aquaculture: developing the promise of aquaculture. *Aquac. Int.* 11, 517–530. doi: 10.1023/B:AQUI.0000013264.38692.91

Fu, T., Zhang, L., Yuan, X., Chen, B., and Yan, M. (2021). Spatio-temporal patterns and sustainable development of coastal aquaculture in Hainan Island, China: 30 years of evidence from remote sensing. *Ocean Coast. Manag.* 214:105897. doi: 10.1016/j.ocecoaman.2021.105897

Fu-Chi, G. (2023). China's shrimp production landscape. Global Shrimp Forum.

Glencross, B. D., Baily, J., Berntssen, M. H. G., Hardy, R., MacKenzie, S., and Tocher, D. R. (2019). Risk assessment of the use of alternative animal and plant raw material resources in aquaculture feeds. *Rev. Aquac.* 12, 703–758. doi: 10.1111/raq.12347

Hall, S. J., Delaporte, A., Phillips, M. J., Beveridge, M., and O'Keefe, M. (2011). Blue frontiers: managing the environmental costs of aquaculture. The WorldFish Center, Penang, Malaysia, 92 p. Available at: https://digitalarchive.worldfishcenter.org/bitstream/handle/20.500.12348/1148/WF_2821.pdf?sequence1= (Accessed July 29, 2023).

Han, C., Li, L., Zhang, G., Dong, S., and Tian, X. (2021). Assessment of elemental profiling combined with chemometrics for authenticating the geographical origins of Pacific white shrimp (*litopenaeus vannamei*). *Food Control* 130:108231. doi: 10.1016/j.foodcont.2021.108231

Hossain, M. A. R., and Hasan, M. R. (2017). An assessment of impacts from shrimp aquaculture in Bangladesh and prospects for improvements. FAO fisheries and aquaculture technical paper no. 618. Food and Agriculture Organization of the United Nations. Available at: https://issuu.com/aquacultureasiapacific/docs/aq22176_aap_julaug_22_fa_lr/s/16417856 (Accessed October 10, 2023).

Hu, F., Zhong, H., Wu, C., Wang, S., Guo, Z., Tao, M., et al. (2021). Development of fisheries in China. *Reprod. Breed.* 1, 64–79. doi: 10.1016/j.repbre.2021.03.003

Huang, Z., Guan, W., Lyu, X., Chen, R., Wu, Y., and Mao, L. (2024). Impacts of acute ammonia-N exposure on the muscle quality of whiteleg shrimp (*Penaeus vannamei*): novel insights into lipid and protein oxidation. *Food Chem.* 437:137781. doi: 10.1016/j.foodchem.2023.137781

IMF. (2023). Global price of Shrimp [PSHRIUSDQ], FRED, Federal Reserve Bank of St. Louis. Available at: https://fred.stlouisfed.org/series/PSHRIUSDQ (Accessed November 8, 2023).

Islam, M. R., and Tabeta, S. (2019). Shrimp vs prawn-rice farming in Bangladesh: a comparative impacts study on local environments and livelihoods. *Ocean Coast. Manag.* 168, 167–176. doi: 10.1016/j.ocecoaman.2018.11.004

Jin, S., Jacquin, L., Xiong, M., Li, R., Lek, S., Li, W., et al. (2019). Reproductive pattern and population dynamics of commercial red swamp crayfish (*Procambarus clarkii*) from China: implications for sustainable aquaculture management. *PeerJ* 7:e6214. doi: 10.7717/peerj.6214

Joffre, O. M., Klerkx, L., and Khoa, T. N. D. (2018). Aquaculture innovation system analysis of transition to sustainable intensification in shrimp farming. *Agron. Sustain. Dev.* 38, 1–11. doi: 10.1007/s13593-018-0511-9

Joshi, J., Srisala, J., Truong, V. H., Chen, I. T., Nuangsaeng, B., Suthienkul, O., et al. (2014). Variation in *Vibrio parahaemolyticus* isolates from a single Thai shrimp farm experiencing an outbreak of acute hepatopancreatic necrosis disease (AHPND). *Aquaculture* 428-429, 297–302. doi: 10.1016/j.aquaculture.2014.03.030

Kautsky, N., Ronnback, P., Tedengren, M., and Troell, M. (2000). Ecosystem perspectives on management of disease in shrimp pond farming. *Aquaculture* 191, 145–161. doi: 10.1016/S0044-8486(00)00424-5

Khan, M. A., Hossain, M. E., Islam, M. S., Rahman, M. T., and Dey, M. M. (2022). Shrimp export competitiveness and its determinants: a novel dynamic ARDL simulations approach. *Aquac. Econ. Manag.* 27, 221–248. doi: 10.1080/13657305.2022.2089772

Khanjani, M. H., and Sharifinia, M. (2022). Biofloc technology with addition molasses as carbon sources applied to *litopenaeus vannamei* juvenile production under the effects of different C/N ratios. *Aquac. Int.* 30, 383–397. doi: 10.1007/s10499-021-00803-5

Krummenauer, D., Samocha, T., Poersch, L., Lara, G., and Wasielesky, W. (2014). The reuse of water on the culture of pacific white shrimp, *litopenaeus vannamei*, in BFT system. *J. World Aquacult. Soc.* 45, 3–14. doi: 10.1111/jwas.12093

Kumar, R. (2022). Shrimp breeding: strategies for success. Aquaculture Asia Pacific Discussion.

Kumar, G., and Engle, C. R. (2016). Technological advances that led to growth of shrimp, Salmon, and Tilapia farming. *Rev. Fish. Sci. Aquac.* 24, 136–152. doi: 10.1080/23308249.2015.1112357

Kumar, V. S., Pandey, P. K., Anand, T., Bhuvaneswari, G. R., Dhinakaran, A., and Kumar, S. (2018). Biofloc improves water, effluent quality and growth parameters of *penaeus vannamei* in an intensive culture system. *J. Environ. Manage.* 215, 206–215. doi: 10.1016/j.jenvman.2018.03.015

Li, X., Li, J., Wang, Y., Fu, L., Fu, Y., Li, B., et al. (2011). Aquaculture industry in China: current state, challenges, and outlook. *Rev. Fish. Sci.* 19, 187–200. doi: 10.1080/10641262.2011.573597

Li, F., and Xiang, J. (2013). Recent advances in researches on the innate immunity of shrimp in China. *Dev. Comp. Immunol.* 39, 11–26. doi: 10.1016/j.dci.2012.03.016

Li, T., Zhang, B., Zhu, C., Su, J., Li, J., Chen, S., et al. (2021). Effects of an ex situ shrimp-rice aquaponic system on the water quality of aquaculture ponds in the Pearl River estuary, China. *Aquaculture* 545:737179. doi: 10.1016/j.aquaculture.2021.737179

Liu, W., Luo, G., Li, L., Wang, X., Wang, J., Ma, N., et al. (2017). Nitrogen dynamics and biofloc composition using biofloc technology to treat aquaculture solid waste mixed with distillery spent wash. *N. Am. J. Aquac.* 79, 27–35. doi: 10.1080/15222055.2016.1223769

Liu, H., Shen, M., He, Y., Li, B., Pu, L., Xia, G., et al. (2023). Analysis of differentially expressed proteins after EHP-infection and characterization of caspase 3 protein in the whiteleg shrimp (*litopenaeus vannamei*). *Fish Shellfish Immunol.* 135:108698. doi: 10.1016/j.fsi.2023.108698

MacLeod, M. J., Hasan, M. R., Robb, D. H. F., and Mamun-Ur-Rashid, M. (2020). Quantifying greenhouse gas emissions from global aquaculture. *Sci. Rep.* 10:11679. doi: 10.1038/s41598-020-68231-8

Mansour, A. T., Ashour, M., Alprol, A. E., and Alsaqufi, A. S. (2022). Aquatic plants and aquatic animals in the context of sustainability: cultivation techniques, integration, and blue revolution. *Sustainability* 14:3257. doi: 10.3390/su14063257

Marshall, A. (1890). *Principles of economics* (*1938th edition*). London: Macmillan.

Meng, X., Wang, Q., Jie Kon, J., Li, J., and Huang, J. (2015). Shrimp farming in China: lessons from its developmental history. Available at: https://VICTORNKODJ/downloads/shrimp-farming-in-China-what-should-we-learn-from-its-developmental-history.Pdf (Accessed July 24, 2023).

N'Souvi, K., Sun, C., and Che, B. (2021). Aquaculture technology adoption and profitability of the polyculture system practiced by prawn and crab farmers: case study of Anhui Province in China. *Aquac. Rep.* 21:100896. doi: 10.1016/j.aqrep.2021.100896

Newton, R., Zhang, W., Xian, Z., McAdam, B., and Little, D. C. (2021). Intensification, regulation and diversification: the changing face of inland aquaculture in China. *Ambio* 50, 1739–1756. doi: 10.1007/s13280-021-01503-3

OEC. (2021). Shrimps and prawns, frozen. Available at: https://oec.world/en/profile/hs92/shrimps-and-prawns-frozen (Accessed August 5, 2023).

Rahman, M. M., Giedraitis, V. R., Lieberman, L. S., Akhtar, M. T., and Taminskiene, V. (2013). Shrimp cultivation with water salinity in Bangladesh: thee implications of an ecological model. *Univers. J. Public Health* 1, 131–142. doi: 10.13189/UJPH.2013.010313

Ram, R. (1987). Exports and economic growth in developing countries: evidence from time-series and cross-section data. *Econ. Dev. Cult. Chang.* 36, 51–72. doi: 10.1086/451636

Ramesh, P., Jasmin, A. S., Tanveer, M., Ganeshan, P., Rajendran, K., Kamilya, D., et al. (2023). Environmental impacts and effects on greenhouse gas emissions in shrimp feed production system for aquaculture – a case study in India. *Environ. Res.* 241:117348. doi: 10.1016/j.envres.2023.117348

Ren, W. (2021). What forces drive the rapid development of mariculture in China: factor-driven or total factor productivity-driven? *Aquac. Res.* 52, 3966–3977. doi: 10.1111/are.15240

Ricardo, D. (1817). "On the principles of political economy and taxation" in *The works and correspondence of David Ricardo, Vol. 1*. ed. P. Sraffa (Cambridge: Cambridge University Press)

Shinn, A. P., Pratoomyot, J., Griffiths, D., Trong, T. Q., Vu, N. T., Jiravanichpaisal, P., et al. (2018). Asian shrimp production and the economic costs of disease. *Asian Fish. Sci.* 31S, 29–58. doi: 10.33997/j.afs.2018.31.s1.003

Smith, A. (1776). An inquiry into the nature and causes of the wealth of nations. History of Economic Thought Books, McMaster University Archive for the History of Economic Thought, Number Smith 1776.

Sun, Y., Hou, H., Dong, D., Zhang, J., Yang, X., Li, X., et al. (2023). Comparative life cycle assessment of whiteleg shrimp (*Penaeus vannamei*) cultured in recirculating aquaculture systems (RAS), biofloc technology (BFT) and higher-place ponds (HPP) farming systems in China. *Aquaculture* 574:739625. doi: 10.1016/j.aquaculture.2023.739625

Thitamadee, S., Prachumwat, A., Srisala, J., Jaroenlak, P., Salachan, P. V., Sritunyalucksana, K., et al. (2016). Review of current disease threats for cultivated penaeid shrimp in Asia. *Aquaculture* 452, 69–87. doi: 10.1016/j.aquaculture.2015.10.028

Van der Pijl, W. (2023). Shrimp trade statistics. Status and future prospects. Global Shrimp Forum.

Venugopal, V., and Sasidharan, A. (2020). Seafood industry effluents: environmental hazards, treatment and resource recovery. *J. Environ. Chem. Eng.* 9:104758. doi: 10.1016/j.jece.2020.104758

Villarreal, H. (2023). Shrimp farming advances, challenges, and opportunities. *World Aquac. Soc.* 54, 1092–1095. doi: 10.1111/jwas.13027

Wang, Y. (2001). "China P.R.: a review of national aquaculture development" in *Aquaculture in the Third Millennium. Technical Proceedings of the Conference on Aquaculture in the Third Millennium, Bangkok, Thailand, 20–25 February 2000*. eds. R. P. Subasinghe, P. Bueno, M. J. Phillips, C. Hough, S. E. McGladdery and J. R. Arthur (Rome: NACA, Bangkok and FAO), 307–316.

Wang, J., Che, B., and Sun, C. (2022). Spatiotemporal variations in shrimp aquaculture in China and their influencing factors. *Sustainability* 14:13981. doi: 10.3390/su142113981

Wang, O., Somogyi, S., and Ablett, R. (2021). The influences of quality attributes and socio-demographics on Chinese consumers' general and online consumptions of Canadian, US and Australian lobsters. *Br. Food J.* 123, 2289–2306. doi: 10.1108/BFJ-12-2020-1101

Wasielesky, W., Froes, C., Fóes, G., Krummenauer, D., Lara, G., and Poersch, L. (2013). Nursery of *litopenaeus vannamei* reared in a biofloc system: the effect of stocking densities and compensatory growth. *J. Shellfish Res.* 32, 799–806. doi: 10.2983/035.032.0323

Wei, Q., He, J., Yang, D., Zheng, W., and Li, L. (2004). Status of sturgeon aquaculture and sturgeon trade in China: a review based on two recent nationwide surveys. *J. Appl. Ichthyol.* 20, 321–332. doi: 10.1111/j.1439-0426.2004.00593.x

Weimin, M. (2005). Status of aquaculture of *Penaeus vannamei* in China. In: Regional technical consultation on the aquaculture of P. Vannamei and other exotic shrimps in Southeast Asia, Manila, Philippines (pp. 84–91). Tigbauan, Iloilo, Philippines: SEAFDEC Aquaculture Department. Available at: https://core.ac.uk/download/pdf/10863547.pdf (Accessed November 4, 2023).

Wurts, W. A. (2000). Sustainable aquaculture in the twenty-first century. *Rev. Fish. Sci.* 8, 141–150. doi: 10.1080/10641260091129206

Xuan, B. B., Sandorf, E. D., and Ngoc, Q. T. K. (2021). Stakeholder perceptions towards sustainable shrimp aquaculture in Vietnam. *J. Environ. Manag.* 290:112585. doi: 10.1016/j.jenvman.2021.112585

Yu, Y., Tang, M., Wang, Y., Liao, M., Wang, C., Rong, X., et al. (2023). Virulence and antimicrobial resistance characteristics assessment of Vibrio isolated from shrimp (*Penaeus vannamei*) breeding system in South China. *Ecotoxicol. Environ. Saf.* 252:114615. doi: 10.1016/j.ecoenv.2023.114615

Zhang, X.-G. (2007). "Aquaculture in China" in *Species and system selection for sustainable aquaculture*. eds. P. S. Leung, C.-S. Lee and P. J. O'Bryen (Hoboken, NJ: Blackwell Publishing), 131–144.

Zhang, X. L., Cui, L., Li, S., Liu, X., Han, X., and Jiang, K. (2019). China fishery statistical yearbook.

Zhu, J., and Liu, W. (2020). A tale of two databases: the use of web of science and Scopus in academic papers. *Scientometrics* 123, 321–335. doi: 10.1007/s11192-020-03387-8

frontiers | Frontiers in Sustainable Food Systems

TYPE Perspective
PUBLISHED 21 February 2024
DOI 10.3389/fsufs.2024.1356492

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RECEIVED 15 December 2023
ACCEPTED 31 January 2024
PUBLISHED 21 February 2024

CITATION
Mizuta DD (2024) Dietary shifts and the need for increased sustainability approaches in the global aquaculture seafood system.
Front. Sustain. Food Syst. 8:1356492.
doi: 10.3389/fsufs.2024.1356492

Dietary shifts and the need for increased sustainability approaches in the global aquaculture seafood system

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Recent shifts in the global dietary preferences have indicated the fast-growing choice for plant-based, or meat-reduced diets. Among the motivations for such choices, which are increasingly advocated by nations and environmental institutions, is the major concern with global environmental sustainability and impacts of food production systems. Incontestably, the animal food source industry is extremely diverse, and seafood production through the aquaculture value chain remains unfamiliar to key stakeholders possibly leading to an uncomprehensive view and often biased perception of the farming industry within the environmental context. Accordingly, I discuss the importance of seafood production systems, such as the fastest seafood production that is the aquaculture sector, to increase their focus on the sustainability arena with more substantial and effective improvements for sustainable production, and most importantly, concomitantly informing end consumers. I mention examples of types of sustainability efforts that can be implemented and highlight the urgency of actively informing customers about implemented practices.

KEYWORDS

dietary shifts, meat-reduced diets, seafood, aquaculture, environmental sustainability, food production systems

Introduction

Discussions about the need for more sustainable food systems have driven major changes in food production and consumption (United Nations, 2023). Meat-reduced or meatless diets have been adopted globally influenced by various factors, such as regional context (availability), culture and beliefs, personal preferences, animal welfare concerns, health promotion, and increasingly, environmental sustainability (Vanderlee et al., 2022); the latter two arguably reflecting up-to-date scientific knowledge. With growing awareness of planetary challenges, concerns about the environmental consequences of meat production have increased exponentially, and more sustainable diets including plant-based food are being suggested as a way to help countries achieve the Sustainable Development Goals (SDGs; Willett et al., 2019) and adhere to the climate goals set by the Intergovernmental Panel on Climate Change (IPCC; Mbow et al., 2019). As a result, self-imposed dietary shifts to support environmental sustainability are a present reality for many, and also foreseen to grow (Willits-Smith et al., 2020).

Diets are distributed along a spectrum with the strict vegan (excludes all foods of animal origin) on one end, followed by vegetarians (excludes meat and meat-derived foods), pescatarians (plant-based diet with inclusion of seafood), flexitarians (plant-based diet and consumption of any meat in limited amounts), and the omnivorous (no meat restrictions) in the opposite extremity (Figure 1; based on Hargreaves et al., 2023). In that spectrum, the seafood market and especially the growing aquaculture industry are strategically positioned to cater for the majority of dietary groups (Figure 1). However, consumers' choices about what to purchase and eat has the potential to alter production trends and markets (O'Malley et al., 2023).

From 2014, the number of seafood alternatives or analogs has increased in availability more than 5 times in some national markets (Boukid et al., 2022). Seafood analogs mimic the structure, texture, and sensorial characteristics of meat usually with a complete plant-based composition, in order to satisfy consumers that enjoy seafood but have concerns about the environmental consequences of this industry (Kazir and Livney, 2021). Moreover, cell-based seafood grown from conventional animals, although in primary development stages, could potentially come to 'popular' adoption in the future, provided constraints such as high price, accessibility, and demand in lieu of conventional seafood are surpassed (Halpern et al., 2021). Nonetheless, it is believed that seafood alternatives may in part lessen the demand for conventional seafood, shaped by society's demand (Marwaha et al., 2022).

Despite the increasing dietary transformation, the aquaculture industry has seen demand grow in recent years and contributes to 49% of total aquatic production (FAO, 2022). Increases in seafood demand come with consumers' questions about the production process, traceability, and environmental considerations. Indeed, if aquaculture is not sustainably planned it can have negative effects, such as genetic introduction in nature from escapes (Soto et al., 2023), overestimation of an area's carrying capacity (Comeau et al., 2023), habitat degradation (Elwin et al., 2019), and potential food safety related to antiquated legislation (Rosa et al., 2020). Issues such as the lack of transparency and environmental responsibility in food industries can lead to rejection from many consumers whose first choice has seemingly shifted from personal preference to a more collective view based on environmental ethics.

Within this scenario, industry-led focus on increased sustainability of aquaculture and adoption of local environmental actions can concomitantly support sustainable goals for global health while also meeting the expectation of environmentally-conscious consumers. This is important because there has been little market-based justification to increase the aquatic farm-gate sustainability as a whole. I focus on the two most science-based triggers for dietary choices, namely health and environmental sustainability, to discuss the shifts, the knowledge behind shift triggers, and finally, suggested actions to connect seafood farming production with the goals of sustainable diets and consumers.

The spread: dietary shifts for sustainability are an affluent economies trend?

Dietary shifts resulting from the preoccupation with the environmental impacts of meat production are not reserved to affluent nations. In fact, meat consumption is usually associated with wealth and richer economies (Forestell, 2018). Increases in the consumption of meat (and fish) can occur as a result of economic expansion and urbanization, as in some non-Western countries such as India, China, and Myanmar, although Southeast Asia and Sub-Saharan Africa have a high number of vegetarians (e.g., Bangladesh and India; Rao et al., 2018; Fukase and Martin, 2020; Zhang et al., 2022). In Vietnam and Kenya, meat supply in recent years has increased, together with the countries' diet-related environmental footprint (Heller et al., 2020). On the other hand, in Indonesia, considerable dietary shifts did not occur with urbanization and the traditional diet high in cereals and plants still predominates both in urban and rural areas, showing that urbanization-triggered dietary shift does not always hold true (Colozza and Avendano, 2019). Notwithstanding, assessments of dietary changes and country-specific data are limited for the majority of non-Western countries (Heller et al., 2020), but those countries are also expected to partake in the healthy-environmental-diet transition due to increasing diet-related disease incidence (Tilman and Clark, 2014).

Although earlier in 2016 a report concluded only Brazil, Germany, Qatar, and Sweden included environmental sustainability in their food-based dietary guidelines (FBDG, Gonzalez Fischer and Garnett, 2016), the number of countries reporting the links of diet with human health and environmental sustainability is increasing. Presently, the FBDGs from 37 nations, including 3 low-income or lower-middle-income countries, mention environmental sustainability. Within the FBDGs two types of documents (scientific documents and consumer summary) the two most common dietary guiding principles were

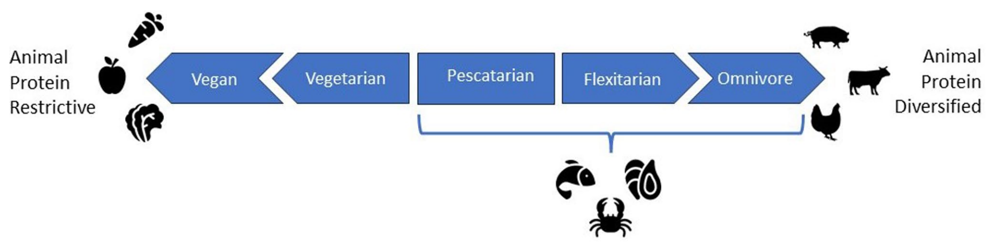

FIGURE 1
The food spectrum of main diets. Towards the right, diets are more inclusive, progressively adding more, and diversified, animal-origin foods and proteins, but also including items from the left (vegetables, fish, etc.); towards the left, the diets are more selective, progressively restricting selected animal-origin foods and proteins. Note that the seafood market caters for the majority of main diets, as highlighted. (*Disclaimer: this graph has been designed using images from Freepik available at Flaticon.com*).

plant-based and animal-based foods, which shows the increased relevance of plant-based food in contemporary diets (James-Martin et al., 2022). Worldwide many FBDGs are advocating for increased adoption of plant-based diets instead of animal-origin protein and reporting "environmental sustainability" as the key factor for this suggested transition (James-Martin et al., 2022).

Additionally, nations that culturally represent more carnivorous diets, with a variety of meat in national dishes, are among the top nations with vegetarian citizens, such as Germany (6%) and Brazil (3%), behind for example India with 25% and the United Kingdom with 7% (Statista, 2023), and Mexico (2%), which has a high number of more non-conventional vegan dieters (Vanderlee et al., 2022). Public interest in limiting consumption of meat is increasing (Forestell, 2018), as eating less of any kind of meat and less of all kinds of meat was expressed as goals by more than 40 and 30%, respectively, of interviewees in Australia, Canada, Mexico, United States, and United Kingdom (Vanderlee et al., 2022).

While in its current status, the dimension of the seafood market and increased demand portrays a safe economic environment and a considerable displacement of conventional seafood by its seafood alternatives is unlikely, acknowledging the dimension of the aforementioned dietary shifts now will allow the seafood industry to better stand for a resilient business and loyal customers.

The triggers: dietary shifts as truly informed decisions

The actual number of people restricting their diets to meat-free or plant-based is still considerably low worldwide, but expanding. Therefore, it is important and expected that consumers are provided with enough information to make sound decisions concerning diets that are more sustainable. That choice should be based on well-informed background knowledge grounded in up-to-date science. Nonetheless, a brief review shows there is not strong evidence against keeping seafood in one's menu based on human health and the environment.

Health

The latest EAT-Lancet report suggests the inclusion of seafood in what is considered a sustainable diet (Mbow et al., 2019), a concept that combines health and environmental concerns (Springmann et al., 2018), and is defined as that with low environmental impacts, which contribute to food and nutrition security and to a healthy life, and is environmentally-friendly, culturally acceptable, accessible, nutritive, and safe (FAO, 2010). In a review of diet health effects and the metabolic syndrome (e.g.: low good cholesterol (HDL), impaired glucose metabolism, high blood pressure and inflammatory biomarkers, risks of heart disease and diabetes), Thomas et al. (2023) concluded that the vegan diet has unsatisfactory levels of HDL, even though it lowers body weight and inflammatory markers; with better prospects of vegetarian and pescatarian diets concerning improved effects of inflammation, and cardiovascular issues. O'Malley et al. (2023) found better health eating indexes for pescatarians, followed by vegetarians, vegans, and omnivores. Pescatarians also had lower risk of heart disease and overall good reduction in risks for all-cause diseases exceeding the performance of vegetarian diets (Tilman and Clark, 2014). Substitutions of conventional seafood by alternatives can be significantly less healthy as some types of products have lower quality protein, more salt, and lack micronutrients when compared to their conventional counterparts, although most alternatives had no additives or preservatives, but nutrition and health effect studies of seafood alternatives are still limited (Boukid et al., 2022).

Environment

Studies have shown discrepancies between the environmental outcomes from production of beef, poultry and pork, to the production of aquatic species and agricultural crops (Tilman and Clark, 2014; Hilborn et al., 2018; Froehlich et al., 2018a; Halpern et al., 2019). Still, there are a number of different environmental stressors that remain unaddressed and should be considered in the analysis of sustainable food systems (Halpern et al., 2019). In spite of that, vegan, vegetarian, pescatarian diets are connected to positive environmental effects in many assessments, in this order. However, in a case study in Europe, none of the main diets (vegetarian, pescatarian, and omnivorous) were sufficient to meet the climate IPCC goals of carbon emissions (Masino et al., 2023). At present, seafood alternatives have very low chances of contributing to fisheries recovery and coastal sustainability, while aquaculture presents an immediate and realistic alternative to fisheries pressure (Halpern et al., 2021). Projections resulting from a switch in diets from omnivorous to pescatarian led to reductions of greenhouse gas emissions in food production (GHGEs; Tilman and Clark, 2014), in some cases better than vegetarian scenarios (Masino et al., 2023). Fundamentally, following energy-balanced dietary guidelines (flexitarian, pescatarian, vegetarian, and vegan diets) are more effective in reducing environmental pressures than following approaches that only consider the environment (cut of consumption of animal products at constant calorie intake; Springmann et al., 2018).

Similar to previously discussed, a recent study analyzing the balance between the health and environmental benefits of the four diet types concluded that vegan and vegetarian choices may bring nutritional deficiencies for groups of people that need special nutritional attention, categorized as children, pregnant and lactating women, and the elderly (Moreno et al., 2022). Additionally, for low-income countries, adhering to global policies of sustainability of diets can be challenging due to the widespread prevalence of malnutrition, and possible ecological burdens associated with providing adequate nutrition for the population. Modeled shifts to plant-forward diet scenarios increased global GHGEs and water footprints when adequate caloric intake was accounted for, mainly due to undernourished countries such as India, Pakistan, and Indonesia (Kim et al., 2020). A less restrictive flexitarian diet, while not as environmentally-friendly as the vegan, considerably reduces environmental impacts compared to Western diets and satisfies the recommended nutritional needs (Moreno et al., 2022). A modest inclusion of low-food chain animals (e.g., forage fish, bivalves) in diets is also compared to vegan diets in terms of environmental footprint across different countries (Kim et al., 2020).

Therefore, not including seafood in a diet for health and environmental reasons alone is still debatable, especially when target cultured species make use of completely different farming systems and environments, and can require (e.g., finfish, crustaceans) or not require (extractive species; e.g. bivalves, seaweed) the use of feed. In fact, the GHGEs from aquaculture were estimated to be 10% of the agriculture emissions, mainly associated with the production of raw feed materials, and secondarily with transportation (Mbow et al., 2019). Nevertheless, production of the global aquaculture industry has a lot of room for sustainability improvement (for details see Jiang et al., 2022).

The actions: the need for innovative practices and informative efforts in aquaculture

Literature review

A literature review from the Scopus database at the time of writing, shows the relationship between the most common diet terms ("vegan", "vegetarian", "pescatarian", "flexitarian" within title, abstract, keywords) and topics of sustainability, demonstrating that they are directly intertwined with the methods of food production systems across the historical usage in research (Figure 2, Research Timeline) of the aforementioned terms. The percentage of environmental research has remained stable in recent years within the long-standing "vegetarian" (3%) and "vegan" (4%) diets, but is more relevant in modern diets ("flexitarian", 5%; and "pescatarian" adoption, 9%; Figure 2, Subject Type A, B, C, D). Keywords from the publications can indirectly inform the relevance of the sustainability research within each diet. Sustainability terms, such as "sustainability" and "climate change," were associated with the vegan, pescatarian and flexitarian diets. But more specific terms such as "greenhouse effect/ gases," "environmental impact," "sustainable development," and "carbon dioxide," were only related with the two more modern diets (Figure 2, Keywords). Accordingly, although pescatarian-focused research is relatively more concentrated within the environmental field, flexitarian-focused research recurrently mentions more sustainable terms, but both diets seem to be aligned with research of environmental context.

In practice

The aquaculture industry has increasingly adopted more sustainable practices in production and processing, for instance, with more efficient feed rates, and increased production of extractive species, with a "sustainability criteria progressively shaping the direction of the industry" (Naylor et al., 2021). However, the overwhelming negative perception of aquaculture by the public

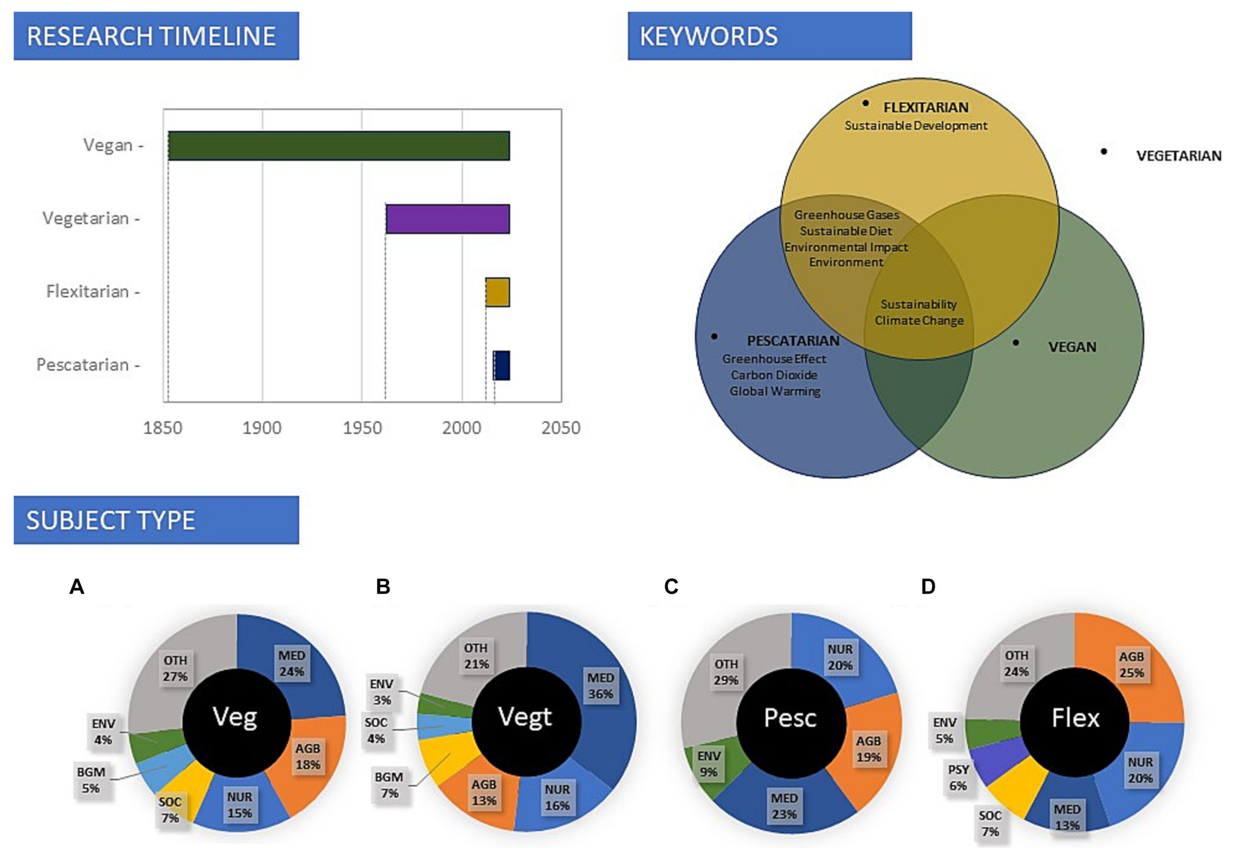

FIGURE 2
Systematic review of literature by research timeline, environmental keywords, and subject type of the main diets: **(A)** Vegan; **(B)** Vegetarian, **(C)** Pescatarian, **(D)** Flexitarian. Subject types include AGB, Agricultural and Biological Sciences; BGM, Biochemistry, Genetics and Molecular Biology; ENV, Environmental Science; NUR, Nursing; MED, Medicine; PSY, Psychology; SOC, Social Sciences; OTH, Other.

persists together with a lack of ocean literacy (Froehlich et al., 2017; Petereit et al., 2022; Zajicek et al., 2023), often resulting in a lack of social acceptability, public opposition to the industry expansion (license to operate), and possible behavioral changes in consumers' food choices. This reiterates the ongoing need for sustainable aquaculture practices and proactive efforts to counter misinformation through substantially improved communication.

Surprisingly, the public view and increasing sustainable measures in the farming process and marketability are not cited as main preoccupations among global aquaculture farmers, who often consider risks such as possible diseases, price fluctuation, and environmental disasters as the main pressing issues related to their business (Alam and Guttormsen, 2019; Cantillo and Van Caillie, 2023). However, sustainability topics have not been completely ignored as some larger operations have acknowledged the significance of seafood certifications, the promotion of sustainable practices for market differentiation, recognition of carbon credits, and assessment of sustainability in food-chain models as opportunities for the sector; with agreement among farmers about the necessity to promote the sustainable production methods to consumers (Schrobback et al., 2021).

The persistent problem is that positive attributes of seafood for health and aquaculture's contributions to environmental sustainability remain largely unrecognized by the majority of consumers who lack knowledge about the seafood farming process, and positive effects of some types of production on the environment (e.g., ecosystem services, wise use of natural resources; Jonell et al., 2016; Shaughnessy et al., 2023). Nevertheless, "familiarity with the topic" and "opinion malleability" about the aquaculture effects were positively related to more acceptance of aquaculture products after consumers were provided with brief related information (Shaughnessy et al., 2023). This is because consumers are mostly unaware of aquaculture practices but interestingly, they are willing to pay more for a farmed product after being educated about its production and possible related ecosystem services (Bolduc et al., 2023). Even food literacy is only moderate among consumers of all dietary classes (including pescatarians and other seafood eaters). However, flexitarians had higher general nutrition knowledge, while critical nutrition knowledge was higher among vegans (Groufh-Jacobsen et al., 2023).

While recent research did not find a positive correlation between scientific knowledge and seafood consumer purchases (Petereit et al., 2022), it did not specifically look into the consumers' knowledge about the farming methods and production stages. Rather, the study associates mistrust in certification labels and vegetarian self-identification with non-purchase of seafood despite the awareness of its health benefits, reinforcing the fact that environmental concerns may overshadow health aspects. It also highlights customer-driven demand for transparency and traceability, which was additionally cited to play a role in direct purchase decisions.

Like any other economic activity, aquaculture has some environmental trade-offs. Unsurprisingly, if more diets shift towards being seafood-heavy, such as the pescatarian diet, there will be increased necessity of actions such as more production of extractive species, waste reduction, and use of alternative feed sources for fed-species (e.g., finfish, crustacea) to attend demand sustainably (Froehlich et al., 2018b). Well-known practices at the farm level can substantially increase the farming industry's sustainability. For instance, the choice of species and alternative aquaculture designs, such as integrated multi trophic aquaculture (IMTA), co-culture of native species, restorative aquaculture, and regenerative aquaculture are some practical examples of how the industry can further exercise sustainability (see Mizuta et al., 2023 for details). Some species and farming designs will more effectively contribute to positive environmental effects than others, but several types of farms and different cultured species can provide multiple ecosystem services (Gentry et al., 2020; Theuerkauf et al., 2021; Barret et al., 2022). Mediterranean farmers assessed about their perceptions of environmentally-friendly practices in aquaculture stated an active implementation of environmental protection measures (organic farming, reduced stocking density), especially in marine areas more than in freshwater farming. However, they were not in complete agreement with the use of alternative eco-friendly farming practices, expressing skepticism over the use of alternative feeds, and ignoring other environmentally-friendly management approach such as co-culture and IMTA systems due to the lack of specialized knowledge for experimentation and full implementation (Perdikaris et al., 2016).

In the post-harvest supply chain, effectively showcasing sustainable practices implemented in the production should be a fundamental aspect of any aquaculture operation. Accredited sustainable certifications and seafood guides (e.g., Seafood Watch; Aquaculture Stewardship Council) can not only attest to sustainable practices but usually positively correlate with purchases by consumers who are concerned with the environmental impacts of seafood production (Jonell et al., 2016). In addition to certification schemes, there is room for alternate governance approaches to ensure effective sustainability outcomes in seafood production and therefore clearer understanding of outcomes (Rector et al., 2023). Lastly, relational food supply chains, where direct networks between farmers and consumers are implemented through geographic proximity and feedback loops, can help small-scale farmers showcase their sustainability practices (Stoll et al., 2019).

Since there is some evidence that the public trusts more scientists and farmers themselves as sources of the latest available information on aquaculture production and products (Shaughnessy et al., 2023), the role of collaborations between the research institutions and the industry is primordial to guide new industry actions, then inform the general public. The role of governmental institutions and NGOs are also fundamental and complementary, especially in advisory, financing, capacity building, promotion of best practices and cross-learning (Paterlow et al., 2023). Ultimately, all actors involved in aquaculture should jointly facilitate frequent improvement of sustainably-forward actions, monitoring and assessment of results, updated information dissemination, and reevaluation of management and production design, in a repeating pattern to ensure positive environmental outcomes and information delivery.

Final thoughts

Moving towards sustainable aquaculture food systems is imperative. Although dietary preference is an absolute personal choice, there is a call for a stronger recognition that aquaculture can have its importance minimized in part by the consumers' uninformed perceptions and related dietary lifestyle changes, despite the contribution that aquaculture can make in providing nutritive protein, and food security, through relatively more sustainable production systems, particularly with extractive species.

Aware of this trend, the aquaculture industry should prioritize the implementation of practices supported by science to reflect the public environmental concerns. As aquaculture progresses towards more sustainable approaches, it is necessary to follow those actions with updated information dissemination focused also on the end user, who are after all the central point of the business. The aquaculture industry already demonstrates, but should increase, two commitments: effective green-action and attested information dissemination not only to cater to "consumers" who demand healthier, safe, nutritious foods, but also to "consumer activists", who desire to incorporate in their daily lives considerations for a healthy planet and would like to make more deliberate diet decisions.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: the data of this study are derived from resources available in Scopus database. Dataset can be made available upon request.

Author contributions

DM: Writing – original draft, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was supported by Atlantic States Marine Fisheries Commission (ASMFC) (Award No. NA22NMF4540361).

Acknowledgments

Special thanks to the laboratory and research technician intern Kirk Casper (VIMS) for his help with literature search, graphs, and proofreading.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Alam, M. A., and Guttormsen, A. G. (2019). Risk in aquaculture: farmers' perceptions and management strategies in Bangladesh. *Aquac. Econ. Manag.* 23, 359–381. doi: 10.1080/13657305.2019.1641568

Barret, L. T., Theuerkauf, S. J., Rose, J. M., Alleway, H. K., Bricker, S. B., Parker, M., et al. (2022). Sustainable growth of non-fed aquaculture can generate valuable ecosystem benefits. *Ecosyst. Serv.* 53:101296:101396. doi: 10.1016/j.ecoser.2021.101396

Bolduc, W., Griffin, R. M., and Byron, C. J. (2023). Consumer willingness to pay for farmed seaweed with education on ecosystem services. *J. Appl. Phycol.* 35, 911–919. doi: 10.1007/s10811-023-02914-3

Boukid, F., Baune, M. C., Gagaoua, M., and Castellari, M. (2022). Seafood alternatives: assessing the nutritional profile of products sold in the global market. *Eur. Food Res. Technol.* 248, 1777–1786. doi: 10.1007/s00217-022-04004-z

Cantillo, J., and Van Caillie, D. (2023). Understanding European aquaculture companies' perceived risks and risk management practices. *Aquac. Econ. Manag.* 27, 599–637. doi: 10.1080/13657305.2022.2162625

Colozza, D., and Avendano, M. (2019). Urbanisation, dietary change and traditional food practices in Indonesia: a longitudinal analysis. *Soc. Sci. Med.* 233, 103–112. doi: 10.1016/j.socscimed.2019.06.007

Comeau, L. A., Guyondet, T., Drolet, D., Sonier, R., Clements, J. C., Tremblay, R., et al. (2023). Revisiting ecological carrying capacity indices for bivalve culture. *Aquaculture* 577:739911. doi: 10.1016/j.aquaculture.2023.739911

Elwin, A., Bukoski, J. J., Jintana, V., Robinson, E. J. Z., and Clark, J. M. (2019). Preservation and recovery of mangrove ecosystem carbon stocks in abandoned shrimp ponds. *Sci. Rep.* 9:18275. doi: 10.1038/s41598-019-54893-6

FAO (2010) Sustainable diets and biodiversity. Proceedings of the International Scientific Symposium Biodiversity and Sustainable Diets United against Hunger. November 3–5, 2010. FAO Headquarters, Rome. Available at: https://www.fao.org/3/i3004e/i3004e.pdf (Accessed November 29, 2023).

FAO (2022) The state of world fisheries and aquaculture 2022. Towards Blue Transformation. Rome, FAO. doi: 10.4060/cc0461en

Forestell, C. A. (2018). Flexitarian diet and weight control: healthy or risky eating behavior? *Front. Nutr.* 5:59. doi: 10.3389/fnut.2018.00059

Froehlich, H. E., Gentry, R. R., Rust, M. B., Grimm, D., and Halpern, B. S. (2017). Public perceptions of aquaculture: evaluating spatiotemporal patterns of sentiment around the world. *PLoS One* 12:e0169281. doi: 10.1371/journal.pone.0169281

Froehlich, H. E., Jacobsen, N. S., Essington, T. E., Clavelle, T., and Halpern, B. S. (2018b). Avoiding the ecological limits of forage fish for fed aquaculture. *Nat. Sustain.* 1, 298–303. doi: 10.1038/s41893-018-0077-1

Froehlich, H. E., Runge, C. A., Gentry, R. R., Gaines, S. D., and Halpern, B. S. (2018a). Comparative terrestrial feed and land use of an aquaculture-dominant world. *PNAS* 115, 5295–5300. doi: 10.1073/pnas.1801692115

Fukase, E., and Martin, W. (2020). Economic growth, convergence, and world food demand and supply. *World Dev.* 132:104954. doi: 10.1016/j.worlddev.2020.104954

Gentry, R. R., Alleway, H. K., Bishop, M. J., Gillies, C. L., Waters, T., and Jones, R. (2020). Exploring the potential for marine aquaculture to contribute to ecosystem services. *Rev. Aquac.* 12, 499–512. doi: 10.1111/raq.12328

Gonzalez Fischer, C., and Garnett, T. (2016) Plates, pyramids, and planets: developments in national healthy and sustainable dietary guidelines: a state of play assessment. Available at: https://www.fao.org/documents/card/en/c/d8dfeaf1-f859-4191-954f-%20e8e1388cd0b7/ (Accessed October 4, 2023).

Groufh-Jacobsen, S., Larsson, C., Van Daele, W., Margerison, C., Mulkerrins, I., Aasland, L., et al. (2023). Food literacy and diet quality in young vegans, lacto-ovo vegetarians, pescatarians, flexitarians and omnivores. *Public Health Nutr.* 26, 3051–3061. doi: 10.1017/S1368980023002124

Halpern, B., Cottrell, R. S., Blanchard, J. L., Bouwman, L., Froelich, H. E., Gephart, J. A., et al. (2019). Putting all foods on the same table: achieving sustainable food systems requires full accounting. *PNAS* 116, 18152–18156. doi: 10.1073/pnas.1913308116

Halpern, B. S., Maier, J., Lahr, H. J., Blasco, G., Costello, C., Cottrell, R. S., et al. (2021). The long and narrow path for novel cell-based seafood to reduce fishing pressure for marine ecosystem recovery. *Fish Fish.* 22, 652–664. doi: 10.1111/faf.12541

Hargreaves, S. M., Rosenfeld, D. L., Moreira, A. V. B., and Zandonadi, R. P. (2023). Plant-based and vegetarian diets: an overview and definition of these dietary patterns. *Eur. J. Nutr.* 62, 1109–1121. doi: 10.1007/s00394-023-03086-z

Heller, M. C., Walchale, A., Heard, B. R., Hoey, L., Khoury, C. K., de Haan, S., et al. (2020). Environmental analyses to inform transitions to sustainable diets in developing countries: case studies for Vietnam and Kenya. *Int. J. Life Cycle Assess.* 25, 1183–1196. doi: 10.1007/s11367-019-01656-0

Hilborn, R., Banobi, J., Hall, S. J., Pucylowski, T., and Walsworth, T. E. (2018). The environmental cost of animal source foods. *Front. Ecol. Environ.* 16, 329–335. doi: 10.1002/fee.1822

James-Martin, G., Baird, D. L., Hendrie, G. A., Bogard, J., Anastasiou, K., Brooker, P. G., et al. (2022). Environmental sustainability in national food-based dietary guidelines: a global review. *Lancet Planet. Health* 6, e977–e986. doi: 10.1016/S2542-5196(22)00246-7

Jiang, Q., Bhattarai, N., Pahlow, M., and Xu, Z. (2022). Environmental sustainability and footprints of global aquaculture. *Resour. Conserv. Recycl.* 180:106183. doi: 10.1016/j.resconrec.2022.106183

Jonell, M., Crona, B., Brown, K., Rönnbäck, P., and Troell, M. (2016). Eco-labeled seafood: determinants for (blue) green consumption. *Sustain. For.* 8:884. doi: 10.3390/su8090884

Kazir, M., and Livney, Y. D. (2021). Plant-based seafood analogs. *Molecules* 26:1559. doi: 10.3390/molecules26061559

Kim, B. F., Santo, R. E., Scatterday, A. P., Fry, J. P., Synk, C. M., Cebron, S. R., et al. (2020). Country-specific dietary shifts to mitigate climate and water crises. *Glob. Environ. Change* 62:101926. doi: 10.1016/j.gloenvcha.2019.05.010

Marwaha, N., Beveridge, M. C. M., and Phillips, M. J. (2022). Fad, food, or feed: alternative seafood and its contribution to food systems. *Front. Sustain. Food Syst.* 6:750253. doi: 10.3389/fsufs.2022.750253

Masino, T., Colombo, P. E., Reis, K., Tetens, I., and Parlesak, A. (2023). Climate-friendly, health-promoting, and culturally acceptable diets for German adult omnivores, pescatarians, vegetarians, and vegans – a linear programming approach. *Nutrition* 109:111977. doi: 10.1016/j.nut.2023.111977

Mbow, C., Rosenzweig, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., et al. (2019) Food security. In: Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, Eds. P. R. Shukla, J. Skea, E. C. Buendia, V. Masson-Delmotte, H.-O. Pörtner and D. C. Roberts Available at: https://ntrs.nasa.gov/citations/20200001724.

Mizuta, D. D., Froehlich, H. E., and Wilson, J. R. (2023). The changing role and definitions of aquaculture for environmental purposes. *Rev. Aquac.* 15, 130–141. doi: 10.1111/raq.12706

Moreno, L. A., Meyer, R., Donovan, S. M., Goulet, O., Haines, J., Kok, F. J., et al. (2022). Perspective: striking a balance between planetary and human health—is there a path forward? *Adv. Nutr.* 13, 355–375. doi: 10.1093/advances/nmab139

Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., et al. (2021). A 20-year retrospective review of global aquaculture. *Nature* 591, 551–563. doi: 10.1038/s41586-021-03308-6

O'Malley, K., Willits-Smith, A., and Rose, D. (2023). Popular diets as selected by adults in the United States show wide variation in carbon footprints and diet quality. *Am. J. Clin. Nutr.* 117, 701–708. doi: 10.1016/j.ajcnut.2023.01.009

Paterlow, S., Asif, F., Béné, C., Bush, S., Manlosa, A. O., Nagel, B., et al. (2023). Aquaculture governance: five engagement arenas for sustainability transformation. *COSUST* 65:101379. doi: 10.1016/j.cosust.2023.101379

Perdikaris, C., Chrysafi, A., and Ganias, K. (2016). Environmentally friendly practices and perceptions in aquaculture: a sectoral case-study from a Mediterranean-based industry. *Rev. Fish. Sci. Aquac.* 24, 113–125. doi: 10.1080/23308249.2015.1112358

Petereit, J., Hoerterer, C., and Krause, G. (2022). Country-specific food culture and scientific knowledge transfer events – do they influence the purchasing behaviour of seafood products? *Aquaculture* 560:738590. doi: 10.1016/j.aquaculture.2022.738590

Rao, N. D., Min, J., DeFries, R., Ghosh-Jerath, S., Valin, H., and Fanzo, J. (2018). Healthy, affordable and climate-friendly diets in India. *Glob. Environ. Change* 49, 154–165. doi: 10.1016/j.gloenvcha.2018.02.013

Rector, M. E., Filgueira, R., Bailey, M., Walker, T. R., and Grant, J. (2023). Sustainability outcomes of aquaculture eco-certification: challenges and opportunities. *Rev. Aquac.* 15, 840–852. doi: 10.1111/raq.12763

Rosa, J., Lemos, M. F. L., Crespo, D., Nunes, M., Freitas, A., Ramos, F., et al. (2020). Integrated multitrophic aquaculture systems – potential risks for food safety. *Trends Food Sci. Technol.* 96, 79–90. doi: 10.1016/j.tifs.2019.12.008

Schrobback, P., Rolfe, J., Rust, S., and Ugalde, S. (2021). Challenges and opportunities of aquaculture supply chains: case study of oysters in Australia. *Ocean Coast. Manag.* 215:105966. doi: 10.1016/j.ocecoaman.2021.105966

Shaughnessy, B. K., Almada, A., Thompson, K., Marvier, M., and Kareiva, P. (2023). Are all benefits equal? An exploratory analysis of coastal perspectives of seafood farming expansion in the United States. *J. World Aquac. Soc.* 54, 899–914. doi: 10.1111/jwas.12956

Soto, D., Arismendi, I., Olivos, J. A., Canales-Aguirre, C. B., Leon-Muñoz, J., Niklitschek, E. J., et al. (2023). Environmental risk assessment of non-native salmonid escapes from net pens in the Chilean Patagonia. *Rev. Aquac.* 15, 198–219. doi: 10.1111/raq.12711

Springmann, M., Wiebe, K., and Sulser, D. T. B. (2018). Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *Lancet Planet. Health* 2, e451–e461. doi: 10.1016/S2542-5196(18)30206-7

Statista (2023) Share of vegetarians in select countries worldwide in 2023. Available at: https://www.statista.com/statistics/1280079/global-country-ranking-vegetarian-share/ (Accessed October 10, 2023).

Stoll, J. S., Bailey, M., and Jonell, M. (2019). Alternative pathways to sustainable seafood. *Conserv. Lett.* 13:e12683. doi: 10.1111/conl.12683

Theuerkauf, S. J., Barrett, L. T., Alleway, H. K., Costa-Pierce, B. A., St. Gelais, A., and Jones, R. C. (2021). Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: pathways, synthesis and next steps. *Rev. Aquac.* 14, 54–72. doi: 10.1111/raq.12584

Thomas, M. S., Calle, M., and Fernandez, M. L. (2023). Healthy plant-based diets improve dyslipidemias, insulin resistance, and inflammation in metabolic syndrome: a narrative review. *Adv. Nutr.* 14, 44–54. doi: 10.1016/j.advnut.2022.10.002

Tilman, D., and Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature* 515, 518–522. doi: 10.1038/nature13959

United Nations (2023). The sustainable development goals report 2023: Special edition Towards a rescue plan for people and planet. Available at: https://www.un.org/sustainabledevelopment/fast-facts-what-are-sustainable-food-systems/.

Vanderlee, L., Gómez-Donoso, C., Acton, R. B., Goodman, S., Kirkpatrick, S. I., Penney, T., et al. (2022). Meat-reduced dietary practices and efforts in 5 countries: analysis of cross-sectional surveys in 2018 and 2019. *J. Nutr.* 152, 57S–66S. doi: 10.1093/jn/nxac057

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the Anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. *Lancet* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4

Willits-Smith, A., Aranda, R., Heller, M. C., and Rose, D. (2020). Addressing the carbon footprint, healthfulness, and costs of self-selected diets in the USA: a population-based cross-sectional study. *Lancet Planet. Health* 4, e98–e106. doi: 10.1016/S2542-5196(20)30055-3

Zajicek, P., Corbin, J., Belle, S., and Rheault, R. (2023). Refuting marine aquaculture myths, unfounded criticisms, and assumptions. *Rev. Fish. Sci. Aquac.* 31, 1–28. doi: 10.1080/23308249.2021.1980767

Zhang, Y., Li, S., Jin, L., and Wu, F. (2022). How will the global food landscape accommodate developing countries' dietary change under urbanization? *Food Secur.* 11:3598. doi: 10.3390/foods11223598

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 03 April 2024
DOI 10.3389/fsufs.2024.1322314

OPEN ACCESS

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RECEIVED 16 October 2023
ACCEPTED 18 March 2024
PUBLISHED 03 April 2024

CITATION
Andam MB, Traifalgar RFM, Laureta LV Jr, Nuñal SN and Nillos MGG (2024) Mysid meal as a dietary replacement for fishmeal in the diets of Pacific white shrimp *Penaeus vannamei* (Boone, 1931) postlarvae. *Front. Sustain. Food Syst.* 8:1322314.
doi: 10.3389/fsufs.2024.1322314

Mysid meal as a dietary replacement for fishmeal in the diets of Pacific white shrimp *Penaeus vannamei* (Boone, 1931) postlarvae

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The current study evaluates the nutritional and feed value of mysid meal (MM) as a substitute for fishmeal (FM) in the Pacific white shrimp (*Penaeus vannamei*) postlarvae diet. Five experimental diets were formulated by replacing 0 (MM0), 25 (MM25), 50 (MM50), 75 (MM75), and 100 % (MM100) of dietary FM with MM. These experimental feeds were fed to *P. vannamei* postlarvae in a 60-day feeding trial. Results revealed that MM could entirely substitute 100 % FM in the white shrimp diet. Furthermore, results showed that 75 % FM replacement with MM elicited a growth-enhancing effect and improved feed nutrient utilization. No significant treatment effects were detected in the survival, total feed intake, and biochemical body composition of *P. vannamei*. The observed improvement in shrimp growth in terms of weight gain (WG), specific growth rate (SGR), and nutrient retention were positively correlated with the substitution level of FM by MM. The feed conversion ratio (FCR) was negatively correlated with the substitution of MM and with the growth indices including WG and SGR. In conclusion, 100% of the FM (40% in the control diet) can be substituted by dietary MM without affecting the survival, growth, feed utilization, and biochemical carcass composition of *P. vannamei*. Polynomial regression analysis of SGR indicates that 65.50% of MM is optimum to replace FM in the diet of *P. vannamei* to attain maximum growth.

KEYWORDS

alternative protein feedstuff, fishmeal replacement, growth enhancement, nutrition, zooplankton-based meal

Introduction

While capture fisheries yields have decreased over the past decades, aquaculture exhibited rapid growth compared to other food-producing sectors to meet the surging food demand for fish and fish products (FAO, 2016, 2020). With the continued growth of aquaculture for decades, there has been an associated expansion of shrimp culture across the world due to the advancement of technologies on intensive high-density shrimp culture systems and the increasingly high market demands and export value of this commodity (Ayisi et al., 2017; Cummins et al., 2017; Li et al., 2022; Yildirim-Aksoy et al., 2022).

However, global farmed shrimp production relies heavily on wild-sourced fishmeal (FM) as a primary protein source for formulated feeds (Cummins et al., 2017; Sánchez-Muros et al., 2020; Li et al., 2023). FM is considered the most expensive macro-ingredient for the formulation of marine shrimp diets due to its favorable nutrient composition, high-quality protein (60–72% CP), complete essential amino acid (AA) and fatty acid profiles, a good source of vitamins and minerals, and a high digestibility (Cruz-Suárez et al., 2009; Lemos et al., 2009; Suárez et al., 2009; Riche, 2015). In recent years, the rapid development of aquaculture, coupled with the significant improvements in the shrimp culture industry, has caused more demand for FM (Li et al., 2022, 2023; Wang et al., 2023; Zheng et al., 2023). In 2016, the aquaculture industry utilized more than 70% of global FM production, and shrimp diets consumed about 31 % of FM for aquafeed production, making it the dominant consumer of ocean-derived FM (Tacon and Metian, 2015; Jannathulla et al., 2019).

Earlier reports on the dietary feed formulations for the Pacific white shrimp (*Penaeus vannamei*) showed that it typically comprises 25–50% FM inclusion, which accounts for the feed and production costs (Samocha et al., 2004; Amaya et al., 2007; Ye et al., 2012; Yun et al., 2017). In shrimp farming, the feed costs account for over 50% of the total production costs due to the high inclusion of dietary FM (Ayisi et al., 2017; Cummins et al., 2017). The rapid expansion of the aquaculture industry, coupled with the consequent increase in demand for FM, has caused a significant surge in FM prices and erratic supply of this crucial feed ingredient (Tacon and Metian, 2008; Duarte et al., 2009; Li et al., 2022; Zheng et al., 2023). Moreover, global FM production can often fluctuate unpredictably due to overfishing and climate-induced fluctuations (El Niño-Southern Oscillation events), making FM production and prices unpredictable (Naylor et al., 2009). The global demand for FM is anticipated to expand as the commercial production of farmed shrimp is projected to surge in the coming years. At some point, this projected demand for FM will likely intensify and eventually outstrip the forage fish populations that can be harvested from the ocean. Since it is unsustainable to extract these finite fish resources beyond their current capacity, finding cost-effective alternative non-fish-based ingredients that are nutritionally equivalent to FM, ideally of a lower trophic position, is required to ensure the sustainability of the aquaculture industry (Moren et al., 2006; Salas-Leiton et al., 2020).

Zooplankton has been proposed as a sustainable source of feed ingredients for aquaculture (Nicol and Endo, 1997, 1999; Melk et al., 2004) since its nutritional compositions are reported to be comparable to FM (Storebakken, 1988). The global productivity of zooplankton biomass typically produces hundreds of millions of tons, and their reproductive turnover rate is fast. Most of this large biomass is not used in commercial products, and only a tiny percentage is harvested (Hewitt et al., 2002; Huntington and Hasan, 2009; Naylor et al., 2009). There is a consensus belief that aquatic biomass that is not harvested and utilized is considered a wasted biological resource. The lack of comprehensive evaluation of these non-fish-based alternatives on shrimp limits their application in aquafeeds. Among possible alternatives under investigation, many underutilized species of zooplankton with large biomass from lower trophic levels, such as mysids, could offer a relatively untapped potential novel ingredient to support the needs of the growing aquaculture industry. Mysid has a high calorific value and is considered an excellent experimental organism for various bio-assays due to its abundance and ease of culturing (Eusebio et al., 2010; Biju and Panampunnayil, 2011). This zooplankton is abundant in the aquatic environment and is documented to have a short reproductive cycle (14–21 d) (Mauchline, 1980; Domingues et al., 1998). Mysid species are vastly underutilized, and their utilization as feed could be vital for the aquaculture industry. The mysid shrimp is characterized by its high protein (52–75% DM) content (Eusebio et al., 2010; Buen-Ursua et al., 2015). Apart from the high protein content, mysids have been receiving attention as a potential ingredient in aquafeeds due to their significant amount of total lipid and fatty acids, which is ideal for growth and metabolism (Izquierdo, 1996; Eusebio et al., 2010). In addition to their high nutritional quality, mysid is suitable for aquaculture as a live feed (Biju et al., 2009). Although information on its nutritional value and biological testing are not well documented relative to FM replacement in shrimp diets, mysids are considered an alternative live food for the nursery culture of marine fish (Eusebio et al., 2010).

Zooplankton-based meals have been suggested as an alternative protein source in fish diets (Virtue et al., 1995; Moren et al., 2006; Salas-Leiton et al., 2020). Zooplankton-based meals were shown to be suitable feed ingredients for *P. monodon* (Smith et al., 2005; Williams et al., 2005) *and P. vannamei* (Nunes et al., 2011, 2019; Soares et al., 2021; Ambasankar et al., 2022; Wei et al., 2022). In addition, Moren et al. (2006) documented that during the feeding trial of Atlantic cod (*Gadus morhua*), it showed no significant difference in growth, while Atlantic salmon (*Salmo salar*) exhibited improved SGR when fed diets where 40% of the FM protein was replaced with Arctic krill (*Thysanoessa inermis*) or amphipod (*Themisto libellula*) meal. Zooplankton biomass (consisting of rotifers, copepods, cladocerans, ostracods, and protozoans) meal was able to replace 100% of FM in the diet of seabass, *Dicentrarchus labrax* fingerlings without adverse effects on the growth performance and feed utilization (Hassan et al., 2020). In addition, Abo-Taleb et al. (2021) found that the optimal FM replacement level for gray mullet was 75% of *Daphnia magna* meal, demonstrating a quadratic regression trend in growth and feed utilization. Using zooplankton-based meals as a potential substitute for FM in *P. vannamei* diets could be a promising alternative. Based on our intensive literature reviews, there is no published study on the feed value of mysid meal (MM) as an FM replacement in shrimp diets. Hence, this study aims to evaluate the feed value of MM as an alternative ingredient for FM on the growth, survival, feed utilization, biochemical composition, nutrient retention indices, and survival of *P. vannamei* postlarvae.

Materials and methods

Description of the study area

The study was conducted at the Multispecies Hatchery Complex of the University of the Philippines Visayas (UP Visayas), College of Fisheries and Ocean Sciences (CFOS)—Institute of

TABLE 1 Proximate analysis of MM and sardine FM for formulating the experimental diets for *P. vannamei*.

	MM	FM
Proximate composition (% dry matter)		
Crude protein[a]	53.15 ± 0.07	57.02 ± 0.16
Crude lipid[a]	4.42 ± 0.12	9.58 ± 0.78
Crude fiber[b]	5.87 ± 0.02	0.04 ± 0.01
Ash[a]	20.92 ± 0.53	19.62 ± 0.07
NFE[c]	15.65 ± 0.33	13.73 ± 0.58

Values are mean ± SEM of three replicates.
[a]Analyzed values from the Fish Nutrition Laboratory, UP Visayas, CFOS-IA, Miagao, Iloilo, Philippines.
[b]Analyzed values from the DOST (Department of Science and Technology), RSTL (Regional Standards and Testing Laboratory), Region VI, La Paz, Iloilo City, Philippines.
[c]Nitrogen-free extract, computed by difference.

Aquaculture (IA) in Miag-ao, Iloilo, Philippines. The area was equipped with aeration and good water facilities.

Sample collection

The mysids, *Mesopodopsis* sp., was procured from local fishermen in Atabayan, Tigbauan, Iloilo, Philippines. The samples were transported and processed as mysid meal (MM) at the Fish Nutrition Laboratory of the UP Visayas, CFOS–IA. Briefly, the mysids were oven-dried at 60°C for 24h, pulverized to a particle size of 100 µm using a mechanical grinder (JML Nutri Blitzer), and refrigerated at −20°C until use for diet formulation.

Experimental feed formulation

The nutritional proximate composition analysis of MM, sardine FM, and experimental feeds are shown in Tables 1, 2. Five experimental diets (37% crude protein) were formulated according to the formulations of Bauer et al. (2012) with modifications to satisfy the nutritional requirements of the white shrimp postlarvae. The treatments consisted of five experimental diets with control (MM0), 25% (MM25), 50% (MM50), 75% (MM75), and 100% (MM100) MM replacement of FM by weight, respectively (Table 2).

All experimental feeds were prepared at the UP Visayas, CFOS–IA, Fish Nutrition Laboratory. All dry ingredients were pulverized using an electric mechanical grinder (JML Nutri Blitzer) and finely ground into powder using a 100 µm mesh sieve. The sieved feedstuffs were weighed and appropriately mixed before including soybean lecithin and fish oil. After that, water (0.45–0.50 L·Kg^{-1}) was poured gradually into the dry feedstuffs to form a moistened dough. The dough was thoroughly mixed and pelletized using a laboratory pelletizer with a 2-mm die. The formed pellet strands were collected and dried to a moisture content of <10% at 60°C. The dried pellets were subsequently crumbled into suitable sizes, wrapped in polyethylene zip-lock containers, and kept at −20°C until use as feed.

Experimental animal and maintenance

The *P. vannamei* postlarvae (PL10) were procured from a reliable commercial *P. vannamei* hatchery at Guimbal, Iloilo, Philippines. Prior to the start of the experiment, the shrimp were screened to be free from White Spot Syndrome Virus and pathogenic *Vibrio parahaemolyticus* by molecular analysis using nested PCR IQ 2000^{TM} Detection and Prevention System, Genereach Biotechnology Corp., Taiwan (Dangtip et al., 2015).

The experimental animals were then acclimated to laboratory conditions for seven days in a 5-ton capacity circular fiberglass tank and fed with commercial feed before the start of the experiment. Optimum water quality parameters for the ideal growth and survival of *P. vannamei* postlarvae were monitored and maintained for the duration of the feeding trial (ammonia: 0–0.25 ppm, dissolved oxygen: >5 ppm, salinity: 30–35 ppt, pH: 7.86–8.05, temperature: 23.3–28.5°C).

Feeding trial and sampling protocol

The study was conducted in an indoor, recirculating water system with a water flow rate of about 0.60–0.80 L·min^{-1} using 20 units of 60-L capacity flat-bottom rectangular plastic tanks in a completely randomized design for a 60-day culture period. The recirculating system comprises a reservoir (1 ton) connected to three biofilter tanks containing charcoal, gravel, and polyethylene fiber as filters and a 100-watt circulation water pump. The experimental containers were equipped with individual aeration and covered with a PVC lid with black mesh netting to reduce disturbance and prevent shrimp from escaping. After the acclimatization, 500 healthy and homogenous-sized *P. vannamei* postlarvae (0.003 ± 0.000 g; mean ± SEM) were randomly assigned to each previously prepared holding tank (25 shrimp·tank^{-1}). Shrimp samples were also collected from the stock tank and used for the initial biochemical analysis of the carcass.

The *P. vannamei* postlarvae were fed thrice daily (08:00, 12:00, and 16:00 h) with the respective dietary treatments at 15% of the body weight. The unconsumed feeds were collected one hour after each feeding and weighed after oven-drying at 60°C to determine the total feed intake (TFI). The TFI was determined by the difference in the quantity of uneaten diets from the total amount of supplied experimental feeds. Periodic sampling was conducted every 2 weeks, in which the experimental animals from each tank (4 tanks·treatment^{-1}) were weighed in bulk and counted to regulate the feeding ration. At the termination of the study, shrimps from each treatment group were collected, individually weighed, euthanized, and subjected to final biochemical body composition analysis. Upon the termination of the feeding trial, the growth indices and feed utilization efficiency parameters of the shrimps in response to the experimental diets were evaluated by the following biometrics (Hardy and Barrows, 2002; Bulbul et al., 2016; Wei et al., 2022).

$$\textbf{Percent Weight Gain}\ (\%WG) = \frac{FBW\ (g) - IBW\ (g)}{IBW\ (g)} x\ 100$$

TABLE 2 Ingredients and proximate nutritional profile (g·1,000 g^{-1}) of dietary treatments for *Penaeus vannamei* postlarvae containing different levels of FM replacement with MM.

Ingredients (%)	Dietary treatments				
	MM0	MM25	MM50	MM75	MM100
Fishmeal (FM)[a]	400.00	300.00	200.00	100.00	0.00
Mysid meal (MM)	0.00	100.00	200.00	300.00	400.00
Soybean meal	220.00	220.00	220.00	220.00	220.00
Copra meal	10.00	60.00	110.00	160.00	197.50
Squid meal	30.00	30.00	30.00	30.00	30.00
Corn starch	197.50	147.50	97.50	47.50	10.00
Yeast	50.00	50.00	50.00	50.00	50.00
Wheat gluten[b]	50.00	50.00	50.00	50.00	50.00
Fish oil[c]	17.50	17.50	17.50	17.50	17.50
Soy lecithin	5.00	5.00	5.00	5.00	5.00
Vit. premix[d]	10.00	10.00	10.00	10.00	10.00
Min. premix[e]	10.00	10.00	10.00	10.00	10.00
Proximate composition (% dry weight) basis					
Crude protein[f]	37.06 ± 0.05	37.22 ± 0.48	37.06 ± 0.37	37.75 ± 0.36	37.48 ± 0.25
Crude lipid[f]	8.17 ± 0.31	8.13 ± 0.25	8.14 ± 0.28	8.15 ± 0.29	8.16 ± 0.34
Crude fiber[g]	3.16 ± 0.45	3.46 ± 0.37	4.23 ± 0.39	4.69 ± 0.20	4.81 ± 0.12
Ash[f]	12.32 ± 0.35	13.15 ± 0.38	13.64 ± 0.35	13.87 ± 0.40	14.12 ± 0.39
NFE[h]	39.29	38.04	36.93	35.54	35.43

[a] Sardine fishmeal.
[b] Vital wheat gluten.
[c] Danish fish oil.
[d] Vitamin mix (1,000 g^{-1}): Alpha-tocopherol (20,000 IU), Cholecalciferol (200,000 IU), Retinol (1,200,000 IU), Biotin (40 mg), Ethoxyquin (500 mg), Folic acid (1,800 mg), Cobalamin (2,000 mg), Riboflavin (8,000 mg), Pyridoxine (5,000 mg), Thiamin (8,000 mg), Calcium Pantothenate (20,000 mg), and Niacin (40,000 mg).
[e] Mineral-mix (1,000 g^{-1}): cobalt (20 mg), selenium (200 mg), iodine (1,800 mg), copper (4,000 mg), zinc (40,000 mg), manganese (10,000 mg), and iron (40,000 mg).
[f] Analyzed values from the Fish Nutrition Laboratory, UP Visayas, CFOS-IA, Miagao, Iloilo, Philippines.
[g] Analyzed values from the DOST-RSTL, Region VI, La Paz, Iloilo City, Philippines.
[h] Nitrogen-free extract, computed by difference.

$$\textbf{Specific Growth Rate } (\textbf{SGR}, \ \%\textbf{day}^{-1}) = \frac{Ln\ FBW\ (g) - Ln\ IBW(g)}{60\ days}\ x\ 100$$

$$\textbf{Feed Intake } (\textbf{FI}, \textbf{g}\cdot\textbf{shrimp}^{-1}) = \frac{Dry\ diet\ given(g) - Dry\ remaining\ recovered\ (g)}{Number\ of\ shrimp}$$

$$\textbf{Feed Conversion Ratio } (\textbf{FCR}) = \frac{Dry\ feed\ intake\ (g)}{FBW\ (g) - IBW\ (g)}$$

$$\textbf{Protein Efficiency Ratio } (\textbf{PER}) = \frac{FBW(g) - IBW\ (g)}{Protein\ intake\ (g)}$$

$$\textbf{Survival Rate } (\textbf{SR}, \%) = \frac{Final\ number\ of\ shrimp\ survived}{Initial\ number\ of\ shrimp\ stocked}\ x\ 100$$

$$\textbf{Nutrient retention } (\%) = \frac{CNC_{Final} - CNC_{Initial}}{Nutrient\ intake}\ x\ 100$$

$$\textbf{CNC}_{\textbf{Final}} = \frac{CNC\ (protein\ or\ lipid,\ g\cdot g^{-1}\ diet)\ x\ FBW\ (g)}{100}$$

$$\textbf{CNC}_{\textbf{Initial}} = \frac{CNC\ (protein\ or\ lipid,\ g\cdot g^{-1}\ diet)\ x\ IBW\ (g)}{100}$$

$$\textbf{Nutrient intake} = \frac{Total\ feed\ intake\ (g)\ x\ Feed\ nutrient\ content\ (protein\ or\ lipid,\ g\cdot g^{-1}\ diet)}{100}$$

Where:
FBW = Final body weight (g) of individual shrimp
IBW = Initial body weight (g) of individual shrimp
CNC = Carcass nutrient content
CP_{Final} = Final carcass protein
$CP_{Initial}$ = Initial carcass protein.

Biochemical composition analyses

The initial and final carcass composition (crude protein, crude lipid, ash) of the test animals, primary protein sources (FM and MM), and the experimental feeds were evaluated in triplicates following the methods of the AOAC (2000). The moisture was determined according to Method 934.01 (AOAC, 2000). Crude protein was evaluated by the Kjeldahl method following Method 981.10 (AOAC, 2000). Crude lipid was quantified according to Bligh and Dyer (1959). Ash content was determined following Method 942.05 (AOAC, 2000). The AA composition of MM was determined using the Shimadzu HPLC analysis system (LC-10A/C-R7A) at the Fish Nutrition Laboratory of the UP Visayas, CFOS–IA. The chemical score index (CSI) of the MM was quantified according to Traifalgar et al. (2019) using the essential amino acids (EAAs) of *P. vannamei* tissue protein as the reference (Forster et al., 2002). The essential amino acid index (EAAI) of the MM was also computed according to Teruel (2002).

$$\textbf{Chemical score}\ (\%) = \frac{\text{g essential amino acid in 100 g}^{-1}\text{ mysid meal protein}}{\text{essential amino acid in 100 g}^{-1}\text{ P. vannamei tissue protein}}\ x\ 100$$

$$\textbf{Essential Amino Acid Index}\ (\textbf{EAAI}) = \sqrt[10]{\frac{100a}{a_r}x\frac{100b}{b_r}\ldots x\frac{100j}{j_r}}$$

Where a, b, . . . j = EAAs in the mysid meal protein (% protein) a_r, b_r, j_r = EAAs in *P. vannamei* tissue protein (% protein).

Statistical analyses

All data in each parameter was analyzed using the SPSS ver. 20.0 Software Statistical Application Program for Windows. Growth indices, feed utilization, biochemical carcass composition, and nutrient retention data of *P. vannamei* were tested for uniformity in variance and normality of distribution before subjecting the effects of different treatments to one-way ANOVA. The experimental data were presented as mean ± SEM. The Tukey's HSD *post hoc* test was run to determine the differences among the five dietary treatment means. Pearson correlation coefficient was also determined to measure the correlation among various parameters. The optimum replacement level of FM by MM in *P. vannamei* diets was done using a quadratic regression analysis. The statistically homogenous means were denoted by similar superscript letters.

Results

Proximate analysis and amino acid profile of mysid meal

Proximate nutritional analysis showed that the mysid meal (MM) contained a protein, lipid, fiber, ash, and carbohydrate content of 53.15 ± 0.07%, 4.42 ± 0.12%, 5.87 ± 0.02%, 20.92 ± 0.53%, and 15.65 ± 0.35%, respectively (Table 1). The nutritional value of this ingredient was found to be high, exhibiting an overall chemical score index (CSI) of 38.85 with an EAAI value of 0.89. This ingredient has an overall EAA/NEAA ratio of 0.90 (Table 3). Compared with the EAA profile of *P. vannamei* tissue protein, each AA content of MM exhibited higher chemical score values except for the leucine, the most limiting AA of this ingredient. In addition, arginine was identified as another limiting AA in MM.

Growth response and feed utilization indices

The survival, growth indices (FBW, %WG, and SGR), and feed utilization (FCR and PER) efficiency of *P. vannamei* postlarvae fed with various dietary treatments are shown in Table 4. The shrimps fed with treatment MM75 significantly obtained the best FBW, %WG, SGR, PER, and FCR among all treatments (Table 4). However, the FBW, %WG, SGR, PER, and FCR values in treatment MM75 were statistically the same ($P > 0.05$) as those obtained in treatments MM25, MM50, and MM100. The *P. vannamei* fed with treatment MM100 (FM-free diet) exhibited growth comparable to that of the MM0 (100% FM-based diet). In addition, the FBW, %WG, SGR, FCR, and PER of shrimps were statistically the same ($P > 0.05$) in treatments MM25, MM50, MM75, and MM100. Moreover, no significant treatment effects were detected in the TFI ($P = 0.338$) and survival ($P = 0.098$) of white shrimps for all the dietary treatments (Table 4). The FBW, % WG, SGR, PER, PR, and LR of *P. vannamei* revealed a significant positive correlation for all the various treatments (Table 5). However, the FCR ($r = -0.56$, $P = 0.01$) of *P. vannamei* showed a significant negative association with the various substitution levels of FM by MM. Furthermore, the FBW, %WG, and SGR of *P. vannamei* revealed a significant positive correlation with the PER, protein retention (PR), and lipid retention (LR) (Table 5). However, FBW, %WG, and SGR of *P. vannamei* revealed a significant negative correlation with the FCR ($P < 0.05$). Quadratic polynomial analysis indicates that a 65.50 % substitution level of FM with mysid meal is optimum to promote maximum growth in *P. vannamei* postlarvae (Figure 1).

Carcass nutrient composition

The whole-body proximate profile of white shrimps fed with various experimental feeds is shown in Table 6. The biochemical carcass composition (i.e., moisture, protein, lipid, and ash content) of *P. vannamei* was not significantly influenced by the increasing levels of dietary MM ($P > 0.05$).

Nutrient retention

Nutrient retention of Pacific white shrimp at the termination of the 60-day growth trial is presented in Table 7. The *P. vannamei*

TABLE 3 EAA profile of *Penaeus vannamei* tissue proteins and mysid meal (chemical score, CSI, EAAI, EAA/NEAA ratio).

Amino acid	Mysid meal (% protein)[1]	*P. vannamei*, EAA profile (% protein)[2]	EAA requirement for shrimp (% protein)	Mysid meal EAA chemical score (%)[3]
Histidine	2.49	1.62	0.80[a]	153.67
Isoleucine	5:00	2.65	1.00[a]	188.49
Leucine	1.82	4.69	1.70[a]	38.43
Lysine	3.79	4.84	1.64[b]	78.34
Valine	1.83	3.10	1.40[c]	58.95
Arginine	2.42	6.10	2.32[d]	39.58
Threonine	2.62	2.52	1.51[e]	104.01
Methionine +cystine	2.93	2.67		109.78
Phenylalanine +tryptophan	7.89	5.39		146.29
Mysid meal CSI[4]				38.83
EAAI				0.89
EAA/NEAA ratio				0.90

[1]Mysid meal EAA (% protein): Actual analyzed values from the Fish Nutrition Laboratory, UP Visayas, CFOS-IA, Miagao, Iloilo, Philippines.
[2]*P. vannamei* EAA (% protein): data derived from Forster et al. (2002).
[3] EAA chemical score = {[EAA amount (g) in 100 g mysid meal protein]/[EAA amount (g) in 100 g shrimp protein]} x 100.
[4]Mysid meal protein CSI = the most limiting AA exhibiting the lowest EAA chemical score (Traifalgar et al., 2019).
[a]Millamena et al. (1999).
[b]Xie et al. (2012).
[c]Teshima et al. (2002).
[d]Zhou et al. (2012).
[e]Zhou et al. (2013).

TABLE 4 Growth, feed utilization indices, and survival of *P. vannamei* postlarvae fed with various levels of MM as a replacement for FM after the 60-day feeding trial.

Treatments	FBW (g)	WG (%)	SGR (%)	TFI (g)	FCR	PER	SR (%)
CTRL	0.90± 0.02[b]	29,983.33 ± 778.77[b]	9.51 ± 0.04[b]	1.83 ± 0.05[a]	2.03 ± 0.05[a]	1.33 ± 0.05[b]	93.00 ± 1.41[a]
MM25	1.04 ± 0.03[ab]	34,400.00 ± 1,130.39[ab]	9.74 ± 0.05[ab]	1.92 ± 0.13[a]	1.86 ± 0.13[ab]	1.45 ± 0.13[ab]	90.00 ± 1.63[a]
MM50	1.13 ± 0.05[a]	37,566.67 ± 1,575.27[a]	9.88 ± 0.07[a]	1.97 ± 0.07[a]	1.75 ± 0.07[ab]	1.54 ± 0.07[ab]	91.00 ± 1.41[a]
MM75	1.15 ± 0.09[a]	38,233.33 ± 2,848.00[a]	9.91 ± 0.12[a]	1.90 ± 0.05[a]	1.67 ± 0.14[b]	1.59 ± 0.14[a]	94.00 ± 1.63[a]
MM100	1.03 ± 0.06[ab]	34,316.67 ± 1,839.64[ab]	9.73 ± 0.09[ab]	1.84 ± 0.03[a]	1.80 ± 0.12[ab]	1.49 ± 0.14[ab]	91.00 ± 1.41[a]
ANOVA *P value*	0.003	0.003	<0.001	0.338	0.015	0.044	0.098

Values (mean ± SEM from four replicate tanks) are significantly different when different lowercase alphabets appear in the same column ($P < 0.05$).

fed with the treatment MM75 exhibited the highest numerical value on protein retention (PR) among all treatments. However, the PR values in the treatment MM75 were not significantly different from those shrimps received with treatments MM25, MM50, and MM100 groups ($P > 0.05$). On the contrary, the lowest PR was exhibited in *P. vannamei* fed with the treatment MM0. However, the PR of *P. vannamei* fed with treatment MM0 was statistically the same ($P > 0.05$) from those shrimps fed with treatment MM25, MM50, and MM100 diets (Table 7). The highest lipid retention (LR) was significantly obtained in *P. vannamei* fed with the treatment MM75. However, there was no significant difference in the LR of shrimps fed with treatments MM0, MM25, and MM50 ($P > 0.05$). The LR of shrimps fed with treatment MM0 was significantly lower than those of shrimps fed with treatments MM25 and MM50 ($P < 0.05$). The PR ($r = 0.46$, $P = 0.04$) and LR ($r = 0.73$, $P = 0.00$) of *P. vannamei* exhibited a significant positive correlation with the different dietary treatments (Table 5). However, the FBW, % WG, and SGR of *P. vannamei* showed a significant positive correlation with the PR and LR (Table 5; $P < 0.05$).

Discussion

The nutritional value of mysid meal (MM) has not been previously evaluated as a dietary protein source ingredient for *P. vannamei*. This study is the first to document the nutritional utilization of MM as a good-quality protein source in the *P. vannamei* diet based on several biological performance indices and biochemical parameters. Amino acid analysis of MM indicates a

TABLE 5 Correlation analysis of *Penaeus vannamei* fed with various levels of MM as an alternative for FM after the 60-day feeding trial.

Parameters	MMRL	FBW (g)	%WG	SGR	TFI (g)	FCR	PER	PR
MMRL								
FBW	**r = 0.48 *P* = 0.03**							
%WG	**r = 0.48 *P* = 0.03**	**r = 1.00 *P* = 0.00**						
TFI	**r = 0.02 *P* = 0.92**	**r = 0.46 *P* = 0.04**	**r = 0.46 *P* = 0.04**					
SGR	**r = 0.50 *P* = 0.02**	**r = 1.00 *P* = 0.00**	**r = 1.00 *P* = 0.00**		**r =0.46 *P* = 0.04**			
FCR	**r = −0.55 *P* = 0.01**	**r = −0.85 *P* = 0.00**	**r = −0.85 *P* = 0.00**	**r = −0.86 *P* = 0.00**	**r = 0.06 *P* = 0.80**			
PER	**r = 0.49 *P* = 0.03**	**r = 0.85 *P* = 0.00**	**r = 0.85 *P* =0.00**	**r = 0.85 *P* = 0.00**	r = −0.06 *P* = 0.78	**r = −0.99 *P* = 0.00**		
PR	**r = 0.46 *P* = 0.04**	**r = 0.83 *P* = 0.00**	**r = 0.83 *P* = 0.00**	**r = 0.83 *P* = 0.00**	r = −0.06 *P* = 0.79	**r = −0.96 *P* = 0.00**	**r = 0.96 *P* = 0.00**	
LR	**r = 0.73 *P* = 0.00**	**r = 0.72 *P* = 0.00**	**r = 0.72 *P* =0.00**	**r = 0.71 *P* = 0.00**	r = −0.13 *P* = 0.59	**r = −0.87 *P* = 0.00**	**r = 0.84 *P* = 0.00**	**r = 0.89 *P* = 0.00**

Values are mean ± SEM from four replicate tanks.
Significantly different results are highlighted in bold ($P < 0.05$). MMRL, mysid meal replacement level; *P*-value, *r* – Pearson correlation coefficient.

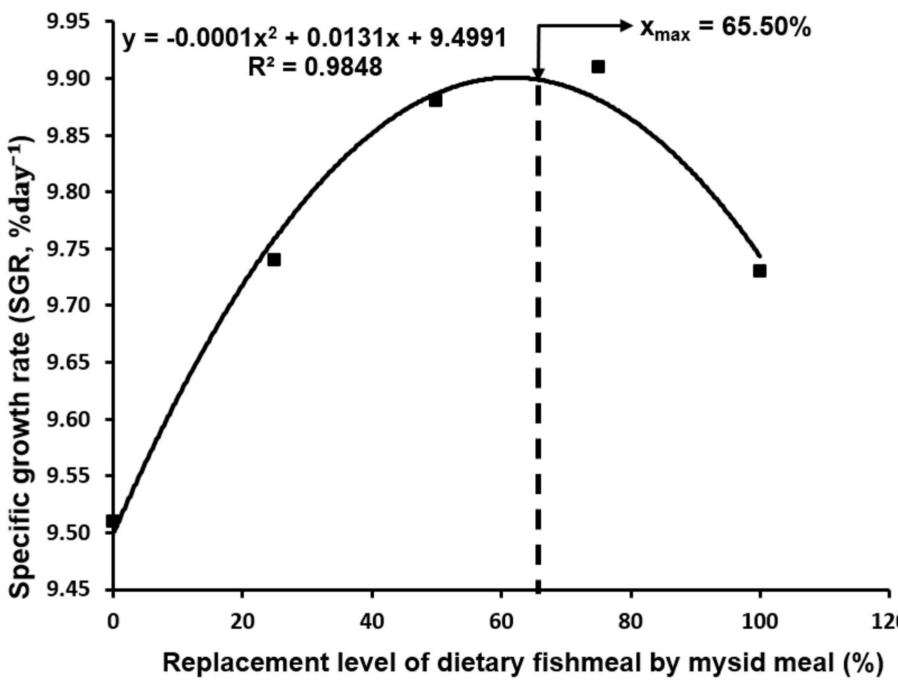

FIGURE 1
Relationship between specific growth rate (SGR, %day^{-1}) and replacement level of dietary fishmeal by mysid meal after the 60-day feeding trial of *Penaeus vannamei* based on quadratic regression analysis. Each point represents the mean of four replicate treatment groups of shrimps. Replacement levels derived with the second-order polynomial (quadratic) model for SGR indicated that the optimal level of dietary mysid meal was 65.50%.

complete and well-balanced AA content with a nutritional value closely similar to or surpassing the AA composition of the *P. vannamei* muscle protein. Moreover, the EAA profile of MM satisfies the ideal dietary EAA requirement of the penaeid shrimp (Table 3). Most EAA content of MM exhibits a higher chemical score closer to or above 100 %. This indicates that these AAs present in MM are sufficient to satisfy the EAA requirement of *P. vannamei* for optimum growth and development. Based on its CSI, the most limiting AA of MM is leucine (38.33%) followed by arginine (39.58%). This implies that MM can only supply 38.33% of leucine and 39.58% required by the *P. vannamei* and that the difference must be supplemented in the diet. Dietary supplementation of

TABLE 6 Biochemical carcass composition of white shrimps fed with various levels of MM as an alternative for FM after the 60-day feeding trial.

Treatments	Moisture (%)	Protein (%)	Lipid (%)	Ash (%)
MM0 (Control)	6.40 ± 0.33[a]	62.46 ± 0.22[a]	4.52 ± 0.37[a]	15.81 ± 0.34[a]
MM25	5.39 ± 1.23[a]	63.22 ± 0.10[a]	4.67 ± 0.25 [a]	16.19 ± 0.70[a]
MM50	4.42 ± 0.57[a]	62.62 ± 0.43[a]	4.47 ± 1.01 [a]	16.97 ± 0.09[a]
MM75	5.74 ± 0.02[a]	62.53 ± 0.21[a]	5.08 ± 0.66[a]	16.89 ± 0.70[a]
MM100	5.95 ± 0.24[a]	62.50 ± 0.20[a]	5.19 ± 0.23[a]	16.56 ± 0.34[a]
ANOVA *P value*	0.157	0.131	0.704	0.197

Values (mean ±SEM from four replicate tanks) are significantly different when different lowercase alphabets appear in the same column ($P < 0.05$).

TABLE 7 Nutrient retention of *Penaeus vannamei* fed with various levels of MM as an alternative for FM after the 60-day feeding trial.

Treatments	Protein retention (%)	Lipid retention (%)
MM0 (Control)	19.30 ± 0.79[b]	6.32 ± 0.26[c]
MM25	20.67 ± 1.06[ab]	6.98 ± 0.36 [bc]
MM50	21.97 ± 0.66[ab]	7.12 ± 0.22[bc]
MM75	23.46 ± 1.73[a]	8.81 ± 0.65[a]
MM100	21.22 ± 1.57[ab]	8.09 ± 0.60[ab]
ANOVA *P value*	0.047	0.001

Values (mean ±SEM from four replicate tanks) are significantly different when different lowercase alphabets appear in the same column ($P < 0.05$).

either natural of synthetic leucine will ensure that growth will be at the optimum and will not be limited with the deficiency of this essential amino acid. In addition, MM contains high crude protein (53.15% DM) comparable to FM protein, and this ingredient has an EAAI value of 0.89, considered a good-quality feed protein source for aquafeeds. The EAAI is another critical parameter to assess the nutritional quality of protein of potential feed ingredients (Peñaflorida, 1989). In addition to identifying the limiting AA, this index has been considered when evaluating the nutritional value of proteins because other necessary AAs may also affect the quality of proteins (Hepher, 1988). Peñaflorida (1989) graded feedstuffs following the report of Oser (1959), which classifies potential protein ingredients with an EAAI value of <0.70 as inadequate protein, about 0.80 as suitable protein, and 0.90 as good-quality protein. The MM used in the present study has slightly lower EAAI values than Peruvian FM (0.92), Herring FM (0.95), shrimp meal (0.98), and squid meal (0.96) (Peñaflorida, 1989). However, the EAA/NEAA ratio of MM in the current study is 0.90, which is comparable to the 0.9-1.09 range in FM-based diets reported by Ween et al. (2017) and Kim et al. (2018), as cited by Sobczak et al. (2021). This result demonstrates that MM is classified as a good-quality protein that could provide adequate EAAs to meet the requirement of *P. vannamei* to achieve optimum growth.

The growth performance indices (FBW, % WG, and SGR), feed utilization efficiency parameters (FCR and PER), and survival of *P. vannamei* fed with MM-based diets were similar in all treatment groups at the end of the feeding trial. Shrimp fed with complete replacement of FM (MM100) showed similar growth performance with the control treatment (MM0), receiving the 100% FM-based diet. However, the shrimp fed with increasing levels of MM-based ingredients (MM25, MM50, and MM75) showed a similar trend with the MM100 treatment toward better growth performance and feed utilization. These results suggest that MM can substitute up to 100 % of the FM, whose content accounted for 40% in the FM-based control treatment, without causing any adverse effects on the biological performance of *P. vannamei*. This current finding is the first to document the complete substitution of FM with MM in the *P. vannamei* diet. A similar result was documented by Wei et al. (2022), who found that the zooplankton-based feed ingredient (i.e., krill meal) can completely replace dietary FM without adverse effects on the growth and feed utilization of *P. vannamei.* Previous research findings also have proved that FM could be substituted entirely by krill meal in the diets of various farmed species such as Atlantic cod (Moren et al., 2006; Tibbetts et al., 2011), Atlantic salmon (Olsen et al., 2006), Atlantic halibut (Tibbetts et al., 2011) and triploid rainbow trout (Wei et al., 2019). A similar observation was documented by Hassan et al. (2020), who reported that replacing FM (control diet containing 35% FM) with zooplankton biomass meal up to 100 % significantly enhanced growth performance and feed utilization of seabass fingerlings. Similarly, Kader et al. (2012a) reported that the dehulled soybean meal supplemented with fish soluble, krill meal, and squid meal could completely replace FM in juvenile red sea bream diets without significantly affecting fish performance. Our findings add to these earlier works that MM could completely replace FM in the white shrimp postlarval diet.

The growth-promoting effects of MM-based diets have been significantly observed in shrimp feed with 75% FM replacement. Analysis by polynomial quadratic equation indicates that 65.50% replacement of FM with MM is optimum to elicit a maximum growth response of *P. vannamei*. Similar to our present results, Abo-Taleb et al. (2021) documented the best growth and feed utilization indices in gray mullet larvae when fed with diets containing 75% substitution of FM *by Daphnia magna* meal. Similarly, the growth-stimulating effects of krill meal have also been reported in studies done in *Salmo salar* (Hatlen et al., 2017), *Procambarus clarki* (Gao et al., 2020), *Penaeus monodon* (Smith et al., 2005), *P. vannamei* (Nunes et al., 2011) and *Larimichthys crocea* (Wei et al., 2019). The underlying physiological mechanisms of the growth-promoting effects of zooplankton-based ingredients in fish and crustaceans are not fully understood and remain to be elucidated in future investigations. The enhanced growth performance observed in aquatic animals fed with plankton-based diets has been primarily associated with enhanced palatability, improved feed intake (FI), and adequate supply of highly available and well-balanced nutrients (Suresh and Nates, 2011; Nunes et al., 2019; Shan et al., 2019). The marked superiority in shrimp growth fed with MM75 over that of the control treatment (MM0) is presumptive evidence for a growth factor in MM. Williams et al. (2005) reported an unknown growth factor in zooplankton-based meals that was present in the insoluble protein component of the meal. This growth factor, associated with zooplankton-based meals, was hypothesized as a protein that activates the neurosecretory hormones of the X-organ-sinus gland complex, which modulates several metabolic processes (i.e., molting, protein synthesis, glucose metabolism, osmoregulation, and reproduction) in crustaceans (Huberman, 2000; Udomkit et al., 2004; Williams et al., 2005).

The proximate whole-body composition analysis of *P. vannamei* indicated that the carcass protein, lipid, moisture, and ash contents were unaffected by FM's replacement level with MM. These findings suggest that MM supplies well-balanced and readily available nutrients and that accelerated growth does not impair the composition of the muscle tissue (Fricke et al., 2023). However, in the current study, dietary MM replacement levels significantly influenced body protein and lipid retention. Protein and lipid retention in treatments fed with MM-based diets are significantly higher than those groups receiving 100% FM-based diets. These high protein and lipid retention must have also contributed to the better growth response in shrimp fed with MM75. The significant enhancement of PR could be attributed to the better AA profile of MM, and the improvement of PR can be linked with the enhancement of protein synthesis (Hernández et al., 2011). In crustaceans, it has been observed that a lower PR is associated with a higher rate of protein catabolism (Bulbul et al., 2016), decreased feed, and inefficient feed utilization (Yue et al., 2012).

PR is considered an important index for the sub-optimal supply and utilization of amino acids (Sanchez-Lozano et al., 2011; Kader et al., 2012b). In this study, the PR values varied between 18.68 and 22.70%, which was relatively high compared to 8.50 to 13.2% reported by Alam et al. (2002) for kuruma shrimp. The result of the study was closer to the findings of Bulbul et al. (2013), who documented a PR ranging from 18.50 to 22.68 % for kuruma shrimp using a combination of plant protein meals to replace FM. Significantly highest PR value was observed in shrimp fed with the MM75 group, indicating better utilization of MM protein by *P. vannamei* in this treatment. This result was supported by a significant growth improvement of *P. vannamei* fed with the MM75 group among treatments. Therefore, the increase in PR would be one of the contributory factors for the significant growth enhancement and improved feed utilization in shrimp fed with the MM75 group. Although there was limited information on the relationship between PR and growth performance, Deng et al. (2006), Sanchez-Lozano et al. (2011), and Kader et al. (2012b) indicated a positive correlation between higher retention of protein and faster growth performances in marine fish species.

The relatively high survival and no significant differences observed in all dietary treatments indicate that the experimental animals are healthy and in good nutritional condition, suggesting that MM is a suitable dietary ingredient to satisfy the nutritional requirement of the white shrimp (Alvarez et al., 2007; Suárez et al., 2009). The significant growth improvement of *P. vannamei* can also be attributed to the high-quality nutrient composition of MM with high crude protein content comparable to FM and complete AA profile (Nordgarden et al., 2003; Espe et al., 2006). The nutritional value of MM as a complete substitution of FM to support the growth and development of *P. vannamei* is considered unprecedented. The findings of this study suggested that MM could be a viable alternative for FM in the *P. vannamei* diet, and this feed ingredient could minimize the pressure on capturing dwindling natural fish stocks for aquaculture feed use.

Conclusion

The current study concludes that MM can successfully replace up to 100% of the FM (40% in the control feed) with no deleterious effects on survival, growth performance, feed utilization, biochemical composition, and nutrient retention of the shrimp. The dietary MM could also elicit growth-promoting effects if utilized at 65.50% replacement of FM in *P. vannamei* post-larval diets.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The animal study was approved by Institutional Animal Care and Use Committee (IACUC) of the University of the Philippines Visayas. The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

MA: Conceptualization, Investigation, Methodology, Visualization, Writing—original draft. RT: Conceptualization, Investigation, Methodology, Supervision, Writing—original draft, Writing—review & editing. LL: Conceptualization, Methodology, Writing—original draft. SN: Conceptualization, Methodology, Writing—original draft. MN: Conceptualization, Methodology, Writing—original draft.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This study was funded by the Commission on Higher Education (CHED) K to 12 Scholarships for Graduate Studies Local (SGS-L) and Department of Science and Technology (DOST)-Science Education Institute (SEI) Accelerated Science and Technology Human Resource Development Program (ASTHRDP).

Acknowledgments

The CHED K to 12 SGS-L and DOST-SEI ASTHRDP are gratefully acknowledged for their financial support during this study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abo-Taleb, H. A., Ashour, M., Elokaby, M. A., Mabrouk, M. M., El-Feky, M. M., Abdelzaher, O. F., et al. (2021). Effect of a new feed *Daphnia magna* (Straus, 1820), as a fish meal substitute on growth, feed utilization, histological status, and economic revenue of grey mullet, *Mugil cephalus* (Linnaeus 1758). *Sustainability* 13, 7093. doi: 10.3390/su13137093

Alam, M. S., Teshima, S. I., Yaniharto, D., Ishikawa, M., and Koshio, S. (2002). Dietary amino acid profiles and growth performance in juvenile kuruma prawn *Marsupenaeus japonicus*. *Comparat. Biochem. Physiol. Part B: Biochem. Mol. Biol.* 133, 289–297. doi: 10.1016/S1096-4959(02)00165-3

Alvarez, J. S., Hernández-Llamas, A., Galindo, J., Fraga, I., García, T., and Villarreal, H. (2007). Substitution of fishmeal with soybean meal in practical diets for juvenile white shrimp *Litopenaeus Schmitt* (Pérez-Farfante and Kensley 1997). *Aquac. Res.* 38, 689–695. doi: 10.1111/j.1365-2109.2007.01654.x

Amaya, E. A., Davis, D. A., and Rouse, D. B. (2007). Replacement of fish meal in practical diets for the Pacific white shrimp (*Litopenaeus vannamei*) reared under pond conditions. *Aquaculture* 262, 393–401. doi: 10.1016/j.aquaculture.2006.11.015

Ambasankar, K., Dayal, J. S., Vasagam, K. K., Sivaramakrishnan, T., Sandeep, K. P., Panigrahi, A., et al. (2022). Growth, fatty acid composition, immune-related gene expression, histology and haematology indices of *Penaeus vannamei* fed graded levels of Antarctic krill meal at two different fishmeal concentrations. *Aquaculture* 553, 738069. doi: 10.1016/j.aquaculture.2022.738069

AOAC (2000). *Official Methods of Analysis of Official Analytical Chemists International, 17th ed.* (Arlington, VA: Association of Official Analytical Chemists).

Ayisi, C. L., Hua, X., Apraku, A., Afriyie, G., and Kyei, B. A. (2017). Recent studies toward the development of practical diets for shrimp and their nutritional requirements. *Hayati J. Biosci.* 24, 109–117. doi: 10.1016/j.hjb.2017.09.004

Bauer, W., Prentice-Hernandez, C., Tesser, M. B., Wasielesky Jr, W., and Poersch, L. H. (2012). Substitution of fishmeal with microbial floc meal and soy protein concentrate in diets for the Pacific white shrimp *Litopenaeus vannamei*. *Aquaculture* 342, 112–116. doi: 10.1016/j.aquaculture.2012.02.023

Biju, A., Gireesh, R., Jayalakshmi, K. J., Haridevi, C. K., and Panampunnayil, S. U. (2009). Seasonal abundance, ecology, reproductive biology, and biochemical composition of *Mesopodopsis orientalis* WM Tattersall (Mysida) from a tropical estuary (Cochin backwater) in India. *Crustaceana* 44, 981–996. doi: 10.1163/156854009X448835

Biju, A., and Panampunnayil, S. U. (2011). Population structure and reproductive biology of *Mesopodopsis orientalis* (Crustacea: Mysida) in a tropical mangrove ecosystem in India. *Mar. Biodivers. Rec.* 4:e43. doi: 10.1017/S1755267211000273

Bligh, E. G., and Dyer, W. J. (1959). A rapid method of total lipid extraction and purification. *Can. J. Biochem. Physiol.* 37, 911–917. doi: 10.1139/y59-099

Buen-Ursua, S. M. A., Azuma, T., Arai, K., and Coloso, R. M. (2015). Improved reproductive performance of tiger tail seahorse, *Hippocampus comes* by mysid shrimp fed singly or in combination with other natural food. *Aquacult. Int.* 23, 29–43. doi: 10.1007/s10499-014-9795-1

Bulbul, M., Kader, M. A., Asaduzzaman, M., Ambak, M. A., Chowdhury, A. J. K., Hossain, M. S., et al. (2016). Can canola meal and soybean meal be used as major dietary protein sources for kuruma shrimp, *Marsupenaeus japonicus*? *Aquaculture* 452, 194–199. doi: 10.1016/j.aquaculture.2015.10.036

Bulbul, M., Koshio, S., Ishikawa, M., Yokoyama, S., and Kader, M. A. (2013). Performance of kuruma shrimp, *Marsupenaeus japonicus* fed diets replacing fishmeal with a combination of plant protein meals. *Aquaculture* 372, 45–51. doi: 10.1016/j.aquaculture.2012.10.023

Cruz-Suárez, L. E., Tapia-Salazar, M., Villarreal-Cavazos, D., Beltran-Rocha, J., Nieto-López, M. G., Lemme, A., et al. (2009). Apparent dry matter, energy, protein and amino acid digestibility of four soybean ingredients in white shrimp *Litopenaeus vannamei* juveniles. *Aquaculture* 292, 87–94. doi: 10.1016/j.aquaculture.2009.03.026

Cummins, V. C., Rawles, S. D., Thompson, K. R., Velasquez, A., Kobayashi, Y., Hager, J., et al. (2017). Evaluation of black soldier fly (*Hermetia illucens*) larvae meal as partial or total replacement of marine fish meal in practical diets for Pacific white shrimp (*Litopenaeus vannamei*). *Aquaculture* 473, 337–344. doi: 10.1016/j.aquaculture.2017.02.022

Dangtip, S., Sirikharin, R., Sanguanrut, P., Thitamadee, S., Sritunyalucksana, K., Taengchaiyaphum, S., et al. (2015). AP4 method for two-tube nested PCR detection of AHPND isolates of *Vibrio parahaemolyticus*. *Aquacult. Rep.* 2, 158–162. doi: 10.1016/j.aqrep.2015.10.002

Deng, J., Mai, K., Ai, Q., Zhang, W., Wang, X., Xu, W., et al. (2006). Effects of replacing fish meal with soy protein concentrate on feed intake and growth of juvenile Japanese flounder, *Paralichthys olivaceus*. *Aquaculture* 258, 503–513. doi: 10.1016/j.aquaculture.2006.04.004

Domingues, P. M., Turk, P. E., Andrade, J. P., and Lee, P. G. (1998). Pilot-scale production of mysid shrimp in a static water system. *Aquaculture Int.* 6, 387–402. doi: 10.1023/A:1009232921784

Duarte, C. M., Holmer, M., Olsen, Y., Soto, D., Marb,à, N., Guiu, J., et al. (2009). Will the oceans help feed humanity? *Bioscience* 59, 967–976. doi: 10.1525/bio.2009.59.11.8

Espe, M., Lemme, A., Petri, A., and El-Mowafi, A. (2006). Can Atlantic salmon (*Salmo salar*) grow on diets devoid of fish meal? *Aquaculture* 255, 255–262. doi: 10.1016/j.aquaculture.2005.12.030

Eusebio, P. S., Coloso, R. M., and Gapasin, R. S. J. (2010). Nutritional evaluation of mysids *Mesopodopsis orientalis* (Crustacea: Mysida) as live food for grouper *Epinephelus fuscoguttatus* larvae. *Aquaculture* 306, 289–294. doi: 10.1016/j.aquaculture.2010.05.004

FAO (2016). *Fishery and Aquaculture Statistics*. Rome: Food and Agriculture Organization of the United Nations.

FAO (2020). "The State of World Fisheries and Aquaculture 2020," in *Sustainability in Action*. Rome: FAO.

Forster, I. P., Dominy, W., and Tacon, A. G. (2002). "The use of concentrates and other soy products in shrimp feeds," in *Avances en Nutrición Acuícola VI. Memoriasdel VI Simposium Internacional de Nutrición Acuícola. 3 al 6 de Septiembre del 2002*, eds L. E. Cruz-Suárez, D. Ricque-Marie, M. Tapia-Salazar, M. G. Gaxiola-Cortés, and N. Simoes (Cancún).

Fricke, E., Slater, M. J., and Saborowski, R. (2023). Brown shrimp (*Crangon crangon*) processing remains enhance growth of Pacific Whiteleg shrimp (*Litopenaeus vannamei*). *Aquaculture* 569, 739367. doi: 10.1016/j.aquaculture.2023.739367

Gao, R., Chen, L., Zhang, W., Zhang, S., Rao, J., and Hu, J. (2020). Effect of dietary Antarctic krill *Euphausia superba* on the growth performance and nonspecific immunity of red swamp crayfish *Procambarus clarkia*. *Fish Shellfish Immunol.* 96, 122–125. doi: 10.1016/j.fsi.2019.12.004

Hardy, R. W., and Barrows, F. T. (2002). "Diet formulation and manufacture," in *Fish Nutrition 3rd Edition*, eds. Halver, J., Hardy, R. (Cambridge: Academic Press), 505–600.

Hassan, S. E., Azab, A. M., Abo-Taleb, H. A., and El-Feky, M. M. (2020). Effect of replacing fish meal in the fish diet by zooplankton meal on growth performance of *Dicentrarchus labrax* (Linnaeus, 1758). *Egypt J. Aquat. Res.* 24, 267–280. doi: 10.21608/ejabf.2020.111756

Hatlen, B., Berge, K., Nordrum, S., Johnsen, K., Kolstad, K., and Mørkøre, T. (2017). The effect of low inclusion levels of Antarctic krill (*Euphausia superba*) meal on growth performance, apparent digestibility and slaughter quality of Atlantic salmon (*Salmo salar*). *Aquaculture Nutr.* 23, 721–729. doi: 10.1111/anu.12439

Hepher, B. (1988). *Nutrition of Pond Fishes*. New York: Cambridge University Press, 404.

Hernández, C., Olvera-Novoa, M. A., Smith, D. M., Hardy, R. W., and Gonzalez-Rodriguez, B. (2011). Enhancement of shrimp *Litopenaeus vannamei* diets based on terrestrial protein sources via the inclusion of tuna by-product protein hydrolysates. *Aquaculture* 317, 117–123. doi: 10.1016/j.aquaculture.2011.03.041

Hewitt, R. P., Watkins, J. L., Naganobu, M., Tshernyshkov, P., Brierley, A. S., Demer, D. A., et al. (2002). Setting a precautionary catch limit for Antarctic krill. *Oceanography* 15, 26–33. doi: 10.5670/oceanog.2002.12

Huberman, A. (2000). Shrimp endocrinology. A review. *Aquaculture* 191, 191–208. doi: 10.1016/S0044-8486(00)00428-2

Huntington, T. C., and Hasan, M. R. (2009). "Fish as feed inputs for aquaculture–practices, sustainability and implications: a global synthesis," in *FAO Fisheries and Aquaculture Technical Paper* (Rome: FAO), 1–61.

Izquierdo, M. S. (1996). Essential fatty acid requirements of cultured marine fish larvae. Aquacult. *Nutr.* 2, 183–191. doi: 10.1111/j.1365-2095.1996.tb00058.x

Jannathulla, R., Rajaram, V., Kalanjiam, R., Ambasankar, K., Muralidhar, M., and Dayal, J. S. (2019). Fishmeal availability in the scenarios of climate change: Inevitability of fishmeal replacement in aquafeeds and approaches for the utilization of plant protein sources. *Aquac. Res.* 50, 3493–3506. doi: 10.1111/are.14324

Kader, M. A., Bulbul, M., Koshio, S., Ishikawa, M., Yokoyama, S., Nguyen, B. T., et al. (2012a). Effect of complete replacement of fishmeal by dehulled soybean meal with crude attractants supplementation in diets for red sea bream, *Pagrus major*. *Aquaculture* 350, 109–116. doi: 10.1016/j.aquaculture.2012.04.009

Kader, M. A., Koshio, S., Ishikawa, M., Yokoyama, S., Bulbul, M., Nguyen, B. T., et al. (2012b). Can fermented soybean meal and squid by-product blend be used as fishmeal replacements for Japanese flounder (*Paralichthys olivaceus*)?. *Aquac. Res.* 43, 1427–1438. doi: 10.1111/j.1365-2109.2011.02945.x

Kim, K. D., Jang, J. W., Kim, K. W., Lee, B. J., Hur, S. W., and Han, H. S. (2018). Tuna by-product meal as a dietary protein source replacing fishmeal in juvenile Korean rockfish *Sebastes schlegeli*. *Fisher. Aquatic Sci.* 21, 1–8. doi: 10.1186/s41240-018-0107-y

Lemos, D., Lawrence, A. L., and Siccardi, I. I. I., A. J. (2009). Prediction of apparent protein digestibility of ingredients and diets by in vitro pH-stat degree of protein hydrolysis with species-specific enzymes for juvenile Pacific white shrimp *Litopenaeus vannamei*. *Aquaculture* 295, 89–98. doi: 10.1016/j.aquaculture.2009.06.011

Li, W., Pan, L., Liu, H., Tan, B., Dong, X., Yang, Q., et al. (2022). Effects of the *Clostridium butyricum* on growth performance, antioxidant capacity, immunity and disease resistance of *Litopenaeus vannamei* fed with cottonseed protein concentrate (CPC) replacement of fishmeal in diet. *Fish Shellfish Immunol.* 126, 283–291. doi: 10.1016/j.fsi.2022.05.030

Li, X., Zhang, X., Yao, W., and Leng, X. (2023). Dietary effects of cottonseed protein concentrate substituting fishmeal on the growth and flesh quality of Pacific white shrimp (*Litopenaeus vannamei*). *Aquacult. Rep.* 29, 101482. doi: 10.1016/j.aqrep.2023.101482

Mauchline, J. (1980). The biology of mysids and euphausiids. *Adv. Marine Biol.* 18, 1–677.

Melk, W., Ellertsen, B., and Skjoldal, H. R. (2004). "Zooplankton: the link to higher trophic levels," in *The Norwegian Sea Ecosystem*, ed. H. R. Skjoldal (Trondheim: Tapir Academic Press), 137–202.

Millamena, O. M., Teruel, M. B., Kanazawa, A., and Teshima, S. (1999). Quantitative dietary requirements of postlarval tiger shrimp, *Penaeus monodon*, for histidine, isoleucine, leucine, phenylalanine and tryptophan. *Aquaculture* 179, 169–179. doi: 10.1016/S0044-8486(99)00160-X

Moren, M., Suontama, J., Hemre, G. I., Karlsen, Ø., Olsen, R. E., Mundheim, H., et al. (2006). Element concentrations in meals from krill and amphipods—possible alternative protein sources in complete diets for farmed fish. *Aquaculture* 261, 174–181. doi: 10.1016/j.aquaculture.2006.06.022

Naylor, R. L., Hardy, R. W., Bureau, D. P., Chiu, A., Elliott, M., Farrell, A. P., et al. (2009). Feeding aquaculture in an era of finite resources. *Proc. Nat. Acad. Sci.* 106, 15103–15110. doi: 10.1073/pnas.0905235106

Nicol, S., and Endo, Y. (1997). *Krill Fisheries of the World (No. 367)*. Hot Springs: Food and Agriculture Org.

Nicol, S., and Endo, Y. (1999). Krill fisheries: development, management and ecosystem implications. *Aquat. Living Resour.* 12, 105–120. doi: 10.1016/S0990-7440(99)80020-5

Nordgarden, U., Oppedal, F., Taranger, G. L., Hemre, G. I., and Hansen, T. (2003). Seasonally changing metabolism in Atlantic salmon (*Salmo salar* L.) I–Growth and feed conversion ratio. *Aquaculture Nutrition* 9, 287–293. doi: 10.1046/j.1365-2095.2003.00256.x

Nunes, A. J., Sabry-Neto, H., Oliveira-Neto, S., and Burri, L. (2019). Feed preference and growth response of juvenile *Litopenaeus vannamei* to supplementation of marine chemoattractants in a fishmeal-challenged diet. *J. World Aquac. Soc.* 50, 1048–1063. doi: 10.1111/jwas.12648

Nunes, A. J. P., Sá, M. V. C., and Sabry-Neto, H. (2011). Growth performance of the white shrimp, *Litopenaeus vannamei*, fed on practical diets with increasing levels of the Antarctic krill meal, *Euphausia superba*, reared in clear-versus green-water culture tanks. *Aquaculture Nutrition* 17, e511–e520. doi: 10.1111/j.1365-2095.2010.00791.x

Olsen, R. E., Suontama, J., Langmyhr, E., Mundheim, H., Ring,ø, E., Melle, W., et al. (2006). The replacement of fish meal with Antarctic krill, *Euphausia superba* in diets for Atlantic salmon, *Salmo salar*. *Aquacult. Nutr.* 12, 280–290. doi: 10.1111/j.1365-2095.2006.00400.x

Oser, B. (1959). "An Integrated Essential Amino Acid Index for Predicting the Biological Value of Proteins," in *Protein and Amino Acid Nutrition*, eds. A. Albanese (New York, USA: Academic Press Inc.), 281–295.

Peñaflorida, V. (1989). An evaluation of indigenous protein sources as potential component in the diet formulation for tiger prawn, *Penaeus monodon*, using essential amino acid index (EAAI). *Aquaculture* 83, 319–330. doi: 10.1016/0044-8486(89)90043-4

Riche, M. (2015). Nitrogen utilization from diets with refined and blended poultry byproducts as partial fish meal replacements in diets for low-salinity cultured Florida pompano, *Trachinotus carolinus*. *Aquaculture* 435, 458–466. doi: 10.1016/j.aquaculture.2014.10.001

Salas-Leiton, E., Hachero-Cruzado, I., Asensio, E., Vilas, C., Zerolo, R., and Cañavate, J. P. (2020). Valorisation and enhanced sustainability of Senegalese sole (*Solea senegalensis*) aquaculture by dietary use of ditch shrimp (*Palaemonetes varians*) meal. *Aquaculture* 522, 735104. doi: 10.1016/j.aquaculture.2020.735104

Samocha, T. M., Davis, D. A., Saoud, I. P., and DeBault, K. (2004). Substitution of fish meal by co-extruded soybean poultry byproduct meal in practical diets for the Pacific white shrimp, *Litopenaeus vannamei*. *Aquaculture* 231, 197–203. doi: 10.1016/j.aquaculture.2003.08.023

Sanchez-Lozano, N. B., Martínez-Llorens, S., Tomas-Vidal, A., and Jover Cerdá, M. (2011). Amino acid retention of gilthead sea bream (*Sparus aurata*, L.) fed with pea protein concentrate. *Aquacult. Nutr.* 17, e604–e614. doi: 10.1111/j.1365-2095.2010.00803.x

Sánchez-Muros, M. J., Renteria, P., Vizcaino, A., and Barroso, F. G. (2020). Innovative protein sources in shrimp (*Litopenaeus vannamei*) feeding. *Rev. Aquacult.* 12, 186–203. doi: 10.1111/raq.12312

Shan, H., Zhao, X., Zhou, Y., Wang, T., and Ma, S. (2019). Effects of freeze-dried powder of the Antarctic krill *Euphausia superba* on the growth performance, molting and fatty acid composition of the Pacific white shrimp *Litopenaeus vannamei*. *Aquac. Res.* 50, 2867–2878. doi: 10.1111/are.14240

Smith, D. M., Tabrett, S. J., Barclay, M. C., and Irvin, S. J. (2005). The efficacy of ingredients included in shrimp feeds to stimulate intake. *Aquacult. Nutr.* 11, 263–272. doi: 10.1111/j.1365-2095.2005.00349.x

Soares, R., Peixoto, S., Davis, R. P., and Davis, D. A. (2021). Feeding behavior and growth of *Litopenaeus vannamei* fed soybean-based diets with added feeding effectors. *Aquaculture* 536, 736487. doi: 10.1016/j.aquaculture.2021.736487

Sobczak, M., Panicz, R., Eljasik, P., Sadowski, J., Tórz, A., Żochowska-Kujawska, J., et al. (2021). Nutritional value and sensory properties of common carp (*Cyprinus carpio* L.) fillets enriched with sustainable and natural feed ingredients. *Food Chem. Toxicol.* 152, 112197. doi: 10.1016/j.fct.2021.112197

Storebakken, T. (1988). Krill as a potential feed source for salmonids. *Aquaculture* 70, 193–205. doi: 10.1016/0044-8486(88)90096-8

Suárez, J. A., Gaxiola, G., Mendoza, R., Cadavid, S., Garcia, G., Alanis, G., et al. (2009). Substitution of fish meal with plant protein sources and energy budget for white shrimp *Litopenaeus vannamei* (Boone, 1931). *Aquaculture* 289, 118–123. doi: 10.1016/j.aquaculture.2009.01.001

Suresh, A. V., and Nates, S. (2011). Attractability and palatability of protein ingredients of aquatic and terrestrial animal origin, and their practical value for blue shrimp, *Litopenaeus stylirostris* fed diets formulated with high levels of poultry byproduct meal. *Aquaculture* 319, 132–140. doi: 10.1016/j.aquaculture.2011.06.039

Tacon, A. G., and Metian, M. (2008). Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: trends and future prospects. *Aquaculture* 285, 146–158. doi: 10.1016/j.aquaculture.2008.08.015

Tacon, A. G., and Metian, M. (2015). Feed matters: satisfying the feed demand of aquaculture. *Rev. Fisher. Sci. Aquacult.* 23, 1–10. doi: 10.1080/23308249.2014.987209

Teruel, M. B. (2002). "Evaluation of feedstuffs and aquafeeds," in *Nutrition in Tropical Aquaculture: Essentials of fish nutrition, feeds, and feeding of tropical aquatic species,* eds. O. M. Millamena, R. M. Coloso, and F. P. Pascual (Tigbauan, Iloilo, Philippines: Aquaculture Department, Southeast Asian Fisheries Development Center), 149–168.

Teshima, S., Alam, M. S., Koshio, S., Ishikawa, M., and Kanazawa, A. (2002). Assessment of requirement values for essential amino acids in the prawn *Marsupenaeus japonicus* (Bate). *Aquac. Res.* 33, 395–402. doi: 10.1046/j.1365-2109.2002.00684.x

Tibbetts, S. M., Olsen, R. E., and Lall, S. P. (2011). Effects of partial or total replacement of fish meal with freeze-dried krill (*Euphausia superba*) on growth and nutrient utilization of juvenile Atlantic cod (*Gadus morhua*) and Atlantic halibut (*Hippoglossus hippoglossus*) fed the same practical diets. *Aquacult. Nutr.* 17, 287–303. doi: 10.1111/j.1365-2095.2010.00753.x

Traifalgar, R. F., Pagapulan, J., Valdez, M. T., Ellamar, J. B., Ocampo, E. J. C., and Ilag, L. L. (2019). Fermented sweet potato meal, a sustainable dietary protein ingredient for juvenile *Penaeus vannamei*, Boone 1931. *Israeli J. Aquacult.-Bamidgeh* 71, 111. doi: 10.46989/001c.20973

Udomkit, A., Treerattrakool, S., and Panyim, S. (2004). Crustacean hyperglycemic hormones *of Penaeus monodon*: cloning, production of active recombinant hormones and their expression in various shrimp tissues. *J. Exp. Mar. Biol. Ecol.* 298, 79–91. doi: 10.1016/j.jembe.2003.08.010

Virtue, P., Johannes, R. E., Nichols, P. D., and Young, J. W. (1995). Biochemical composition of *Nyctiphanes australis* and its possible use as an aquaculture feed source: lipids, pigments and fluoride content. *Mar. Biol.* 122, 121–128. doi: 10.1007/BF00349285

Wang, Y., Xu, Z., Li, M., Shuai, K., Lei, L., Li, X., et al. (2023). Supplemental bile acids in low fishmeal diet improved the growth, nutrient utilization of Pacific white shrimp (*Litopenaeus vannamei*). *Aquaculture Reports* 28, 101452. doi: 10.1016/j.aqrep.2022.101452

Ween, O., Stangeland, J. K., Fylling, T. S., and Aas, G. H. (2017). Nutritional and functional properties of fishmeal produced from fresh by-products of cod (*Gadus morhua* L.) and saithe (*Pollachius virens*). *Heliyon* 3:e00343. doi: 10.1016/j.heliyon.2017.e00343

Wei, Y., Chen, H., Jia, M., Zhou, H., Zhang, Y., Xu, W., et al. (2019). Effects of dietary Antarctic krill *Euphausia superba* meal on growth performance and muscle quality of triploid rainbow trout *Oncorhynchus mykiss* farmed in seawater. *Aquaculture* 509, 72–84. doi: 10.1016/j.aquaculture.2019.05.013

Wei, Y., Wang, X., Xie, F., Shen, H., Gao, W., Zhang, W., et al. (2022). Influences of replacing dietary fish meal with Antarctic krill meal on growth performance, immunity and muscle quality of white shrimp *Litopenaeus vannamei*. *Aquacult. Rep.* 25, 101256. doi: 10.1016/j.aqrep.2022.101256

Williams, K. C., Smith, D. M., Barclay, M. C., Tabrett, S. J., and Riding, G. (2005). Evidence of a growth factor in some crustacean-based feed ingredients in diets for the giant tiger shrimp *Penaeus monodon. Aquaculture* 250, 377–390. doi: 10.1016/j.aquaculture.2005.04.002

Xie, F., Zeng, W., Zhou, Q., Wang, H., Wang, T., Zheng, C., et al. (2012). Dietary lysine requirement of juvenile Pacific white shrimp, *Litopenaeus vannamei*. *Aquaculture* 358, 116–121. doi: 10.1016/j.aquaculture.2012.06.027

Ye, J. D., Liu, X. H., Kong, J. H., Wang, K., Sun, Y. Z., Zhang, C. X., et al. (2012). The evaluation of practical diets on the basis of digestible crude protein, lysine, and methionine for *Litopenaeus vannamei*. *Aquacult. Nutr.* 18, 651–661. doi: 10.1111/j.1365-2095.2011.00932.x

Yildirim-Aksoy, M., Eljack, R., Beck, B. H., and Peatman, E. (2022). Nutritional evaluation of frass from black soldier fly larvae as potential feed ingredient for Pacific white shrimp, *Litopenaeus vannamei*. *Aquacul. Rep.* 27, 101353. doi: 10.1016/j.aqrep.2022.101353

Yue, Y. R., Liu, Y. J., Tian, L. X., Gan, L., Yang, H. J., and Liang, G. Y. (2012). Effects of replacing fish meal with soybean meal and peanut meal on growth, feed utilization and haemolymph indexes for juvenile white shrimp *Litopenaeus vannamei*, Boone. *Aquac. Res.* 43, 1687–1696. doi: 10.1111/j.1365-2109.2011.02976.x

Yun, H., Shahkar, E., Hamidoghli, A., Lee, S., Won, S., and Bai, S. C. (2017). Evaluation of dietary soybean meal as fish meal replacer for juvenile whiteleg shrimp, *Litopenaeus vannamei* reared in biofloc system. *Int. Aquatic Res.* 9, 11–24. doi: 10.1007/s40071-017-0152-7

Zheng, Y., Hou, C., Chen, J., Wang, H., Yuan, H., Hu, N., et al. (2023). Integrating microbiome and transcriptome analyses to understand the effect of replacing fishmeal with *Tenebrio molitor* meal in Pacific white shrimp (*Litopenaeus vannamei*) diets. *Aquaculture* 575, 739818. doi: 10.1016/j.aquaculture.2023.739818

Zhou, Q. C., Wang, Y. L., Wang, H. L., and Tan, B. P. (2013). Dietary threonine requirements of juvenile Pacific white shrimp, *Litopenaeus vannamei*. *Aquaculture* 392, 142–147. doi: 10.1016/j.aquaculture.2013.01.026

Zhou, Q. C., Zeng, W. P., Wang, H. L., Wang, T., Wang, Y. L., and Xie, F. J. (2012). Dietary arginine requirement of juvenile Pacific white shrimp, *Litopenaeus vannamei*. *Aquaculture* 364, 252–258. doi: 10.1016/j.aquaculture.2012.08.020

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 04 April 2024
DOI 10.3389/fsufs.2024.1376112

OPEN ACCESS

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RECEIVED 24 January 2024
ACCEPTED 14 March 2024
PUBLISHED 04 April 2024

CITATION
Akter S, Haque MdA, Sarker MdA-A, Atique U, Iqbal S, Sarker PK, Paray BA, Arai T and Hossain MB (2024) Efficacy of using plant ingredients as partial substitute of fishmeal in formulated diet for a commercially cultured fish, *Labeo rohita*.
Front. Sustain. Food Syst. 8:1376112.
doi: 10.3389/fsufs.2024.1376112

Efficacy of using plant ingredients as partial substitute of fishmeal in formulated diet for a commercially cultured fish, *Labeo rohita*

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Reliance on fish meal can be reduced by incorporating plant-based ingredients, making aquaculture more economical, sustainable and environmental friendly. In this study, the efficacy of plant protein ingredients (PPI) such as mustard oil cake (MOC), soybean meal (SBM) and rice bran (RB) as Partial substitute of fishmeal (FM) was investigated for a commercially important fish, *Labeo rohita* in cages for 90 days. Three experimental diets, labeled as Diet 1, Diet 2, and Diet 3, were formulated to be isonitrogenous (with protein content ranging from 32.20 to 32.29%) and iso-caloric (with gross energy ranging from 4.12 to 4.17 kcal/g). These diets contained different proportions of PPI (45, 68, and 79%) and FM (46, 23, and 11%, respectively). Square-shaped cages with a volume of $1 m^3$ (1 m × 1 m × 1 m) were stocked with 40 fish/m^3 each with an average initial weight of 52.97 g in triplicates. Fish were hand-fed to apparent satiation twice daily for 7 days a week at a feeding rate of 5% in the initial month and 3% for the rest of the culture period. 50% of the caged fish was sampled monthly to monitor growth performance and at the termination of the experiment, all the fish was harvested to measure production economics performance. The results indicated improved growth performance and higher feed utilization at Diet 2, yielding significantly ($p < 0.05$) higher fish production compared to Diet 3, while these parameters were insignificant with Diet 1. By replacing FM with PPI, the total feed cost compared to Diet 1 was reduced to 20.62 and 32.76% for Diet 2 and Diet 3, respectively. The replacement of 50% FM in Diet 2 also yielded a 15.61% higher total economic net return than the Diet 1 group. However, a higher inclusion rate of PPI in Diet 3 potentially reduced fish growth, with a consequent decline of 41.61% total economic net return compared to the Diet 1 group. In conclusion, the replacement of 50% FM in Diet 2 compared to Diet 1 returned a higher benefit–cost ratio (1.72) among the feeding groups. Therefore, this FM replacement experiment suggested a 50% FM replaced diet as an unconventional, cost-effective, and readily available novel protein source without compromising the inherent nutritional quality of fish and feed in the cage culture of *L. rohita*. The results could be widely applicable to the fast-growing approach of cage culture technology across Asia and beyond.

KEYWORDS

feed formulation, growth metrics, proximate chemical composition, dietary protein sources, Indian major carps

Introduction

The increasing trend of fish feed cost poses a challenge in intensive culture systems (Haider et al., 2016; Iqbal et al., 2020a; Bjørndal et al., 2024), with dietary protein being identified as the costliest component in the production of manufactured fish food. Generally, the cost of feed constitutes around 56.45–58.49% of the total production expenses in aquaculture industry (Hossain et al., 2022). In specific cases, it may even escalate to 60–70% (Khan M. A. et al., 2018; Khan N. et al., 2018; Prodhan and Khan, 2018; Hossain et al., 2020a,b). This is primarily attributed to the heightened requirements for protein, contributing significantly to the overall costs. Fishmeal (FM) is widely employed as a protein source in the majority of formulated diets and is considered as the costliest component in fish diets (Moniruzzaman and Fatema, 2022). Additionally, it plays a crucial role in providing essential nutrients that promote fish growth and ensure their long-term well-being (Batool et al., 2018; Haider et al., 2018; Bjørndal et al., 2024). FM is well balanced with respect to essential amino acids, fatty acids and minerals, has a low carbohydrate content, and is free of anti-nutritional factors with high palatability and digestibility (Gatlin et al., 2007; Bhuyain et al., 2019). As a result, the rapid growth of aquaculture demands for higher FM (NRC (National Research Council), 2011). Small pelagic fishes such as anchovies, sardines, mackerel, capelin, and menhaden are known to contribute about 90% of produced FM worldwide (Tacon and Metian, 2009). However, FM resources are finite, continuous pressure on these fish species' natural stock due to overfishing is likely to increase the scarcity and price of FM in the near future (Hardy, 2008; Savonitto et al., 2021). There is also acute scarcity in the supply of FM because of the equally high demand of this protein source from other animal husbandry practices and uncertainty in collecting wild trash fish, which is the primary source of FM (Naylor et al., 2000). Therefore, a higher cost and fluctuating FM supply necessitate replacing FM with cheaper, alternative protein sources with acceptable amino acid composition (Santigosa et al., 2011; Köprücü and Sertel, 2012; Al-Thobaitia et al., 2018). In this case, the more affordable and alternative FM replacement options could include plant protein ingredients (PPI), animal byproducts, and other novel protein feedstuffs (Kishawy et al., 2021).

The effectiveness of various PPI as a partial and complete replacement of FM in aquafeeds has been investigated by several researchers (Suprayudi et al., 2015; Aziza and El-Wahab, 2019) whereas, soybean, barley, corn, cottonseed, wheat, mustard oil cake, rice bran etc. can replace FM and are widely used in aquafeeds (El-Saidy and Gaber, 2002; Gatlin et al., 2007; Zamal et al., 2008, Koumi et al., 2009, Brinker and Friedrich, 2012; Khan et al., 2013; Ibrahem and Ibrahim, 2014). However, the inclusion of PPI (>50%) are sometimes reported to reduce the growth performance compared to that of fish fed FM-based diets (Collins et al., 2013; Yaghoubi et al., 2016; Turchini et al., 2019). Because PPI are possessing anti-nutritional factors and indigestible carbohydrates, protein digestion and absorption of amino acids are less efficient in fish (Lall and Anderson, 2005). On the other hand, using only FM to the diets sometimes results in the waste of excessive protein which increases the load of nitrogen and phosphorus in the water and deteriorate the water quality in fish pond (Hardy, 2010). Study shows that the partial replacement of FM by PPI can reduce Phosphorous (Ketola and Harland, 1993) and Nitrogen excretion (as ammonia) by reducing protein levels (Cheng et al., 2003). Therefore, additional research is needed to adequately determine the inclusion rate of PPI in the partial replacement of FM in fish diet which could be readily available, cheap and environmentally friendly (Hernández et al., 2016; Hossain et al., 2021). Studies indicate that diets allowing for the partial or complete substitution of FM can be feasible through a meticulous formulation process (Espe et al., 2006; Kousoulaki et al., 2012).

Labeo rohita, locally known as rohu, is a culturally and economically significant fish species in Bangladesh, playing a vital role in aquaculture. Its vigorous biology and adaptability make it a preferred species for sustainable fish farming, contributing significantly to economic livelihoods, nutritional security, and the overall resilience of local communities (Jewel et al., 2020a; Pervin et al., 2020). The significance of developing aquaculture for *L. rohita* with low-cost feed in Bangladesh cannot be overstated as it is one of the sustainable practices. Because, by utilizing affordable feed options, aquaculture becomes more accessible to a broader spectrum of farmers, fostering widespread participation and contributing to poverty reduction. *L. rohita*, being a major cultivable species in the country, ensures that the production of this fish with low-cost feed provides an affordable protein source, positively impacting the nutritional well-being of the population. Additionally, the adoption of cost-effective feed formulations reduces the overall production costs, enhancing the competitiveness and profitability of aquaculture ventures in Bangladesh (Akter et al., 2018; Pervin et al., 2020; Jewel et al., 2023a).

In Bangladesh, high feed costs in aquaculture industry impose a significant economic burden on rural farmers, leading to reduced profitability and limiting the accessibility of aquaculture activities. Additionally, these elevated costs can contribute to food security concerns by potentially increasing fish prices and impacting the affordability of this essential protein source for local communities.

A primary factor contributing to this is the rising expense of fish feed ingredients, particularly the cost of FM in Bangladesh. Hence, replacing fish meal with plant-based protein sources has the potential to decrease costs. Considering the availability and crude protein content, a combination of Mustard oil cake (MOC), soybean meal (SBM) and rice-bran (RB) can be a suitable replacement option for FM. It is widely prevalent and extensively utilized as a component in

10.3389/fsufs.2024.1376112

aquafeed across the country. Because, mustard is one of the major oilseed crops occupying 78% of the cultivated area and contributing nearly 62% of the cultivated area of the total oilseed production in Bangladesh (Bangladesh Bureau of Statistics (BBS), 2003). MOC serves as a relatively good source of crude protein (Bhuyain et al., 2019). Additionally, it is more cost-effective compared to other oil cakes in Bangladesh. Moreover, SBM stands out as the most frequently employed plant ingredient, boasting high protein content (approximately 48% crude protein) and a relatively stable amino acid profile (Ye et al., 2019; Meng et al., 2020; Pervin et al., 2020). RB or polish, a by-product of rice, is abundantly available throughout the year in Bangladesh. Several studies also demonstrated that RB contain 13–15% protein and 11–12% lipid (Saunders, 1990; Alencar and Alvarenger, 1991; Nyirenda et al., 2000) which signifies its role as a suitable ingredient to be used for FM replacer. However, research on low-cost feed development using locally available ingredients specially using PPI for *L. rohita* culture in Bangladesh is very limited. Hence, this study aims to (i) assess the nutritional effectiveness of MOC, SBM, and RB as a replacement for FM in fish diets, (ii) investigate the economic impact of different FM replacement levels in a cage culture system (CSS), (iii) analyze the proximate composition of harvested fish for nutritional quality assessment, and (iv) conduct an economic analysis to determine the profitability of using PPI as a FM substitute in *L. rohita* culture. The insights gained from the development of low-cost aquafeeds can be extended to advance sustainable aquaculture practices for various species. This not only contributes to economic empowerment and food security but also emphasizes a commitment to responsible and inclusive aquaculture practices in Bangladesh and other developing nations.

TABLE 1 Formulation and proximate composition of experimental diets.

Ingredients (%)	Diet 1	Diet 2	Diet 3
Fishmeal	46	23	11
MOC (water treated)	0	23	35
Wheat flour	10	10	10
Rice bran	25	15	8
Soybean meal	10	20	26
Soybean oil	7	7	7
Vitamin premix[a]	1.5	1.5	1.5
Choline chloride	0.5	0.5	0.5
Vitamin E (50%)	0.1	0.1	0.1
Total	100.1	100.1	100.1
Feed formulation cost	44 BDT/kg	35 BDT/kg	31 BDT/kg
Proximate composition (Mean ± SEM)			
Crude Protein	32.29 ± 1.33	32.20 ± 1.50	32.25 ± 1.25
Lipid	9.80 ± 0.86	9.79 ± 1.01	9.73 ± 0.95
Moisture	6.33 ± 0.75	6.44 ± 0.66	6.62 ± 0.48
Ash	12.24 ± 1.03	12.21 ± 0.89	12.33 ± 1.12
Gross energy (kcal/g)	4.12 ± 0.52	4.15 ± 0.36	4.17 ± 0.46

*MOC, mustard oil cake, (Diet 1 (46% FM), Diet 2 (23% FM), and Diet 3 (11% FM). Crude protein (%) in FM = 57.26, MOC = 33.06, wheat flour = 11.80, rice bran = 14.50, soybean meal = 37.73, soybean oil = 46.30.

[a]Vitamin premix (mg/kg of premix): vitamin A-156000 IU, vitamin D3-31200 IU, vitamin E-299, vitamin K3-26, vitamin B1-32.5, vitamin B2-65, vitamin B6-520, vitamin B12-0.16, nicotinic acid-520, folic acid-10.4, copper-130, iodine-5.2, manganese-780 and selenium-1.95. Premix was supplied by Renata Animal Health Pharma Co. Ltd. Bangladesh. Gross energy calculated according to NRC (1993).

Materials and methods

Study area and installation of cages

The experiment was conducted for 90 days, from February to May 2017, in nine experimental cages at the Department of Fisheries, University of Rajshahi, Bangladesh. A total of three ponds were used for installing these nine cages, whereas each had three cages. The cages were square-shaped, with a volume of 1 m^3 (1 m × 1 m × 1 m) and built with metallic frames fully wrapped with a nylon net of 1 cm mesh size. Cages for each treatment were landed securely at a fixed place in a well-prepared fish pond with the help of bamboo poles. The cages were arranged in one column and firmly fixed by the bamboo poles set longitudinally and vertically. The cages were kept floating in pond water, keeping about 1 m distance from the pond bottom. Fish was hand-fed with a floating feeding tray attached inside each cage, facilitating the regular feeding of fish.

Feed formulation

The feed ingredients with their percent compositions used in the experimental diet formulation and per kg feed production cost of the prepared diets are shown in Table 1. The selected ingredients for this experiment were collected from the local market. The feed ingredients (finely ground and sieved) were weighed accordingly, thoroughly mixed with a mixture, moistened with water to form the dough, and pelletized using a manual food grinder with a diameter of 2 mm. Three diets were formulated with the selected ingredients. Three diets were prepared using the selected ingredients. Diet 1 contained 46% FM with a crude protein (CP) content of 32.29%. Additionally, the FM concentration in Diet 1 (46%) was decreased to 50 and 75% in Diet 2 (FM 23%) and Diet 3 (FM 11%), respectively. To compensate for the reduced CP in these two diets, various combinations of PPI were included. Diet 2 and 3 are containing 68 and 79% plant protein and are lower in animal-derived protein sources (FM 23 and 11% in diet 2 and 3, respectively). Finally, the prepared sinking pelleted feeds were sun-dried for 3 days and stored in airtight polythene bags at room temperature until feeding.

Experimental setup and fish sampling

A total of three ponds were used for this experimental setup. Three cages were used for one specific experimental diet. Each cage was considered as replicate and therefore, each experimental diet of each pond was consisting of three replicated cages positioned as a row. Three treatments were assigned as Diet 1 (FM 46%), Diet 2 (FM 23%), and Diet 3 (FM 11%). The fingerlings with an initial average body weight of 52.97 g were collected from local vendors and released at a stocking density of 40 fish/m^3 in each cage. Fish were hand-fed to apparent satiation twice daily (9:00 am and 4:00 pm) for 7 days a week throughout the study period. The feeding rate was 5% in the initial month and 3% for the rest of the culture period. Every day, feed given to the fish was weighed, and the uneaten pellets were removed from the feeding tray at least 2 h after the feed was given. The uneaten feed weight was estimated daily, and feed intake was calculated for each feeding group by subtraction between the weight of daily feed given and feed uneaten. Sampling (50% fish from each cage) was done monthly to monitor growth performance and to adjust the feeding ration accordingly. At the final harvest, all the fish in each cage were collected, their final growth and production were measured, and economics was calculated.

Proximate composition of diets and fish

Diets and fish muscles were analyzed to measure crude protein, lipid, moisture, ash, and carbohydrate according to the steps followed by the Association of Official Analytical Chemists (AOAC (Association of Official Analytical Chemists), 2005). Ten fish were initially used for the analysis of proximate composition. Protein, lipid, moisture and ash content of the stocked fish were 11.07, 2.40, 84.60, and 1.07%, respectively. Furthermore, at final harvest, three fish were randomly selected from each feeding group, weighed, and sacrificed and the muscle tissue was collected. Crude protein was determined by the Kjeldahl method using the automatic Kjeldahl system; lipid by petroleum ether extraction using the Soxhlet method; ash by combustion at 550°C for 24 h, moisture by oven drying at 105°C for 24 h to a constant weight. A bomb calorimeter was used to determine the gross energy content of the diet. All the samples were analyzed in triplicates. The proximate composition of the formulated diets analyzed in the present study is presented in Table 1.

Water quality monitoring

Water quality parameters *viz.* water temperature (WT), hydrogen ion concentration (pH), dissolved oxygen (DO), ammonia (NH_3), and total alkalinity (TA) were studied fortnightly between 9:00 am to 10:00 am. WT was recorded with the help of a Celsius thermometer, while pH was measured using a pH indicator paper (Lojak). However, DO, TA and NH_3 concentrations were determined with the water quality testing kit (HACH kit FF-2, United States).

Fish growth and production performances

After 90 days of the culture, all fish biomass was harvested from the cages. The following parameters were used to monitor fish growth and production performance during the sampling and after the harvesting.

$$\text{Weight gain}\,(g) = \text{Mean final weight}\,(g) - \text{Mean initial weight}\,(g)$$

$$\text{Specific growth rate}\,(\text{SGR\%, bw / d}) = \frac{\left[\begin{array}{c} Ln(finalweight) - \\ Ln(initialweight) \end{array}\right]}{Cultureperiod(day)} \times 100$$

$$\text{Feed conversion ratio (FCR)} = \frac{\text{Feed fed (dry weight)}}{\text{Live weight gain}\,(g)}$$

$$\text{Protein efficiency ratio (PER)} = \frac{\text{Live weight gain}\,(g)}{\text{Crude protein fed}\,(\text{g dry weight})}$$

$$\text{Survival rate}\,(\%) = \frac{\text{No.of fish harvested}}{\text{No.of fish stocked}} \times 100$$

$$\text{Yield}\,\left(kg / m^3\right) = \text{Weight of fish harvested}$$

Economic analysis

An economic analysis was performed to estimate the net economic return and benefit–cost ratio of the experimental diets used for the culture of *L. rohita* in CCS. The prices were expressed in Bangladesh Taka (BDT). The unit cost for cage preparation was BDT 150. Fingerlings were purchased as BDT 6/pieces while the selling price was BDT 200/kg in Diet 1, Diet 2, and BDT 180/kg in Diet 3. The following equation was used according to Asaduzzaman et al. (2010).

$$R = I - (FC + VC)$$

Where, R = net economic return, I = income from *L. rohita* sale, FC = fixed/common costs, VC = variable costs.

The benefit–cost ratio was determined as:

$$\text{Benefit} - \text{cost ratio (BCR)} = \text{Total economic return / Total cost}$$

Statistical analysis

The data obtained were presented as means ± standard deviation (SD). One-way analysis of variance (ANOVA) was performed using SPSS (Statistical Package for Social Science, ver. 20.0) to determine the effect of diets in different treatments. Detected differences were compared by Duncan's multiple range test (DMRT), considering a significance level of $p < 0.05$. The percentages and ratios were analyzed using arcsine transformed data before conducting the one-way analysis of variance (ANOVA).

Results

Growth performance evaluation

The growth performance of *L. rohita* fed on varying fish feeds based on FM concentrations reared in triplicate treatments is shown in Table 2. The fish growth increment comparison based on monthly intervals is presented in Figure 1. The growth of *L. rohita* varied significantly among the Diets, with Diet 2 fed group showing a significantly higher final weight (153.62 ± 2.18 g) gain in comparison with Diet 3 group (129.50 ± 6.09 g). The maximum weight gain (101.30 ± 3.02 g) in *L. rohita* was observed in Diet 2 group, nonetheless, showing significant difference from Diet 3 group. Similarly, a significantly ($p < 0.05$) higher SGR was observed in Diet

TABLE 2 Growth performance of *L. rohita* in different feeding groups.

Parameters	Diet 1	Diet 2	Diet 3	*P*-value
Initial weight (g)	53.60 ± 1.59^{a}	52.32 ± 1.30^{a}	53.00 ± 1.91^{a}	0.648
Final weight (g)	151.91 ± 2.09^{a}	153.62 ± 2.18^{a}	129.50 ± 6.09^{b}	0.000
Weight gain (g)	98.31 ± 2.48^{a}	101.30 ± 3.02^{a}	76.50 ± 4.88^{b}	0.000
SGR (%/day)	1.16 ± 0.03^{a}	1.20 ± 0.04^{a}	0.99 ± 0.04^{b}	0.001
Survival rate (%)	95.83 ± 1.44^{a}	95.00 ± 2.50^{a}	94.17 ± 2.89^{a}	0.702

Mean values with the same superscript in the same row indicate non-significant differences ($P < 0.05$).

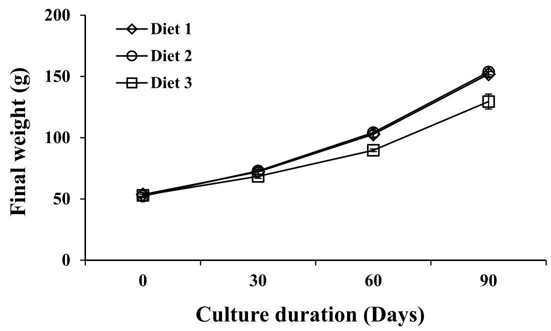

FIGURE 1
Final weights (g) of *L. rohita* in different months of the experimental trial. Diet 1 (46% FM), Diet 2 (23% FM), and Diet 3(11% FM).

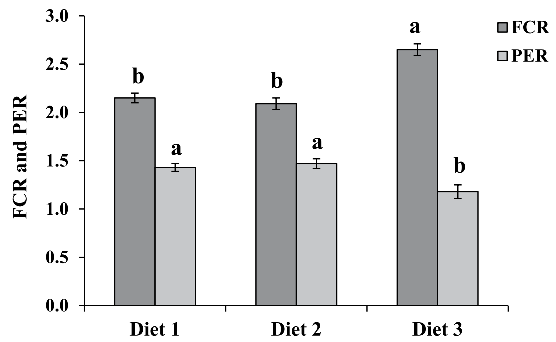

FIGURE 2
Feed conversion ratio (FCR) and protein efficiency ratio (PER) of *L. rohita* in different feeding groups. Different superscript letter indicates significant difference. Diet 1 (46% FM), Diet 2 (23% FM), and Diet 3 (11% FM).

2 (1.20 ± 0.04% bw/day) followed by Diet 1 (1.16 ± 0.03% BW/day) and Diet 3 (0.99 ± 0.04% BW/day). However, final weight, weight gain and SGR were showing insignificant differences among the Diet 1 and Diet 2 group. Furthermore, the survival of fish did not vary significantly among the treatments.

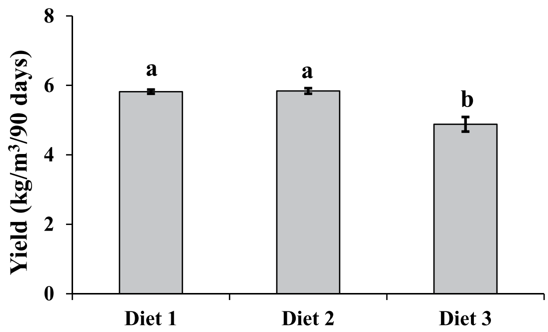

FIGURE 3
Yield of *L. rohita* in different feeding groups. Different superscript letter indicates significant difference. Diet 1 (46% FM), Diet 2 (23% FM), and Diet 3 (11% FM).

Feed utilization

Feed utilization parameters examined for the experimental treatments are shown in Figure 2. During this study, FCR was significantly lower in Diet 2 group (2.09 ± 0.06) followed by Diet 1 (2.15 ± 0.05) and Diet 3 (2.65 ± 0.06). Furthermore, the FM replacement in the different treatments significantly affected PER of fish. A considerably higher PER was recorded in Diet 2 (1.47 ± 0.05) and lower in Diet 3 (1.18 ± 0.07).

Fish yield

During the present study, the highest yield was obtained from Diet 2 group (5.84 ± 0.08 kg/m^3/90 days), followed by the Diet 1 (5.82 ± 0.06 kg/m^3/90 days) and Diet 3 group (4.88 ± 0.21 kg/m^3/90 days). There was no significant difference ($p < 0.05$) between the yields of the Diet 1 and Diet 2 group, while the yield of *L. rohita* in Diet 3 group was significantly different from both treatments (Figure 3).

Proximate composition of fish

The final carcass composition assessment of fish fed on different feed types formulated with varying levels of FM replacement is presented in Table 3. There were no significant differences ($p < 0.05$) between Diet 1 and Diet 2 group, while Diet 3 group was significantly different ($p < 0.05$) from Diet 1 and Diet 2 groups. The protein and lipid contents were higher in the Diet 1 group (14.45 ± 0.27 and 4.85 ± 0.04%) followed by Diet 2 (14.38 ± 0.06 and 4.78 ± 0.03%) and Diet 3 group (13.68 ± 0.02 and 4.36 ± 0.05%), respectively. However, the moisture content turned out to be significantly ($p < 0.05$) higher in Diet 3 (80.14 ± 0.25%) and lower in Diet 1 (79.13 ± 0.36). In the same pattern, the ash content was significantly higher in Diet 3 (1.48 ± 0.02%) and lower in Diet 1 (1.24 ± 0.02%). However, the carbohydrates did not vary considerably among the treatments.

TABLE 3 Proximate composition of *L. rohita* in different feeding groups.

Parameters	Diet 1	Diet 2	Diet 3	*P*-value
Protein (%)	14.45 ± 0.27[a]	14.38 ± 0.06[a]	13.68 ± 0.02[b]	0.003
Lipid (%)	4.85 ± 0.04[a]	4.78 ± 0.03[b]	4.36 ± 0.05[c]	0.006
Ash (%)	1.24 ± 0.02[c]	1.38 ± 0.02[b]	1.48 ± 0.02[a]	0.000
Moisture (%)	79.13 ± 0.36[b]	79.46 ± 0.18[b]	80.14 ± 0.25[a]	0.011

Mean values with the same superscript in the same row indicate insignificant differences ($p > 0.05$).

TABLE 4 Benefit–cost analysis of *L. rohita* in different feeding groups after 90 days of culture period.

Variables	Price rate (BDT*)	Diet 1	Diet 2	Diet 3
Fixed cost				
Net cage (1 m^3)		649.98	649.98	649.98
Other materials cost for cage supporting (bamboo, rope, anchors, bricks)	150 BDT/unit	150.00	150.00	150.00
Subtotal		799.98	799.98	799.98
Cost in one cycle**		133.33	133.33	133.33
Variable cost				
Fish fingerling	6 BDT/pieces	240.00	240.00	240.00
Feed cost	Diet 1 = 44 BDT/kg; Diet 2 = 35BDT/kg; Diet 3 = 31 BDT/kg	354.20	281.75	238.39
Labor and fish harvesting		25.00	25.00	25.00
Total cost		752.53	680.08	636.72
Financial return				
Fish sale as the total return		1164.52[b]	1167.23[a]	877.61[b]
Total net return		411.99[b]	487.15[a]	240.89[c]
BCR		1.55[b]	1.72[a]	1.38[c]

Mean values with the same superscript in the same row indicate non-significant differences ($P > 0.05$).
*BDT, Bangladeshi Taka, 1 USD = BDT 84.72 (2017). The market price of L. rohita was BDT 200/kg in Diet 1, Diet 2 and BDT 180/kg in Diet 3.
**Assuming durability of each cage for six culture cycles.

Economic performance evaluation

A comparison of economic returns from the fish groups treated with varying degrees of FM replacement is shown in Table 4. The highest cost was estimated from the Diet 1 group (BDT 752.53), followed by Diet 2 (BDT 680.08) and Diet 3 group (BDT 636.72). However, significantly higher total economic return as the fish sale of Diet 2 (BDT 1167.23) followed by Diet 1 (BDT 1164.52) and Diet 3 (BDT 877.61). The total net economic return was significantly higher in Diet 2 (BDT 487.15), while the lowest was Diet 3 (BDT 240.89). Furthermore, the Diet 2 group provided a considerably higher BCR (1.72) than the other two treatments.

Water quality assessment

The mean values of water quality parameters recorded from the three experimental treatments during the study period are displayed in Table 5. Formulation of feed based on varying replacement levels of FM did not affect the water quality of CCS, indicating no significant impact of increased plant protein on the suitability of water quality.

Discussion

This study attempted to investigate replacing FM with PPI for *L. rohita* reared in CCS. Significantly higher finishing weight of fish was achieved in Diet 2 group and lower in Diet 3. Weight gain and SGR alluded to substantially higher performance in Diet 2 that declined in, Diet 3. The replacement of animal protein sources (FM) up to a certain level with plant protein sources was not detrimental, as was evident in the findings of Furuya et al. (2004) and Lin and Luo (2011). Even a 50% replacement of FM in diets has been reported to be favorable for the overall fish growth performance (Viola et al., 1982; Jahan et al., 2012). However, replacing 75% animal-source protein reduced fish growth in the present experiment in Diet 3. Incorporating PPI higher than the sub-optimal level might negatively affect fish growth. Although, we have not measured the level of anti-nutritional factors (ANFs) present in PPI in our study. However, we presume that the greater PPI might increase toxic components (ANFs) and imbalance the amino acid profile responsible for intestinal irritation and reduced growth (Olvera-Novoa et al., 2002). This understanding corroborates the earlier outcomes by Hua and Bureau (2012), who opposed the total replacement of FM protein with plant protein as it could be detrimental to the cultured organisms. Complete FM

TABLE 5 Water quality parameters in different feeding groups (Mean ± SD).

Parameters	Diet 1	Diet 2	Diet 3	*p*-value
Temperature (°C)	25.78 ± 0.09[a]	25.86 ± 0.15[a]	25.96 ± 0.10[a]	0.236
pH	7.04 ± 0.02[a]	7.04 ± 0.05[a]	7.05 ± 0.03[a]	0.990
DO (mg/l)	5.07 ± 0.05[a]	5.02 ± 0.05[a]	5.08 ± 0.04[a]	0.344
NH_3 (mg/l)	0.13 ± 0.01[a]	0.13 ± 0.00[a]	0.12 ± 0.01[a]	0.252
Total alkalinity (mg/l)	79.99 ± 0.70[a]	80.50 ± 1.28[a]	80.61 ± 0.65[a]	0.695

Mean values with the same superscript in the same row indicate insignificant differences ($P > 0.05$).

replacement is also reported to decrease protease activities in the intestine and hepatopancreas in Juvenile Tilapia (Lin et al., 2010). Jalili et al. (2013) also found reduced digestive enzyme activities and subsequent lower growth in rainbow trout fed the diet with 75 and 100% FM replacement. In the present study, 75% replacement of FM by PPI in Diet 3 may be the reason for the reduced growth performance of *L. rohita* to the other treatments.

The proportion of protein and non-protein energy sources is necessary while preparing a balanced diet. An excess protein in the diet causes higher ammonia, affecting fish growth performance (Kaushik and Medale, 1994). When adequate non-protein energy sources are available in the diet, it could minimize the use of protein as an energy source and enhance fish's growth performance (Iqbal et al., 2020b). Carps are the most efficient exploiters of carbohydrates (Kumar et al., 2005). The intrusion of carbohydrates in the form of PPI in Diet 2 could impart a protein-sparing effect that may enhance the feed utilization by fish. The protein-sparing effect of suboptimal levels of carbohydrates was also reported in silver barb by Mohanta et al. (2007). An appropriate level of carbohydrate in the diet can reduce protein degradation and amino acid oxidation which results in improved growth (Frick et al., 2008). However, several studies also reported that dietary carbohydrate beyond the optimal level can cause lower growth and feed utilization in fish (Tan et al., 2009; Gao et al., 2010; Yu et al., 2022). Therefore, lower growth and feed utilization in Diet 3 group was lower despite of the higher carbohydrate level. Therefore, replacing FM in the diet did not affect fish survival. Jahan et al. (2007) found no significant difference between the treatments regarding survival rate in a partial replacement experiment of FM with SBM for the fry of *Cirrhinus cirrhosus*. Replacement of FM in fish diets can significantly affect the total fish yield, whereas the higher production was recorded in Diet 2 group with a 50% replacement of FM. However, the higher inclusion rate of PPI in Diet 3 caused a significant reduction in the total yield.

The FCR decreased in the fish of Diet 2 compared to the Diet 1 fish and increased significantly in Diet 3. The earlier investigations have argued that low FCR indicates higher feed utilization efficiency, balancing bioavailability and partitioning dietary nutrients toward growth (Angelidis et al., 2005). Zamal et al. (2009) reported a high-energy diet produced a lower FCR and higher nutrient retention in the fish body. Therefore, 50% FM replacement in feed increased the feed efficiency, but it decreased in growing proportion for PPI in the feed (Diet 3). The present findings are supported by the conclusions of Devi et al. (1999), who reported relatively better (lower) FCR in *L. rohita* fingerlings fed on a diet including 20% SBM.

Similarly, they found a higher FCR while increasing the proportion of SBM up to 40 and 60%. PER is related to the dietary protein intake and its conversion into fish weight gain (Koumi et al., 2009). The fish fed on varying levels of a FM replacement diet showed a significantly higher PER in Diet 2 and lower in Diet 3. The lower PER obtained in Diet 3 might be due to the imbalance of amino acid profile as affected by the higher inclusion rate of PPI, which was also supported by Espe et al. (2008). Plant protein sources generally have lower biological value and palatability properties (Estevez et al., 2011), which may be responsible for lower feed utilization in Diet 3 group. However, a balanced proportion of FM and PPI in Diet 2 might provide essential amino acids and increase fish feed utilization. The study by Espe et al. (2006, 2010) and Estevez et al. (2011) also showed that the palatability of a plant protein-based diet could be enhanced by adding essential amino acids and other animal proteins protein sources.

Replacement of 50 and 75% FM in Diet 2 and Diet 3 resulted in a 20.62 and 32.76% reduction in total feed cost, while 15.61% higher net economic return was obtained from Diet 2 compared to the Diet 1 group. A study conducted by Khan et al. (2013) reported that 24% of feed formulation costs could be reduced by the replacement of FM with rice polish (up to 20%) and MOC (up to 22%) without changing the nutritional quality in an experiment on *Oreochromis niloticus*. However, a higher inclusion rate of PPI in Diet 3 reduced the fish growth and subsequent reduction of 41.61% net economic return compared to Diet 1 in the present study. Finally, the replacement of 50% FM provided a higher BCR (1.72) compared to the other treatments. Apart from fish feed types, various environmental factors such as water temperature, turbidity, pH and ammonia play a crucial role in the CSS that must be considered (Ara et al., 2020, 2023; Jewel et al., 2020b, 2023b; Bashak et al., 2021).

Replacement of fish meal with FM at different levels significantly impacted the muscle protein and lipid content of *L. rohita*. Fish in Diet 2 retained a higher protein level compared to other treatments. However, lipid content was reduced considerably in Diet 3 compared to the Diet 1 group, potentially due to a higher inclusion rate of PPI in the diet. A similar observation by Devi et al. (1999) has reported higher protein and lower lipid levels in the muscle tissues of *L. rohita* fingerlings fed with a plant protein-based diet (SBM-based rations) compared to the Diet 1 group (0% SBM). Contradictory results were observed by Khan M. A. et al. (2018) and Khan N. et al. (2018). They reported that incorporating plant protein by replacing FM did not significantly affect the whole-body composition of Indian major carps, *Catla catla*, *L. rohita* and *C. cirrhosus.* A significant effect of FM replacement on the proximate composition of fish during the present study may be linked to anti-nutritional factors in PPI, although several studies reported the influence of FM replacement with plant protein sources on the proximate composition of fish (Olli and Krogdahl, 1995; Elangovan and Shim, 2000).

Conclusion

The present study affirmed that 50% replacement of FM by PPI could be economically efficient in reducing the feed formulation cost by approximately 20.45% without changing the proximate composition (nutritional quality) of *L. rohita* reared in the CSS. A replacement of 50% FM with PPI also increased the total net return by 15.61%, which was the most economical among all the experimental treatments for the cage culture of *L. rohita* in ponds. This study can also be extended to other leading aquaculture fish species to test the potential of using PPI as an alternative protein source of FM to reduce the increasing pressure on FM demand. This approach aligns with sustainable practices by promoting environmentally friendly alternatives and encouraging knowledge-sharing among practitioners. Therefore, the development of aquaculture for *L. rohita* using low-cost feed will not only supports economic empowerment and food security but also embodies a commitment to responsible and inclusive aquaculture practices in Bangladesh or other developing nations. However, in the current investigation, ANFs of PPI were not examined, which may restrict the acceptability of the designed diet. As a result, the current study recommends that the PPI's ANFs be examined before to their usage in feed composition.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

The animal study was approved by University of Rajshahi, Bangladesh. The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

SA: Data curation, Writing – original draft. AH: Data curation, Writing – original draft. A-AS: Supervision, Writing – review & editing. UA: Software, Writing – review & editing. SI: Software, Writing – review & editing. PS: Data curation, Funding acquisition, Writing – review & editing. BP: Writing – review & editing. TA: Writing – review & editing. MH: Resources, Software, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This study was supported by Researchers Supporting Project Number (RSP2024R144), King Saud University, Riyadh, Saudi Arabia.

Acknowledgments

The authors are grateful for financial support from the National Science and Technology Fellowship from the Ministry of Science and Technology, The Government of People's Republic of Bangladesh. The authors would like to extend their sincere appreciation to the Researchers Supporting Project Number (RSP2024R144), King Saud University, Riyadh, Saudi Arabia.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

References

Akter, N., Alam, M. J., Jewel, M. A. S., Haque, M. A., Khatun, S., and Akter, S. (2018). Evaluation of dietary metallic iron nanoparticles as feed additive for growth and physiology of Bagridae catfish *Clarias batrachus* (Linnaeus, 1758). *Int. J. Fish. Aquat. Stud.* 6, 371–377.

Alencar, M. C., and Alvarenger, C. B. B. D. (1991). Rice bran-1 chemical composition and its potential as food. *Arquivos de Biologia Technol* 34, 95–108.

Al-Thobaitia, K., Al-Ghanima, Z., Ahmeda, E. M., and Sulimana, M. S. (2018). Impact of replacing fish meal by a mixture of different plant protein sources on the growth performance in Nile Tilapia (*Oreochromis niloticus* L.) diets. Braz. *J. Biol.* 78, 525–534. doi: 10.1590/1519-6984.172230

Angelidis, P., Pournara, I., and Photis, G. (2005). Glass eels (*Anguilla anguilla*) growth in a recirculating system. *Medit. Mar. Sci.* 6, 99–106. doi: 10.12681/mms.196

AOAC (Association of Official Analytical Chemists) (2005) *Official methods of analysis* (*16th ed.*). Association of Official Analytical Chemists, Arlington, Virginia.

Ara, J., Hossain, M. S., Jewel, M. A. S., and Haque, M. A. (2023). Production and economics of Gangetic mystus (*Mystus cavasius*) farming under different feed restriction periods in cages of floodplain ecosystem. *J. Fish.* 11:113203. doi: 10.17017/j.fish.580

Ara, J., Jewel, M. A. S., Hossain, M. A., Haque, M. A., and Siddique, M. A. B. (2020). Determination of suitable species for cage fish farming in Chalan beel, Bangladesh. *Int. J. Fish. Aquat. Stud.* 8, 315–320.

Asaduzzaman, M., Wahab, M. A., Verdegem, M. C. J., Adhikary, R. K., Rahman, S. M. S., Azim, M. E., et al. (2010). Effects of carbohydrate source for maintaining a high C:N ratio and fish driven re-suspension on pond ecology and production in periphyton-based freshwater prawn culture systems. *Aquaculture* 301, 37–46. doi: 10.1016/j.aquaculture.2010.01.025

Aziza, A., and El-Wahab, A. A. (2019). Impact of partial replacing of dietary fish meal by different protein sources on the growth performance of Nile Tilapia (*Oreochromis niloticus*) and whole body composition. *J. Appl. Sci.* 19, 384–391. doi: 10.3923/jas.2019.384.391

Bangladesh Bureau of Statistics (BBS) (2003) *Government of the People's republic of Bangladesh, agricultural survey system, chapter 6 yearbook 2003 BBS*, Dhaka, Bangladesh: Bangladesh Government, Dhaka.

Bashak, S. K., Paul, A. K., Hossain, M. A., Atique, U., Iqbal, S., Uddin, M. N., et al. (2021). Growth performance and culture economics of mud eel semi-intensively cultured under varying stocking densities in rain-fed earthen ponds. *Punjab Univ. J. Zool.* 36, 101–110. doi: 10.17582/JOURNAL.PUJZ/2021.36.1.101.110

Batool, S. S., Khan, N., Atique, U., Azmat, H., Iqbal, K. J., Mughal, D. H., et al. (2018). Impact of Azomite supplemented diets on the growth and body composition of catfish (*Pangasius hypophthalmus*). *Pak. J. Zool.Suppl.* 13, 08–12.

Bhuyain, M. A. B., Hossain, M. I., Haque, M. A., Jewel, M. A. S., Hasan, J., and Akter, S. (2019). Determination of the proximate composition of available fish feed ingredients in Bangladesh. *Asian J. Agricul.t Res.* 13, 13–19. doi: 10.3923/ajar.2019.13.19

Bjørndal, T., Dey, M., and Tusvik, A. (2024). Economic analysis of the contributions of aquaculture to future food security. *Aquaculture* 578:740071. doi: 10.1016/j.aquaculture.2023.740071

Brinker, A., and Friedrich, C. (2012). Fish meal replacement by plant protein substitution and guar gum addition in trout feed. Part II: effects on faeces stability and rheology. *Biorheology* 49, 27–48. doi: 10.3233/BIR-2012-0605

Cheng, Z. J., Hardy, R. W., and Usry, J. L. (2003). Plant protein ingredients with lysine supplementation reduce dietary protein level in rainbow trout (*Oncorhynchus mykiss*) diets, and reduce ammonia nitrogen and soluble phosphorus excretion. *Aquacult* 218, 553–565. doi: 10.1016/S0044-8486(02)00502-1

Collins, S. A., Øverland, M., Skrede, A., and Drew, M. D. (2013). Effect of plant protein sources on growth rate in salmonids: Meta-analysis of dietary inclusion of soybean, pea and canola/rapeseed meals and protein concentrates. *Aquacult* 400-401, 85–100. doi: 10.1016/j.aquaculture.2013.03.006

Devi, C., Vijayaraghavan, S., and Srinvasulu, C. (1999). Effect of soybean meal (*Glycine max*) feeding on the bio-chemical composition of *Labeo rohita* fingerlings. *J. Aquacult. Trop.* 14, 181–185.

Elangovan, A., and Shim, K. F. (2000). The influence of replacing fish meal partially in the diet with soybean meal on growth and body composition of juvenile tin foil barb (*Barbodes altus*). *Aquaculture* 189, 133–144. doi: 10.1016/S0044-8486(00)00365-3

El-Saidy, D. M. S., and Gaber, M. M. A. (2002). Complete replacement of fish meal by soybean meal with dietary l-lysine supplement for Nile tilapia *Oreochromis niloticus*, fingerlings. *World Aquacult. Soci.* 33, 297–306. doi: 10.1111/j.1749-7345.2002.tb00506.x

Espe, M., Hevroy, E. H., Liaset, B., Lemme, A., and El-Mowafi, A. (2008). Methionine intake affect hepatic Sulphur metabolism in Atlantic salmon, *Salmo salar*. *Aquaculture* 274, 132–141. doi: 10.1016/j.aquaculture.2007.10.051

Espe, M., Lemme, A., Petri, A., and El-Mowafi, A. (2006). Can Atlantic salmon (*Salmo salar*) grow on diets devoid of fish meal? *Aquaculture* 255, 255–262. doi: 10.1016/j.aquaculture.2005.12.030

Espe, M., Mansingh, R. R., Du, Z. Y., Liaset, B., and El-Mowafi, A. (2010). Methionine limitation results in increased hetaptic FAS activity, higher liver 18:1 to 18:0 fatty acid ratio and hepatic TAG accumulation in Atlantic salmon, Salmo salar. *Amino Acids* 39, 449–460. doi: 10.1007/s00726-009-0461-2

Estevez, A., Trevino, L., Kotzamanis, Y., Karacostas, I., Tort, L., and Gisbert, E. (2011). Effects of different levels of plant proteins on the ongrowing of meagre (*Argyrosomus regius*) juveniles at low temperatures. *Aquacult. Nutri.* 17, e572–e582. doi: 10.1111/j.1365-2095.2010.00798.x

Frick, N. T., Bystriansky, J. S., Ip, Y. K., Chew, S. F., and Ballantyne, J. S. (2008). Carbohydrate and amino acid metabolism in fasting and aestivating African lungfish (*Protopterus dolloi*). *Comp. Biochem. Physiol. A Mol. Integr. Physiol.* 151, 85–92. doi: 10.1016/j.cbpa.2008.06.003

Furuya, W. M., Pezzato, L. E., Barros, M. M., Pezzato, A. C., Furuya, V. R. B., and Miranda, E. C. (2004). Use of ideal protein concept for precision formulation of amino acid levels in fish-meal-free diets for juvenile Nile tilápia (*Oreochromis niloticus* L.). *Aquac. Res.* 35, 1110–1116. doi: 10.1111/j.1365-2109.2004.01133.x

Gao, W., Liu, Y. J., Tian, L. X., Mai, K. S., Liang, G. Y., Yang, H. J., et al. (2010). Effect of dietary carbohydrate-to-lipid ratios on growth performance, body composition, nutrient utilization and hepatic enzymes activities of herbivorous grass carp (*Ctenopharyngodon idella*). *Aquac. Nutr.* 16, 327–333. doi: 10.1111/j.1365-2095.2009.00668.x

Gatlin, D. M., Barrows, F. T., Brown, P., Dabrowski, K., Gaylord, T. G., Hardy, R. W., et al. (2007). Expanding the utilization of sustainable plant products in aqua feeds: a review. *Aquac. Res.* 38, 551–579. doi: 10.1111/j.1365-2109.2007.01704.x

Haider, M. S., Ashraf, M., Azmat, H., Khalique, A., Javid, A., Atique, U., et al. (2016). Nutritive evaluation of fish acid silage in *Labeo rohita* fingerlings feed. *J. Appl. Anim. Res.* 44, 158–164. doi: 10.1080/09712119.2015.1021811

Haider, M. S., Javid, A., Azmat, H., Abbas, S., Ashraf, S., Altaf, M., et al. (2018). Effect of processed fish waste on growth rate and digestive enzymes activities in *Cyprinus carpio*. *Pak. J. Zool. Suppl.* 13, 191–198.

Hardy, R. W. (2008). "Utilization of plant proteins in fish diets; effects of global demand and supplies of grains and oilseeds" in *Resource management: natural, human and material resources for the sustainable development of aquaculture* (Krakow, Poland: Aquaculture Europe 2008)

Hardy, R. W. (2010). Utilization of plant proteins in fish diets: effects of global demand and supplies of fish meal. *Aquac. Res.* 41, 770–776. doi: 10.1111/j.1365-2109.2009.02349.x

Hernández, C., González-Santos, A., Valverde-Romero, M., González-Rodríguez, B., and Domínguez-Jiménez, P. (2016). Partial replacement of fishmeal with meat and bone meal and tuna byproducts meal in practical diets for juvenile spotted rose snapper *Lutjanus guttatus*. *Lat. Am. J. Aquat. Res.* 44, 56–64. doi: 10.3856/vol44-issue1-fulltext-6

Hossain, M. M., Ali, M. L., Khan, S., Haque, M. M., and Shahjahan, M. (2020a). Use of Asian watergrass as feed of grass carp. *Aquac. Rep.* 18:100434. doi: 10.1016/j.aqrep.2020.100434

Hossain, M. A., Hossain, M. A., Haque, M. A., Harun-Ur-Rashid, M., and Rahman, M. M. (2021). Optimization of dietary protein level for good aquaculture practice based carp fattening in ponds under drought prone area of Bangladesh. *Arch. Agri. Environ. Sci.* 6, 26–34. doi: 10.26832/24566632.2021.060104

Hossain, M. A., Hossain, M. A., Haque, M. A., Mondol, M. M. R., Rashid, M. H. U., and Das, S. K. (2022). Determination of suitable stocking density for good aquaculture practice-based carp fattening in ponds under drought-prone areas of Bangladesh. *Aquaculture* 547:737485. doi: 10.1016/j.aquaculture.2021.737485

Hossain, M. M., Rahman, M. H., Ali, M. L., Khan, S., Haque, M. M., and Shahjahan, M. (2020b). Development of a low-cost polyculture system utilizing *Hygroryza aristata* floating grass in the coastal wetlands of Bangladesh. *Aquaculture* 527:735430. doi: 10.1016/j.aquaculture.2020.735430

Hua, K., and Bureau, D. P. (2012). Exploring the possibility of quantifying the effects of plant protein ingredients in fish feeds using meta-analysis and nutritional model simulation-based approaches. *Aquaculture* 356-357, 284–301. doi: 10.1016/j.aquaculture.2012.05.003

Ibrahem, M. D., and Ibrahim, M. A. (2014). The potential effects of Spirulina platensis (*Arthrospira platensis*) on tissue protection of Nile tilapia (*Oreochromis niloticus*) through estimation of P53 level. *J. Adv. Res.* 5, 133–136. doi: 10.1016/j.jare.2013.03.009

Iqbal, S., Atique, U., Mahboob, S., Haider, M. S., Iqbal, H. S., al-Ghanim, K. A., et al. (2020a). Effect of supplemental selenium in fish feed boosts growth and gut enzyme activity in juvenile Tilapia (*Oreochromis niloticus*). *J. King Saud. Univ. Sci.* 32, 2610–2616. doi: 10.1016/j.jksus.2020.05.001

Iqbal, S., Atique, U., Mughal, M. S., Younus, M., Rafique, M. K., Iqbal, H. S., et al. (2020b). Selenium-supplemented diet influences histological features of liver and kidney in Tilapia (*Oreochromis niloticus*). *Jordan J. Biol. Sci.* 13, 453–461.

Jahan, D. A., Hussain, L., and Islam, M. A. (2007). Partial replacement of fishmeal protein by soybean meal protein in the diet of mrigal, *Cirrhinus cirrhosus* (ham.) fry. *Bangladesh. Fish Res.* 11, 181–188.

Jahan, D. A., Hussain, L., Islam, M. A., Khan, M. M., and Nima, A. (2012). Use of soybean meal as partial substitute of fish meal in the diets of *L. rohita*, *Labeo rohita* (ham.) fry. *Agriculture* 10, 68–76. doi: 10.3329/agric.v10i2.13143

Jalili, R., Tukmechi, A., Agh, N., Noori, F., and Ghasemi, A. (2013). Replacement of dietary fish meal with plant sources in rainbow trout (*Oncorhynchus mykiss*); effect on growth performance, immune responses, blood indices and disease resistance. *Iranian J. Fish Sci.* 12, 577–591.

Jewel, M. A. S., Ara, J., Haque, M. A., Hossain, M. A., Noorashikin, M. N., and Das, S. K. (2023b). Effect of stocking density on the growth, body composition, and blood parameters of cage-reared Gangetic mystus catfish (*Mystus cavasius*). *Aquac. Rep.* 28:101428. doi: 10.1016/j.aqrep.2022.101428

Jewel, M. A. S., Haque, M. A., Pervin, M. E., Akter, S., Ali, S. M. W., Noorashikin, M. N., et al. (2023a). Regulatory mechanisms of nutrient metabolism and the impacts of iron and zinc nanoparticles on growth and physiology of Rohu, *Labeo rohita*. *Anim. Feed Sci. Technol.* 304:115759. doi: 10.1016/j.anifeedsci.2023.115759

Jewel, M. A. S., Hossain, M. I., Haque, M. A., Sarker, M. A. A., Khatun, M. S., Nesa, A., et al. (2020b). A semi intensive approach on growth and profit margin of Indian major carps (*Catla catla*, Labeo rohita and *Cirrhinus cirrhosus*) with cost effective standard feed formulation. *AACL Bioflux* 13, 183–193.

Jewel, M. A. S., M. W. Ali, S., Haque, M. A., U. Ahmed, M. G., Iqbal, S., Atique, U., et al. (2020a). Growth and economics of silver barb (*Barbonymus gonionotus*) in Rice-fish-vegetable integrated culture system at different stocking densities in a Rainfed arid zone. *Egypt J. Aquat. Biol. Fish.* 24, 459–476. doi: 10.21608/ejabf.2020.117948

Kaushik, S. J., and Medale, F. (1994). Energy requirement, utilization, and dietary supply to salmonids. *Aquaculture* 121, 81–97.

Ketola, H. G., and Harland, B. F. (1993). Influence of phosphorus in rainbow trout diets on phosphorus discharges in effluent water. *Trans. Am. Fish. Soc.* 122, 1120–1126. doi: 10.1577/1548-8659(1993)122<1120:IOPIRT>2.3.CO;2

Khan, N., Atique, U., Ashraf, M., Mustafa, A., Mughal, M. A., Rasool, F., et al. (2018). Effect of various protein feeds on the growth, body composition, hematology and endogenous enzymes of catfish (*Pangasius hypophthalmus*). *Pak J. Zool. Suppl.* 13, 112–119.

Khan, M. A., Guttormsen, A., and Roll, K. H. (2018). Production risk of pangas (*Pangasius hypophthalmus*) fish farming. *Aquacult. Econ. Manag.* 22, 192–208. doi: 10.1080/13657305.2017.1284941

Khan, M. S. K., Siddique, M. A. M., and Zamal, H. (2013). Replacement of fish meal by plant protein sources in Nile tilapia (*Oreochromis niloticus*) diet: growth performance and utilization. *Iranian J. Fish. Sci.* 12, 864–872.

Kishawy, A. T. Y., Assi, A. F. K., Badawi, M. E., and Hassanein, E. S. I. (2021). Performance and economic efficiency of replacing fish meal with rice protein concentrate in *Oreochromis niloticus* diets. *Adv. Anim. Vet. Sci.* 9, 246–252.

Köprücü, K., and Sertel, E. (2012). The effects of less-expensive plant protein sources replaced with soybean meal in the juvenile diet of grass carp (*Ctenopharyngodon idella*): growth, nutrient utilization and body composition. *Aquac. Int.* 20, 399–412. doi: 10.1007/s10499-011-9471-7

Koumi, A. R., Atse, B. C., and Kouame, L. P. (2009). Utilization of soya protein as an alternative protein source in *Oreochromis niloticus* diet: growth performance, feed utilization, proximate. *Afr. J. Biotechnol.* 8, 91–97.

Kousoulaki, K., Olsen, H. J., Albrektsen, S., Langmyhr, E., Mjøs, S. A., Campbell, P., et al. (2012). High growth rates in Atlantic salmon (*Salmo salar* L.) fed 7.5% fish meal in the diet. Micro-, ultra- and nanofiltration of stickwater and effects of different fractions and compounds on pellet quality and fish performance. *Aquaculture* 338–341, 134–146. doi: 10.1016/j.aquaculture.2012.01.017

Kumar, S., Sahu, N. P., Pal, A. K., Choudhury, D., Yengkokpam, S., and Mukherjee, S. C. (2005). Effect of dietary carbohydrate on haematology, respiratory burst activity and histological changes in *L. rohita* juveniles. *Fish Shellfish Immunol.* 19, 331–344. doi: 10.1016/j.fsi.2005.03.001

Lall, S. P., and Anderson, S. (2005). Amino acid nutrition of salmonids: dietary requirements and bioavailability. *Cah. Options Méditerr.* 63, 73–90.

Lin, S., and Luo, L. (2011). Effects of different levels of soybean meal inclusion in replacement for fish meal on growth, digestive enzymes and transaminase activities in practical diets for juvenile tilapia, *Oreochromis niloticus* × *O. aureus*. *Anim. Feed Sci. Technol.* 168, 80–87. doi: 10.1016/j.anifeedsci.2011.03.012

Lin, S., Mai, K., Tan, B., and Liu, W. (2010). Effects of four vegetable protein supplementation on growth, digestive enzyme activities, and liver functions of juvenile Tilapia, *Oreochromis niloticus* × *Oreochromis aureus*. *J. World Aquacult. Soc.* 41, 583–593. doi: 10.1111/j.1749-7345.2010.00398.x

Meng, F., Li, B., Xie, Y., Li, M., and Wang, R. X. (2020). Substituting fishmeal with extruded soybean meal in diets did not affect the growth performance, hepatic enzyme activities, but hypoxia tolerance ofDolly Varden (*Salvelinus malma*) juveniles. *Aquac. Res.* 51, 379–388. doi: 10.1111/are.14385

Mohanta, K. N., Mohanty, S. N., and Jena, J. K. (2007). Protein-sparing effect of carbohydrate in silver barb, *Puntius gonionotus* fry. *Aquac. Nutr.* 13, 311–317. doi: 10.1111/j.1365-2095.2007.00482.x

Moniruzzaman, M., and Fatema, U. K. (2022). Proximate analysis of local ingredients as a prospective resource for feed production in Bangladesh. *J. Multidiscip. Sci.* 4, 1–9. doi: 10.33888/jms.2022.411

NRC, (1993). *Nutrient requirement of fishes*. Washington: National Academy of Sciences.

Naylor, R. L., Goldberg, R. J., Primavera, J. H., Kautsky, N., Beveridg, M. C. M., Clay, J., et al. (2000). Effect of aquaculture on world fish supplies. *Nature* 405, 1017–1024. doi: 10.1038/35016500

NRC (National Research Council). (2011). *Nutrient requirements of fish and shrimp*. Washington, DC: The National Academies Press.

Nyirenda, J., Mwabumba, M., Kaunda, E., and Sales, J. (2000). Effect of substituting animal protein sources with soybean meal in diets of *Oreochromis karongae* (Trewavas, 1941). *Naga ICLARM Quart.* 23, 13–15.

Olli, J. J., and Krogdahl, A. (1995). Alcohol soluble components of soybeans seem to reduce fat digestibility in fishmeal-based diets for Atlantic salmon, *Salmo salar* L. *Aquac. Res.* 26, 831–835. doi: 10.1111/j.1365-2109.1995.tb00876.x

Olvera-Novoa, M. A., Olivera-Castillo, L., and Martínez-Palacios, C. A. (2002). Sunflower seed meal as a protein source in diets for *Tilapia rendalli* (Bounlanger, 1896) fingerlings. *Aquac. Res.* 33, 223–229. doi: 10.1046/j.1365-2109.2002.00666.x

Pervin, M. A., Jahan, H., Akter, R., Omri, A., and Hossain, Z. (2020). Appraisal of different levels of soybean meal in diets on growth, digestive enzyme activity, antioxidation, and gut histology of tilapia (*Oreochromis niloticus*). *Fish Physiol. Biochem.* 46, 1397–1407. doi: 10.1007/s10695-020-00798-5

Prodhan, M. M. H., and Khan, M. A. (2018). Management practice adoption and productivity of commercial aquaculture farmsin selected areas of Bangladesh. *J. Bangladesh Agri. Uni.* 16, 111–116. doi: 10.3329/jbau.v16i1.36491

Santigosa, E., García-Meilán, I., Valentín, J. M., Navarro, I., Pérez-Sánchez, J., and Gallardo, M. Á. (2011). Plant oils' inclusion in high fish meal-substituted diets: effect on digestion and nutrient absorption in gilthead sea bream (*Sparus aurata* L.). *Aquac. Res.* 42, 962–974. doi: 10.1111/j.1365-2109.2010.02679.x

Saunders, R. M. (1990). The properties of rice bran as a foodstuff. *Cereal Foods World* 35, 632–636.

Savonitto, G., Barkan, R., Harpaz, S., Neori, A., Chernova, H., Terlizzi, A., et al. (2021). Fishmeal replacement by periphyton reduces the fish in fish out ratio and alimentation cost in gilthead sea bream *Sparus aurata*. *Sci. Rep.* 11:20990. doi: 10.1038/s41598-021-00466-5

Suprayudi, M. A., Inara, C., Ekasari, J., Priyoutomo, N., Haga, Y., Takeuchi, T., et al. (2015). Preliminary nutritional evaluation of rubber seed and defatted rubber seed meals as plant protein sources for common carp *Cyprinus carpio* L. juvenile diet. *Aqua. Res.* 46, 2972–2981. doi: 10.1111/are.12452

Tacon, A. G. J., and Metian, M. (2009). Fishing for aquaculture: non-food use of small pelagic forage fish-a global perspective. *Rev. Fish. Sci.* 17, 305–317. doi: 10.1080/10641260802677074

Tan, Q. S., Wang, F., Xie, S. Q., Zhu, X. M., Lei, W., and Shen, J. Z. (2009). Effect of high dietary starch levels on the growth performance, blood chemistry and body composition of gibelio crucian carp (*Carassius auratus* var. gibelio). *Aquac. Res.* 40, 1011–1018. doi: 10.1111/j.1365-2109.2009.02184.x

Turchini, G. M., Trushenski, J. T., and Glencross, B. D. (2019). Thoughts for the future of aquaculture nutrition: realigning perspectives to reflect contemporary issues related to judicious use of marine resources in aquafeeds. *North Am. J. Aquat.* 81, 13–39. doi: 10.1002/naaq.10067

Viola, S., Mlokady, S., Rappaport, U., and Arieli, Y. (1982). Partial and complete replacement of fishmeal by soybean meal in feeds for intensive culture of carps. *Aquaculture* 26, 223–236. doi: 10.1016/0044-8486(82)90158-2

Yaghoubi, M., Mozanzadeh, M. T., Marammazi, J. G., Safari, O., and Gisbert, E. (2016). Dietary replacement of fish meal by soy products (soybean meal and isolated soy protein) in silvery-black porgy juveniles (*Sparidentex hasta*). *Aquaculture* 464, 50–59. doi: 10.1016/j.aquaculture.2016.06.002

Ye, H. Q., Xu, M. L., Liu, Q. Y., Sun, Z. Z., Zou, C. Y., Chen, L. L., et al. (2019). Effects of replacing fish meal with soybean meal on growth performance, feed utilization and physiological status of juvenile obscure puffer, *Takifugu obscurus*. *Toxicol. Pharmacol.* 216, 75–81.

Yu, H., Liang, H., Ren, M., Ge, X., Ji, K., Huang, D., et al. (2022). A study to explore the effects of low dietary protein levels on the growth performance and nutritional metabolism of grass carp (*Ctenopharyngodon idella*) fry. *Aquaculture* 546:737324. doi: 10.1016/j.aquaculture.2021.737324

Zamal, H., Barua, P., and Uddin, B. K. (2009). Ipil ipil leaf meal as supplements to soybean and fish meal. *Int. Aqua. Feed Magaz.* 12, 36–42.

Zamal, H., Das, U. K., and Barua, P. (2008). Human resources development for sustainable aquaculture in bangladesh, social change. 1, 11–13.