TYPE Review
PUBLISHED 11 July 2025
DOI 10.3389/fsufs.2025.1553335

OPEN ACCESS

EDITED BY
Pallab Sarker,
University of California, Santa Cruz,
United States

REVIEWED BY
Ágnes Szepesi,
University of Szeged, Hungary
Priscila Sarai Flores-Aguilar,
Autonomous University of Queretaro, Mexico

*CORRESPONDENCE
Ana Paula Oliveira
✉ ana.oliveira@iseclisboa.pt

RECEIVED 08 January 2025
ACCEPTED 30 June 2025
PUBLISHED 11 July 2025

CITATION
Oliveira AP, Baltazar I and Santos JP (2025) Overcoming barriers to aquaponics adoption in schools: a practical implementation guide. *Front. Sustain. Food Syst.* 9:1553335.
doi: 10.3389/fsufs.2025.1553335

Overcoming barriers to aquaponics adoption in schools: a practical implementation guide

Ana Paula Oliveira[1,2]*, Isabel Baltazar[1] and João Pedro Santos[1]

[1]Instituto Superior de Educação e Ciências de Lisboa (ISEC Lisboa), Lisbon, Portugal, [2]Centro de Investigação, Desenvolvimento e Inovação em Turismo (CiTUR)—Polo Estoril, Estoril, Portugal

Aquaponics emerges as a promising approach to sustainable food production by integrating aquaculture (fish farming) and hydroponics (soil-less plant cultivation) within a closed-loop system that fosters a symbiotic relationship between aquatic organisms and plants. This study presents the development of a practical and accessible guide for constructing small-scale aquaponics systems tailored for educational settings. A systematic review of academic databases was conducted to consolidate dispersed knowledge into a clear, step-by-step methodology. It also highlighted the unique potential of aquaponics in schools, where it can serve as a dynamic tool for teaching a wide range of subjects, while simultaneously raising students' awareness of the climate crisis and the urgent need for alternative food sources. Aquaponics provides an excellent opportunity for integrating STEM education or Problem-Based Learning (PBL) method, enriching the learning experience with real-world applications. Beyond its educational advantages, aquaponics systems present a holistic and forward-thinking approach to agriculture, addressing environmental, economic, and social dimensions. Adopting aquaponics not only contributes to sustainable food practices but also nurtures a generation with a deeper understanding of the interconnected global challenges and solutions in a rapidly changing world.

KEYWORDS
aquaponics, food production, sustainability, education, STEM, PBL

1 Introduction

According to the United Nations (UN), on November 15, 2022, the global population reached 8 billion people, with projections indicating a rise to 9 billion by 2037 (ONU News United Nations Organization, 2022). This population surge, coupled with unsustainable practices in conventional agriculture, water scarcity, soil degradation, and inefficiencies in food distribution and resource use (Joyce et al., 2019; Mishra et al., 2020; Guimarães and Lima, 2021; Ibrahim et al., 2023), highlights the urgent need for sustainable food production alternatives. Aligned with the UN's 2030 Agenda for Sustainable Development, there is a growing imperative to "*ensure sustainable food production systems and implement resilient agricultural practices that enhance productivity, maintain ecosystems, and fortify adaptability to climate change, extreme weather conditions, droughts, floods, and other disasters, while progressively improving land and soil quality*" (UN, 2016).

In response to these challenges, the enhancement of techniques and technologies that meet current needs while optimizing resource efficiency becomes pivotal for economic, social, and environmental viability. Aquaponics emerges as one such technique, integrating aquaculture and hydroponics into a closed-loop eco-culture (Verma et al., 2023; Goddek et al., 2019; Krastanova et al., 2022; Channa et al., 2024). This symbiotic system allows for the recirculation of water and nutrients, reducing waste and resource consumption (Ibrahim et al., 2023; Verma et al., 2023; Goddek et al., 2019; Araújo, 2019). Aquaponics is a sustainable and ecological food production system that uses natural fertilization from fish to nourish plants while conserving water through a closed-loop irrigation cycle (Verma et al., 2023; Krastanova et al., 2022; Channa et al., 2024; Bambhaniya et al., 2023; Gabr et al., 2024; Stoyanova et al., 2024). When properly designed, fish can also be harvested for consumption upon reaching maturity. The system's growing popularity stems from its ability to produce healthy, pesticide-free food (Krastanova et al., 2022; Channa et al., 2024; Stoyanova et al., 2024). Aquaponics also supports the environmental and socio-economic sustainability of smart cities, especially in urban areas with limited land and water resources (Krastanova et al., 2022; Channa et al., 2024; Santos, 2016; Obirikorang et al., 2021). Moreover, innovations such as artificial intelligence (AI) and Internet of Things (IoT) integration offer solutions to key challenges in aquaponics, including technical complexity and system monitoring (Channa et al., 2024).

Aquaponics supports multiple UN Sustainable Development Goals (SDGs) by enabling the production of healthy, pesticide-free food while significantly reducing land and water use. Specifically, it contributes to SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 12 (Responsible Consumption and Production) (UN, 2016; Verma et al., 2023; UNESCO, 2010). Despite its alignment with these sustainability objectives, aquaponics faces regulatory challenges, particularly in obtaining organic certification under the European Union's stringent agricultural regulations [Ibrahim et al., 2023; European Parliament and Council of the European Union (EU), 2018]. In addition to its alignment with the SDGs, aquaponics also addresses several of the National Academy of Engineering's Grand Challenges, including the development of carbon sequestration technologies, management of the nitrogen cycle, and the provision of clean water (NAE, 2008; Duarte et al., 2015).

While aquaponics presents numerous sustainability advantages, it also poses operational challenges that merit attention. One of the critical concerns is the occurrence of infections, whether bacterial, fungal, or parasitic, which can spread rapidly within the closed-loop system. For fish, infections can lead to stress, reduced feeding, slower growth rates, secondary diseases, and increased mortality (Defoirdt et al., 2011). For plants, waterborne pathogens may cause root rot, wilting, stunted growth, or nutrient uptake deficiencies (Yep and Youbin Zheng, 2019). Given the interdependence of system components, a localized infection can compromise the health of the entire ecosystem, highlighting the importance of continuous monitoring, early detection, and effective management strategies.

Aquaponics has also gained attention for its educational potential. Several previous studies have explored the implementation of aquaponics in classroom settings as a tool for promoting scientific literacy, interdisciplinary learning, and student engagement in STEM fields (Goddek et al., 2019; Junge et al., 2019; Baykır et al., 2022; Dias and Navarro, 2024). These initiatives have demonstrated aquaponics' effectiveness in fostering systems thinking and environmental awareness among students. However, many of these educational implementations involve technologically advanced or commercially developed systems, which may not be accessible or feasible for all schools, particularly those with limited resources or technical expertise.

The present study builds upon this foundation by focusing on a practical, scalable, and low-cost approach to implementing aquaponics systems specifically designed for educational settings. Unlike prior studies that may rely on preassembled kits or high-tech monitoring systems, this work emphasizes accessible materials, simplified construction, and alignment with school curricula, making it suitable for broader adoption across diverse educational contexts.

From this comparative perspective, a clear need emerges for new knowledge that addresses the barriers to adoption of aquaponics in schools – such as lack of teacher training, system maintenance during school breaks, and limited financial and technical support. To respond to this gap, the central research questions guiding this work are:

- What are the primary challenges schools face in adopting aquaponics systems?
- How can a practical, adaptable implementation guide help overcome these barriers?
- What are the potential educational and sustainability outcomes of integrating aquaponics in formal education?

By consolidating current knowledge and offering a step-by-step framework for school-based aquaponics, this study aims to contribute to the wider dissemination of sustainable practices while enriching science education through experiential learning.

2 Materials and methods

This study employed a systematic literature review to support the development of a practical and pedagogically grounded aquaponics implementation guide. The review followed a structured approach based on established methodologies for systematic reviews in educational and environmental research (Newman and Gough, 2020; Bearman et al., 2012; Aikens et al., 2016), ensuring transparency and reproducibility in data collection, selection, and analysis.

2.1 Data sources and search strategy

Academic literature was collected from four major sources: PubMed, Web of Science, Scopus, and Google Scholar. The search was conducted using combinations of keywords including: aquaponics, educational aquaponics, aquaponics in schools, aquaponics system design, aquaponics challenges, and aquaponics advantages and disadvantages. The review focused on peer-reviewed journal articles, conference proceedings, theses, and institutional reports published in English or Portuguese from 2010 to 2024. Sources in Portuguese were included due to the relevance of regional case studies and were identified as such in citations.

2.2 Inclusion and exclusion criteria

Publications were selected based on their relevance to the three main research objectives:

(i) outlining design principles and steps for implementing aquaponics systems,
(ii) identifying the advantages and challenges of aquaponics as a sustainable food production system, and

(iii) examining its application as an educational tool at various academic levels.

Studies were included if they presented empirical data, technical system descriptions, educational interventions, or reviews directly related to aquaponics. Duplicate entries, non-peer-reviewed articles (except for government or institutional reports), and sources lacking methodological transparency were excluded.

2.3 Data organization and thematic analysis

After the initial screening and eligibility assessment, the selected studies were analyzed through thematic coding (Sánchez-Meca, 2022), allowing the classification of findings into the following categories:

- System design and implementation: covering materials, construction steps, system components, and variations in setup;
- Advantages and disadvantages: addressing sustainability, productivity, cost-efficiency, and common challenges such as disease management or maintenance;
- Educational applications: focusing on aquaponics as a pedagogical tool, integration into curricula, and its role in promoting STEM learning and environmental awareness.

2.4 Integration and synthesis

The findings were synthesized to develop a practical implementation guide, supported by evidence-based practices and adapted for educational environments with limited technical and financial resources. Where applicable, best practices were adapted from existing models described in the literature (Mengist et al., 2020; Acosta Castellanos and Queiruga-Dios, 2022), and attention was given to highlighting gaps in the current body of knowledge, thus framing opportunities for future research.

3 Results and discussion

3.1 Aquaponic systems guide

Aquaponics combines aquaculture (the cultivation of aquatic organisms) and hydroponics (soilless plant cultivation) (Ibrahim et al., 2023). This integrated system recirculates water and nutrients, enabling the simultaneous production of fish and vegetables (Channa et al., 2024; Canastra, 2017; Moya et al., 2014; Nozzi et al., 2016; Fernandes, 2017). As a result, aquaponics offers a sustainable model with dual outputs and income streams (Araújo, 2019).

Aquaponics systems, while varying in scale and design, are unified by key components essential for ecological and sustainable production. These core components include the aquaculture environment (for fish farming), the hydroponics (for plant farming), and a biological filter or biofilter (for the colonization of nitrifying bacteria) (Figure 1). Depending on specific methodologies or fish densities, a solids filter (mechanical filter) (Figure 1) may be required to remove particles that can adhere to plant roots and hinder water, oxygen, and nutrient absorption (Krastanova et al., 2022; Channa et al., 2024; Fernandes, 2017; Rakocy, 2012). Additionally, continuous water circulation requires a pump, powered by an appropriate energy source, to maintain system functionality.

Establishing an aquaponics system begins with addressing five key initial questions, each linked to specific actions and tasks (Figure 2). These questions form the foundation of a structured approach, serving as a comprehensive guide for setting up and managing the aquaponics system effectively. This method ensures a systematic process, helping to address critical factors and streamline the path from planning to operation.

3.1.1 Aquaculture system

In aquaponics systems with fish densities below 10 kg/m^3, tank sizes typically range from 100 to 1,000 L (Carneiro et al., 2015). Water flow in these tanks must balance water velocity and renewal rate. The flow should be gentle enough to avoid stressing the fish, yet sufficient to remove waste and prevent accumulation (Krastanova et al., 2022). For densities up to 10 kg/m^3, at least half the tank's volume should be replaced hourly. For higher densities, a complete water change per hour is necessary; for instance, a 500-liter tank with more than 5 kg of fish requires a pump with a minimum capacity of 500 L/h (Carneiro et al., 2015).

When selecting fish species for aquaponics, factors like water temperature, pH, fish density, and availability of juveniles and feed must be considered. For small systems, densities should remain under 25 kg/m^3 (Krastanova et al., 2022; Carneiro et al., 2015; Velazquez-Gonzalez et al., 2022). The choice of species depends on tank size and whether the fish are for consumption or ornamental purposes. Commonly used aquaponic species worldwide are listed in Table 1.

The Nile tilapia (*Oreochromis niloticus*) is the most widely used species in aquaponics due to its high productivity, disease resistance, and favorable growth characteristics (Krastanova et al., 2022). For ornamental species, koi carp (*Cyprinus carpio*) and goldfish (*Carassius auratus*) are ideal choices because of their resilience to water quality variations and high-density conditions (Krastanova et al., 2022; Channa et al., 2024; Carneiro et al., 2015).

When selecting fish, it is important to consider their dietary habits. Carnivorous fish require high-quality commercial feed, typically in the form of granules, and should be kept with similarly sized individuals to prevent aggression and predatory behavior (Krastanova et al., 2022). Omnivorous fish, on the other hand, are more adaptable and can comfortably coexist with other species. Thrive on a diverse diet that includes foods produced within the aquaponics system, such as aquatic plants and live food (e.g., worms), which helps reduce feeding costs (Krastanova et al., 2022; Carneiro et al., 2015; Velazquez-Gonzalez et al., 2022). Regardless of diet, fish metabolism adapts to food availability. Feeding guidelines suggest 1% of body weight daily for adults and 7% for juveniles (Channa et al., 2024; Carneiro et al., 2015; Velazquez-Gonzalez et al., 2022).

3.1.2 Hydroponic system

In hydroponic systems, the main techniques used are Media-Based Systems (MBS), Nutrient Film Technique (NFT), and Deep Water Culture (DWC) (Figure 3) (Channa et al., 2024; Yang et al., 2023). MBS (Figure 3A), also known as vertical systems, are common in small-scale aquaponics, suitable for low fish densities where daily fish feed consumption is 25–50 g per m^2 of plant area (Velazquez-Gonzalez et al., 2022). The substrate (expanded clay,

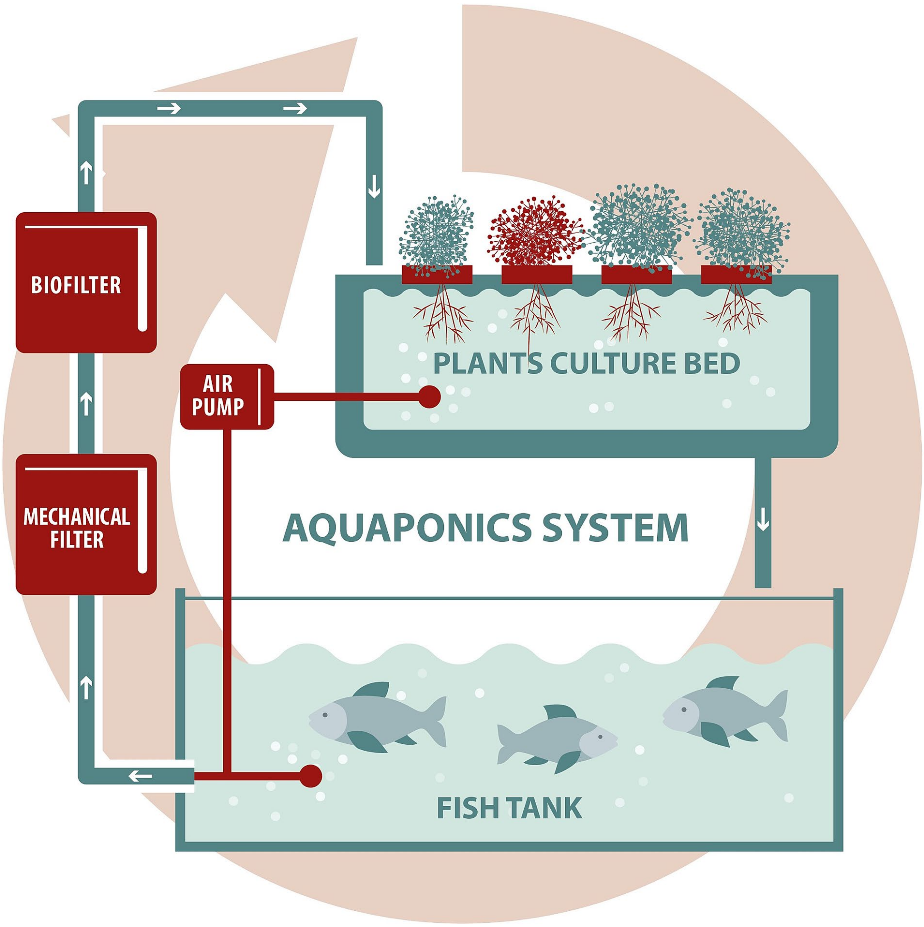

FIGURE 1
Small-scale aquaponics system components layout: plants culture bed (hydroponic system); fish tank (aquaculture system); mechanical filter; biological filter.

volcanic rocks, gravel, or similar materials) supports plants and provides a surface for nitrifying bacteria. NFT (Figure 3B) organizes plants in horizontal rows using PVC tubes with a shallow, nutrient-rich water flow (1–2 L/min) to nourish and oxygenate roots. The tubes are angled at 8–12% for gravity-driven water flow. This technique is often used in large-scale operations due to its space efficiency (Fernandes, 2017; Velazquez-Gonzalez et al., 2022; Yang et al., 2023). The DWC (Figure 3C), or raft system, is preferred for medium and large-scale aquaponics. Plants are placed on floating rafts, usually polystyrene, which may include support containers with substrates like expanded clay or rock wool. These rafts float in cultivation channels connected to the fish tanks (Carneiro et al., 2015; Yang et al., 2023).

Aquaponics can support a wide variety of crops, including lettuce, basil, cabbage, strawberries, tomatoes, and cucumbers (Table 2). Generally, any plant suitable for hydroponics can thrive in aquaponics, provided the system meets the plant's needs for space, nutrients, aeration, temperature, sunlight, and pH (Krastanova et al., 2022; Carneiro et al., 2015).

Plants are classified into low-and high-nutrient requirements (Table 2), with growth rates linked to the fish density in the system. Some plants demand more nutrients than others, affecting system management. According to Krastanova et al. (2022), plants with lower nutrient requirements thrive with a fish feed input of 20–50 g/m^2, whereas those with higher nutrient needs require 50–80 g/m^2. Rakocy (2012) found that the ideal feed-to-area ratio for raising Nile tilapia alongside crops like lettuce and basil in an aquaponic setup ranges between 60 and 100 g/day/m^2, ensuring balanced nutrient supply for both fish and plants.

For optimal growth, plants in aquaponic systems need 16 essential nutrients. While carbon, oxygen, and hydrogen are supplied by water, most other nutrients are derived from fish feed, except potassium (K) and iron (Fe), which are often lacking (Krastanova et al., 2022). Other elements like phosphorus (P), sulfur (S), manganese (Mn), boron (B), and molybdenum (Mo) also tend to be scarce (Krastanova et al., 2022). Rakocy (2012) highlight the need for external nutrient supplementation to ensure proper plant nutrition imbalances and poor solid waste management can lead to nutrient accumulation, low pH, and deficiencies in some micronutrients.

3.1.3 Filters

The biofilter is a crucial component in all aquaponics systems, providing conditions for nitrifying bacteria to convert nitrogenous compounds (Channa et al., 2024). It houses aerobic, autotrophic bacteria such as *Nitrosomas* spp., *Nitrosococcus* spp., and *Nitrobacter*

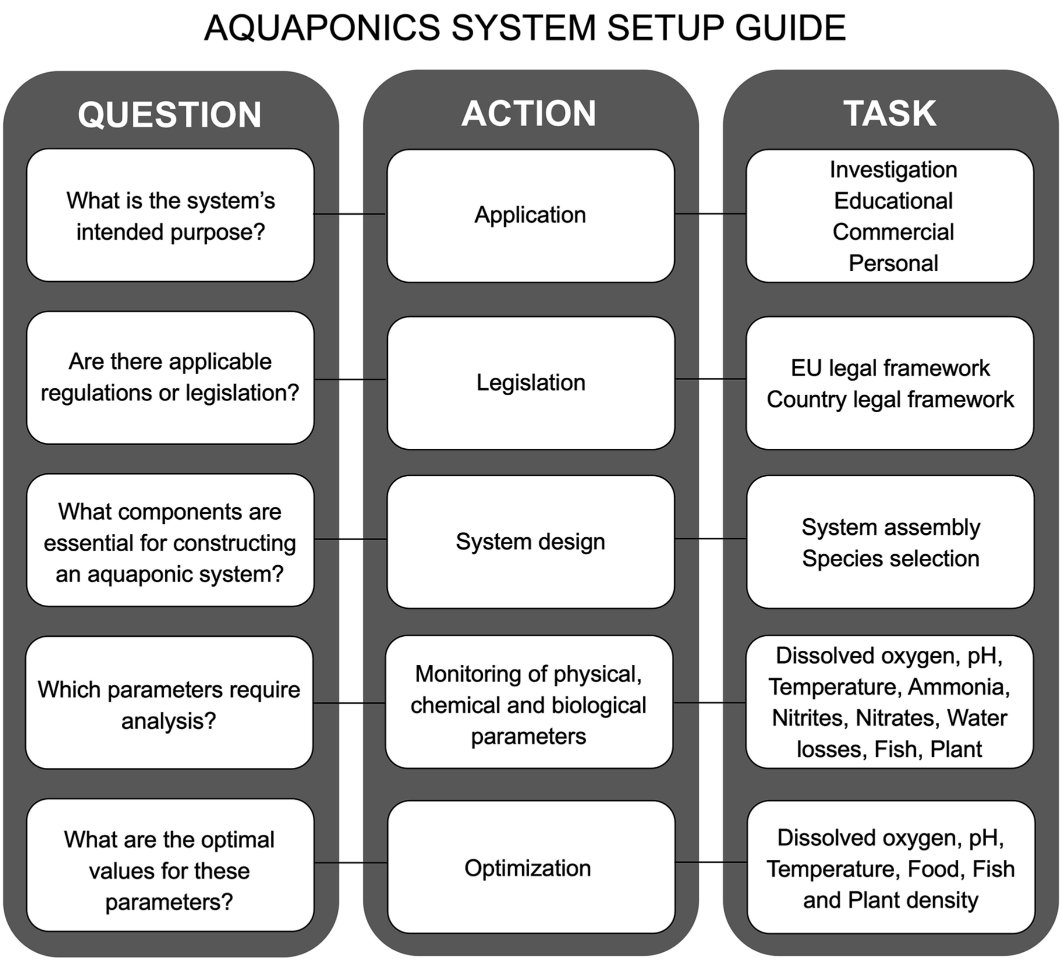

FIGURE 2
Guide for setting up an aquaponics system.

TABLE 1 Fish species most used in aquaponics.

Species name	
Common	Scientific
African catfish	*Clarias gariepinus*
Barbel	*Barbus barbus*
Boga	*Iberochondrostoma lusitanicum*
Common carp	*Cyprinus carpio*
Nile tilapia	*Oreochromis niloticus*
Rainbow trout	*Oncorhynchus mykiss*
River lamprey	*Lampetra fluviatilis*
Shrimp	*Macrobrachium rosenberghii*
Tambaqui	*Colossoma macropomum*

Source: adapted from Krastanova et al. (2022).

spp., which use carbon dioxide (CO_2) and bicarbonate (HCO_3^-) as carbon sources and oxygen for oxidation (Nozzi et al., 2016). Regular monitoring is crucial, as rising ammonia levels signal potential problems with biofilter efficiency or improper feed rate settings. Biofilter failures can result from factors such as bacterial die-off, chemical contamination, oxygen deficiency, or improper pH levels (Krastanova et al., 2022; Canastra, 2017).

For solid waste management, low fish densities (<5 kg/m^3) produce minimal waste, which the biofilter can handle. However, at densities above 10 kg/m^3, a mechanical filter is needed to remove solid waste. Mechanical filtration is typically done via sedimentation in conical-bottom decanters, allowing easy removal of settled particles (Channa et al., 2024). This collected waste, rich in organic matter, can be repurposed as fertilizer or processed in an anaerobic biodigester for biogas production (Canastra, 2017; Carneiro et al., 2015). Suspended solids that bypass mechanical filters should be captured using fine screens or sieves to maintain water quality.

3.1.4 Monitoring

Monitoring parameters in an aquaponic system is essential for maintaining the health and vitality of fish, plants, and beneficial bacteria (Krastanova et al., 2022).

Water quality is a critical factor in aquaponics, as it must support fish, plants, and bacteria. Maintaining the pH is vital: nitrifying bacteria thrive between 7.0 and 8.0 (Krastanova et al., 2022; Canastra, 2017), while hydroponic plants (see Table 2) prefer 5.5 to 6.5 (Velazquez-Gonzalez et al., 2022). Freshwater fish used in aquaponics (see Table 1) thrive at a pH of 7.5 to 9.0 (Krastanova et al., 2022). Thus,

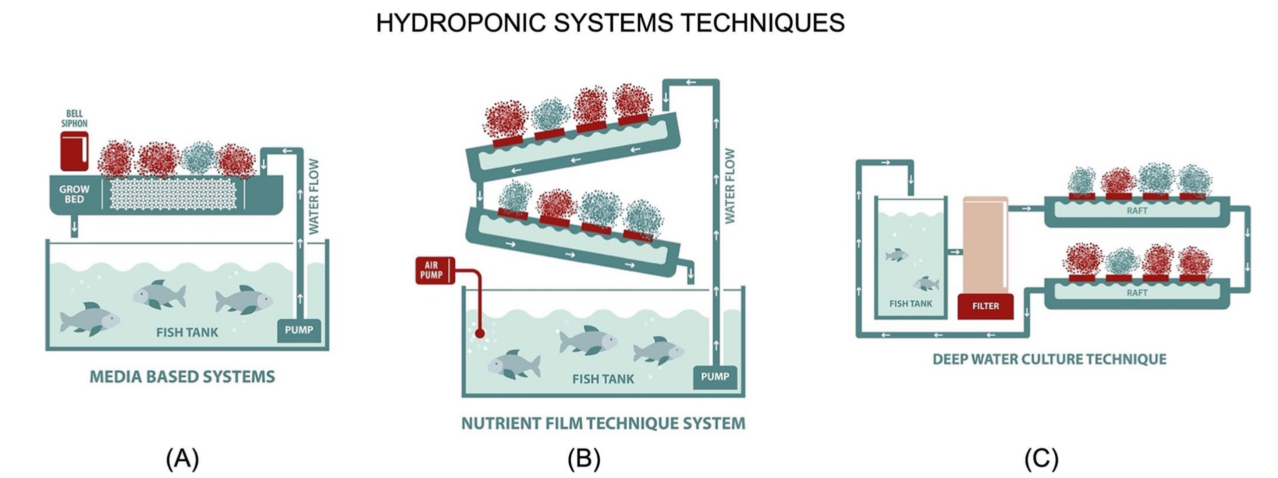

FIGURE 3
Techniques used in hydroponic systems: **(A)** media-based systems, **(B)** nutrient film technique, **(C)** deep water culture.

TABLE 2 Plants most used in aquaponics, according to their nutrient needs.

Low-nutrient plants		High-nutrient plants	
Common name	Scientific name	Common name	Scientific name
Basil	*Ocimum basilicum*	Cabbage	*Brassica oleracea var. capitata*
Lettuce	*Lactuca saliva*	Cucumber	*Cucumis sativus*
Mint	*Mentha spicata*	Strawberry	*Fragaria vesca*
Parsley	*Petroselinum crispum*	Tomato	*Solanum lycopersicum*

Source: adapted from Krastanova et al. (2022) and Velazquez-Gonzalez et al. (2022).

keeping a pH close to 7.0 is optimal for all components (Figure 4A; Table 3).

Water temperature is a critical factor in aquaponic systems, as it directly impacts the health and growth of fish, plants, and nitrifying bacteria. Fish species have specific temperature ranges they can tolerate, influenced by the local climate, which is an essential consideration when selecting species. For fish, temperatures above 32°C leading to mortality, while lower temperatures may reduce appetite and increase susceptibility to disease (Krastanova et al., 2022). Hydroponic vegetables thrive in temperatures between 20°C and 25°C, whereas nitrifying bacteria perform optimally within a range of 17°C to 34°C (Ibrahim et al., 2023; Krastanova et al., 2022; Carneiro et al., 2015). Maintaining these temperature ranges is crucial for the overall health and stability of the system (Figure 4B; Table 3).

Dissolved oxygen levels are crucial for sustaining both aerobic and anaerobic organisms, with a recommended range of 4 to 12 mg/L (Ibrahim et al., 2023; Krastanova et al., 2022; Velazquez-Gonzalez et al., 2022) (Table 3). To maintain these oxygen levels, effective aeration methods such as air compressors (air pumps), aerators, diffuser stones, or gravity-fed water flow can be employed (Canastra, 2017; Carneiro et al., 2015).

Ammonia concentration depends on pH and temperature, existing as toxic non-ionized ammonia (NH_3) and less harmful ionized ammonia (NH_4^+). An increase in pH by one unit can raise non-ionized ammonia tenfold (Canastra, 2017; Yang et al., 2023; Hu et al., 2015). Therefore, total ammonia should be kept below 2.0 mg/L (Krastanova et al., 2022) (Table 3).

Excess nitrite is harmful and should ideally remain below 0.5 mg/L (Krastanova et al., 2022; Canastra, 2017; Yang et al., 2023; Hu et al., 2015) (Table 3). If levels rise, actions such as halting feeding, partial water changes, or adding sodium chloride (NaCl) can help prevent absorption by fish.

Nitrate, a product of nitrite oxidation by nitrifying bacteria like *Nitrobacter* spp., is generally tolerated by aquatic animals at levels above 200 mg/L (Table 3) and is considered non-toxic (Krastanova et al., 2022; Yang et al., 2023; Hu et al., 2015).

Biological parameters, including fish and plant health, can be monitored by assessing population growth and changes. Fish growth is assessed by measuring their length and weight, while plant growth is evaluated by counting leaves, measuring the main stem, and, if applicable, counting the number of fruits. Population assessment for both fish and plants involves tracking the difference between the initial number of organisms introduced into the system, the number of deaths, and the final population count at the end of the experiment.

3.2 Aquaponics as a sustainable alternative

Aquaponics presents an eco-friendly alternative for fish and vegetable cultivation, minimizing environmental impact through its judicious use of water and efficient recycling of organic waste (Ibrahim et al., 2023; Channa et al., 2024; Carneiro et al., 2015; Velazquez-Gonzalez et al., 2022). Although rooted in age-old practices (Krastanova et al., 2022; Channa et al., 2024), aquaponics faced

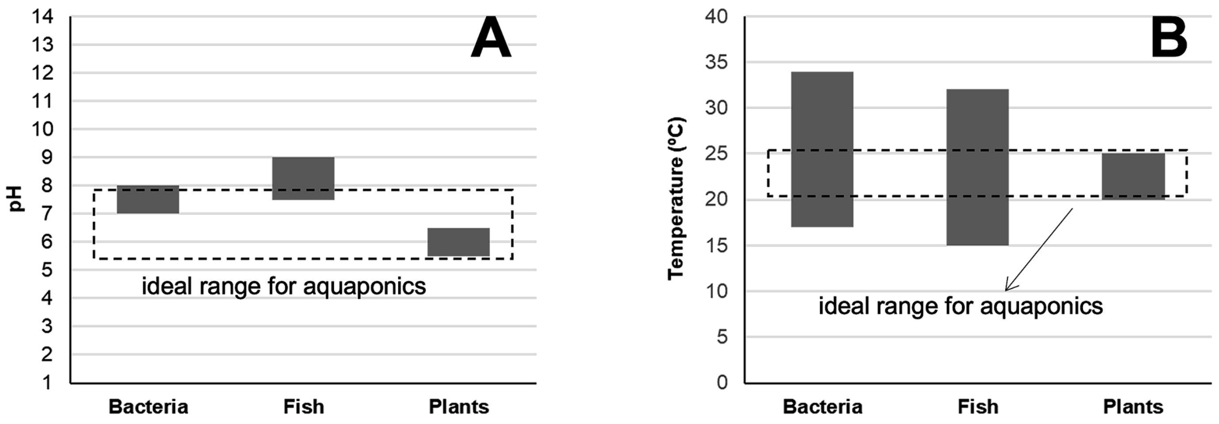

FIGURE 4
Water **(A)** pH and **(B)** temperature ranges for bacteria, fish, and plants in an aquaponic system, with the dotted rectangles indicating the optimal value ranges for each parameter.

TABLE 3 Monitoring water quality in an aquaponic system: key physical–chemical parameters, recommended analysis methods, and ideal ranges.

Parameter	Analysis method	Ideal range of values
pH	Potentiometry or probe	5.6–7.3
Temperature	Thermometer or probe	20–25°C
Dissolved oxygen	Winkler method or probe	4–12 mg/L
Ammonia	Distillation and titration	< 2.0 mg/L
Nitrites	Spectrophotometry	< 0.5 mg/L
Nitrates	Spectrophotometry	< 200 mg/L

Source: adapted from Krastanova et al. (2022), Channa et al. (2024), and Velazquez-Gonzalez et al. (2022).

limitations in traditional systems, demanding extensive physical space until a few decades ago. The introduction of water recirculation significantly enhanced productivity in these systems (Carneiro et al., 2015; Velazquez-Gonzalez et al., 2022).

One of the major advantages of aquaponics is its efficient water reuse, which minimizes waste and significantly reduces the discharge of pollutants into the environment (Ibrahim et al., 2023; Velazquez-Gonzalez et al., 2022). Unlike traditional agriculture and aquaculture, aquaponics requires substantially less water (Krastanova et al., 2022). Once filled, an aquaponics system can operate for extended periods without needing significant water changes. Occasional adjustments are necessary to maintain optimal water levels, compensating for losses due to evaporation and plant evapotranspiration. Effective water-quality management is also crucial, and as noted by Sasi et al. (2023), the use of plasmas in aquaponic systems offers a potential solution to this challenge. In comparison to hydroponics, which depends on constant water replacement with fresh nutrient solutions (Ibrahim et al., 2023; Channa et al., 2024; Velazquez-Gonzalez et al., 2022), aquaponics excels in sustainability.

To provide a clearer comparison among different agricultural systems, Table 4 offers a comprehensive evaluation of aquaponics, hydroponics, and conventional soil-based agriculture based on critical sustainability and productivity indicators. These indicators include water usage, energy consumption, chemical input requirements, waste generation, land/soil utilization, nutrient sourcing, space efficiency, productivity levels, environmental impact, automation potential, setup costs, and urban suitability. The assessment employs a color-coded scale to enhance the interpretability of results. The scale ranges from minimal (blue), very low (green), low (light green), low to moderate (light yellow), moderate (yellow), low to high (light orange), to high impact (orange), facilitating a visual differentiation of performance across systems.

Overall, aquaponics demonstrates a more favorable profile, with 58.3% of its parameters exhibiting minimal to low environmental and resource impact. In contrast, traditional agriculture shows a predominance of less sustainable attributes, with 58.3% of its evaluated parameters falling within the low to high or high impact categories. This comparative analysis underscores the potential of aquaponics as a more sustainable alternative to conventional agricultural practices.

The significant reduction in water and soil requirements enables aquaponics to be practiced in regions unsuitable for traditional aquaculture or agriculture, such as deserts, areas with degraded or contaminated soil, and saline environments (Rakocy, 2012; Yep and Youbin Zheng, 2019). By relying on a closed-loop system and water recirculation, aquaponics drastically reduces water wastage, making it ideal for resource-scarce settings (Fernandes, 2017; Hoevenaars et al., 2018). Additionally, integrating aquaponics into urban environments brings production closer to consumers, reducing the need for long-distance transportation. This not only lowers the ecological footprint but also ensures fresher, higher-quality products for local markets.

To synthesize the key advantages of aquaponic systems, Table 5 presents a structured summary organized into five thematic categories: Resource Efficiency, Environmental Impact, Productivity, Biological Benefits, and Technological Advancements. This classification highlights aquaponics' multidimensional contributions to sustainable food production and system resilience. Collectively, these categories illustrate the system's capacity to promote both environmental sustainability and operational resilience in modern agricultural practices.

The European Parliament (European Commission: Directorate-General for Environment, 2014) acknowledges aquaponics for its

TABLE 4 Comparison of aquaponics, hydroponics, and traditional agriculture based on key sustainability and productivity indicators.

Indicator	Aquaponics	Hydroponics	Traditional agriculture
Water use	Very low; ~90% savings through recirculation (Ibrahim et al., 2023; Krastanova et al., 2022; Rakocy, 2012; Velazquez-Gonzalez et al., 2022)	Moderate; requires frequent nutrient solution changes (Ibrahim et al., 2023; Channa et al., 2024; Velazquez-Gonzalez et al., 2022)	High; major losses from irrigation, runoff, and evaporation
Energy use	Moderate; Electricity needed for pumps, filters, possible AI/IoT (Channa et al., 2024; Chandramenon et al., 2024)	Moderate to high; pumps, climate control often needed	Low to moderate; depends on scale and mechanization
Chemical inputs	Minimal; avoids synthetic fertilizers and pesticides (Fernandes, 2017)	Very low; requires synthetic nutrient solutions; minimal pesticides	High; fertilizers, herbicides, and pesticides commonly used
Waste generation	Minimal; waste is reused or repurposed (e.g., as fertilizer/biogas) (Canastra, 2017; Carneiro et al., 2015)	Low to moderate; nutrient waste can accumulate; disposal needed	High; agricultural runoff causes pollution
Land/soil use	None; soil-free system	None; soil-free system	High; Requires fertile soil; affected by erosion and degradation
Nutrient source	Very low; organic (from fish feed and waste) (Krastanova et al., 2022; Rakocy, 2012)	High; synthetic nutrient mixes	Low to high; synthetic and organic (fertilizers, compost, manure)
Space efficiency	High; vertical and integrated designs	High; compact setups, especially vertical systems	Low; extensive land use
Productivity	High; dual output (fish + crops), intensive production (Rakocy, 2012; Somerville et al., 2014)	High; focused on fast-growing crops	Moderate; subject to weather, soil, and seasonal variations
Environmental impact	Low; low emissions, water reuse, minimal discharge (Fernandes, 2017; Velazquez-Gonzalez et al., 2022)	Moderate; less land, but potential nutrient discharge	High; deforestation, water use, chemical pollution
Automation potential	High; integration with AI, IoT, remote monitoring (Channa et al., 2024; Chandramenon et al., 2024)	Moderate; sensors and controls available	Low; typically less automated in small-scale systems
Setup cost	High; includes tanks, pumps, sensors, initial training	Moderate; equipment + nutrient costs	Low to high; depends on machinery, irrigation, land costs
Suitability for urban	Minimal; excellent; fits in compact or indoor spaces	Minimal; excellent; popular in greenhouses and urban farms	Moderate; limited; needs larger open spaces

A color scale highlights performance levels, ranging from minimal (blue), very low (green), low (light green), low to moderate (light yellow), moderate (yellow), low to high (light orange), to high impact (orange).

primary advantages, including (i) water recycling and reuse, (ii) high productivity concerning quantity/space ratio, and (iii) a diminished environmental footprint. However, aquaponics also presents several challenges when compared to conventional agriculture and aquaculture methods, including (Yep and Youbin Zheng, 2019; Canastra, 2017; Carneiro et al., 2015; Hu et al., 2015):

- Continuous reliance on electricity to power pumps and maintain system operations;
- Limitations on the use of pesticides and antibiotics;
- Requirement for expertise in key areas such as engineering, hydraulics, biology, phytotechnics, and fish farming;
- Initial investment and maintenance costs;
- Emissions of nitrous oxide (N_2O) from the nitrifying bacteria in the system, contributing to greenhouse gases:
- Restrictions on the types of fish and plants that can be cultivated, influenced by system design, environmental factors, and local regulations.

Nevertheless, some of these challenges can be overcome. For example, the reliance on electricity can be mitigated by incorporating renewable energy sources such as solar panels to power the system. The expertise required for operation can be addressed through training programs and the development of user-friendly monitoring technologies, which simplify management and make the systems more accessible. Additionally, the guide provided here serves to further expand knowledge and understanding.

3.3 Aquaponics as an educational tool

Aquaponics' adaptability to small-scale setups makes it ideal for use in compact or underutilized spaces (Velazquez-Gonzalez et al., 2022). Among the various advantages previously mentioned, its potential to enhance scientific literacy and educational value stands out. In educational environments, aquaponics serves as an effective tool for teaching natural sciences, including both life and physical

TABLE 5 Summary of the key advantages of aquaponic systems, grouped into five thematic areas.

Thematic areas	Aquaponics key advantages	Supporting references
Resource Efficiency	- ~ 90% reduced water use - Minimal waste production - Optimal use of natural resources	Ibrahim et al. (2023), Krastanova et al. (2022), Rakocy (2012), and Velazquez-Gonzalez et al. (2022)
Environmental Impact	- Low environmental footprint with renewable energy - No soil or pesticides - Reuse of fish waste - No fossil-fuel machinery	Fernandes (2017) and Velazquez-Gonzalez et al. (2022)
Productivity	- Dual production (fish and vegetables) - High-density production in limited space - Consistent, high-quality outputs	Rakocy (2012) and Somerville et al. (2014)
Biological Benefits	- Abundant nitrogen supply - Efficient nutrient cycling - Algae and fungi control - Reduced risk of exotic species introduction	Rakocy (2012) and Somerville et al. (2014)
Technological Edge	- AI and IoT integration for automation and monitoring	Channa et al. (2024) and Chandramenon et al. (2024)

sciences, across all educational levels (Junge et al., 2019; Baykır et al., 2022; Hart et al., 2013; Thompson et al., 2023), contributing significantly to environmental awareness.

Aquaponics introduces concepts such as water recirculation, interconnections among plants, fish, and microorganisms, rational food production, nutrition, and sustainability. These aspects provide a practical opportunity for harnessing the didactic-pedagogical potential of the system (Souza et al., 2022). By offering hands-on learning opportunities, aquaponics allows students to collect data, analyze trends, and explore correlations among physical, chemical, and biological factors (Channa et al., 2024; Thompson et al., 2023). It also supports the use of simulations within a controlled environment, providing a dynamic platform for experiential learning (Ibrahim et al., 2023; Khandakar et al., 2024). Teachers can utilize aquaponics to explore a wide range of topics and engage students in diverse activities (Thompson et al., 2023). Table 6 presents suggested activities that can be carried out using aquaponics, along with the corresponding knowledge and skills developed. Additionally, aquaponics offers opportunities for system automation, enabling the integration and advancement of new technologies, devices, applications, and methodologies that optimize water, energy, and labor efficiency (Channa et al., 2024; Khandakar et al., 2024; Abbasi et al., 2022).

Hence, skills such as problem-solving, systems thinking, and scientific processes (including data collection and observation) can be easily incorporated into aquaponics activities, given their recognized effectiveness as educational tools (Baykır et al., 2022; Thompson et al., 2023). Considering the inherently low maintenance nature of aquaponics, incorporating technology offers a potential solution during school holiday periods. Automated systems can effectively manage and monitor key parameters, presenting an educational asset and introducing a novel approach to learning within the realms of electronics and programming (Channa et al., 2024; Khandakar et al., 2024; Abbasi et al., 2022).

3.3.1 STEM education

An aquaponic system can provide an enjoyable and effective way for students to engage with Science, Technology, Engineering and Mathematics (STEM) education (Junge et al., 2019; Baykır et al., 2022; Thompson et al., 2023), offering an excellent opportunity for hands-on learning. The STEM Education model, as an instructional approach, centers on holistically engaging students through a multidisciplinary framework. By simultaneously addressing various subjects, this model helps students to assimilate new concepts and understand their practical applications in real-life scenarios. This approach actively promotes creativity and critical thinking, prompting students to seek innovative solutions, think unconventionally, and tackle complex problems. Encouraging inquiry and exploration of diverse perspectives, it cultivates the ability to make informed decisions. Additionally, the integration of technology and discipline-specific tools is a core component of the STEM education, improving the overall learning experience (Thompson et al., 2023).

Moreover, STEM education adds value by enhancing student motivation, as it allows them to see tangible applications in their daily lives, facilitating more effective knowledge acquisition compared to traditional teaching methods. Another key aspect of this approach is its emphasis on applying acquired knowledge, aligning with the principle of "learning by doing." Students are encouraged to put their knowledge into practice, allowing them to see its real-world implications and develop problem-solving skills. Ultimately, this teaching method better prepares students for the job market, helping them stand out and equipping to face the challenges of their future careers.

In the STEM education model, the teacher's role evolves from a traditional content provider to that of a mentor. Instead of delivering ready-made answers, teachers support and guide students, fostering a more interactive and exploratory learning environment.

3.3.2 PBL method

Problem-Based Learning (PBL) emerges as a response to the gap between training and professional practice, seeking to replace outdated teaching methods where memorization prevails. Unlike traditional approaches that disrupt knowledge transfer, PBL, along with other contemporary teaching models, adopts autonomous and active learning methods to cater to students with diverse abilities (Thompson et al., 2023; Gomes et al., 2017).

In PBL, students take center stage in the learning process, actively encouraged to ask questions, investigate, collaborate, and find solutions. This constructivist teaching strategy places students in

TABLE 6 Aquaponics-based educational activities: subjects, topics, and skills development.

Theme	Suggested teaching activities	Discipline	Skills
Agriculture	Activities about the origins of plant species and their relationship with the development of civilizations. Activities about indigenous and exotic species	History Geography	Contextualize, compare, and evaluate the impacts of different socioeconomic models on the use of natural resources and the promotion of the planet's economic and socioenvironmental sustainability (such as the adoption of agro-biodiversity and agroforestry systems by different communities, among others)
Biogeochemical cycles	Activities about the role of water, oxygen, and nitrogen compounds	Sciences Biology	Analyze and use interpretations about the dynamics of Life, Earth, and the Cosmos
Cell as unit of life	Observation of plant cells under an optical microscope from cultivated vegetables	Sciences Biology	Explain the basic organization of cells and their role as a structural and functional unit of living beings
Fluid dynamics	Construction of prototypes and assemblies of hydraulic systems	Physics	Analyze natural phenomena and technological processes, based on interactions and relationships between matter and energy, to propose individual and collective actions that improve production processes
Mathematics finance	Preparation of price and production cost spreadsheets for marketing family farming	Mathematics Economy Computing	Develop and/or discuss projects that address, above all, issues of social urgency, based on ethical, democratic, sustainable, and supportive principles
Nutrition and health	Nutritional analysis of foods produced at school and the importance of these nutrients for physiology and health	Sciences Biology	Public health programs and indicators
Photosynthesis and plant nutrition	Practical and theoretical activities with concrete materials from the system, such as plants and microorganisms	Sciences Biology	Analyze natural phenomena and technological processes, based on the interactions and relationships between matter and energy
Preparation of solutions	Practical and theoretical activities for preparing solutions, titrations for possible corrections of water quality and nutritional supplements for vegetables	Chemistry	Investigate problem situations and evaluate applications of scientific and technological knowledge and their implications in the world, using procedures and languages typical of Natural Sciences
Probability and statistics	Monitoring plant and fish growth with data recording and construction of tables and graphs	Mathematics	Develop logical reasoning, the spirit of investigation and the ability to produce convincing arguments, using mathematical knowledge
Quantities and measures	Preparation of technical drawings and projects for aquaponic systems	Mathematics Physics Computing	Floor plans and aerial views. Problems about measurements involving quantities such as length, mass, time, temperature, area, capacity, and volume
Sustainability	Selection of eco-friendly, recycled, or reused materials in system design. Evaluating the environmental sustainability of aquaponics through a life cycle analysis	Sciences	Cultivate a heightened environmental consciousness; Recognize the impact of human activities on ecosystems and the importance of sustainable practices
Taxonomy	Characterize and classify the living beings present in the aquaponics system. Development of specialized sub-systems for observing microorganisms using water from the aquaponics system	Sciences Biology	Analyze and characterize evolutionary relationships of living beings
Water analysis	Measurements of water variables such as pH, temperature, alkalinity, dissolved oxygen, ammonia, nitrite, nitrate	Chemistry	Investigate problem situations and evaluate applications of scientific and technological knowledge and their implications in the world, using procedures and languages typical of Natural Sciences

Source: adapted from Krastanova et al. (2022), Channa et al. (2024), and Sousa and Hoyos (2023).

scenarios with unknown problems, equipping them with the necessary tools and skills to solve those challenges (Thompson et al., 2023; Lonergan et al., 2022). This active teaching method guides reasoning and promotes the development of conceptual skills, fostering autonomous and active learning, making knowledge acquisition more straightforward through experience.

PBL learning projects are generally complex and challenging, requiring the application of concepts and skills from different areas of knowledge. PBL learning projects are typically intricate and demanding, requiring the application of concepts and skills from various knowledge domains. This approach incorporates a range of strategies, from trial-and-error methods to more focused techniques, all designed to promote student independence and initiative. Each student is encouraged to engage in individual research, and their active participation is vital, as they are expected to bring forth problems for collaborative exploration and resolution. This methodology cultivates a strong sense of responsibility, sharpens logical reasoning, and enhances teamwork skills among students.

In the PBL method, the teacher's role shifts to that of a facilitator, guiding students and providing essential support throughout the learning process.

4 Conclusion

Aquaponics holds significant potential for revolutionizing sustainable food production. It emerges as a promising alternative that aligns with planetary boundaries and adheres to United Nations guidelines encapsulated in the SDGs.

From an environmental perspective, aquaponics significantly reduces the ecological footprint associated with conventional agriculture. By recycling and reusing water within a closed-loop system, it minimizes water usage – an essential factor in areas experiencing water scarcity. Furthermore, this method diminishes reliance on synthetic fertilizers and pesticides, promoting organic and chemical-free cultivation practices.

Regarding social impact, aquaponics microsystems offer a decentralized and flexible solution for local food production. This is particularly vital in urban environments where traditional agriculture may be impractical due to constraints in space and resources. Aquaponics can be implemented at a small scale, allowing communities, schools, and even individual households to participate in sustainable food cultivation. Its scalability makes it accessible to diverse demographics, thereby promoting food security and strengthening community resilience.

Economically, the potential of aquaponics lies in its ability to generate multiple revenue streams. The integrated system produces both fish and vegetables simultaneously, thereby diversifying income opportunities for farmers. Moreover, the efficient use of resources, coupled with the ability to operate in non-traditional agricultural spaces, can contribute to the economic viability of aquaponics microsystems. This approach not only maximizes productivity but also minimizes operational costs, making it a sustainable alternative for modern food production.

Furthermore, the educational potential of aquaponics is noteworthy. Despite its apparent simplicity, aquaponics involves complex processes that provide a unique opportunity for schools to teach a variety of subjects while simultaneously raising students' awareness of the climate crisis and the urgent need for alternative food sources It offers a hands-on, practical learning experience for students and enthusiasts alike, covering various disciplines such as biology, chemistry, and environmental science. An aquaponic microsystem functions as a dynamic living laboratory, fostering a deep understanding of ecological relationships and sustainable practices. As a result, schools play a pivotal role in cultivating a generation of students who are not only aware of the interconnected challenges facing our world but also equipped with the knowledge and skills to develop innovative solutions.

The present study builds upon this foundation by proposing a practical, scalable, and low-cost approach to implementing aquaponics systems tailored specifically for educational environments. Unlike previous models that depend on high-tech equipment or commercially preassembled kits, this study emphasizes accessible materials, simplified design, and curricular integration to ensure feasibility across diverse educational contexts. In doing so, it addresses critical barriers to adoption, such as insufficient teacher training, challenges in maintaining systems during school breaks, and limited financial or technical support.

By exploring the primary obstacles schools face, evaluating the effectiveness of an adaptable implementation guide, and assessing the educational and sustainability outcomes of classroom-based aquaponics, this work contributes new knowledge aimed at fostering broader adoption in formal education. In conclusion, small-scale aquaponics not only offers a viable solution for sustainable food production but also serves as a powerful educational tool – cultivating ecological literacy, empowering learners, and inspiring action toward a more sustainable future.

Author contributions

AO: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. IB: Formal analysis, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. JS: Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

This work was conducted as part of the final project for the Bachelor's degree in Renewable Energies and Environment at the Higher Institute of Education and Sciences (ISEC Lisboa), undertaken by the author João Santos. Thanks, are also due to our colleague António Bajanca for his excellent work on the figures and graphical abstract design. We also express our gratitude to the ISEC Lisboa for supporting this research through the research project "plaNtas Energéticas eM aquapOnia—NEMO".

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.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

References

Abbasi, R., Martinez, P., and Ahmad, R. (2022). An ontology model to represent aquaponics 4.0 system's knowledge. *Inf. Process. Agric.* 9, 514–532. doi: 10.1016/j.inpa.2021.12.001

Acosta Castellanos, P. M., and Queiruga-Dios, A. (2022). From environmental education to education for sustainable development in higher education: a systematic review. *Int. J. Sustain. High. Educ.* 23, 622–644. doi: 10.1108/IJSHE-04-2021-0167

Aikens, K., McKenzie, M., and Vaughter, P. (2016). Environmental and sustainability education policy research: a systematic review of methodological and thematic trends. *Environ. Educ. Res.* 22, 333–359. doi: 10.1080/13504622.2015.1135418

Araújo, C. (2019). A aquaponia: desafios e oportunidades para a produção de peixes e hortaliças no estado do Pará – Estudo de caso: projetos de aquaponia no município de Bragança-Pará. Master thesis, Mestrado em Gestão de Recursos Naturais e Desenvolvimento Local na Amazônia. Belém: Universidade Federal do Pará, 137.

Bambhaniya, I., Kamleshbhai, B. P., and Bajaniya, V. C. (2023). "Unlocking sustainable agriculture: aquaponics system" in Dimension in agricultural sciences: A way forward for sustainability. eds. R. Abishek, T. Ilakiya, T. Poovarasan and G. Yazhini (Uttar Pardesh, India: JEC Publication), 54–70.

Baykır, A., Mirici, S., and Sönmez, D. (2022). Aquaponics systems as an educational tool: effects on students' achievement and teachers' views. *Int. J. Curric. Instr.* 15, 693–714.

Bearman, M., Smith, C. D., Carbone, A., Slade, S., Baik, C., Hughes-Warrington, M., et al. (2012). Systematic review methodology in higher education. *High. Educ. Res. Dev.* 31, 625–640. doi: 10.1080/07294360.2012.702735

Canastra, I. (2017). Aquaponia: Construção de um sistema de aquaponia a uma escala modelo e elaboração de um manual didático. Master thesis, Mestrado em Recursos Biológicos Aquáticos. Porto: Universidade do Porto/Faculdade de Ciências, 143.

Carneiro, P. C., Morais, C. A., Nunes, M. U., Maria, A. N., and Fujimoto, R. Y. (2015). Produção integrada de peixes e vegetais em aquaponia. Aracaju: Embrapa Tabuleiros Costeiros. Available online at: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1025991/1/Doc189.pdf (accessed on 27 May 2025).

Chandramenon, P., Aggoun, A., and Tchuenbou-Magaia, F. (2024). Smart approaches to aquaponics 4.0 with focus on water quality – comprehensive review. *Comput. Electron. Agric.* 225:109256. doi: 10.1016/j.compag.2024.109256

Channa, A. A., Munir, K. M., Hansen, M., and Tariq, M. F. (2024). Optimisation of small-scale aquaponics systems using artificial intelligence and the IoT: current status, challenges, and opportunities. *Encyclopedia* 4, 313–336. doi: 10.3390/encyclopedia4010023

Defoirdt, T., Sorgeloos, P., and Bossier, P. (2011). Alternatives to antibiotics for the control of bacterial disease in aquaculture. *Curr. Opin. Microbiol.* 14, 251–258. doi: 10.1016/j.mib.2011.03.004

Dias, T. V. B., and Navarro, R. D. (2024). Aquaponics in science education. *Rev. Gestão Soc. Ambient.* 18:e07169. doi: 10.24857/rgsa.v18n6-183

Duarte, A. J., Malheiro, B., Ribeiro, C., Silva, M. F., Ferreira, P., and Guedes, P. (2015). Developing an aquaponics system to learn sustainability and social compromise skills. *J. Technol. Sci. Educ.* 5, 235–253. doi: 10.3926/jotse.205

European Commission: Directorate-General for Environment. (2014). Living well, within the limits of our planet – 7th EAP – The new general union environment action programme to 2020. Publications Office.

European Parliament and Council of the European Union (EU) (2018). 848 regulation. Organic production and labeling of organic products and repealing council regulation (EC) no 834/2007 (30 may). *Off. J. Eur. Union* 150, 1–92. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R0848

Fernandes, C. (2017). Estudo da mariponia como sistema de produção hortícola e aquícola. Master thesis, Mestrado em Aquacultura, Instituto Politécnico de Leiria/Escola Superior de Turismo e Tecnologia do Mar. Peniche, 81.

Gabr, M. E., Alhajeri, N. S., Al-Fadhli, F. M., and Jabri, S. A. (2024). Aquaponics system for sustainable water, energy, and food nexus: a review. *Port-Said Eng. Res. J.* 28, 28–41. doi: 10.21608/pserj.2024.252618.1291

Goddek, S., Joyce, A., Kotzen, B., and Dos-Santos, M. (2019). "Aquaponics and global food challenges" in Aquaponics food production systems. eds. S. Goddek, A. Joyce, B. Kotzen and G. M. Burnell (Springer Cham), 3–17.

Gomes, R., Brito, E., and Varela, A. (2017). Intervenção na formação no ensino superior: a aprendizagem baseada em problemas (PBL). *Rev. Interacções* 12, 44–57. doi: 10.25755/int.11812

Guimarães, D. C. L., and Lima, S. C. (2021). "A agricultura e o consumo de água" in Inovação e tecnologia nas ciências agrárias. eds. P. H. A. Moura and V. F. C. Monteiro (Ponta Grossa, Brasil: Atena Editora), 219–225.

Hart, E. R., Webb, J. B., and Danylchuk, A. J. (2013). Implementation of aquaponics in education: an assessment of challenges and solutions. *Sci. Educ. Int.* 24, 460–480.

Hoevenaars, K., Junge, R., Bardocz, T., and Leskovec, M. (2018). EU policies: new opportunities for aquaponics. *Ecocycles* 4, 10–15. doi: 10.19040/ecocycles.v4i1.87

Hu, Z., Lee, J. W., Chandran, K., Kim, S., Brotto, A. C., and Khanal, S. K. (2015). Effect of plant species on nitrogen recovery in aquaponics. *Bioresour. Technol.* 188, 92–98. doi: 10.1016/j.biortech.2015.01.013

Ibrahim, L. A., Shaghaleh, H., El-Kassar, G. M., Abu-Hashim, M., Elsadek, E. A., and Hamoud, Y. A. (2023). Aquaponics: a sustainable path to food sovereignty and enhanced water use efficiency. *Water* 15:4310. doi: 10.3390/w15244310

Joyce, A., Goddek, S., Kotzen, B., and Wuertz, S. (2019). "Aquaponics: closing the cycle on limited water, land and nutrient resources" in Aquaponics food production systems. eds. S. Goddek, A. Joyce, B. Kotzen and G. M. Burnell (Cham, Switzerland: Springer Cham), 19–34.

Junge, R., Bulc, T. G., Anseeuw, D., Yildiz, H. Y., and Milliken, S. (2019). "Aquaponics as an educational tool" in Aquaponics food production systems. eds. S. Goddek, A. Joyce, B. Kotzen and G. M. Burnell (Cham, Switzerland: Springer Cham), 561–595.

Khandakar, A., Elzein, I. M., Nahiduzzaman, M., Ayari, M. A., Ashraf, A. I., Korah, L., et al. (2024). Smart aquaponics: an innovative machine learning framework for fish farming optimization. *Comput. Electr. Eng.* 119:109590. doi: 10.1016/j.compeleceng.2024.109590

Krastanova, M., Sirakov, I., Ivanova-Kirilova, S., Yarkov, D., and Orozova, P. (2022). Aquaponic systems: biological and technological parameters. *Biotechnol. Biotechnol. Equip.* 36, 305–316. doi: 10.1080/13102818.2022.2074892

Lonergan, R., Cumming, T. M., and O'Neill, S. C. (2022). Exploring the efficacy of problembased learning in diverse secondary school classrooms: characteristics and goals of problem-based learning. *Int. J. Educ. Res.* 112:101945. doi: 10.1016/j.ijer.2022.101945

Mengist, W., Soromessa, T., and Legese, G. (2020). Method for conducting systematic literature review and meta-analysis for environmental science research. *MethodsX* 7:100777. doi: 10.1016/j.mex.2019.100777

Mishra, R. P., Das, S. K., Kumar, N., and Mishra, J. P. (2020). Sustainable aquaponics system and its challenges: a review. *Int. J. Curr. Microbiol. Appl. Sci.* 9, 577–588. doi: 10.20546/ijcmas.2020.905.065

Moya, E., Sahagún, C., Carrillo, J., Alpuche, P., Álvarez-González, C., and Martínez-Yáñez, R. (2014). Herbaceous plants as part of biological filter for aquaponics system. *Aquac. Res.* 47, 1716–1726. doi: 10.1111/are.12626

NAE. (2008). *Grand challenges for engineering*. National Academy of engineering, 56 pp. Available online at: https://viterbischool.usc.edu/wp-content/uploads/2016/12/GrandChallenges.pdf (accessed on 27 May 2025).

Newman, M., and Gough, D. (2020). "Systematic reviews in educational research: methodology, perspectives and application" in Systematic reviews in educational research. eds. O. Zawacki-Richter, M. Kerres, S. Bedenlier, M. Bond and K. Buntins (Wiesbaden: Springer Fachmedien), 3–22.

Nozzi, V., Parisi, G., Crescenzo, D., Giordano, M., and Carnevali, O. (2016). Evaluation of *Dicentrarchus labrax* meats and the vegetable quality of *Beta vulgaris var. cicla* farmed in freshwater and saltwater aquaponic systems. *Water* 8, 423–437. doi: 10.3390/w8100423

Obirikorang, K. A., Sekey, W., Gyampoh, B. A., Ashiagbor, G., and Asante, W. (2021). Aquaponics for improved food security in Africa: a review. *Front. Sustain. Food Syst.* 5:705549. doi: 10.3389/fsufs.2021.705549

ONU News United Nations Organization (2022). Available online at: https://news.un.org/pt/audio/2022/11/1805377 (accessed on 25 September 2024).

Rakocy, J. (2012). "Aquaponics—integrating fish and plat culture" in Aquaculture production systems. ed. J. H. Tidwell (Iowa, USA: John Wiley & Sons, Inc.), 344–386.

Sánchez-Meca, J. (2022). Systematic reviews and meta-analyses in education: a tutorial. *RiiTE Interuniv. J. Res. Educ. Technol.* 13, 5–40. doi: 10.6018/riite.545451

Santos, M. J. P. L. (2016). Smart cities and urban areas – aquaponics as innovative urban agriculture. *Urban For. Urban Green.* 20, 402–406. doi: 10.1016/j.ufug.2016.10.004

Sasi, S., Prasad, K., Weerasinghe, J., Bazaka, O., Ivanova, E. P., Levchenko, I., et al. (2023). Plasma for aquaponics. *Trends Biotechnol.* 41, 46–62. doi: 10.1016/j.tibtech.2022.08.001

Somerville, C., Cohen, M., Pantanella, E., Stankus, A., and Lovatelli, A. (2014). Small-scale aquaponic food production—integrated fish and plant farming. Rome, Italy: FAO, 288.

Sousa, A. B., and Hoyos, D. C. M., (2023). Aquaponia: Uma ferramenta inovadora para o ensino de ciências. In Abordagens educacionais voltadas ao desenvolvimento mundial; Seven, Eds.; Seven Editora: Paraná, Brasil; 463–468.

Souza, J. S. S., Souza, R. T. Y. B., and Souza, L. O. (2022). A aquaponia como ferramenta didáticometodológica no ensino de ciências e matemática: experiências e propostas didáticas no contexto amazonense. *Rev. Bras. Ensino Cienc. Tecnol.* 15, 1–20. doi: 10.3895/rbect.v15n2.13864

Stoyanova, S., Ivaylo Sirakov, I., and Velichkova, K. (2024). Sustainable production: integrating medicinal plants with fish farming in aquaponics—a mini review. *Sustainability. For.* 16:6337. doi: 10.3390/su16156337

Thompson, K. R., Webster, C. D., Pomper, K. W., and Krall, R. M. (2023). Use of aquaponics project-based environments to improve students' perception of science, technology, engineering, and mathematics (STEM) disciplines and career pathways. *Interdiscip. J. Environ. Sci. Educ.* 19:e2309. doi: 10.29333/ijese/13102

UN. (2016). Guia sobre Desenvolvimento Sustentável: 17 objetivos para transformar o nosso mundo. UNRIC: Centro de Informação Regional das Nações Unidas para a Europa Ocidental; 38. Available online at: https://www.instituto-camoes.pt/images/ods_2edicao_web_pages.pdf (accessed on 27 May 2025).

UNESCO. (2010). *Engineering: Issues, challenges and opportunities for development*. UNESCO Publishing; 396. Available online at: https://www.acofi.edu.co/wp-content/uploads/2013/08/Issues-challenges.pdf (accessed on 27 May 2025)

Velazquez-Gonzalez, R. S., Garcia-Garcia, A. L., Ventura-Zapata, E., Barceinas-Sanchez, J. D. O., and Sosa-Savedra, J. C. (2022). A review on hydroponics and the technologies associated for medium-and small-scale operations. *Agriculture* 12:646. doi: 10.3390/agriculture12050646

Verma, A. K., Chandrakant, M. H., John, V. C., Peter, R. M., and John, I. E. (2023). Aquaponics as an integrated Agri-aquaculture system (IAAS): emerging trends and future prospects. *Technol. Forecast. Soc. Change* 194:122709. doi: 10.1016/j.techfore.2023.122709

Yang, T., Samarakoon, U. C., and Altland, J. E. (2023). Comparison of growth, phytochemical content, nutrient uptake, and water consumption of lettuce under two hydroponic system designs: nutrient film technique and deep-water culture. *Acta Hortic.* 1377, 747–754. doi: 10.17660/ActaHortic.2023.1377.91

Yep, B., and Youbin Zheng, Y. (2019). Aquaponic trends and challenges—a review. *J. Clean. Prod.* 228, 1586–1599. doi: 10.1016/j.jclepro.2019.04.290