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Amphibious rice policy and development for climate adaptation effort in Indonesia: integrating bibliometric and field insights

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Amphibious rice varieties are a promising solution to improve rice production resilience under climate change, especially with increasing uncertainty in rainfall patterns. This study uses two complementary methods: bibliometric analysis to explore global research trends on amphibious rice, and field research to optimize the Biobestari variety. The bibliometric analysis identifies key topics, collaborations, and publication patterns. The primary study tests Biobestari using two planting spacing methods, double row with alternating row width (*Jajar Legowo* is an Indonesian term), square planting and five levels of fertilizer application. The agronomic and economic performance of each combination was evaluated. Results show that amphibious rice, combined with efficient planting and eco-friendly fertilizers, improves productivity and achieves a profit ratio of 1.91. This suggests that amphibious rice is well suited for areas with irregular rainfall. Its adoption should be supported by government programs and farmer training. The study highlights the importance of integrating genetic improvement, good farming practices, economic feasibility, and policy support to build climate-resilient rice systems.

KEYWORDS

agricultural socioeconomics, amphibious rice, bibliometric concept, Biobestari variety, rice management policy

1 Introduction

Rice is a crucial cereal crop, second only to wheat, and essential for food security in many regions worldwide. Rice is the primary source of carbohydrates, fulfilling the daily calorie requirements of a significant portion of the global population, especially in Asia (Alam et al., 2024). This is reflected in data indicating that the largest rice-producing nations are predominantly located in Asia, including China, India, Bangladesh, Indonesia, and Vietnam (Fadah et al., 2024; Geng et al., 2025). However, food security concerns are rising due to declining rice production, mainly driven by climate change, which disrupts rainfall patterns and reduces yield stability (Touch et al., 2024; Rezvi et al., 2023; Punia et al., 2024). These alterations create less than optimal growing conditions that adversely affect crop productivity, including that of rice (Nawaz et al., 2022). Research (Hussain et al., 2020) predicts that climate change and global warming may potentially lead to a reduction in rice production by up to 51%. For example, climate change has caused a 15% decrease in rice production (Dhamira and Mada, 2020; Hakim et al., 2025). This decline presents a significant challenge for the Indonesian government as it strives to achieve food self-sufficiency. Consequently, innovations focused on enhancing climate change resilience in rice cultivation are of paramount importance.

Climate change resilience in rice cultivation can be achieved using various approaches. Research conducted by Anshori A. et al. (2023) and Anshori et al. (2024b, 2024a), Fikri et al. (2023), Chen et al. (2024), and Sarma et al. (2024) emphasized the significance of improved cultivation techniques in enhancing resilience. The implementation of various technologies, such as ameliorants, balanced fertilizers, and advanced cultivation practices, has been proven to mitigate the risks associated with climate change. Moreover, Chun et al. (2016) and Debnath et al. (2021) indicate that crop modeling strategies are essential for identifying optimal planting times and cropping patterns, which ultimately help maintain high profitability on agricultural land. This factor is vital for resilience to climate change. Additionally, research by Erythrina et al. (2021), Mauki et al. (2023), and Zagre et al. (2024), highlights the importance of socioeconomic development in combating climate change by fostering climate-responsive communities. Collectively, these components illustrate that resilience to climate change requires a more comprehensive approach. However, all these strategies serve as supportive elements of a fundamental aspect of resilience: the genetic capacity of the plants themselves (Sabar et al., 2024). Crops endowed with robust genetic traits for resilience to climate change can significantly enhance their production potential. Therefore, focusing on genetic improvements is essential to maximize rice production. The selection and enhancement of rice varieties are pivotal for building resilience to climate change.

Genetic enhancement of climate change resilience can be tailored according to specific agro-climatic types. Rice can be broadly categorized into three types based on its cultivation ecology: paddy rice, upland rice for drylands, and swamp rice (Bwire et al., 2024). Each type has been thoroughly documented in terms of its development. Notably, Erythrina et al. (2021) reported that wetland rice can achieve a yield potential exceeding 9 tons per hectare, whereas Izhar et al. (2025) found that upland rice has a yield potential of more than 7 tons per hectare. Additionally, the development of swamp rice was discussed in Khairullah et al. (2024) and Alwi et al. (2025). Nevertheless, the ever-changing dynamics of climate change can

swiftly alter the agroecology of rice within a single growing season (Maity and Maity, 2022). For example, when paddy rice experiences drought, it may need to adapt to the characteristics of upland rice for the majority of its growth cycle and vice versa (Hussain et al., 2020; Ricart et al., 2025). This situation underscores the importance of developing multi-ecological adaptability in rice cultivation. Therefore, it is crucial to cultivate rice varieties that can adapt to fluctuating climate patterns within a single life cycle. An innovative approach is to develop amphibious rice.

Amphibious rice is a unique variety that can adapt to both rice fields and dry land conditions (Aryana and Wangiyana, 2016; Wihardjaka et al., 2024). These environments are characterized by contrasting characteristics: rice fields exhibit anaerobic conditions due to high water saturation, whereas dry lands provide favorable aerobic conditions (Farooq et al., 2022). Consequently, the root systems of amphibious rice must be developed to adapt to both environments (Wihardjaka et al., 2024). The development of amphibious rice is particularly relevant in the context of climate change, which necessitates systematic studies (Tri, 2017). Research should consider various aspects of resilience to assess the effectiveness of its development strategies (Tri, 2017; Du et al., 2022; Wihardjaka et al., 2024). Assessment methodologies may utilize two approaches: one based on publication data and the other on primary data. These approaches complement each other in evaluating the significance of research on amphibious rice (Dawadi et al., 2021). Publication analysis often involves bibliometric analysis, which maps scientific interactions and developments and provides clarity on the evolution of the topic. This method has been widely applied in reviews of rice research trends. By contrast, primary data research focuses on direct experimentation and is built on hypotheses and statistical analysis. Integrating bibliometric analysis with primary research offers a comprehensive framework for exploring amphibious rice varieties. This combined approach has not been systematically studied, making it a valuable avenue for assessing the potential of amphibious rice in enhancing resilience to climate change. The primary objective of this study was to outline the development of amphibious rice from various perspectives to support the resilience of rice production to climate change.

The imperative to mitigate the adverse effects of climate change on rice production underscores the necessity of advancing rice production technologies with multi-ecological adaptability. Although current research has explored cultivation techniques, crop modeling, and socioeconomic strategies to enhance climate resilience, there is a notable lack of systematic investigation into amphibious rice. This variety is promising due to its capacity to thrive in both flooded paddy and upland conditions. This study employs a comprehensive approach, integrating bibliometric analysis of publication data with primary experimental research, to thoroughly evaluate the development and resilience potential of amphibious rice.

This dual methodology, which has not been systematically utilized in previous studies, provides a robust framework for assessing the genetic and ecological adaptability of amphibious rice (Figure 1). The study is guided by the hypothesis that combining bibliometric and primary study can effectively enhance the resilience and productivity of amphibious rice under climate change. Thus the objective of this approach is to propose the most effective strategies for formulating policies related to amphibious rice cultivation, thereby addressing the urgent need for innovative solutions to ensure the resilience of rice production in the face of unpredictable climate variations.

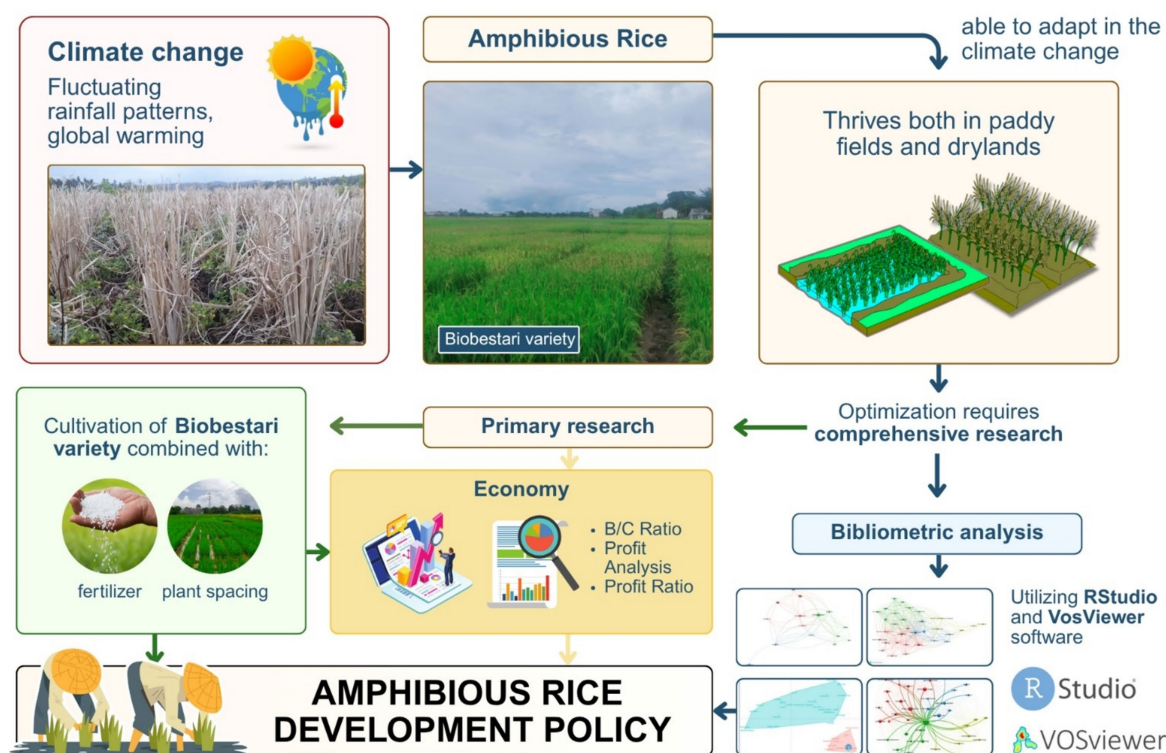


FIGURE 1

A comprehensive analysis of the dynamic policy framework for amphibious rice, employing bibliometric analysis and primary study.

2 Materials and methods

This research was conducted using two complementary approaches: bibliometric analysis and a primary field study focused on optimizing amphibious rice cultivation. The bibliometric component evaluated development trends and research networks in the field of amphibious rice, including themes related to economic potential and climate adaptation. These findings served as a reference and foundation for the design of the primary study. The primary study itself was conducted and completed from December 2024 to March 2025 and involved structured agronomic evaluations and economic assessments. Climate data collected during the experimental period are presented in Table 1, while soil characteristics from the study site are summarized in Table 2. Together, these analyses support the development of amphibious rice strategies for enhancing climate resilience in Indonesian agriculture.

2.1 Bibliometric analysis

The bibliometric analysis presented in this study is based on research conducted by Anshori M. F. et al. (2023) and Ardie et al. (2025), which comprises three main steps: bibliography data mining from the Scopus database, bibliometric analysis utilizing R Studio and VosViewer software, and data interpretation. Data mining was conducted twice,

each time using different keywords relevant to the topic of discussion. The first mining targeted the development of amphibious rice varieties using the query ALL (amphibious AND rice AND variety). This query yielded 240 documents from various sources in the Scopus database, including journals, conference proceedings, and other materials. The second round of data mining focuses on the social, economic, and institutional aspects of rice cultivation. For this purpose, the following search query was used: TITLE-ABS-KEY (rice AND variety) AND ALL (rural AND development) AND ALL (socioeconomics) OR ALL (agricultural AND institution). The query retrieved 183 documents from multiple sources. The entire dataset was analyzed systematically, with an analysis tailored to address the specific research questions of the study.

Bibliometric analysis should be customized to effectively address specific research questions. The primary focus of this study was to examine the interactions between countries in terms of collaboration (Query 1) and mapping keyword interactions (Queries 1 and 2). This research question can be thoroughly explored using the capabilities of the VosViewer and RStudio software. VosViewer is specifically designed to identify interactions through methods such as co-authorship, citation, co-occurrence, bibliographic coupling, and co-citation (Anshori M. F. et al., 2023; Kirby, 2023; Ullah et al., 2023; Ardie et al., 2025). These interactions facilitate the examination of potential collaborations among countries, researchers, affiliations, and keywords related to the topic of interest (Anshori M. F. et al., 2023). This software allows visualization of interaction mapping relevant to the research

question. Conversely, RStudio is open-source software that utilizes specific packages for statistical analysis (Ghazy et al., 2024). The package employed in this study is called biblioshiny, which harnesses Shiny’s capabilities to analyze and describe the bibliography of a collection of mined databases (Aria and Cuccurullo, 2017). The role of this package in bibliometric analysis is distinct from that of VosViewer, as it provides a comprehensive description of the bibliographic information in the database, addressing aspects that VosViewer may not cover (Anshori M. F. et al., 2023; Ardie et al., 2025). The combined application of both software packages in bibliometric analysis has been documented in studies by Yuan (2022) Anshori M. F. et al. (2023). The integration of VosViewer and RStudio (Biblioshiny package) allowed complementary insights: VosViewer mapped co-authorship and keyword networks visually, while RStudio provided deeper quantitative metrics (e.g., publication trends, annual growth rate, and thematic evolution). This analysis enabled cross-validation of clusters and ensured robust interpretation aligned with the study objectives.

TABLE 1 Climate data on research location from December 2024 to March 2025.

Week	TN	TX	TAVG	RH_AVG	RR	SS	FF_AVG
1	24.50	30.53	26.94	85.63	46.43	3.04	1.38
2	24.43	29.61	26.33	85.57	38.36	2.69	1.43
3	24.23	28.04	25.30	92.00	83.97	1.43	1.43
4	24.19	29.84	26.47	85.43	21.14	3.49	1.29
5	24.07	30.86	26.57	83.43	4.46	4.23	1.57
6	24.19	31.44	26.97	81.86	18.23	4.60	1.43
7	24.33	30.69	26.46	85.57	29.29	4.07	1.29
8	23.96	30.16	26.13	87.14	28.91	2.44	1.29
9	23.84	29.40	25.87	87.29	39.20	2.37	1.14
10	23.96	30.19	26.36	82.86	30.41	3.59	1.43
11	23.50	30.87	26.64	85.71	56.40	3.03	1.14
12	24.07	31.36	26.81	81.57	5.00	3.44	1.00
13	23.77	31.33	26.47	82.71	8.37	4.51	1.14
14	24.31	32.49	27.21	81.00	6.20	5.86	1.57
15	24.24	31.31	26.64	83.86	4.46	4.93	1.14
16	23.51	29.03	25.54	87.86	38.74	1.73	1.57
17	23.93	32.04	27.05	80.75	7.98	4.30	1.13

TN, minimum temperature (°C); TX, maximum temperature (°C); Tavg, average temperature (°C); RH_avg, average humidity (%); RR, rainfall (mm). ss: length of sunshine (hour); ff_avg: average wind speed (m/s).

TABLE 2 Soil data from the research location.

Soil depth (cm)	Sand	Silt	Clay	Texture	C	N	C/N	P ₂ O ₅	Ca	Mg	K	Na	CEC
	(%)				(%)			(ppm)	(cmol (+)kg ⁻¹)				
(0–10)	18	46	36	Dusty Clay Loam	1.65	0.17	10	7.95	3.45	0.95	0.35	0.10	20.25
(10–20)	15	50	34	Dusty Clay Loam	1.85	0.12	15	9.15	4.15	0.75	0.16	0.15	18.65

C, carbon; N, nitrogen; C/N, carbon-nitrogen ratio; Ca, calcium; Mg, magnesium; K, potassium; Na, sodium; CEC, cation exchange capacity.

Consequently, the utilization of both tools is essential for thorough analysis and mapping of the developmental potential of amphibious rice.

2.2 Primary study (research design and implementation procedures)

This primary research study aimed to enhance amphibian rice cultivation in Maradekaya Village, located in Bajeng, Gowa Regency, South Sulawesi. The focus was on the Biobestari variety, an upland rice type developed by Indonesia’s National Research and Innovation Agency. The primary study was conducted from December 2024 to March 2025, the research employed a nested group randomized design, with replications nested within the planting distances. Two spacing patterns were used in this study. The first was a double row with alternating row widths (*Jajar Legowo*) (40-20-10) (t1). And square with a 20 × 20 cm layout (t2). There were five distinct fertilizer treatment levels: no fertilizer (f0), 300 kg.ha⁻¹ of subsidized NPK fertilizer and 100 kg.ha⁻¹ of subsidized urea (f1), 300 kg.ha⁻¹ of subsidized NPK fertilizer and 100 kg.ha⁻¹ of non-subsidized urea (f2), 300 kg.ha⁻¹ of subsidized NPK fertilizer, 100 kg.ha⁻¹ of non-subsidized urea, and 1 kg.ha⁻¹ of trichocompost (f3), and 300 kg.ha⁻¹ of subsidized NPK fertilizer, 100 kg.ha⁻¹ of non-subsidized urea, and 3.3 mL/L of biofertilizer (f4). All combinations of spacing and fertilizer packages were replicated three times, resulting in a total of 30 experimental units. Each unit covered a plot area of 12 m².

The procedural implementation was based on a modified approach from [14, 15]. The initial steps involved land plowing and stockpiling. Following the preparation of the land, plots measuring 3 m by 4 m were established, maintaining a 1 m distance between each plot. The seeds were soaked for a full day before being placed into the nursery bed. After nurturing the seedlings for 15 days, they were transplanted into the field with spacing based on the treatment.

Replanting, weeding, watering, fertilizing, and pest control are vital activities for the care of planted seedlings. Thirty days after planting, weeding is performed using both chemical and manual methods. Depending on the variety, any dead seedlings will be replaced with new plants 7 days later. After mechanical weeding, pesticides are applied via a sprayer. Irrigation begins 6 days after the initial fertilization, which occurs 20 days after planting. Water is introduced to the experimental field, reaching a depth of 5 cm above the soil surface. To maintain moisture levels and achieve a clay-like soil texture, irrigation is temporarily halted after the second fertilization. Five days later, watering resumes, this time elevating the water level to approximately 10 cm above the soil surface during the primordial phase to prevent tiller formation. Fertilization is executed according to the specified treatment levels for each plot, occurring twice: once 7 days after planting and again 28 days

after planting. The pesticides used for pest and disease management are carefully selected based on the specific types and phenological stages of the pests or diseases affecting the rice plants. Harvesting takes place when the grain at the base of the panicle has hardened and two-thirds of the rice panicle has reached physiological maturity, indicated by the yellowing of the straw. Data collection occurs during the harvesting process, before the actual harvest of the crop.

2.3 Observation parameters and data analysis

The observations focused on three essential economic factors in rice production: number of panicles per clump, panicle weight, and overall yield. We performed a detailed analysis of the results using an analysis of variance at a 5% error level, presenting clear comparisons among various cultivation technology packages through informative graphs. Additionally, we assessed the economic significance of the yield using two methods: the benefit-to-cost (B/C) ratio and the profit ratio, with the control technology (S2F0) serving as a reference (Susilawati et al., 2018; Mauki et al., 2023; Yadav and Yadav, 2023). To further enhance our findings, we employed Principal Coordinate Analysis (PCoA) to explore the influence of each fertilizer factor on potential benefits and income (Wang et al., 2022; Musdir et al., 2024). All analyses were conducted using RStudio software.

3 Results

3.1 Analysis of country interaction in amphibious rice variety development

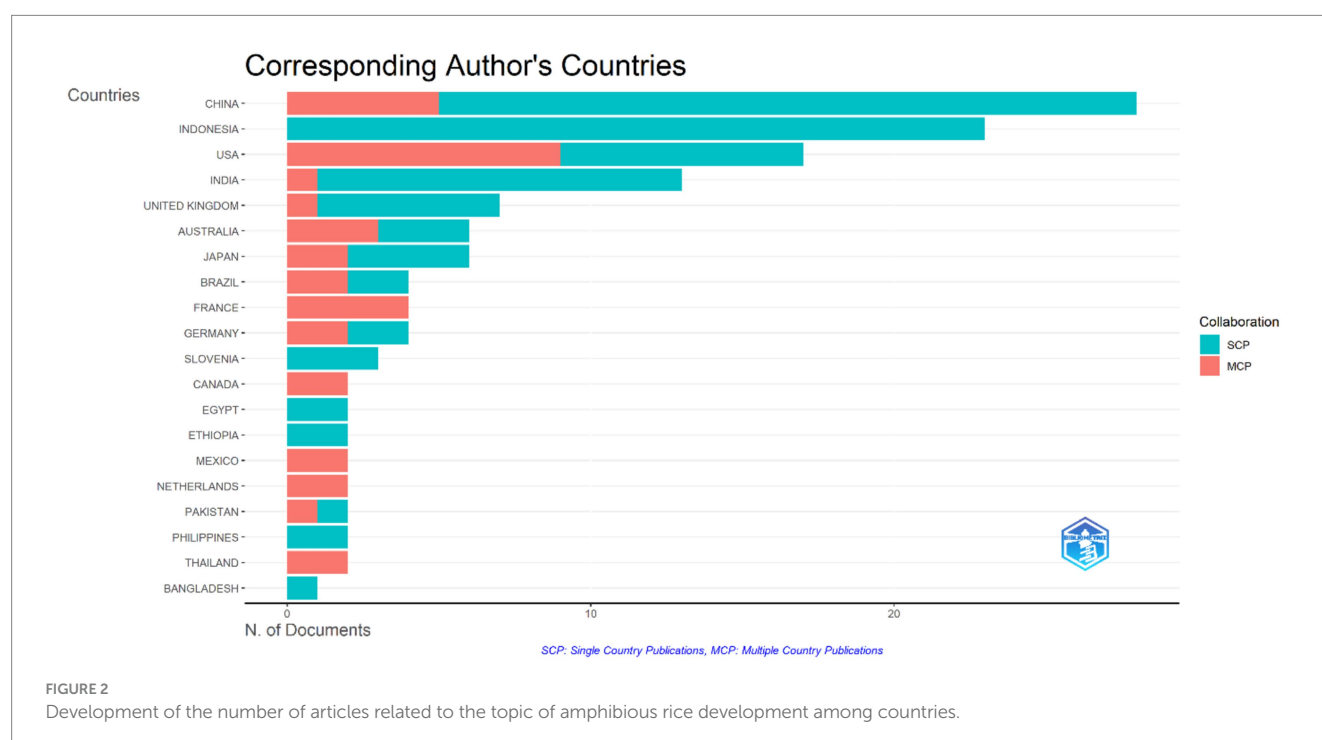
Amphibious rice has been developed in several countries, as depicted in Figure 2, which illustrates the interactions among

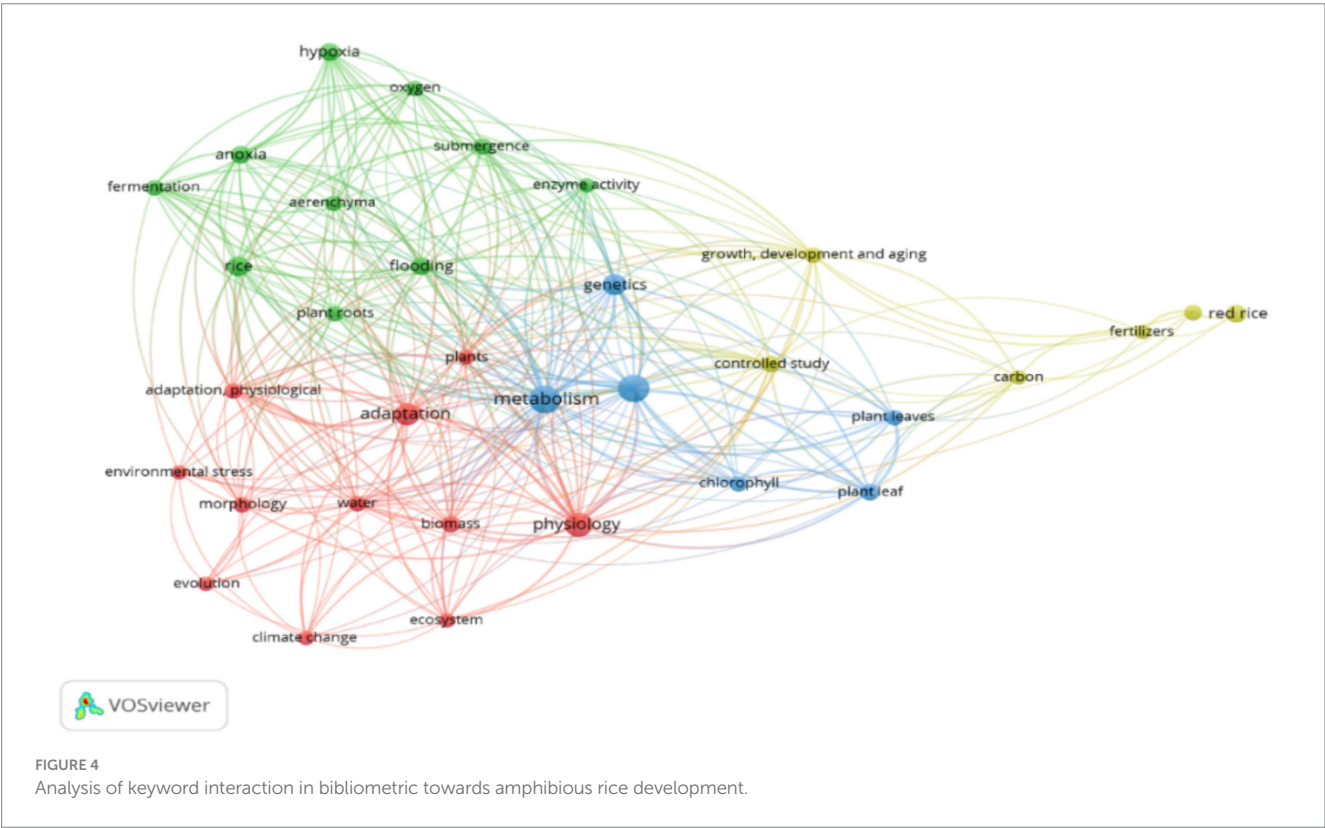
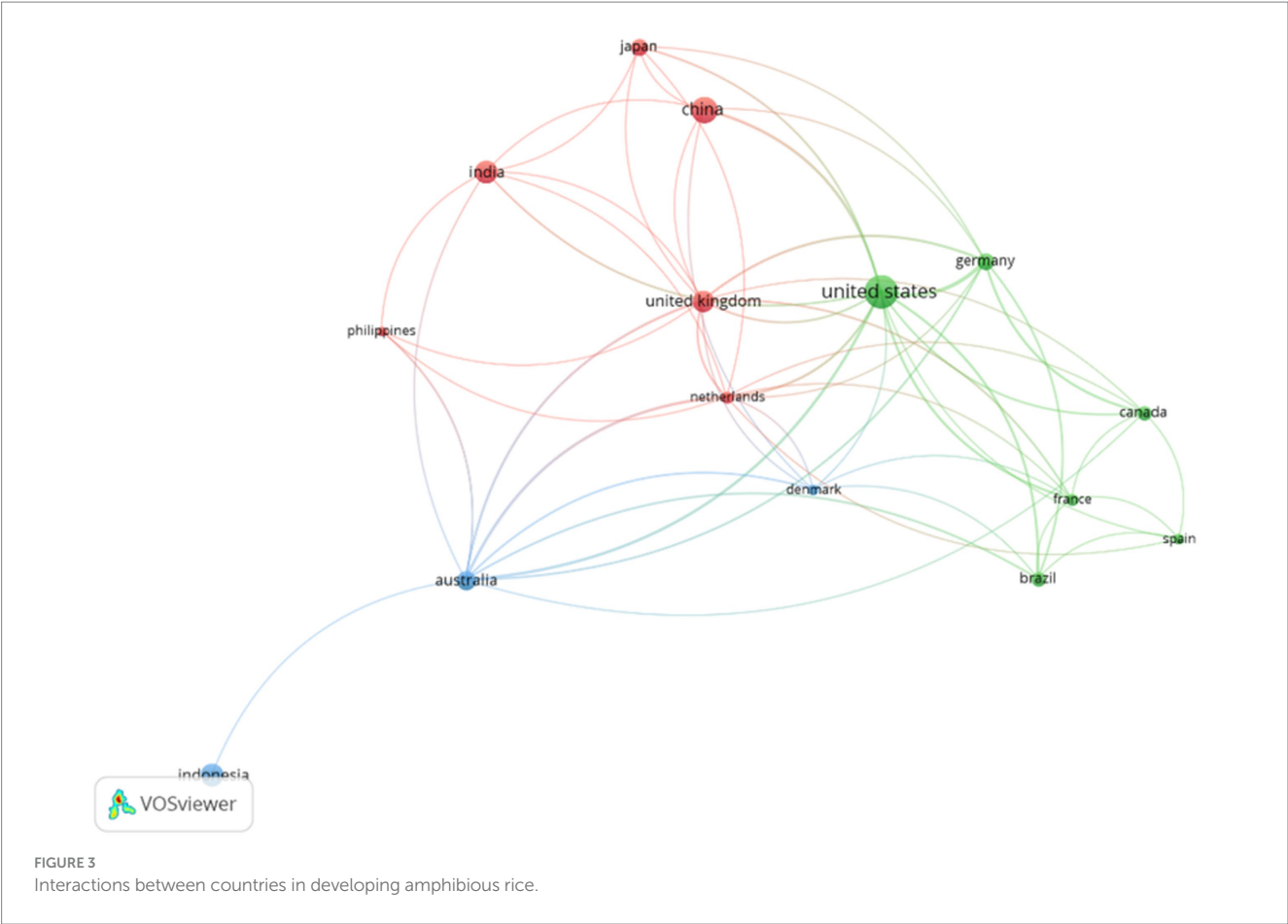
corresponding authors from various nations. Overall, China has led the publication of numerous articles on the development of amphibious rice varieties, followed by Indonesia and the USA. However, in terms of collaboration, the USA exhibited a notably high level of cooperative research, whereas Indonesia had the fewest collaborative publications on this subject.

Collaboration between countries on articles is shown in Figure 3. This figure identifies three groups that illustrate patterns of authorship collaboration relevant to this topic. The first group, highlighted in green, comprises the United States, Germany, Brazil, Canada, France, and Spain. The United States serves as the central hub for this group and ranks as the largest center in the co-authorship interaction analysis of this topic. The second group, marked in red, includes China, Japan, India, the United Kingdom, the Netherlands, and the Philippines, with China exhibiting the most significant interaction within this group. The final group, indicated in blue, consisted of Australia, Denmark, and Indonesia. However, it is noteworthy that Indonesia has a considerably longer interaction distance than the other countries within this group.

3.2 Keyword interaction analysis in the development of amphibious rice varieties

The development of amphibious rice is depicted in Figure 4, which was derived from six bibliometric keyword interaction studies. This figure highlights four distinct groups of keywords associated with the advancement of amphibious rice varieties. The first category (red) encompasses keywords, such as adaptation, physiology, plant, adaptation physiology, biomass, water, environmental stress, morphology, evaluation, and ecosystem. The fundamental keywords in this group were “adaptation” and “physiology.” The second cluster (green) included keywords such as rice, fermentation, anoxia, hypoxia,





aerenchyma, flooding, plant root, enzyme activity, submergence, and oxygen, with “rice” serving as the core term. The third cluster (yellow) features keywords related to growth, development, aging, controlled studies, carbon, fertilizer, and red rice. The centerpiece of this cluster is “controlled study.” Finally, the fourth cluster (blue) consists of keywords such as metabolism, genetics, chlorophyll, plant leaves, and plant leaves, with “metabolism” being the primary term in this group.

The factor analysis of the keywords with six occurrences is shown in Figure 5. This figure highlights two prominent clusters of keywords associated with amphibious rice development. The larger cluster, shown in green, encompasses several key terms, including plant leaves, controlled study, carbon, fertilizer, cultivation, food supply, plant botany, flooding, and physiology. Conversely, the smaller cluster, indicated in red, comprises key terms, such as adaptation, enzyme activity, rice, *Oryza sativa*, and physiological adaptation.

3.3 Optimization of amphibious rice cultivation using the Biobestari variety

The primary evaluation of this optimization study centered on the Biobestari variety, a new amphibious rice type known for its potential yield of approximately 7.5 tons per hectare, with an average yield of 5.8 tons per hectare (Agroindonesia, 2020). This promising yield justifies the need for in-depth cultivation optimization experiments. The optimization of amphibious rice cultivation for the Biobestari variety is based on three key characteristics that contribute to the economic value

of rice: number of panicles per plant, panicle weight, and overall yield. As depicted in Figure 6, single-row planting methods demonstrate the potential for producing a higher number of panicles than double row methods. Fertilizer application pattern also significantly influenced the number of tillers, particularly in the single-row configuration. The F4 fertilizer package treatment in the single-row system yielded the highest number of tillers, averaging approximately 10 panicles per plant. The potential for optimizing cultivation technology packages based on panicle weight is illustrated in Figure 7. Generally, the double row configuration demonstrates greater potential than the single-row configuration. Furthermore, the effectiveness of the fertilizer package significantly improved and tended to increase with the addition of the fertilizer components. Notably, the F3 and F4 fertilizer packages within the double row plant spacing exhibited the highest panicle weights, ranging from 9 to 10 g per panicle, compared with the others. However, no significant interaction was observed between spacing and fertilizer package on panicle number and panicle weight.

The yield evaluation of the Biobestari amphibious rice cultivation technology package is shown in Figure 8. The results indicate that the double row spacing pattern has a higher yield potential than that of the single-row pattern. Furthermore, the fertilizer package showed a positive trend, with yield increasing as more components were added, irrespective of the row spacing pattern. However, the interaction between these two treatments did not significantly affect the number or weight of panicles. The most effective combination identified in this evaluation was the F4 fertilizer package applied with double row spacing, achieving a yield of 8.05 tons per hectare. This combination,

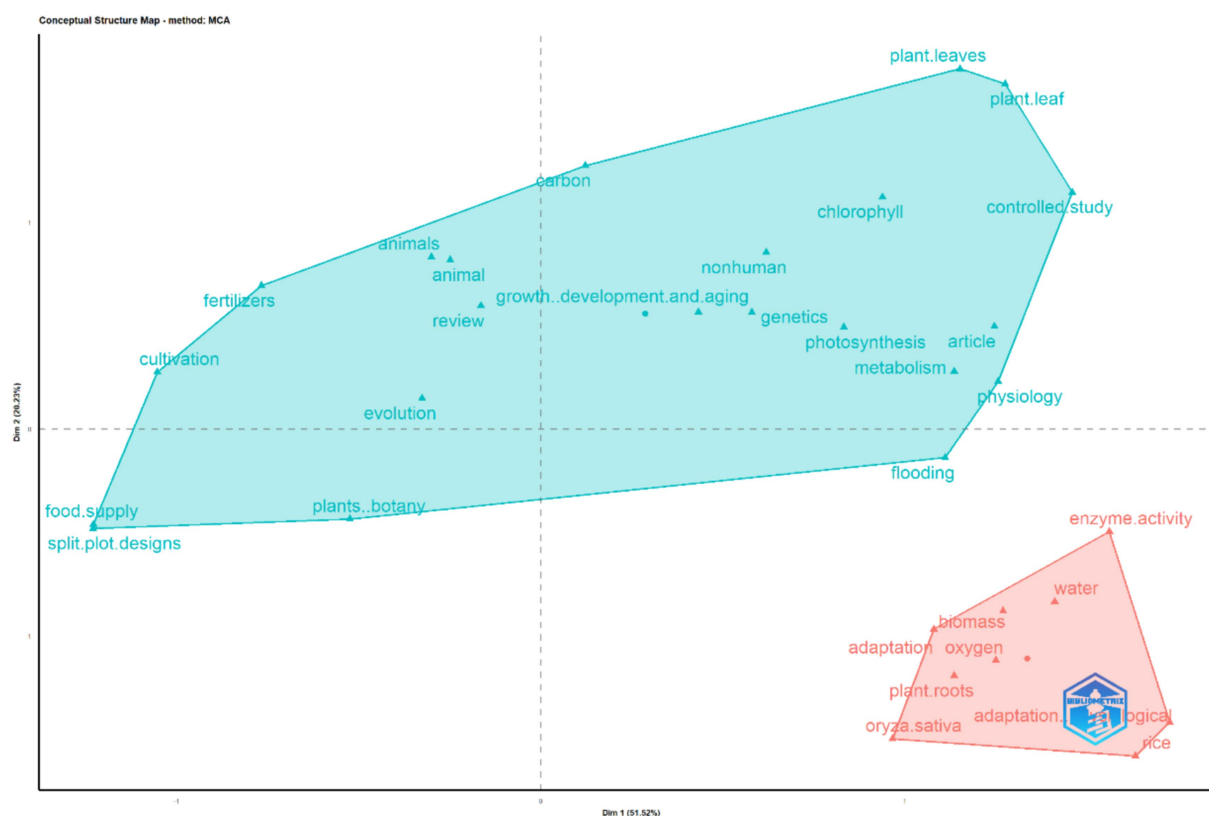


FIGURE 5
Factor analysis of a set of keywords in a data base.

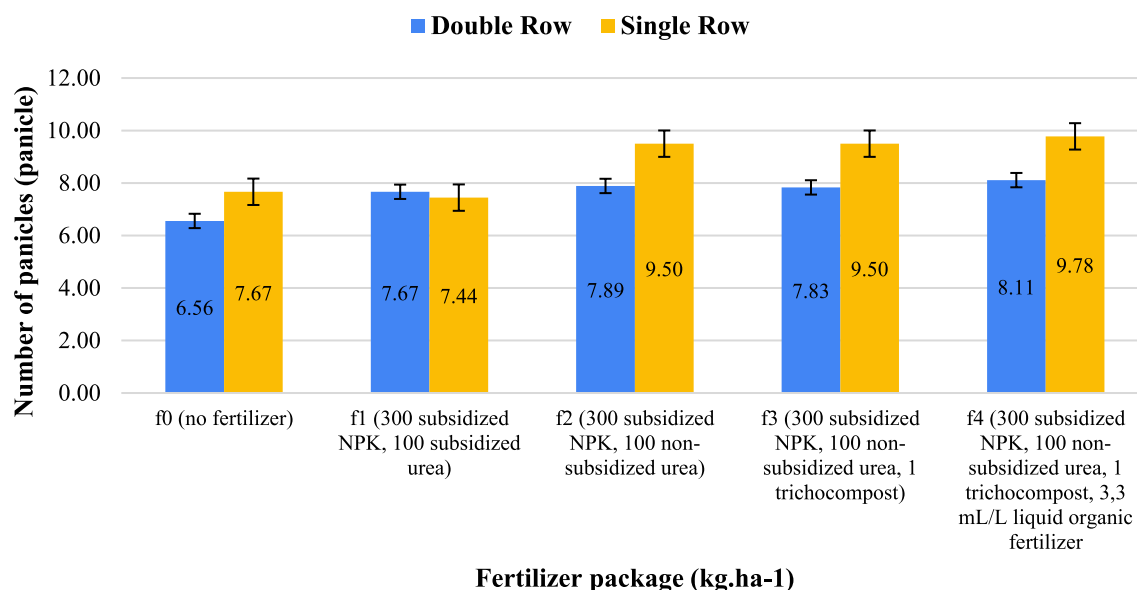


FIGURE 6

Number of panicles of Biobestari variety against various fertilizer packages and planting distance.

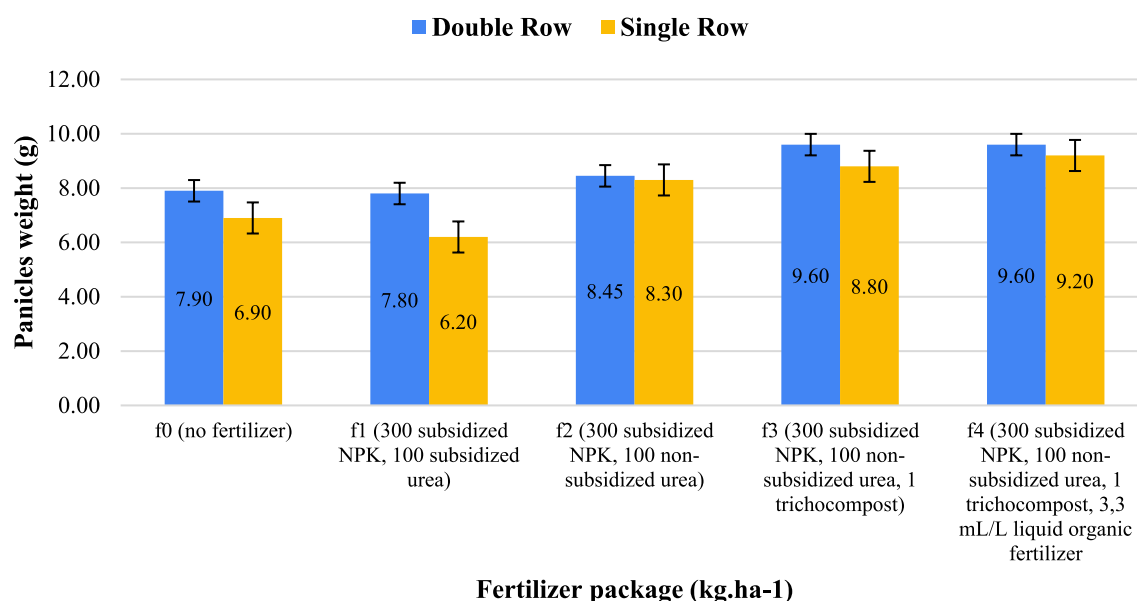


FIGURE 7

Panicles weight of Biobestari variety to various fertilizer packages and plant spacing.

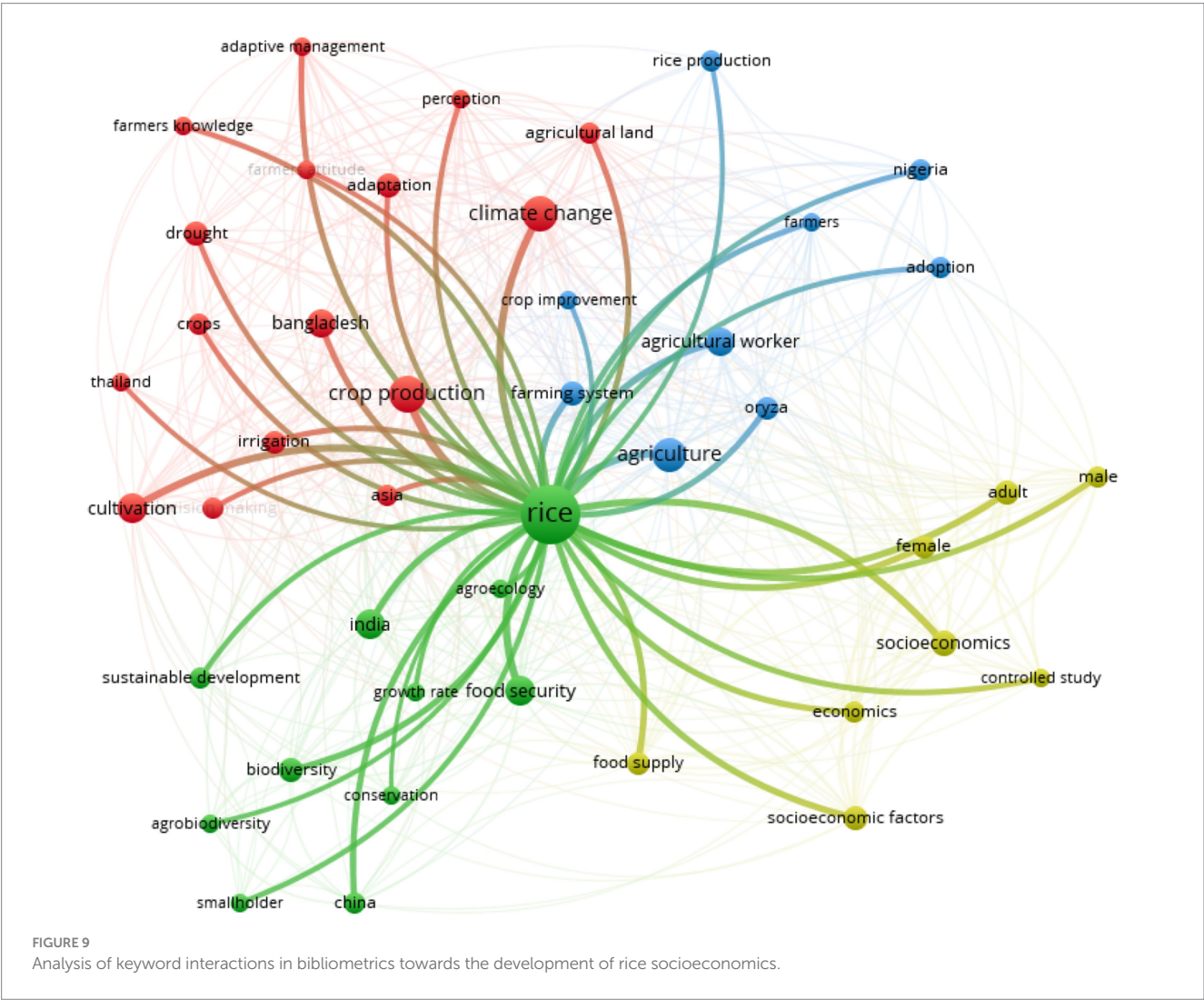
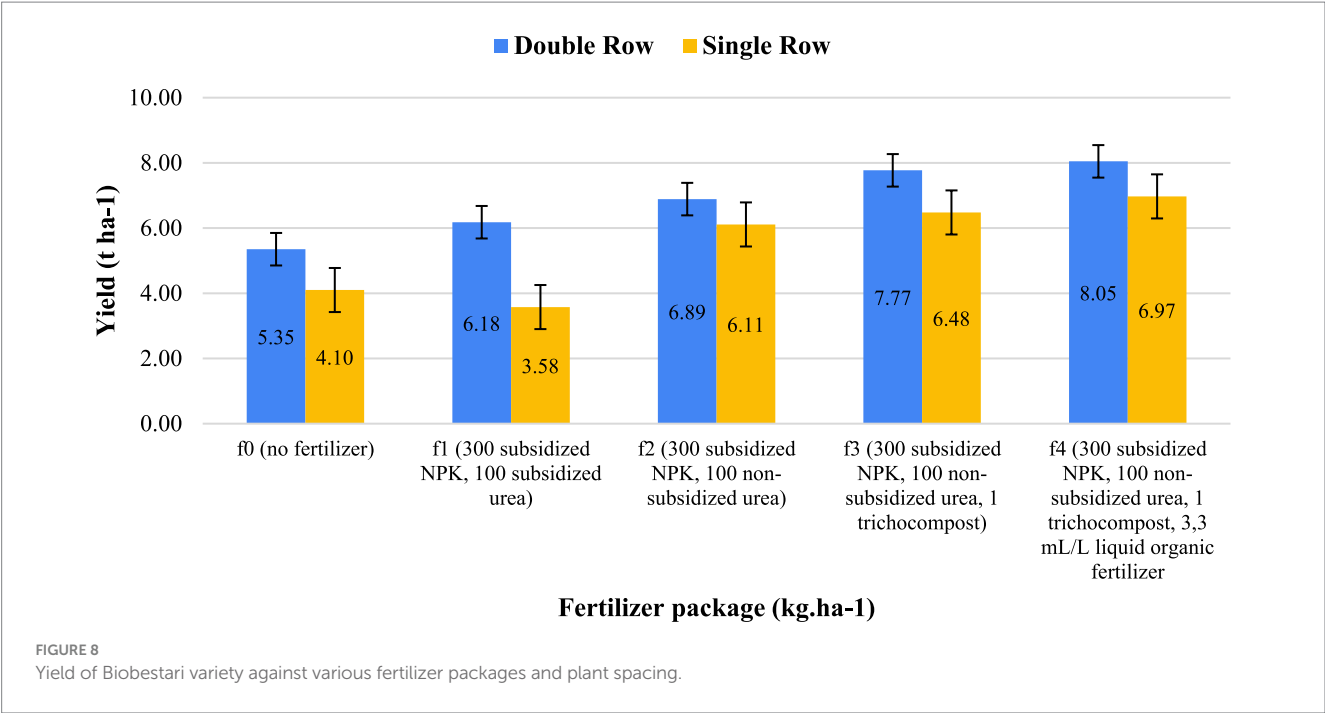
however, exhibited a considerably high variance compared to the F3 fertilizer package used with double row spacing, which produced a yield of 7.77 tons per hectare and had a relatively low standard deviation.

3.4 Analysis of socio-economic interaction of rice in Indonesia

Analysis of the overall spacing and fertilization package was conducted with a focus on its agronomic potential. This approach seeks to identify and recommend optimal interactions between

spacing and fertilizer for the Biobestari variety, which serves as a representative amphibious rice variety. Therefore, assessing the economic potential of optimizing the cultivation of amphibious rice, particularly the biobestari variety, is certainly viable.

The socioeconomic linkages in rice development are depicted in Figure 9, which is derived from its occurrence five times in the bibliometric keyword interaction study. The figure shows four distinct clusters pertinent to the topic. The first cluster (green) encompasses keywords such as rice, food security, agroecology, India, growth rate, biodiversity, sustainable development, agrobiodiversity, smallholder, China, and conservation, with “rice” serving as the core keyword. The



second cluster (red) included terms such as crop production, Asia, climate change, agricultural land, perception, adaptation, Bangladesh, irrigation, cultivation, Thailand, drought, farmer knowledge, and crops. The central themes of this cluster are encapsulated in the keywords 'crop production' and 'climate change.' The third cluster (blue) consists of keywords such as agriculture, farming systems, agricultural workers, *Oryza*, crop improvement, farmers, Nigeria, adaptation, and rice production, with the core concept centered around the term "agriculture." Finally, the fourth cluster (yellow) features terms such as food supply, socioeconomic factors, economics, controlled study, socioeconomic status, fame, and gender, although it does not have a clearly defined core keyword.

3.5 Economic analysis in optimizing amphibious rice cultivation in Indonesia: case study of Biobestari variety

Economic analysis surrounding the optimization of amphibious rice cultivation begins with the concept of farming business analysis. As outlined in Tables 3, 4, it is evident that, in general, the double-row system results in higher expenses than the single-row system. Furthermore, the F4 fertilization package, which includes non-subsidized urea, trichocompost, and biofertilizer, incurs higher costs than the other fertilization packages at both planting distances, specifically, IDR 11,610,000 (712.39 USD) for the double row and IDR 10,272,000 (630.29 USD) for the single row.

Nevertheless, when evaluating potential income, the double row system generates greater revenue than the single-row system, particularly with the F4 fertilization package, which yields an IDR of 52,300,000 (3,209.13 USD). Consequently, the profit from the F4 double row setup reached IDR 40,690,000 (2,496.74 USD) which was only slightly higher than that of the F3 package at IDR 39,878,000 (2,446.91 USD). The F3 package is quite similar to F4, but excludes biofertilizers. In contrast, the

lowest profit was recorded with the F1 package (subsidized urea fertilizer) in the single row, resulting in only IDR 17,986,000 (1,103.62 USD). Moreover, the benefit–cost (B/C) ratio for all cultivation optimization treatments was above 0, with both F0 treatments in double row and single row exhibiting higher B/C ratios in comparison to other treatments. In terms of profit ratios for the single row without a fertilization package, the F3 (1.87) and F4 (1.91) packages in the double row demonstrated superior profit ratios relative to other fertilization options. However, one of the key limitations of this study lies in the economic calculations presented in Tables 3, 4, which were based on local market prices and the prevailing subsidy structures at the time of data collection. These estimates may not fully reflect broader national, as input costs and grain prices can vary significantly between regions and are subject to fluctuations over time due to market dynamics and changes in agricultural policies.

The findings from the comprehensive analysis, encompassing both the technology packages and economic evaluation, are illustrated in the PcoA biplot analysis presented in Figure 10. This figure categorizes all the technology packages into four distinct groups. The first quadrant includes S2F0 and S2F1, and the second quadrant contains S1F3 and S1F4. The third quadrant includes S1F1, S1F2, S2F2, S2F3, and S2F4. The fourth quadrant is represented by S1F0. Notably, all character vectors fell within the second quadrant, except for subsidized urea, which was situated in the first quadrant.

4 Discussion

4.1 Overview of amphibious rice development in Indonesia based on bibliometric analysis

Based on co-authorship and interaction data, the topic of amphibious rice was categorized according to specific interests and existing cultivation systems. The concepts currently used in the USA,

TABLE 3 Farm business analysis of each technology package (in thousands) (in IDR).

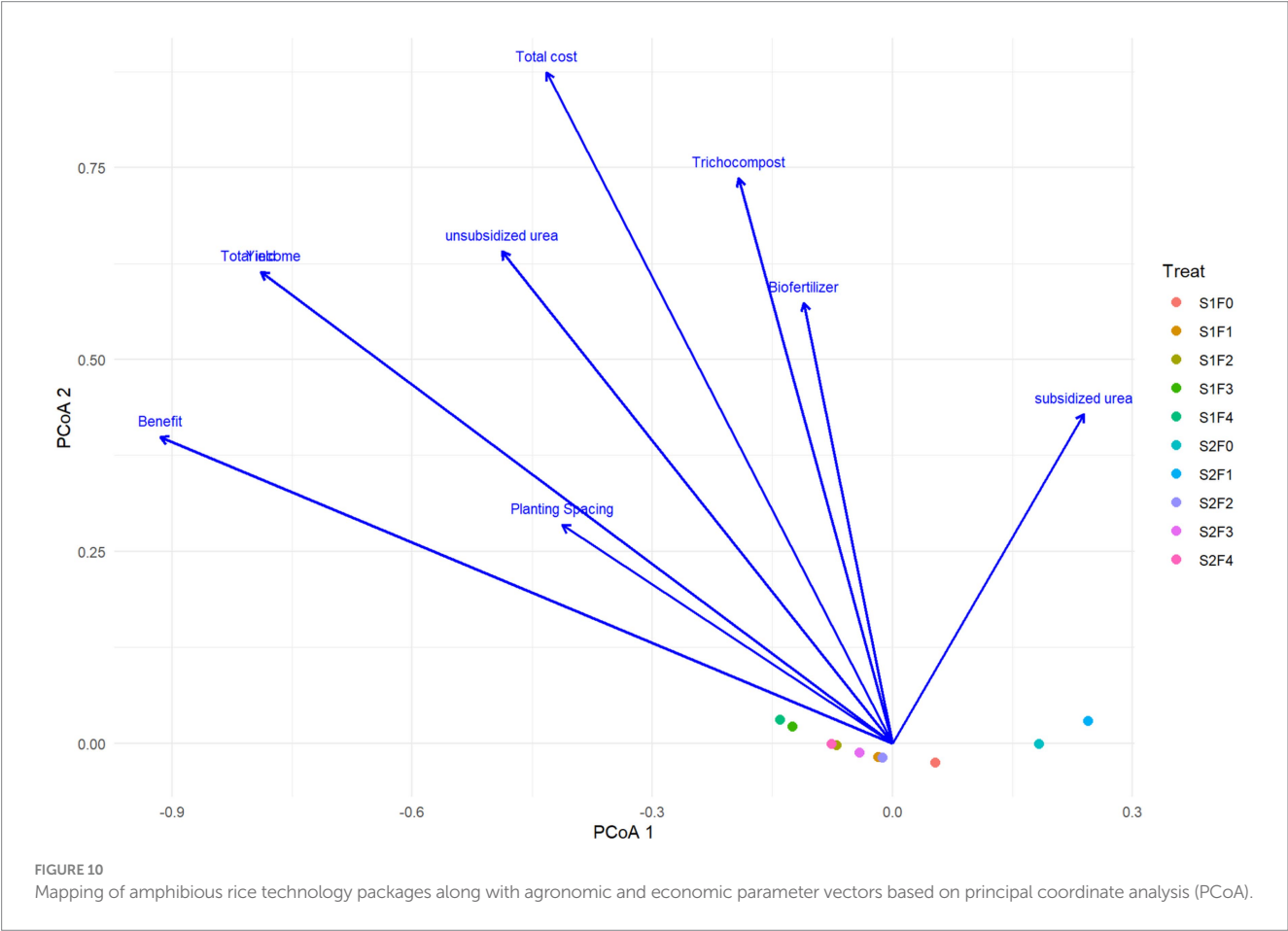
Component	Double row					Single row				
	F0	F1	F2	F3	F4	F0	F1	F2	F3	F4
Planting cost	1,280	1,280	1,280	1,280	1,280	640	640	640	640	640
Subsidized urea	0	300	0	0	0	0	300	0	0	0
Non-subsidized urea	0	0	800	800	800	0	0	800	800	800
Trichocompost	0	0	0	1,500	1,500	0	0	0	1,500	1,500
Biofertilizer	0	0	0	0	800	0	0	0	0	800
Production facilities	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Maintenance	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Harvesting	3,478	4,017	4,477	5,051	5,230	2,665	2,325	3,972	4,211	4,532
Total expenses (IDR)	6,758	7,597	8,557	10,631	11,610	5,305	5,265	7,412	9,151	10,272
Total income (IDR)	34,785	40,166	44,774	50,509	52,300	26,648	23,251	39,721	42,114	45,315
Profit (IDR)	28,026	32,569	36,217	39,878	40,690	21,344	17,986	32,309	32,962	35,044
B/C ratio	4.15	4.29	4.23	3.75	3.50	4.02	3.42	4.36	3.60	3.41
Profit ratio	1.31	1.53	1.70	1.87	1.91	1.00	0.84	1.51	1.54	1.64

The optimal treatments are highlighted in yellow and indicated in bold, F0 = no fertilizer, F1 = 300 kg.ha⁻¹ of subsidized NPK fertilizer and 100 kg.ha⁻¹ of subsidized urea, F2 = 300 kg.ha⁻¹ of subsidized NPK fertilizer and 100 kg.ha⁻¹ of non-subsidized urea, F3 = 300 kg.ha⁻¹ of subsidized NPK fertilizer, 100 kg.ha⁻¹ of non-subsidized urea, and 1 kg.ha⁻¹ of trichocompost, F4 = 300 kg.ha⁻¹ of subsidized NPK fertilizer, 100 kg.ha⁻¹ of non-subsidized urea, and 3.3 mL/L of biofertilizer.

TABLE 4 Farm business analysis of each technology package (in USD).

Component	Double row					Single row				
	F0	F1	F2	F3	F4	F0	F1	F2	F3	F4
Planting cost	78.54	78.54	78.54	78.54	78.54	39.27	39.27	39.27	39.27	39.27
Subsidized urea	0	18.41	0	0	0	0	18.41	0	0	0
Non-subsidized urea	0	0	49.09	49.09	49.09	0	0	49.09	49.09	49.09
Trichocompost	0	0	0	92.04	92.04	0	0	0	92.04	92.04
Biofertilizer	0	0	0	0	49.09	0	0	0	0	49.09
Production facilities	61.36	61.36	61.36	61.36	61.36	61.36	61.36	61.36	61.36	61.36
Maintenance	61.36	61.36	61.36	61.36	61.36	61.36	61.36	61.36	61.36	61.36
Harvesting	213.41	213.41	213.41	213.41	213.41	213.41	213.41	213.41	213.41	213.41
Total expenses	414.67	466.15	525.06	652.32	712.39	325.51	323.06	454.80	561.51	630.29
Total income	2,134.41	2,464.59	2,747.33	3,099.23	3,209.13	1,635.12	1,426.68	2,437.28	2,584.12	2,780.53
Profit	1,719.68	1,998.43	2,222.28	2,446.91	2,496.74	1,309.67	1,103.62	1,982.48	2,022.55	2,150.30
B/C ratio	4.15	4.29	4.23	3.75	3.50	4.02	3.42	4.36	3.60	3.41
Profit ratio	1.31	1.53	1.70	1.87	1.91	1.00	0.84	1.51	1.54	1.64

The optimal treatments are highlighted in yellow and indicated in bold, F0 = no fertilizer, F1 = 300 kg.ha⁻¹ of subsidized NPK fertilizer and 100 kg.ha⁻¹ of subsidized urea, F2 = 300 kg.ha⁻¹ of subsidized NPK fertilizer and 100 kg.ha⁻¹ of non-subsidized urea, F3 = 300 kg.ha⁻¹ of subsidized NPK fertilizer, 100 kg.ha⁻¹ of non-subsidized urea, and 1 kg.ha⁻¹ of trichocompost, F4 = 300 kg.ha⁻¹ of subsidized NPK fertilizer, 100 kg.ha⁻¹ of non-subsidized urea, and 3.3 mL/L of biofertilizer. (exchange rate: 1 USD = 16,297.26 IDR per 23 July 10.12 UTC).



China, and several other countries are quite similar, as reflected in the adjacent interaction patterns that demonstrate the alignment of researchers' ideas across nations. Overall, this research group focuses on developing rice varieties that can adapt to limited water availability (Panda et al., 2021; Shafi et al., 2023; Zampieri et al., 2023; Kang et al., 2025). While some studies have concentrated on managing two types

of water stress, drought and flooding (Rahman et al., 2016; Bin Rahman and Zhang, 2022), many efforts have been directed towards reducing methane emissions from rice fields. These fields are known to contribute significantly to methane production during inundated (Wihardjaka et al., 2024). The alternate wetting and drying (AWD) technique has been proposed to mitigate methane formation (Setyanto et al., 2018; Echegaray-Cabrera et al., 2024; Loaiza et al., 2024). However, adopting AWD can potentially decrease the production potential of paddy rice if the varieties utilized are not drought-tolerant (Sembiring et al., 2023; Wihardjaka et al., 2024; Kang et al., 2025). Additionally, various alternative approaches are being explored to fully realize the potential of rice varieties to thrive on suboptimal land. Thus, the development of varieties that can adapt to drought stress is essential for optimizing AWD techniques and advancing amphibious rice varieties in the USA.

Indonesia has played a pivotal role in collaborative efforts in the development of amphibious rice. The extensive volume of scholarly articles originating from this country underscores the fact that the concept of amphibious rice is firmly entrenched in local practices, reflecting the unique wisdom and potential of each region within Indonesia (Aryana and Wangiyana, 2016; Wangiyana et al., 2021). While the conceptual framework for amphibious rice in Indonesia tends to align more closely with the Chinese model, two studies specifically focused on strategies for reducing carbon emissions (Wihardjaka et al., 2024). This suggests that Indonesia demonstrates a distinct pattern of collaboration and interaction in the domain of amphibious rice development.

The concept of amphibious rice can be explored from four perspectives based on keyword interaction analysis, as depicted in Figure 4. The dominant clusters are red and green, whereas blue and yellow act as the supporting categories. The red cluster emphasizes the objective of developing amphibious rice, which serves as a resilient alternative in response to unpredictable rainfall patterns (Aryana and Wangiyana, 2016; Noviana et al., 2021). These patterns have become increasingly erratic over time (Chauhan et al., 2022; Nawaz et al., 2022; Dharmarathne et al., 2024), making it challenging for farmers to determine optimal planting times, especially in water-reliant tropical regions, such as Indonesia (Ansari et al., 2023). The advancement of amphibious rice varieties can effectively mitigate significant yield losses caused by water scarcity (Noviana et al., 2021).

The green cluster outlines the development and establishment of amphibious rice varieties that can thrive under both dry and wet conditions, resulting in modifications to their root systems (Kim et al., 2020; Yamauchi et al., 2021). Rice plants are distinguished by their ability to form aerenchyma, a specialized modification of the cortex tissue that facilitates optimal oxygen delivery during periods of submersion (Steffens et al., 2011; Yamauchi et al., 2021). This adaptation enables amphibious rice varieties to develop robust root structures, ensuring adequate oxygen, nutrient, and water uptake when confronted with fluctuating water availability throughout their life cycles. Moreover, the development of amphibious varieties is intrinsically linked to their capacity to utilize limited water resources, including their rooting potential. A critical aspect of this is managing excessive water loss using strategies such as regulating stomatal openings, conserving water during stomatal formation, and employing simple metabolites to maintain tissue osmotic levels (Zhang et al., 2022; Zampieri et al., 2023; Kang et al., 2025). Figure 5 illustrates the various factors that bolster the genetic potential of amphibious rice.

This emphasizes the need for comprehensive studies on the cultivation patterns and physiological aspects of these rice varieties to optimize their production potential. This perspective is supported by Aryana and Wangiyana (2016) and Wangiyana et al. (2021). Therefore, the advancement and optimization of amphibious rice varieties represent a key component in achieving sustainable agricultural production amidst dynamic climate change.

4.2 Production potential in Indonesia amphibious rice development

Enhancing the assessment based on recorded publication data can be accomplished by analyzing the yield potential. Table 5 presents publications related to amphibious rice development in Indonesia, indexed in Scopus. Research efforts in this area have primarily been led by Sadimantara and Wangiyana. An overview of these publications reveals that the average yield for amphibious rice development is approximately 5.26 ton ha⁻¹, encompassing a variety of research topics. Notably, the highest yield was documented in a study by Aryana and Wangiyana (2016), which reported an average of 6.8 ton ha⁻¹ for irrigation systems in lowland areas. The lowest yield was also found in another study by Aryana and Wangiyana (2016), who focused on irrigation systems in highland regions.

The amphibious rice varieties were assessed using data from the Indonesian Ministry of Agriculture shown in Table 6. Generally, the average yield of upland rice varieties falls below 6 tons per hectare. The variety with the highest average yield is Inpago 8 and 9. In contrast, the lowest average yield was Inpago 6, producing only 3.9 ton ha⁻¹. Importantly, all varieties examined had a potential yield exceeding 6 ton ha⁻¹, except Inpago 6. The standout varieties, Inpago 8 and Inpago 9, exhibit impressive yield potentials of 8.1 ton ha⁻¹ and 8.5 ton ha⁻¹, respectively.

Review of various sources reveals that the productivity of amphibious rice, as reported in publications and descriptions of its

TABLE 5 Yield analysis based on amphibious rice publications in Indonesia.

Publication	Yield (t ha ⁻¹)	Topic
Aryana and Wangiyana (2016)	6.80	Irrigation system in the lowland
Aryana and Wangiyana (2016)	5.10	Irrigation system in Middleland
Aryana and Wangiyana (2016)	4.10	Irrigation system in the highland
Tri (2017)	6.66	Evaluation of amphibious rice varieties
Sadimantara et al. (2018)	4.89	Screening lines
Sadimantara et al. (2020)	6.40	Screening lines
Sadimantara et al. (2021b)	4.85	Evaluation lines
Sadimantara et al. (2021a)	4.75	Evaluation lines
Wangiyana et al. (2021)	5.18	Evaluation lines based on cultivation
Wihardjaka et al. (2024)	5.04	Evaluation of amphibious rice varieties
Average yield	5.26	

TABLE 6 Average and potential yields of different varieties based on descriptions from Ministry of Agriculture in Indonesia.

Variety	Means (t ha ⁻¹)	Yield potential (t ha ⁻¹)	Institution	Source
Situ Bagendit	4.0	5.0	Ministry of Agriculture, Indonesia	Sunandar et al. (2015)
Inpari 10	4.8	7.0	Ministry of Agriculture, Indonesia	Sunandar et al. (2015)
Towuti	4.0	7.0	Ministry of Agriculture, Indonesia	Aryawati et al. (2021)
Inpago 4	4.1	6.1	Ministry of Agriculture, Indonesia	Sunandar et al. (2015)
Inpago 5	4.0	6.2	Ministry of Agriculture, Indonesia	Sunandar et al. (2015)
Inpago 6	3.9	5.8	Ministry of Agriculture, Indonesia	Sunandar et al. (2015)
Inpago 7	4.6	7.4	Ministry of Agriculture, Indonesia	Sunandar et al. (2015)
Inpago 8	5.2	8.1	Ministry of Agriculture, Indonesia	Sunandar et al. (2015)
Inpago 9	5.2	8.4	Ministry of Agriculture, Indonesia	Sunandar et al. (2015)
Situ Patenggang	4.6	5.6	Ministry of Agriculture, Indonesia	Sunandar et al. (2015)

varieties, ranges from 4.44 to 5.26 tons per hectare. However, the average yield of 4.94 tons per hectare remained noticeably below its potential. This highlights the significant impact of environmental factors on maximizing the yield of different rice varieties. Therefore, it is crucial to implement innovative cultivation practices to enhance the amphibious rice production. Furthermore, the bibliometric analysis places this research within the blue and yellow clusters. According to [Wangiyana et al. \(2021\)](#), it is essential to integrate agronomic practices, especially the use of organic materials, to improve the growth potential of amphibious rice. Therefore, research aimed at developing amphibious rice should prioritize the collection of primary data through cultivation engineering approaches.

4.3 Optimization of amphibious rice cultivation: primary study with the Biobestari variety

Optimization of cultivation through environmental engineering is a pivotal aspect of crop intensification ([Abduh et al., 2021](#); [Boros et al., 2024](#)). This approach necessitates the integration of several critical elements of cultivation practices, specifically focusing on plant spacing and fertilization strategies ([Hindersah et al., 2022](#); [Girsang et al., 2023](#)). Plant spacing is closely associated with patterns of competition among plants for essential resources, including nutrients, microclimatic advantages, and accessible growing space ([Hindersah et al., 2022](#); [Zheng et al., 2022](#); [Yuliawan et al., 2023](#); [Rafuiddin et al., 2024](#)). Furthermore, this concept is intrinsically linked to population density, which is significantly correlated with overall productivity levels ([Yang, 2014](#); [Tian et al., 2017](#); [Lin et al., 2019, 2022](#)). The potential for enhanced productivity is specific to each crop variety, particularly when plant spacing is strategically coupled with an appropriate fertilization system ([Abduh et al., 2021](#); [Hindersah et al., 2022](#); [Rafuiddin et al., 2024](#)). The interaction between plant spacing and fertilization influences critical growth parameters such as tillering potential, photosynthetic efficiency, and the assimilation of photosynthates into spikelets, thereby directly contributing to increased rice production ([Chang et al., 2023](#); [Ling et al., 2024](#)), including in amphibious rice. Fertilization systems, as integral components of these interactions, exhibit distinct patterns that can significantly influence plant growth, contingent on the specific constituents employed ([Hilty et al., 2021](#); [Musa et al., 2023](#)). Generally,

two predominant categories of fertilizers—chemical and organic—have pronounced effects on the production potential of rice crops ([Liu et al., 2018](#); [Liu Y. et al., 2024](#); [Dincă et al., 2022](#); [Wang et al., 2023](#)). Chemical fertilizers are characterized by a high concentration of essential plant nutrients and are typically of synthetic origin ([Abebe et al., 2022](#)). While their application can substantially benefit crop yields, excessive reliance on these fertilizers may compromise the physical, chemical, and biological integrity of the soil, leading to a sustainable decline in rice productivity if remedial measures are not implemented ([Kakar et al., 2020](#); [Abebe et al., 2022](#); [Dincă et al., 2022](#)). Furthermore, such dependency can adversely affect the nutrient composition of the soil, thereby affecting the quality of agricultural produce ([Kakar et al., 2020](#)). Conversely, the potential of organic fertilizers is linked to the provision of essential microelements and growth-regulating hormones, which are vital for augmenting crop production ([Liu M. et al., 2024](#)). These organic substances support the maintenance of the physical, biological, and chemical functionalities ([Sheoran et al., 2019](#); [Kakar et al., 2020](#); [Gupta et al., 2022](#); [Khan et al., 2024](#); [Liu Y. et al., 2024](#)). The synergistic application of chemical and organic fertilizers is particularly critical when considering their interplay with plant spacing in amphibious rice cultivation. Consequently, a primary direction for evaluating amphibious rice involves elucidating the potential interactions between plant spacing, chemical fertilizers, and organic fertilizers.

Based on the evaluation of these three characteristics, the interaction between spacing and fertilizer packages demonstrated minimal variation across the three traits. This observation suggests that the changes and improvements are consistent for each fertilizer package in relation to the spacing pattern; thus, there was no alteration in the pace and rhythm of growth for any fertilizer package concerning the spacing pattern ([Schober et al., 2024](#)). However, each independent factor exhibited a significant variation. These findings indicate that the spacing system must be integrated with the optimization of fertilizer packages to enhance upland rice production. This phenomenon was also noted by [Wangiyana et al. \(2021\)](#), where no interaction was found between the spacing pattern and intercropping. A thorough analysis was performed for each component. This result may indicate that the two factors affect plant growth independently, with no synergistic effect. One possible explanation is that spacing affects light interception and tiller emergence, while fertilizer affects nutrient availability and assimilation, through different physiological mechanisms. Similar findings have been reported by [Rathwa et al.](#)

(2023) and Ninad et al. (2017), planting spacing primarily influences tiller emergence and nutrient access by altering light interception and root competition, while fertilizer treatments mainly affect panicle development and grain filling through nutrient availability and uptake efficiency. The absence of a significant interaction may suggest that the effects of each factor reached a physiological threshold independently, where the response of one factor was already maximized, leaving limited scope for further enhancement by the other. In such cases, one treatment may dominate or obscure the potential effect of the second, resulting in a statistically non-significant interaction despite observable main effects. Therefore, the viability of each combination of plant spacing and fertilizer packaging requires further in-depth investigation, particularly in relation to amphibious rice, specifically the Biobestari variety.

The optimization results for the amphibious rice variety Biobestari revealed a noteworthy pattern, particularly concerning spacing arrangement. The number of panicles per plant was lower in the double row system than in the single-row system. This observation aligns with the findings from (Dunn et al., 2020; Yuliawan et al., 2023), which indicated that denser populations typically yield fewer panicles per clump than those with more spacious arrangements. Conversely, the double row system exhibited a greater potential for panicle weight and overall yield than the single-row system. This is consistent with the research by Santosa et al. (2020), who noted a higher potential for rice panicle weight in double row configurations. This suggests that row density influences the growing space available for tillers within each rice clump. Additionally, the double row system enhances air circulation, improves the microclimate, and increases nutrient availability, all of which contribute to the potential for greater panicle weight (Tang et al., 2025). These findings highlight a synergy that could enhance productivity, as the double row system accommodates a larger population than the single-row system within the same planting area (Santosa et al., 2020; Tang et al., 2025). Thus, the double row system is more suitable for the Biobestari variety of amphibious rice varieties.

Fertilizer package optimization is a dynamic cultivation technique that enhances fertilization by adding components or by improving quality. In rice cultivation, significant changes have been observed with urea fertilization. Urea fertilizer plays a crucial role as a nitrogen source that is essential for rice crops (Prasad et al., 2020; Akter et al., 2022; Reddy et al., 2025). This highlights that the growth sensitivity of rice is highly contingent on both the quantity and quality of the nitrogen fertilizer. In Indonesia, there are two types of urea fertilizers: subsidized and non-subsidized (Suminartika et al., 2025). Subsidized fertilizer is priced relatively low compared with non-subsidized options (Adiraputra and Supyandi, 2021; Fahmid et al., 2022; Hatta et al., 2022; Suminartika et al., 2025). However, non-subsidized fertilizers are generally more effective than subsidized ones (Adiraputra and Supyandi, 2021; Fahmid et al., 2022; Suminartika et al., 2025). This study shows that non-subsidized urea fertilizer (F3) supports amphibious rice growth better than subsidized urea fertilizer (F2) in both single and double row planting. The superior effectiveness of non-subsidized fertilizers can be attributed to their lack of an oil coating layer, which allows nutrients to be absorbed directly by plants (Hidayat and Ishak, 2023; Ramdani et al., 2024). In contrast, subsidized fertilizers often feature a barrier designed for slow nutrient release (Adiraputra and Supyandi, 2021; Wu et al., 2024). This difference contributes to the variance in effectiveness between the two

types of urea fertilizers. Despite this, the use of subsidized fertilizers is still recommended over the use of urea fertilizer, especially for farmers with a tight budget. However, for better amphibious rice production, including the Biobestari variety, non-subsidized urea fertilizer is recommended.

Trichocompost, a combination of decomposed organic compost and *Trichoderma* spp., has been shown to improve soil structure and enhance plant growth (Cuevas and Banaay, 2022; Thuy and Trai, 2025). *Trichoderma* functions as a biostimulant by enhancing root development and promoting resistance to pathogens, contributing to healthier and more resilient crops (Faruk, 2018; Lasmini et al., 2022; Doni et al., 2023; Wonglom et al., 2024). Biofertilizers also play an important role by enriching soil microbial populations and accelerating nutrient mineralization, ultimately increasing nutrient availability to plants (Nosheen et al., 2021). Although the performance of biofertilizers can vary depending on site-specific conditions, their combined use with organic amendments has shown promise in supporting amphibious rice growth, particularly under sub-optimal environments.

Based on agronomic evaluations, the double row planting system applied with fertilization packages F3 and F4 emerged as the most effective options for optimizing the Biobestari variety of amphibious rice. While F4 yielded the highest average profit, it also showed considerable variability in yield outcomes that are likely influenced by environmental factors affecting biofertilizer performance, such as soil pH, organic matter, microbial composition, and local climate (Pei et al., 2025). This variability poses a financial risk, particularly for smallholder farmers who have limited access to capital and are more vulnerable to income instability. In contrast, F3 produced slightly lower average returns but with greater consistency across replications, making it a more secure option for farmers operating under risk or resource constraints. This trade-off between potential profit and yield stability is a critical consideration in selecting fertilizer strategies (Biswas et al., 2024). While the agronomic and economic results of this study highlight the potential of amphibious rice, particularly with the F3 and F4 fertilization packages. Several practical challenges must be acknowledged, one of the main barriers to adoption is the limited availability and accessibility of certified amphibious rice seed. In many rural areas, seed systems are still underdeveloped, and farmers may lack access to high-quality planting material. Furthermore, successful cultivation of amphibious rice often requires more precise field management practices, including water level control and timely fertilizer application, which can be difficult for farmers without adequate training or extension support.

Although this study focuses on optimizing amphibious rice cultivation, it is important to compare its performance with conventional rice varieties commonly used in Indonesian agricultural systems. For example, Ciherang and IR64 are typically grown in lowland irrigated fields, offering high yields under stable water conditions but are considered susceptible to drought or prolonged waterlogging (Nugraha et al., 2017; Lal et al., 2018). On the other hand, upland rice varieties such as Situ Bagendit and Inpari 24 are more suitable for dryland farming but tend to perform poorly in waterlogged or flood-prone environments (Cahyono and Altandjung, 2023; Rahayu et al., 2024). Amphibious varieties like Biobestari are designed to bridge this gap by tolerating dry seasons and temporary flooding, making them potentially more resilient in areas with unpredictable rainfall.

However, notable limitation of this study is that the primary study experiment was conducted at a single location and limited to a single cropping season. Given Indonesia's diverse agroecological ranging in climate, soil types, and elevation. Thus, results derived from one site may not fully capture the variability in amphibious rice performance across the broader landscape. Additionally, year-to-year climatic fluctuations can significantly influence crop responses, particularly for stress-adaptive varieties like amphibious rice. Therefore, to strengthen the robustness and external validity of the findings, future research should incorporate multi-location and multi-season trials. Such expanded designs would provide more comprehensive insights into the adaptability, productivity, and economic feasibility of amphibious rice.

4.4 Socio-economic in optimizing amphibious rice cultivation in Indonesia: primary study of Biobestari variety

The findings from the bibliometric keyword interaction analysis identified four critical issues essential for the development of rice varieties, particularly concerning their socio-economic potential. The first cluster, represented by the green group, emphasizes that the potential of rice extends beyond merely increasing yields; it is also intricately linked to resource conservation and the equitable distribution of agricultural products. This correlation suggests that the socioeconomic dimensions of rice variety development are closely tied to the sustainability of cultivation systems, which ultimately supports economic stability (Gharsallah et al., 2021; Krishnankutty et al., 2021; Zagre et al., 2024). Implementing an integrated cultivation system that incorporates conservation principles can enhance rice production stability and economic viability (Gharsallah et al., 2021). The second cluster, indicated by the red group, focused on crop production in the context of climate change and farmer adaptation. It underscores the importance of accounting for environmental factors in the development of cultivation technologies (Shahid et al., 2021; Bera et al., 2024; Paul et al., 2024). The third cluster, depicted in blue, highlights the development approach for amphibious rice, which requires an active dissemination strategy that engages farmers. Finally, the yellow cluster addresses broader socioeconomic topics. The lack of clarity in this area may indicate a lack of cohesion in the socioeconomic study of rice. The development concept is predicated on the direct integration of the social and economic potential of rice cultivation, ensuring that a comprehensive understanding of these socioeconomic aspects is incorporated into strategies for climate change resilience and mitigation (Heckelman et al., 2018; Bera et al., 2024; Nagaraj et al., 2024).

Bibliometric studies indicate that socio-economic aspects of rice innovation, particularly amphibious rice, are still insufficiently examined and lack cohesive exploration. Key issues such as gender roles in farming, access to land and financial services, and policy or institutional support are often addressed in isolation rather than as part of a unified framework. This fragmented approach hinders a comprehensive understanding of how amphibious rice can be adopted fairly across various farming groups. Gender dynamics, including women's involvement in decision-making and their access to agricultural inputs, are especially underrepresented, despite their vital contributions in many rice-growing areas. The primary study did not

include structured socio-economic data collection, such as household surveys, focus group discussions, or farmer interviews. As a result, key insights into farmer behavior, adoption constraints, and community-level responses to amphibious rice technologies remain unexplored. These gaps underline the necessity for richer socio-economic inquiry in upcoming research. By incorporating household-level data, farmer perspectives, and gender-specific insights. To capture these dimensions more comprehensively, future research should incorporate mixed-method approaches that include socio-economic profiling, qualitative accounts from farmers, and gender-disaggregated data.

The development and adoption of rice varieties are deeply embedded within the broader socio-economic perspective, as shown by keyword interactions related to rice development from a socio-economic perspective. Factors such as sustainability, climate adaptation, farmers' social systems, and both macro and microeconomic conditions play a crucial role in determining the success of any cultivation technology, including amphibious rice. However, a key limitation of the present study is the absence of perspectives from key stakeholders, particularly farmers, extension agents, and policymakers, who are central to real-world implementation. Without their input, strategies may overlook practical constraints, barriers to adoption, or context-specific knowledge that influences feasibility at the field level. To address this, future research should prioritize participatory approaches that actively involve stakeholders in the co-design and evaluation of amphibious rice systems. At the same time, future studies should aim for a stronger integration of socio-economic analysis, including cost-benefit evaluations, input-use efficiency, and farm-level feasibility, to ensure that amphibious rice can be scaled in ways that are both sustainable and inclusive.

Based on the PCoA map, the significance of the increase in profit is attributed to the use of unsubsidized urea fertilizer. This underscores two critical aspects of rice development: the planting distance system and the type of urea used. The double row planting system is a key component of amphibious rice cultivation. This system is not merely a spatial modification; it serves as an agronomic strategy to enhance the productivity per unit of land. The implications for economic optimization are particularly relevant in light of pressures such as agricultural land conversion and the fragmentation of land ownership in developing countries (Sutardi et al., 2023). However, the concept of effect appears to be less dynamic, as evidenced by the short diversity vectors presented in Figure 10. Nonetheless, it consistently demonstrated production differences between cropping patterns. This contrasts with the pattern exhibited by the application of urea fertilizer as the primary nitrogen source for the crop. The use of non-subsidized urea fertilizer significantly influences the profitability of technology optimization, indicating that the appropriate choice of urea type is strongly correlated with the profits generated. Administering the correct dosage and type of urea will also help to minimize the excessive use of subsidized urea. Thus, the adoption of non-subsidized urea and the double row planting system emerged as key factors for achieving economic optimization in amphibious rice cultivation. Additionally, incorporation of trichocompost and biofertilizers is recommended to further enhance the profitability of sustainable amphibious rice agriculture.

These findings align with the global literature trends related to sustainable agriculture, as shown in bibliometric mapping. Consistent topic clusters, such as climate change adaptation, socioeconomic

conditions, and technology adaptation in the bibliographic database, confirm that economic efficiency in modern agricultural systems cannot be separated from social and ecological dynamics. The Biobestari variety, an amphibious rice type, is particularly relevant in the context of climate change, especially for managing soil moisture fluctuations in marginal and semi-swamp lands.

5 Future perspectives and conclusions

Research conducted through both publication analyses and experimental methods underscores the importance of developing amphibious rice for the sustainability of rice production, especially in Indonesia. Our findings indicate that amphibious rice is crucial for enhancing the resilience of rice production in the face of climate change, particularly concerning variability in rainfall patterns. To achieve resilience, a comprehensive approach is needed that integrates multiple adaptation strategies, such as advancements in genetics, improved cultivation practices, economic sustainability, and the strengthening of institutional frameworks.

The genetic development of amphibious rice varieties is based on a physiological concept that integrates the potential of two distinct environments, particularly concerning water availability. Effective water balance management is central to this process, as it directly influences biomass formation. Enhancing traits such as root development, stomatal regulation, osmotic adjustment through osmoprotectants, and hormonal control, especially of abscisic acid that helps maintain this balance. Additionally, optimizing the interplay between photosynthesis and respiration contributes to improved water use efficiency. These strategies are crucial for developing rice varieties resilient to climate stress. A shuttle breeding approach, which selects genotypes across contrasting environments, supports the creation of such adaptive varieties and informs future land-use and breeding strategies.

This cultivation approach is essential for maximizing the genetic potential of amphibious rice. Optimizing plant spacing and fertilization enhances yield and economic viability, with the double row system proving particularly effective, especially for the Biobestari variety. This method works effectively when combined with specific fertilization strategies, notably the use of non-subsidized urea, trichocompost, and biological fertilizers. Urea, which is rich in nitrogen, plays an active role in influencing rice productivity; thus, careful consideration of the type and dosage of nitrogen fertilizer is essential to boost amphibious rice yields. This approach seeks to minimize excessive urea usage. A sustainable cultivation method can be achieved through the integration of trichocomposts and biofertilizers. Trichocompost in particular enhances the growth of amphibious rice by improving the agroecological conditions of rice cultivation. This benefit is further supported by biological fertilizers, although their potential in the Biobestari variety may exhibit a high standard deviation in research outcomes. Nonetheless, these fertilizers are believed to promote sustainable soil enhancement, highlighting their importance to the overall cultivation strategy. Therefore, sustainable and effective use of inputs is key to optimizing the genetic potential of amphibious rice cultivation. Future research should also consider interactions among genetics, environmental factors, and management practices. A comprehensive understanding of these interactions will be pivotal for assessing the effectiveness of amphibious rice in advancing food self-sufficiency.

Optimizing amphibious rice cultivation systems through a combined approach of planting distance and fertilization packages necessitates careful economic considerations. The double row system combined with the F4 package (non-subsidized urea, trichocompost, and biofertilizer) produced the highest net income and a strong profit ratio of 1.91, making it the most profitable approach. Although F3 (without biofertilizer) showed similar results, biofertilizer remains vital for long-term system balance. PCoA results highlight non-subsidized urea as a key driver of productivity, with a benefit–cost ratio (BCR) nearly double that of conventional methods. This strategy supports climate-smart agriculture by sustaining yields while minimizing resource degradation and offers strong potential for adoption in water-stressed, low-productivity areas.

The study highlights the potential of integrating the double row planting system with bio-inputs—such as trichocompost and biofertilizers as a practical and scalable strategy for improving both productivity and sustainability in rice cultivation. This approach is particularly valuable for smallholder farmers, who often face limited access to resources and heightened vulnerability to climate change. To enable widespread adoption, targeted policy support is essential. Key interventions include the implementation of green technology incentive schemes, farmer-centered extension and training programs, and the strategic reallocation of subsidies from chemical fertilizers toward organic and biological alternatives. This strategy not only boosts farmers' incomes, but also fortifies the resilience of agriculture against the challenges posed by climate change and volatility in input prices.

Ultimately, by integrating the double row system with bio-inputs represent more than just agronomic improvement, it reflects a transformative shift toward climate-smart and farmer-centered agricultural development. By prioritizing sustainability, input efficiency, and resilience. This approach addresses systemic challenges faced by smallholder farmers, including resource scarcity, market volatility, and environmental degradation. Embedding these strategies into national agricultural policy not only enhances productivity but also reinforces food sovereignty, ecological balance, and social equity. As Indonesia and other climate-vulnerable nations seek to safeguard food systems in an era of uncertainty, the adoption of such integrated models offers a clear and actionable path forward.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Author contributions

AAS: Writing – original draft, Conceptualization, Resources, Validation, Funding acquisition. YM: Conceptualization, Validation, Software, Writing – original draft, Formal analysis, Methodology. MA: Methodology, Formal analysis, Data curation, Validation, Conceptualization, Writing – review & editing. AY: Writing – review & editing, Methodology, Conceptualization. MF: Supervision, Writing – review & editing, Data curation, Methodology, Visualization. AHB: Conceptualization, Methodology, Writing – review & editing. FD:

Writing – review & editing, Supervision, Data curation, Validation. AD: Formal analysis, Writing – review & editing, Validation, Data curation, Software. ID: Writing – review & editing, Validation, Data curation. YN: Validation, Writing – review & editing. BP: Writing – review & editing, Data curation, Validation. HS: Writing – review & editing, Validation. AN: Validation, Writing – review & editing. MC: Writing – review & editing, Validation. AKB: Investigation, Writing – review & editing. MFA: Formal analysis, Writing – original draft, Data curation, Validation, Software, Investigation.

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Conflict of interest

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