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REVIEW PAPER OPEN ACCESS

Crayfish aquaponics systems: Current status, design considerations and future development opportunities

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ABSTRACT

The increasing demand for sustainable food production, coupled with challenges such as freshwater scarcity, environmental degradation, and climate change, has intensified interest in integrated farming systems that maximize resource efficiency while minimizing environmental impacts. Among these, aquaponics has emerged as a promising approach by integrating aquaculture and hydroponic crop production within a recirculating system. Although finfish dominate existing aquaponics research and commercial production, freshwater crayfish have gained increasing attention because of their high market value, environmental adaptability, and potential for diversified production. This review synthesizes current knowledge on the design and development of crayfish aquaponics systems based on peer-reviewed literature and authoritative publications published between 2000 and 2026. The review examines the biological characteristics of commercially important crayfish species, engineering and operational considerations, plant production and nutrient dynamics, economic feasibility, environmental sustainability, and emerging technological innovations relevant to crayfish aquaponics. The literature indicates that successful system performance depends on species-specific management strategies, appropriate stocking densities, effective shelter provision, balanced nutrient cycling, and optimized integration between crayfish biomass and plant production. Despite encouraging advances, significant knowledge gaps remain regarding commercial-scale production, nutrient balancing, system optimization, digital technologies, climate resilience, and comprehensive economic evaluation. Addressing these challenges will require interdisciplinary research integrating aquaculture, plant science, engineering, environmental management, economics, and precision agriculture. By consolidating current evidence and identifying priority research areas, this review provides a comprehensive reference for researchers, producers, and policymakers and offers a framework for advancing the development of efficient, resilient, and commercially viable crayfish aquaponics systems that contribute to sustainable food production and circular bioeconomy objectives.

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INTRODUCTION

The increasing global demand for food, coupled with challenges such as climate change, freshwater scarcity, environmental degradation, and declining arable land, has intensified the search for sustainable food production systems. Among the emerging approaches, aquaponics has gained considerable attention because of its ability to integrate aquaculture and hydroponics into a single recirculating system that efficiently utilizes water, nutrients, and space (Bosma *et al.*, 2017; David *et al.*, 2022; Verma *et al.*, 2023).

Aquaponics is a closed-loop production system in which waste generated by aquatic organisms is biologically converted into nutrients that support plant growth. In return, plants and associated microbial communities help remove excess nutrients and improve water quality before it is recirculated back to the culture tanks. This symbiotic relationship enables the simultaneous production of aquatic animals and crops while reducing water consumption and nutrient discharge compared with conventional farming systems (Greenfeld *et al.*, 2021; David *et al.*, 2022; Zhu *et al.*, 2024).

Most aquaponics research has focused on finfish species such as tilapia, catfish, carp, and trout because of their established culture technologies and compatibility with recirculating aquaculture systems (Bosma *et al.*, 2017; Bordignon *et al.*, 2024). However, there is growing interest in incorporating alternative aquatic species that may provide additional economic and ecological advantages. Among these, freshwater crayfish have emerged as promising candidates due to their high market value, consumer demand, adaptability to diverse environmental conditions, and suitability for intensive production systems (Jones, 2001; Saoud and Garza de Yta, 2012; Rigg *et al.*, 2020).

Crayfish play a unique role in aquaponic environments. Unlike finfish, they are benthic organisms characterized by territorial behavior, periodic molting, shelter dependence, and distinct feeding habits. These biological characteristics influence system design requirements, including tank configuration, habitat structure, water quality management, and nutrient dynamics. Consequently, the direct transfer of design principles from conventional fish-based aquaponics systems may not adequately address the specific requirements of crayfish culture (Saoud and Garza de Yta, 2012; Wang *et al.*, 2025; Zhang *et al.*, 2026).

Although numerous studies have examined aquaponics systems and crayfish aquaculture independently, research integrating both disciplines remains limited. Existing studies are often fragmented, focusing on specific aspects such as crayfish production, plant growth, water quality, or economic performance without providing a comprehensive assessment of the factors influencing successful system design and operation. As a result, knowledge gaps remain regarding species selection, system optimization, nutrient cycling, commercial feasibility, and long-term sustainability of crayfish-based aquaponics systems (Verma *et al.*, 2023; Spradlin and Saha, 2022).

This review synthesizes current knowledge on the design and development of crayfish aquaponics systems. Specifically, it examines the biological characteristics of crayfish relevant to aquaponics, engineering and operational considerations, plant production performance, economic and environmental sustainability, and emerging research opportunities. By consolidating available evidence and identifying critical research gaps, this review aims to provide a foundation for future investigations and support the development of efficient, resilient, and commercially viable crayfish aquaponics systems.

REVIEW METHODOLOGY

This study employed a narrative review approach supported by a systematic literature search to synthesize existing knowledge on the design and development of crayfish aquaponics systems. The review aimed to identify, evaluate, and integrate published literature related to crayfish biology, aquaponic system design, water quality management, nutrient cycling, plant production, economic feasibility, and environmental sustainability.

Literature search strategy

Relevant literature was collected from major academic databases, including Google Scholar, ScienceDirect, SpringerLink, Scopus, and JSTOR. Searches were conducted using combinations of the keywords such as "crayfish aquaponics", "crayfish culture", "aquaponic system design", "crustacean aquaculture", "integrated aquaculture", "recirculating aquaculture systems", "nutrient cycling in aquaponics", "sustainable aquaculture", "aquaponics economics", "aquaponics sustainability". Boolean operators (AND, OR) were used to refine search results and improve relevance.

Inclusion and exclusion criteria

The review included peer-reviewed journal articles, conference papers, academic theses, technical reports, and authoritative institutional publications published between 2000 and 2026. Studies were selected if they focused on aquaponics, crayfish aquaculture, integrated farming systems, nutrient management, water quality, system engineering, or sustainability aspects relevant to crayfish aquaponics and provided sufficient methodological and technical information to address the objectives of the review.

On the other hand, studies which did not provide sufficient methodological information; were unrelated to aquaponics or crayfish production systems; or consisted primarily of opinion articles without supporting scientific evidence, were excluded.

Literature screening and data extraction

The identified literature was initially screened based on titles and abstracts to determine relevance. Full-text articles were subsequently reviewed to assess eligibility according to the inclusion criteria. Relevant information was extracted and organized into thematic categories, including Crayfish biology and culture requirements; Aquaponic system design and engineering; Water quality management; Nutrient cycling and biofiltration; Plant production performance; Economic feasibility; and Environmental sustainability.

Data synthesis

The collected literature was analyzed using thematic synthesis. Findings from different studies were compared and integrated to identify common trends, emerging technologies, critical design considerations, and existing knowledge gaps. Emphasis was placed on factors influencing the successful integration of crayfish into aquaponic systems and on opportunities for future research and development.

The synthesized information was subsequently organized into thematic sections to provide a comprehensive overview of the status and prospects of crayfish aquaponics systems.

Biological characteristics of crayfish relevant to aquaponics

Successful integration of crayfish into aquaponics systems requires a thorough understanding of their biological and ecological characteristics. Unlike finfish commonly used in aquaponics, crayfish exhibit distinct behavioral patterns, feeding habits, and environmental requirements that directly influence system design, management practices, and overall productivity (Kubec *et al.*, 2019). Their growth performance, nutrient contribution, and interactions with the culture environment must be carefully considered to optimize both aquatic and plant production components. Understanding these biological characteristics provides the foundation for developing efficient, species-appropriate crayfish aquaponics systems.

Species commonly used in aquaculture

Several freshwater crayfish species have been identified as suitable candidates for commercial aquaculture and potential integration into aquaponics systems. Among the most widely cultured species are the redclaw crayfish (*Cherax quadricarinatus*), red swamp crayfish (*Procambarus clarkii*), and yabby (*Cherax destructor*) (Saoud *et al.*, 2013; Haubrock *et al.*, 2021; Zhang *et al.*, 2026) (Table 1).

Table 1. Common freshwater crayfish species with potential applications in aquaponics systems

Species	Common Name	Major characteristics	Advantages for aquaponics	Limitations
Cherax quadricarinatus	Redclaw crayfish	Fast growth, high market value, tolerant to environmental fluctuations	Suitable for intensive culture, relatively less aggressive, high commercial demand	Requires warm water temperatures
Procambarus clarkii	Red swamp crayfish	Highly adaptable, rapid reproduction, hardy species	Wide environmental tolerance and established production technologies	Aggressive behavior and invasive potential
Cherax destructor	Yabby	Tolerant to variable water conditions	Adaptable to diverse culture environments	Slower growth compared with redclaw in some production systems

The redclaw crayfish is considered one of the most promising species for aquaculture due to its rapid growth rate, relatively peaceful behavior, tolerance to varying environmental conditions, and high market value. Native to northern Australia and Papua New Guinea, this species has been successfully cultured in various tropical and subtropical regions (Jones, 2010).

The red swamp crayfish is extensively cultured in many countries because of its adaptability, hardiness, and high reproductive capacity. However, its aggressive behavior and invasive potential require careful management in controlled production systems (Huner, 2002; Loureiro *et al.*, 2015).

The yabby is another commercially important species known for its environmental tolerance and suitability for culture under diverse conditions. Yabbies are recognized for their hardiness and ability to tolerate fluctuating environmental conditions, making them suitable for culture in diverse production environments (Lawrence and Jones, 2002).

Species selection is a critical factor in crayfish aquaponics because growth performance, behavior, stocking density requirements, and environmental tolerance vary considerably among species. Therefore, species-specific biological characteristics should be carefully evaluated before system establishment (Jones, 2001; Saoud and Garza de Yta, 2012; Rigg *et al.*, 2020).

Growth and molting behavior

Growth in crayfish occurs through a process known as molting, during which the animal sheds its exoskeleton and develops a larger one. Unlike finfish, which grow continuously, crayfish experience periodic growth increments associated with each molt cycle (Wang *et al.*, 2025; Zhang *et al.*, 2026).

Molting is a physiologically demanding process that exposes crayfish to increased vulnerability from predation, injury, and cannibalism. During this period, newly molted individuals possess soft exoskeletons and require protected environments until hardening is complete. Consequently, aquaponics systems intended for crayfish culture must incorporate adequate shelter structures such as PVC pipes, rock formations, mesh compartments, or artificial refuges.

Growth rates are influenced by several factors, including water temperature, stocking density, feed quality, water quality conditions, and species genetics. High stocking densities may increase competition and aggressive interactions, reducing growth performance and survival rates. Therefore, system design should account for sufficient space allocation and habitat complexity to support healthy growth and minimize stress (Westhoff and Rosenberger, 2016; Yu *et al.*, 2020).

Understanding molting dynamics is essential because they directly affect stocking strategies, shelter requirements, feeding management, and overall system productivity.

Feeding habits and nutrient production

Crayfish are generally omnivorous organisms capable of consuming a wide variety of plant materials, algae, detritus, aquatic invertebrates, and formulated feeds.

This dietary flexibility contributes to their adaptability and suitability for integrated farming systems (Saoud and Garza de Yta, 2012; Reynolds *et al.*, 2013).

In aquaponics environments, crayfish contribute to nutrient cycling through the excretion of metabolic waste products and the breakdown of uneaten feed materials. These wastes serve as important nutrient sources for nitrifying bacteria, which convert ammonia into nitrite and subsequently nitrate, forms that are readily absorbed by plants.

The quantity and composition of nutrient inputs depend largely on feeding rates, feed composition, biomass density, and system management practices. Efficient feeding strategies are therefore essential to maintain water quality while maximizing nutrient availability for plant growth.

Although crayfish can contribute significantly to nutrient generation within aquaponics systems, excessive feeding may result in organic matter accumulation, increased biological oxygen demand, and deterioration of water quality. Consequently, feed management remains a critical component of sustainable crayfish aquaponics production.

Environmental requirements

Water quality management is one of the most important factors affecting crayfish health, growth, and survival. Crayfish generally require stable environmental conditions characterized by adequate dissolved oxygen levels, appropriate pH ranges, low concentrations of toxic nitrogen compounds, and suitable water temperatures (Westhoff and Rosenberger, 2016).

Temperature influences metabolism, feeding activity, growth rates, and molting frequency.

Most commercially cultured freshwater crayfish species perform best within moderate to warm temperature ranges, although optimal conditions vary among species.

Dissolved oxygen is particularly important because oxygen depletion can lead to stress, reduced growth, and mortality. Adequate aeration and water circulation are therefore necessary components of crayfish aquaponics systems.

Ammonia and nitrite are highly toxic to crayfish, especially under intensive production conditions. Effective biofiltration systems are required to convert these compounds into less harmful nitrate, thereby maintaining water quality and supporting plant nutrient uptake.

In addition to water chemistry, crayfish require structurally complex habitats that provide protection, reduce aggressive encounters, and support natural behaviors. Environmental stability, combined with appropriate habitat design, is essential for maintaining high survival rates and achieving sustainable production (Wang *et al.*, 2025; Voolstra *et al.*, 2025).

Overall, the biological characteristics of crayfish demonstrate that successful aquaponics integration requires specialized system designs that differ from conventional fish-based approaches.

Understanding these biological characteristics is essential because they directly influence the design and management requirements of crayfish aquaponics systems. Consequently, the following section examines the engineering and operational considerations necessary to accommodate crayfish-specific culture requirements.

Design considerations for crayfish aquaponics systems

The successful integration of crayfish into aquaponics systems depends largely on the design and management of the production environment. Unlike conventional fish-based aquaponics systems, crayfish culture presents unique challenges arising from species-specific behaviors such as territoriality, burrowing tendencies, shelter dependence, and periodic molting.

Consequently, system design must balance the biological requirements of crayfish with the nutrient demands of plants while maintaining stable water quality conditions (CEAUnion, n.d.).

Tank configuration and shelter design

Tank design is a critical component of crayfish aquaponics systems because physical structures directly influence animal welfare, growth performance, and survival. Crayfish are benthic organisms that spend most of their time on or near the substrate and actively seek shelter, particularly during molting periods when they become vulnerable to predation and cannibalism (Duffy *et al.*, 2011).

To reduce aggressive interactions and improve survival rates, production units should incorporate adequate shelters such as PVC pipes, ceramic tubes, plastic crates, mesh structures, rock piles, or other artificial refuges (Zhou *et al.*, 2023). The provision of shelters increases habitat complexity and allows individuals to establish territories, thereby reducing stress and competition (Mazlum, 2007).

Tank dimensions and floor area are generally more important than water depth for crayfish culture because of their bottom-dwelling behavior. Systems designed with larger bottom surface areas may support greater stocking densities and improve spatial distribution of animals. Multi-level shelter systems have also been explored to maximize the utilization of available space while maintaining adequate refuge opportunities and minimizing territorial conflicts under crowded conditions (Qin *et al.*, 2023).

The design of culture tanks should facilitate efficient waste removal, ease of monitoring, and accessibility for routine maintenance. Proper tank configuration contributes not only to animal performance but also to the overall stability and productivity of the aquaponics system (Table 2).

Table 2. Key Design considerations for crayfish aquaponics systems

Design component	Purpose	Expected benefit
Shelter structures	Reduce aggression and cannibalism	Improved survival
Biofiltration unit	Convert ammonia to nitrate	Improved water quality
Aeration system	Maintain dissolved oxygen	Enhanced growth and survival
Water circulation system	Distribute nutrients and oxygen	Improved system stability
Monitoring equipment	Track water quality parameters	Early problem detection

Water quality management

Maintaining optimal water quality is fundamental to the success of crayfish aquaponics systems. Water quality affects growth, molting frequency, feed utilization, immune response, and overall survival (Wang *et al.*, 2025; Voolstra *et al.*, 2025).

Among the most critical parameters are temperature, dissolved oxygen, pH, ammonia, nitrite, and nitrate concentrations. Fluctuations outside acceptable ranges can induce physiological stress and reduce production efficiency. Crayfish are particularly sensitive to elevated ammonia and nitrite levels, making effective biological filtration essential (Wang *et al.*, 2025) (Table 3).

Temperature influences metabolic activity, feeding behavior, and growth rates. Dissolved oxygen concentrations must remain sufficient to support respiration and microbial processes within the system. Likewise, maintaining a stable pH is necessary for both crayfish health and nitrification efficiency (Greenfeld *et al.*, 2021; David *et al.* (2022).

Regular monitoring of water quality parameters enables early detection of potential problems and facilitates timely management interventions (Gao *et al.*, 2021). Automated sensors and monitoring technologies may further enhance system performance and operational efficiency (Witzel *et al.*, 2019).

Biofiltration and nutrient cycling

Biofiltration serves as the biological engine of aquaponics systems by converting waste products into forms that can be utilized by plants.

In crayfish aquaponics systems, metabolic wastes and uneaten feed generate ammonia, which is converted into nitrite and subsequently nitrate through microbial nitrification processes (Bosma *et al.*, 2017; Greenfeld *et al.*, 2021).

Table 3. Critical water quality parameters for crayfish aquaponics systems

Parameter	Importance
Temperature	Influences metabolism and growth
Dissolved oxygen	Supports respiration and microbial activity
pH	Affects nitrification and physiological processes
Ammonia	Toxic at elevated concentrations
Nitrite	Toxic intermediate compound
Nitrate	Plant nutrient source

This transformation is critical for maintaining water quality while simultaneously supplying nutrients required for plant growth (Gao *et al.*, 2021; Verma *et al.*, 2023; Zhu *et al.*, 2024).

Efficient biofiltration systems support both animal production and plant growth by maintaining water quality while promoting nutrient recovery (Gao *et al.*, 2021; Verma *et al.*, 2023; Zhu *et al.*, 2024). Common biofilter designs include media-based filters, moving-bed biofilm reactors, trickling filters, and biological aerated filters.

The effectiveness of nutrient cycling depends on several interacting factors, including feed inputs, crayfish biomass, microbial community composition, hydraulic retention time, and plant nutrient uptake rates. Imbalances may lead to nutrient accumulation, reduced water quality, or nutrient deficiencies affecting plant productivity (Gao *et al.*, 2021; Chowdhury and Asiabanpour, 2024; Jayaprakash *et al.*, 2024).

Advances in biofiltration technologies continue to improve nutrient-use efficiency and contribute to the sustainability of integrated aquaponics systems.

Stocking density and system productivity

Stocking density is a key management factor influencing growth performance, survival, behavior, and economic returns in crayfish aquaponics systems. While higher stocking densities may increase production output, excessive crowding can intensify competition, stress, aggressive interactions, and cannibalism, resulting in reduced growth and survival rates (Saoud *et al.*, 2013; Yu *et al.*, 2020; Rigg *et al.*, 2020).

Optimal stocking density depends on species characteristics, system design, shelter availability, water quality conditions, and management practices. Studies have demonstrated that the provision of adequate shelters and habitat complexity can reduce aggressive encounters and improve survival under higher stocking densities by minimizing direct interactions among individuals (Yu *et al.*, 2020; Kubec *et al.*, 2015; Rigg *et al.*, 2020).

System productivity should be evaluated using both aquatic and plant production outputs. In integrated aquaponics systems, productivity is influenced not only by crayfish biomass production but also by the capacity of plants and microbial communities to assimilate nutrients generated from aquaculture wastes. Consequently, maintaining an appropriate balance between crayfish biomass and plant growing area is essential to ensure effective nutrient cycling and stable system performance (Bosma *et al.*, 2017; Greenfeld *et al.*, 2021; Verma *et al.*, 2023).

The carrying capacity of crayfish aquaponics systems is determined by the interaction among animal biomass, feed inputs, biofiltration efficiency, plant nutrient demand, and water quality management. Therefore, future system optimization efforts should focus on establishing species-specific stocking density recommendations, improving nutrient conversion efficiencies, and identifying management strategies that maximize biological performance, resource-use efficiency, and economic viability (David *et al.*, 2022; Verma *et al.*, 2023; Zhu *et al.*, 2024).

Beyond system design and management considerations, the success of crayfish aquaponics ultimately depends on the effective utilization of nutrients by plants. Therefore, the next section examines plant production and nutrient utilization within crayfish aquaponics systems.

Plant production in crayfish aquaponics

Plant production is a fundamental component of aquaponics systems, serving both productive and ecological functions. In addition to generating marketable crops, plants contribute to water quality improvement through nutrient uptake, thereby supporting the health and productivity of cultured aquatic organisms (Greenfeld *et al.*, 2021; Spradlin and Saha, 2022; Verma *et al.*, 2023). In crayfish aquaponics systems, plant performance is closely linked to nutrient generation, water quality management, and overall system balance. The selection of suitable crops and the optimization of nutrient utilization are therefore critical for maximizing system efficiency and sustainability.

Suitable plant species

The choice of plant species significantly influences the productivity and economic viability of aquaponics systems. Plants commonly cultivated in aquaponics include leafy vegetables, herbs, fruiting crops, and ornamental plants due to their ability to efficiently utilize dissolved nutrients.

Leafy vegetables such as lettuce (*Lactuca sativa*), pak choi (*Brassica rapa* subsp. *chinensis*), kale (*Brassica oleracea*), and spinach (*Spinacia oleracea*) are among the most widely grown aquaponic crops because of their rapid growth, relatively low nutrient requirements, and strong market demand (Saha *et al.*, 2016; Babatunde *et al.*, 2022; Fernández-Cabanás *et al.*, 2022). Herbs including basil (*Ocimum basilicum*), mint (*Mentha* spp.), and parsley (*Petroselinum crispum*) have also demonstrated favorable performance in recirculating production systems (Fernández-Cabanás *et al.*, 2022; Nadia *et al.*, 2023).

Fruiting crops such as tomatoes (*Solanum lycopersicum*), cucumbers (*Cucumis sativus*), and peppers (*Capsicum* spp.) can be successfully cultivated in aquaponics systems; however, these species typically require higher nutrient concentrations and more intensive management. Consequently, balancing crayfish biomass and plant nutrient demand becomes increasingly important when producing fruiting crops (Babatunde *et al.*, 2022; Nadia *et al.*, 2023; Jayaprakash *et al.*, 2024).

Plant selection in crayfish aquaponics should consider nutrient availability, growth characteristics, market value, environmental adaptability, and compatibility with system objectives. Diversified cropping strategies may further improve nutrient utilization efficiency and enhance economic resilience (Spradlin and Saha, 2022; Verma *et al.*, 2023).

Nutrient availability and uptake

Nutrient dynamics play a central role in the performance of aquaponics systems. Nutrients originate primarily from crayfish metabolic wastes, uneaten feed and microbial decomposition processes (Gao *et al.*, 2021; Greenfeld *et al.*, 2021). Through biological filtration, ammonia released by crayfish is converted into nitrate, which serves as an important nitrogen source for plants (Gao *et al.*, 2021; Chowdhury and Asiabanpour, 2024).

In addition to nitrogen, aquaponics systems may supply phosphorus, potassium, calcium, magnesium, and various micronutrients required for plant growth. However, nutrient concentrations are influenced by feed composition, feeding rates, crayfish biomass, water exchange practices, and biofilter performance (Gao *et al.*, 2021; Jayaprakash *et al.*, 2024).

Maintaining a balance between nutrient generation and nutrient uptake is essential for system stability. Insufficient plant uptake may result in nutrient accumulation and water quality deterioration, whereas excessive plant demand may lead to nutrient deficiencies that limit crop growth (Greenfeld *et al.*, 2021; Verma *et al.*, 2023). Nutrient supplementation may occasionally be required, particularly for elements that are commonly deficient in aquaponic systems, such as iron, potassium, and calcium (Greenfeld *et al.*, 2021; Jayaprakash *et al.*, 2024).

Effective nutrient management contributes not only to plant productivity but also to water quality maintenance and overall system sustainability (David *et al.*, 2022; Verma *et al.*, 2023).

Plant–crayfish interactions

The relationship between plants and crayfish in aquaponics systems extends beyond simple nutrient exchange. Plants function as biological filters that help remove dissolved nutrients and improve water quality, thereby creating a more favorable environment for crayfish culture (Gao *et al.*, 2021; Greenfeld *et al.*, 2021). Conversely, crayfish provide the nutrient inputs necessary to support plant growth through their metabolic activities (Romano *et al.*, 2022; Verma *et al.*, 2023).

The efficiency of this relationship depends on the balance between crayfish stocking density, feed inputs, microbial activity, and plant growing area (Bosma *et al.*, 2017; Greenfeld *et al.*, 2021). Well-balanced systems can achieve synergistic interactions that enhance resource utilization while minimizing waste discharge (David *et al.*, 2022; Verma *et al.*, 2023).

Research has demonstrated that integrated aquaponics systems can improve water-use efficiency and reduce environmental impacts compared with separate aquaculture and crop production systems. However, achieving optimal integration remains challenging because nutrient production and plant requirements may vary throughout the production cycle (Greenfeld *et al.*, 2021; David *et al.*, 2022; Zhu *et al.*, 2024).

Future studies should focus on improving nutrient balancing strategies, evaluating alternative crop species, and optimizing system configurations that maximize both crayfish and plant productivity. Such efforts will contribute to the development of more resilient and economically viable crayfish aquaponics systems.

While plant productivity is an important indicator of system performance, the broader adoption of crayfish aquaponics depends on its economic viability and environmental sustainability. These aspects are discussed in the following section.

Economic and environmental sustainability of crayfish aquaponics systems

The long-term adoption of crayfish aquaponics systems depends not only on their technical feasibility but also on their economic viability and environmental sustainability. As integrated food production systems, aquaponics combines aquatic animal culture and plant cultivation in a manner that seeks to optimize resource utilization while minimizing environmental impacts (Greenfeld *et al.*, 2021; David *et al.*, 2022; Verma *et al.*, 2023). The potential of crayfish aquaponics to contribute to sustainable food production has attracted increasing attention from researchers, producers, and policymakers seeking alternative approaches to address food security, resource scarcity, and environmental challenges (David *et al.*, 2022; Romano *et al.*, 2022; Zhu *et al.*, 2024).

Economic viability and production efficiency

Economic sustainability is a critical factor influencing the adoption and commercialization of crayfish aquaponics systems. The integration of crayfish and plant production offers opportunities for diversified income streams, allowing producers to generate revenue from both aquatic and horticultural products (Bosma *et al.*, 2017; David *et al.*, 2022). This dual-output approach may enhance profitability and reduce economic risks associated with dependence on a single commodity (Romano *et al.*, 2022; Verma *et al.*, 2023) (Table 4).

Several factors influence the economic performance of aquaponics systems, including initial capital investment, operating costs, energy consumption, labor requirements, feed expenses, production yields, and market prices. Infrastructure costs associated with tanks, pumps, filtration units, aeration systems, and monitoring equipment often represent significant barriers to adoption, particularly for small-scale producers (Bosma *et al.*, 2017; Verma *et al.*, 2023).

Table 4. Economic benefits and constraints of crayfish aquaponics systems

Aspect	Potential benefits	Potential constraints
Production	Dual income streams	Production complexity
Water use	Reduced consumption	Initial infrastructure costs
Nutrient management	Resource recycling	Nutrient imbalance issues
Land use	High productivity per unit area	Technical expertise required
Marketing	High-value crayfish and crops	Market fluctuations

Table 5. Environmental sustainability contributions of crayfish aquaponics

Sustainability dimension	Contribution
Water conservation	Reduced freshwater use
Nutrient recovery	Recycling of waste nutrients
Pollution reduction	Lower effluent discharge
Food production	Integrated production of protein and vegetables
Circular economy	Conversion of wastes into productive inputs

Despite these challenges, integrated systems may improve resource-use efficiency by reducing water consumption, recycling nutrients, and maximizing production within limited land areas (Greenfeld *et al.*, 2021; David *et al.*, 2022; Zhu *et al.*, 2024). The production of high-value crayfish species alongside marketable vegetable crops may further improve economic returns and enhance system competitiveness (Bosma *et al.*, 2017; Verma *et al.*, 2023).

Economic assessments should consider both direct financial indicators, such as profitability and return on investment, and indirect benefits including risk diversification, improved resource efficiency, and potential environmental savings (David *et al.*, 2022; Romano *et al.*, 2022).

Future studies are needed to evaluate the economic performance of commercial-scale crayfish aquaponics systems under different production conditions and market environments.

Resource use efficiency and environmental benefits

One of the principal advantages of aquaponics systems is their ability to improve resource-use efficiency compared with conventional aquaculture and crop production systems (Greenfeld *et al.*, 2021; David *et al.*, 2022; Verma *et al.*, 2023) (Table 5).

Through nutrient recycling and water recirculation, aquaponics reduces the need for freshwater inputs and minimizes nutrient-rich effluent discharge into surrounding ecosystems (Gao *et al.*, 2021; Greenfeld *et al.*, 2021).

In crayfish aquaponics systems, nutrients generated from feed inputs and crayfish metabolism are recovered and utilized by plants, thereby transforming potential waste products into valuable production resources. This closed-loop approach contributes to improved nutrient-use efficiency and supports circular production principles (Romano *et al.*, 2022; Zhu *et al.*, 2024).

Water conservation is particularly important in regions experiencing freshwater scarcity or increasing competition for water resources. Compared with traditional soil-based agriculture and flow-through aquaculture systems, aquaponics may significantly reduce water consumption while maintaining productive output (Greenfeld *et al.*, 2021; David *et al.*, 2022; Verma *et al.*, 2023).

The integration of aquatic and plant production may also contribute to reduced environmental pollution by limiting nutrient discharge, decreasing reliance on synthetic fertilizers, and improving overall system sustainability. These environmental benefits align with global efforts to promote sustainable agriculture and climate-resilient food systems (David *et al.*, 2022; Romano *et al.*, 2022; Zhu *et al.*, 2024).

Challenges to sustainability

Despite their potential advantages, crayfish aquaponics systems face several sustainability challenges that may affect long-term performance and adoption. Energy consumption associated with water circulation, aeration, heating, and monitoring systems can increase operating costs and contribute to environmental impacts, particularly when non-renewable energy sources are used (Bosma *et al.*, 2017; Verma *et al.*, 2023).

Nutrient balancing remains a persistent challenge because the nutrient requirements of plants do not always correspond precisely with the nutrient outputs generated by crayfish production. Consequently, nutrient deficiencies or accumulations may occur, requiring additional management interventions or supplementation (Gao *et al.*, 2021; Greenfeld *et al.*, 2021).

Disease outbreaks, equipment failures, fluctuations in market demand, and environmental disturbances may also affect system stability and profitability (David *et al.*, 2022; Verma *et al.*, 2023). Furthermore, limited technical knowledge and the lack of species-specific production guidelines for crayfish aquaponics may hinder commercial development (Verma *et al.*, 2023; Zhu *et al.*, 2024).

Addressing these challenges will require continued research, technological innovation, and the development of best management practices tailored to crayfish-based systems.

Contribution to sustainable food systems

Crayfish aquaponics systems have the potential to contribute to broader sustainability goals by supporting efficient resource utilization, diversified food production, and environmental stewardship. The simultaneous production of aquatic protein and fresh vegetables within a single integrated system aligns with contemporary approaches to sustainable agriculture and circular bioeconomy principles (Romano *et al.*, 2022; Zhu *et al.*, 2024).

As global populations continue to increase and pressures on natural resources intensify, integrated production systems such as crayfish aquaponics may play an increasingly important role in enhancing food security and promoting resilient agricultural systems (David *et al.*, 2022; Verma *et al.*, 2023; Zhu *et al.*, 2024). . However, realizing this potential will depend on continued improvements in system design, production efficiency, economic performance, and environmental management (Greenfeld *et al.*, 2021; Verma *et al.*, 2023).

Future research should therefore focus not only on maximizing productivity but also on evaluating the broader social, economic, and environmental impacts of crayfish aquaponics systems across different scales of operation and geographical contexts (David *et al.*, 2022; Romano *et al.*, 2022; Zhu *et al.*, 2024).

Despite the demonstrated benefits of crayfish aquaponics systems, several technical, economic, and environmental uncertainties remain. Identifying these knowledge gaps is essential for guiding future research and development efforts.

RESEARCH GAPS AND FUTURE DIRECTIONS

Despite increasing interest in integrated aquaponics systems, the development of crayfish-based aquaponics remains at a relatively early stage. Existing studies have demonstrated the biological feasibility of combining crayfish production with plant cultivation; however, significant knowledge gaps continue to limit the optimization and commercial adoption of these systems (David *et al.*, 2022; Verma et al, 2023; Zhu *et al.*, 2024). Addressing these gaps will be essential for improving productivity, sustainability, and economic viability.

Limited species-specific research

Much of the current knowledge on aquaponics has been derived from systems utilizing finfish species such as tilapia, catfish, and carp (Bosma *et al.*, 2017; Verma *et al.*, 2023).

Consequently, many system design recommendations are based on biological and management principles that may not fully reflect the unique characteristics of crayfish (Saoud *et al.*, 2013; Rigg *et al.*, 2020).

Although several crayfish species have shown potential for aquaponic production, comparative studies evaluating species-specific performance under different aquaponic conditions remain limited (Rigg *et al.*, 2020; Verma *et al.*, 2023). Future research should investigate growth, survival, nutrient production, stocking density requirements, and environmental tolerances of commercially important crayfish species to establish evidence-based production guidelines.

Optimization of nutrient balancing and system design

Maintaining an appropriate balance between crayfish biomass, nutrient generation, microbial activity, and plant nutrient demand remain one of the most important challenges in crayfish aquaponics systems (Gao *et al.*, 2021; Greenfeld *et al.*, 2021). Variations in feed inputs, plant species selection, stocking density, and environmental conditions can influence nutrient availability and system performance (Chowdhury and Asiabanpour, 2024; Jayaprakash *et al.*, 2024).

Future studies should focus on developing predictive models that optimize nutrient cycling and improve synchronization between aquatic and plant production components (Greenfeld *et al.*, 2021; Verma *et al.*, 2023). Research on innovative biofiltration technologies, nutrient supplementation strategies, and integrated system configurations may further enhance resource-use efficiency (David *et al.*, 2022; Zhu *et al.*, 2024).

Stocking density, shelter design, and animal welfare

The territorial behavior and molting characteristics of crayfish present unique management challenges that are less pronounced in conventional fish-based aquaponics systems. Although shelters are widely recognized as important for reducing aggression and cannibalism (Kubec *et al.*, 2019; Yu *et al.*, 2020), limited information is available regarding optimal shelter designs, refuge densities, and spatial configurations (Yu *et al.*, 2020; Rigg *et al.*, 2020).

Future investigations should evaluate the effects of habitat complexity, stocking density, and environmental enrichment on crayfish welfare, growth performance, and survival. Such studies would contribute to the development of management practices that improve both productivity and animal welfare (Saoud *et al.*, 2013; Kubec *et al.*, 2019).

Economic assessment and commercial scalability

Most existing crayfish aquaponics studies have been conducted at laboratory, pilot, or experimental scales (Bosma *et al.*, 2017; Verma *et al.*, 2023). Consequently, information regarding commercial-scale production, profitability, and long-term economic sustainability remains limited (David *et al.*, 2022; Romano *et al.*, 2022).

Future research should incorporate comprehensive economic analyses, including production costs, market opportunities, return on investment, risk assessment, and sensitivity analyses. Comparative evaluations of different production scales and business models would provide valuable information for producers and investors considering commercial adoption (Bosma *et al.*, 2017; Verma *et al.*, 2023).

Emerging technologies and digital innovations

Recent advances in aquaculture and precision agriculture have created opportunities to improve the monitoring and management of aquaponics systems. Technologies such as automated water-quality sensors, Internet of Things (IoT)-based monitoring platforms, artificial intelligence (AI), machine learning, and data-driven decision support systems have shown promise in enhancing production efficiency and system reliability (Chowdhury and Asiabanpour, 2024; Jayaprakash *et al.*, 2024).

Future research should explore the integration of these technologies into crayfish aquaponics systems to improve environmental monitoring, disease detection, feeding management, predictive maintenance, and overall operational performance (Jayaprakash *et al.*, 2024; Zhu *et al.*, 2024).

Climate resilience and sustainability assessment

As climate variability and resource limitations continue to affect agricultural production systems worldwide, there is increasing interest in evaluating the resilience of aquaponics systems under changing environmental conditions (Romano *et al.*, 2022; Zhu *et al.*, 2024).

However, limited information is available regarding the long-term environmental performance and climate resilience of crayfish aquaponics systems (David *et al.*, 2022; Verma *et al.*, 2023).

Future studies should assess energy consumption, carbon footprints, water-use efficiency, life-cycle sustainability, and adaptation strategies under different climatic and geographical conditions. Such research would strengthen the role of crayfish aquaponics within sustainable and climate-resilient food production systems (David *et al.*, 2022; Romano *et al.*, 2022; Zhu *et al.*, 2024).

Toward integrated and sustainable crayfish aquaponics systems

The future development of crayfish aquaponics will depend on interdisciplinary research that integrates biology, engineering, environmental science, economics, and digital technologies (David *et al.*, 2022; Verma *et al.*, 2023). Advancing these systems from experimental concepts to commercially viable production models will require collaboration among researchers, industry stakeholders, policymakers, and producers (Bosma *et al.*, 2017; Romano *et al.*, 2022). By addressing existing knowledge gaps and fostering innovation, future research can contribute to the development of efficient, resilient, and sustainable crayfish aquaponics systems capable of supporting food security, environmental stewardship, and rural economic development (David *et al.*, 2022; Verma *et al.*, 2023; Zhu *et al.*, 2024).

Table 6. Major research gaps and future research priorities in crayfish aquaponics

Research area	Key research gap	Future research priority
Crayfish species selection	Limited species-specific aquaponics studies	Comparative evaluation of commercially important crayfish species
Nutrient management	Incomplete understanding of nutrient dynamics and balancing	Development of nutrient optimization models
System design	Lack of standardized crayfish-specific system configurations	Optimization of tank design, shelters, and biofiltration systems
Animal welfare	Limited information on stocking density and habitat requirements	Establishment of welfare-based management guidelines
Plant production	Insufficient data on crop suitability and productivity	Evaluation of diverse crop species under crayfish aquaponics conditions
Economic viability	Few commercial-scale assessments	Cost-benefit and scalability studies
Emerging technologies	Limited application of smart farming technologies	Integration of IoT, AI, and automated monitoring systems
Sustainability	Insufficient long-term environmental assessments	Life cycle and climate-resilience evaluations

Based on the synthesis of the reviewed literature, the major knowledge gaps and corresponding future research priorities for crayfish aquaponics systems are summarized in Table 6. These gaps highlight priority areas for future investigation and provide a framework for advancing the development of efficient, sustainable, and commercially viable crayfish aquaponics systems.

CONCLUSION

Crayfish aquaponics represents a promising approach to sustainable and integrated food production by combining aquatic animal culture and plant cultivation within a resource-efficient recirculating system. This review synthesized current knowledge on the biological characteristics of crayfish relevant to aquaponics, system design and operational considerations, plant production performance, and the economic and environmental dimensions of system sustainability.

The reviewed literature indicates that crayfish possess several characteristics that make them suitable candidates for aquaponics systems, including their adaptability to diverse environmental conditions, market value, and potential for integration with crop production. However, their benthic behavior, territoriality, shelter dependence, and molting requirements necessitate management strategies and system designs that differ from those commonly employed in finfish-based aquaponics systems.

Effective implementation of crayfish aquaponics requires careful consideration of tank configuration, shelter provision, water quality management, biofiltration efficiency, nutrient balancing, and stocking density. In addition, the successful integration of plant production depends on maintaining appropriate relationships between nutrient generation, microbial processes, and plant nutrient demand. When properly managed, crayfish aquaponics systems can contribute to improved resource-use efficiency through nutrient recycling, reduced water consumption, and minimized environmental impacts.

Despite these advantages, the review identified several knowledge gaps that continue to limit the advancement and commercialization of crayfish aquaponics. These include limited species-specific research, insufficient information on nutrient dynamics and system optimization, inadequate economic assessments, and a lack of long-term sustainability evaluations. Furthermore, the application of emerging technologies such as automated monitoring systems, artificial intelligence, and data-driven management tools remains largely unexplored in crayfish-based aquaponics systems.

Future research should therefore focus on developing species-specific production guidelines, optimizing nutrient management strategies, evaluating commercial-scale feasibility, and assessing environmental performance under diverse production conditions. Interdisciplinary approaches integrating biology, engineering, economics, and digital technologies will be essential for advancing the development of efficient and resilient crayfish aquaponics systems.

Overall, crayfish aquaponics offers considerable potential as an innovative and sustainable food production strategy. Continued research, technological innovation, and stakeholder collaboration will be critical to transforming these systems from emerging production models into commercially viable and environmentally responsible components of future food systems.

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