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A Systematic Review of Aquamimicry and Biofloc Technologies in White Leg Shrimp (*Litopenaeus vannamei*) Aquaculture

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ABSTRACT

The growing global emphasis on sustainable aquaculture has driven the adoption of innovative farming approaches, including aquamimicry and biofloc technology (BFT), for the culture of whiteleg shrimp (*Litopenaeus vannamei*). The sector faces persistent challenges, including declining water quality, dependence on commercial feed, high production costs and fluctuating survival rates. As demand grows for eco-efficient culture systems, aquamimicry and BFT have emerged as promising alternatives due to their capacity for nutrient recycling, natural food production and reduced environmental impact. A systematic literature search was conducted in Scopus and PubMed databases for peer-reviewed articles published between 2013 and 2025. Studies were screened using predefined inclusion criteria, and the review process followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The study presents a comparative assessment of growth performance, proximate composition of *L. vannamei*, microbial load variation and key water quality indicators under different culture systems. Weighted mean analysis of the included studies showed survival rates of 86.77 ± 13.83% ($n = 9$) for aquamimicry and 83.62 ± 12.97% ($n = 22$) for BFT, while FCR averaged 1.63 ± 0.63 and 1.59 ± 0.46, respectively. Effect size analysis indicated small differences between systems with no statistically significant variation ($p > 0.05$). In contrast, overall biomass yield was greater in the BFT system. The findings highlight the need for further research integrating emerging monitoring tools and management technologies to improve system efficiency and sustainability. The strategic adoption of aquamimicry and BFT offers a promising pathway to reduce production costs, improve productivity and strengthen environmental resilience in *L. vannamei* aquaculture.

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1 | Introduction

Aquaculture has emerged as the most rapidly expanding segment of the global food production system and plays a crucial role in supplying animal protein to a growing human population projected to approach 9 billion by mid-century (Tran et al. 2023). With an estimated annual growth rate of about 5.80%, global aquaculture output is expected to rise substantially, increasing from approximately 73.80 million tonnes in 2014 to over 140 million tonnes by 2050 (FAO 2016). Although fish are among the most efficient converters of feed into edible protein, sustaining this expansion will require greater inputs of formulated feeds and nutrient supplements to maintain productivity levels (Christophe et al. 2015).

Aquaculture, including finfish, crustaceans, molluscs and aquatic plants (Thierry and Tacon 2021), has grown steadily over recent decades, with an average annual increase of 5.30% between 2001 and 2018 (FAO 2020). Global production reached 82.10 million tonnes in 2018, with inland aquaculture contributing 62% and marine/coastal systems 38% (FAO 2020). Crustacean aquaculture, in particular, grew 2.90% per year over the past two decades, producing 9.40 million tonnes valued at US $69.30 billion (FAO 2020). Early gains were driven by area expansion, while recent growth reflects system intensification and technological innovation (Olivier et al. 2018; M. G. C. Emerenciano et al. 2022).

Rising global food requirements, driven by population growth projected to reach approximately 9.60 billion by 2050, continue to place pressure on food production systems worldwide (Berners-Lee et al. 2018; Ehrlich and Harte 2015). Addressing this challenge remains a priority for both scientific research and policy formulation (Ehrlich and Harte 2015). Despite substantial progress, the aquaculture sector faces notable constraints in achieving future production targets, with global output forecasted to reach around 109 million tonnes by 2030 and approximately 140 million tonnes by 2050 (FAO 2020; Mair et al. 2023).

Among farmed aquatic species, *Litopenaeus vannamei*, commonly referred to as the whiteleg shrimp, has demonstrated exceptional expansion within global aquaculture. The Pacific white shrimp currently dominates crustacean farming, contributing approximately 59% of total crustacean production in 2018 (FAO 2020). Global production increased dramatically from about 0.15 million metric tonnes in 2000 to nearly 5 million metric tonnes in recent years, with an estimated market value of US $302 million (FAO 2022). By 2020, *L. vannamei* had become the most extensively cultivated aquatic species worldwide, reaching a production volume of 5.81 million metric tonnes (FAO 2020). This species now forms the backbone of shrimp aquaculture industries in major producing countries, including Indonesia (Astiyani et al. 2020; Novriadi et al. 2021; Wijayanto et al. 2017), Vietnam (Quyen et al. 2020), Ecuador (Rivera et al. 2018) and Thailand (Tookwinas et al. 2005). Its widespread adoption is attributed to strong market demand, efficient feed conversion, high commercial value, which together support superior growth and survival performance (Roy et al. 2009).

L. vannamei is a euryhaline species and remains the most widely cultured crustacean globally, accounting for approximately 53% of total crustacean aquaculture production (FAO 2020). Its capacity to tolerate broad salinity ranges, perform well at high stocking densities, and deliver strong economic returns has positioned it as the preferred species for intensive farming systems (G. Liu et al. 2017; K. Catalani et al. 2023). The species is highly adaptable, thriving in diverse environments ranging from inland freshwater systems to coastal and tropical marine habitats, and can withstand salinity levels from as low as 2% to as high as 30% (Y. Liu et al. 2023). The rapid expansion of *L. vannamei* aquaculture has generated significant socio-economic benefits, including job creation, enhanced food security and increased availability of affordable, high-quality protein (Tian et al. 2024). In addition, farming systems for this species incorporate a wide array of production technologies and are compatible with polyculture practices (FAO 2020).

Despite its impressive growth, the shrimp aquaculture sector continues to face persistent challenges, including disease outbreaks, inadequate wastewater management, limited access to sustainable feed ingredients and constraints in the supply of high-quality broodstock (Tian et al. 2024). Disease epidemics remain a major source of economic loss (Zeng, Zhou, et al. 2020), while dependence on fishmeal and fish oil has contributed to rising production costs and market volatility (Cheng et al. 2020; Engle et al. 2020). In response, producers are increasingly adopting high-density and biosecure farming systems to reduce disease risk (Khanjani et al. 2023). Nevertheless, environmental degradation associated with overcrowding and poor water quality can compromise shrimp immune function, underscoring the importance of effective health management and disease prevention strategies for sustainable *L. vannamei* production (J. H. Kim et al. 2021; Moss et al. 2012).

Historically, antibiotics were widely used to control disease in aquaculture during the 1970s and 1980s (Ringø 2020). Over time, however, such practices have proven increasingly ineffective and have contributed to the development of antibiotic-resistant bacteria (Assefa and Abunna 2018). Furthermore, the presence of antibiotic and pesticide residues in farmed aquatic products poses potential risks to human health, including allergic reactions and toxicity (Chowdhury et al. 2022), and may disrupt the intestinal microbiota of both cultured organisms and consumers (Ringø and Song 2016). Growing antimicrobial resistance concerns and stricter antibiotic regulations in the European Union, the United States and China have accelerated interest in sustainable shrimp culture systems that minimize chemical inputs (Chowdhury et al. 2022; Ringø and Song 2016).

Water scarcity has emerged as a critical global environmental challenge (Malekmohammadi 2025). The interaction of climate variability, prolonged drought events, rapid population expansion and inefficient water governance has intensified the imbalance between freshwater availability and demand (Khan et al. 2024). In parallel, intensive shrimp farming has contributed to significant ecological degradation in coastal ecosystems, particularly across Southeast Asia (Anh et al. 2010). Currently, more than 41% of the world's population resides in regions susceptible to drought, highlighting the urgent necessity for water-conserving and environmentally responsible aquaculture production systems (Khanjani et al. 2022). Recent technological innovations, however, have strengthened biosecurity measures, optimized water quality control and lowered production costs, thereby

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fostering the development of more resilient and sustainable aquaculture practices (Panigrahi et al. 2020; Valenti et al. 2021).

Microbial-driven production strategies, notably biofloc technology (BFT) and aquamimicry, have gained considerable attention as promising solutions for improving aquaculture sustainability and efficiency. Aquamimicry is based on the fermentation of carbon-rich agricultural by-products such as rice bran, soybean meal and wheat bran, often supplemented with probiotic microorganisms (e.g., *Bacillus* spp.), to stimulate the proliferation of naturally occurring zooplankton, particularly copepods rich in protein, lipids and pigments that serve as live feed for cultured species (Deepak et al. 2020; Ghosh and Hasanuzzaman 2025). This approach improves water quality, stabilizes pH, reduces feed expenses and enhances bioremediation processes within culture systems (Khanjani et al. 2023; Nisar et al. 2022). In shrimp farming, aquamimicry has been associated with enhanced growth performance, stronger immune responses and reduced dependence on chemical additives and antibiotics, making it an environmentally sound and economically viable production method (Mehrim et al. 2025; Islam et al. 2024). Although aquamimicry is a relatively recent innovation, first developed in Thailand in 1990 (Romano 2017), it offers substantial potential for the sustainable expansion of aquaculture.

BFT is a microbial-driven aquaculture system that enhances production efficiency, biosecurity and nutrient recycling in *L. vannamei* culture (Nisar et al. 2022). Beyond functioning as a water treatment mechanism, bioflocs serve as a supplemental natural feed source, reducing dependence on external feed inputs while maintaining growth performance (M. Emerenciano et al. 2012). The system also limits water exchange, mitigates environmental pollution and improves biosafety (Ramiro et al. 2024). In practice, BFT promotes the proliferation of beneficial microbial communities that stimulate innate immunity and strengthen resistance to pathogenic infections, thereby enhancing survival and growth through activation of digestive enzymes and immune function (S. K. Kim et al. 2014; Cardona et al. 2015; Long et al. 2015; Miao et al. 2017). The quality and stability of bioflocs depend on the source and proportion of organic carbon inputs such as molasses, corn, wheat, glucose, acetate, glycerol and tapioca and the carbon: nitrogen (C:N) ratio, which regulates microbial metabolism and the nutritional composition of protein, lipids, carbohydrates and fatty acids (Panigrahi et al. 2018; Ekasari et al. 2014). Reported optimal C:N ratios for *L. vannamei* range from 10 to 20 (Panigrahi et al. 2018; Ekasari et al. 2014; Esparza-Leal et al. 2015; Chakrapani et al. 2021; Xu et al. 2018), collectively supporting improved growth, water quality and immune competence. Compared to natural or plankton-based systems such as aquamimicry, BFT relies more on controlled microbial management and external carbon supplementation, offering higher production consistency but requiring careful monitoring and energy input. Overall, BFT integrates microbial ecology and system management to provide a cost-effective and environmentally sustainable approach for intensive shrimp culture (Zafar and Rana 2022; Bossier and Ekasari 2017).

Both aquamimicry and BFT have been widely adopted in shrimp aquaculture due to their ability to maintain stable, ecologically balanced culture conditions (Ramiro et al. 2024; Khanjani et al. 2022). *L. vannamei* exhibits strong adaptability to aquamimicry-based systems, making it particularly well suited for sustainable production strategies (Eissa et al. 2025). Empirical evidence indicates that BFT can sustain high stocking densities while maintaining optimal productivity in *L. vannamei* farming (da Silveira et al. 2020; Krummenauer et al. 2011). When BFT is combined with aquamimicry principles and operated under zero-water-exchange conditions, environmental impacts can be substantially reduced (K. Catalani et al. 2023). Feed conversion ratios (FCRs) as low as 1.25 have been reported in BFT-based systems, compared with approximately 1.68 in conventional shrimp farming practices (Avnimelech et al. 2012). Similarly, shrimp cultured under aquamimicry conditions often exhibit higher survival rates, attributed to enhanced availability of natural live feed and beneficial microbial interactions (Nisar et al. 2022). In addition, bioflocs produce bioactive signaling molecules and quorum-sensing inhibitors that suppress luminous vibriosis (Panigrahi et al. 2021), while stimulating non-specific immune responses in *L. vannamei*, potentially serving as early indicators of disease resistance (Khanjani et al. 2023). Collectively, aquamimicry and BFT contribute to the achievement of multiple Sustainable Development Goals (SDGs), including Goal 12 (Responsible Consumption and Production) and Goal 14 (Life Below Water) (Haque and Mahmud 2025).

This systematic review critically evaluates aquamimicry and biofloc technologies in the culture of whiteleg shrimp (*L. vannamei*), focusing on their effects on key production metrics such as growth performance, survival and feed efficiency, as well as on water quality management. By synthesizing the available literature, the review identifies the strengths, limitations and knowledge gaps associated with each system and provides evidence-based recommendations for their effective and sustainable integration in shrimp aquaculture. Overall, the study aims to provide actionable insights for farmers, researchers and policymakers to optimize production while maintaining environmental sustainability.

2 | Material and Methods

2.1 | Identification, Retrieval and Screening of Relevant Literature

A structured and exhaustive review of the literature was conducted following the methodological principles outlined by Xiao and Watson (2019). To enhance transparency and reproducibility, the review adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines throughout the search, screening and selection processes. In line with the recommendations of Green et al. (2006) and previous systematic reviews (Anastasiou et al. 2023; Gambelli et al. 2019), two major bibliographic databases, Scopus and PubMed, were selected as primary sources for literature retrieval. Peer-reviewed studies addressing aquamimicry and BFT in the culture of *L. vannamei* were identified and compiled for detailed evaluation. All retrieved records were subsequently examined manually to confirm their relevance and suitability for inclusion in the review (Figure 1).

A comprehensive literature search was conducted (2013–2025) using multiple scientific databases including Scopus and PubMed. Boolean search operators (AND) were used to combine

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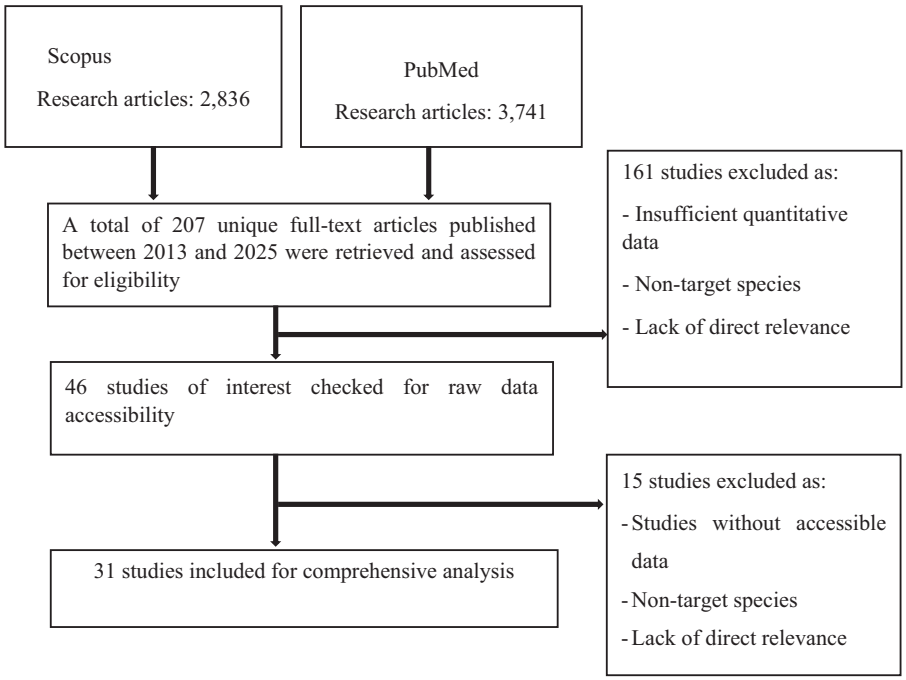


FIGURE 1 | Flow diagram depicting the systematic literature search and study selection procedure.

keywords related to aquamimicry, BFT and shrimp culture. The full search strings used in each database are provided in Table S1 to ensure reproducibility.

This search strategy yielded a total of 6577 records, comprising 2836 articles from Scopus and 3741 from PubMed. From 6577 identified records, 6370 duplicates and irrelevant studies were removed, leaving 207 records for full-text assessment. Following eligibility screening, 31 studies were included in the final analysis (Table S2) (Figure 1).

2.2 | Eligibility Criteria

The eligibility criteria for study selection were defined following the recommendations of the PRISMA guidelines to ensure transparency and reproducibility. Studies were included if they were peer-reviewed journal articles focusing on aquamimicry and BFT for the culture of *L. vannamei*. Only studies published between 2013 and 2025 and written in English were considered. Eligible articles were required to report quantitative or experimental data related to *L. vannamei* production performance, including growth rate, survival rate, FCR, water quality parameters or overall system performance. Articles that did not focus on *L. vannamei* culture or were not related to aquamimicry or BFT production systems were excluded. Review articles, conference abstracts, studies without quantitative data and studies on non-relevant species were excluded from the analysis. Duplicate records identified during the database screening process were also excluded to ensure that each study was considered only once in the final dataset.

2.3 | Analytical Framework and Data Synthesis

After completion of the screening process, a descriptive synthesis was conducted by extracting and evaluating key variables from the selected studies. The number of eligible publications and their corresponding datasets were organized using Microsoft Excel and examined through descriptive statistical methods. All extracted information was systematically recorded, integrated and cross-checked to ensure reliability and internal consistency. The synthesized outcomes are presented in the form of tables and figures to improve clarity and support effective interpretation of the results.

2.4 | Statistical Analysis

A quantitative systematic analysis was conducted to compare the production performance of aquamimicry and BFT culture systems. Weighted mean values were calculated to account for differences in sample sizes among datasets. Standardized effect sizes were estimated using Cohen's d to quantify the magnitude of differences between the two culture systems. The pooled standard deviation was used to standardize mean differences (MD) across studies. Ninety-five per cent confidence intervals (CI) (95%) were calculated to assess the precision of the estimated effects. Statistical significance between aquamimicry and BFT datasets was evaluated using independent sample t-tests. Effect size interpretation followed conventional thresholds (negligible < 0.19, small 0.20–0.49, medium 0.50–0.79 and large > 0.80). All statistical analyses were performed using IBM SPSS (version 25) Statistics and Microsoft Excel.

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3 | Result and Discussion

3.1 | Historical Development of Aquamimicry and BFT

Aquamimicry emerged in Southeast Asian shrimp farming in the 1990s, particularly in Thailand, as an ecosystem-based approach that mimics natural estuarine processes to improve water quality, nutrient recycling and shrimp health (Khanjani et al. 2022; Deepti et al. 2024; Islam et al. 2024). The formal establishment of the aquamimicry system occurred in 2013, led by experienced Thai shrimp farmers, Mr. Sutee Prasertmark and Mr. Veerasan Prayotamornkul (Khanjani et al. 2022; Zeng, Khoruamkid, et al. 2020). According to Romano (2017), aquamimicry is designed to emulate natural aquatic ecosystems by encouraging the growth of algae and zooplankton, which serve as live feed, and by utilizing beneficial bacteria to maintain water quality (Ghosh and Hasanuzzaman 2025; Sangsayan et al. 2025). The system integrates fermented rice bran, probiotics and naturally developing plankton to recreate ecological dynamics typical of natural waters (Khanjani et al. 2023). Key management practices involve regular addition of fermented carbon or grain-based substrates such as rice bran, soybean meal and wheat bran, in combination with probiotics (e.g., *Bacillus* spp.) and supplementary water additives (K. M. Catalani 2020; dos Santos, Coelho-Filho, Gonçalves, et al. 2022; dos Santos, Coelho-Filho, Assunção, et al. 2022; Nisar et al. 2022; Khanjani et al. 2023).

Microorganisms and their enzymes enhance the solubility of carbon sources and facilitate nutrient breakdown. Specific bacteria (e.g., *Lactobacillus* spp., *Bacillus* spp.), fungi and yeasts (e.g., *Saccharomyces* spp.) produce hydrolytic enzymes that reduce fibre and carbohydrate content while increasing protein availability (Khanjani et al. 2023; Romano et al. 2018). Water supplements such as sodium bicarbonate are sometimes employed to stabilize pH. Unlike conventional shrimp farming, aquamimicry emphasizes ecological balance, microbial diversity and sustainable production, eliminating the need for antibiotics or harmful chemicals (Ghosh and Hasanuzzaman 2025). This approach has been adopted and adapted in multiple countries, including Australia, Bangladesh, Brazil, Brunei, China, Ecuador, Egypt, India, Korea, Malaysia, Mexico, Peru, Singapore, Sri Lanka, the United States and Vietnam (Zeng, Khoruamkid, et al. 2020). Notably, research conducted in Nakhon Nayok province, Thailand, has examined the diversity of intestinal microbial communities in *L. vannamei*, as well as in sediment and culture water under aquamimicry systems (Zeng, Khoruamkid, et al. 2020).

BFT was developed in the 1970s by the French Research Institute for Exploitation of the Sea (IFREMER-COP) at the Pacific Oceanic Centre. It was initially applied to species including *Penaeus monodon*, *Fenneropenaeus merguiensis*, *L. vannamei* and *L. stylirostris* (Kaviarasu et al. 2021; J. Lal et al. 2024). Research in Israel and the United States during the late 1980s and early 1990s, particularly at the Waddell Mariculture Centre, advanced BFT through trials with tilapia and *L. vannamei* (M. Emerenciano et al. 2013). A landmark industrial-scale implementation in Tahiti (French Polynesia) in 1988 utilized 1000 m^2 concrete tanks with minimal water exchange, achieving yields of 20–25 tonnes per hectare per year across two production cycles

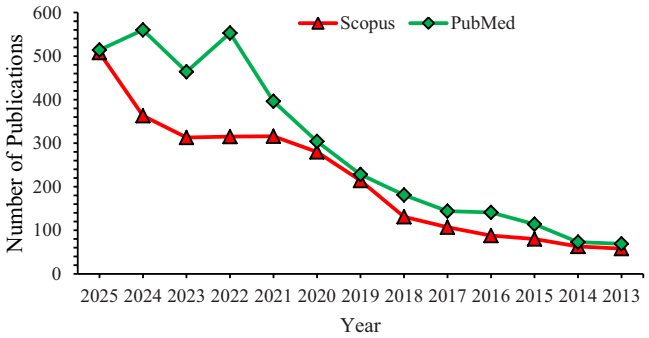


FIGURE 2 | Annual publication trends on aquamimicry and biofloc technology (BFT) in *L. vannamei* farming from 2013 to 2025.

(M. Emerenciano et al. 2011). Although early trials in Tahiti during the 1980s highlighted the potential of microbial aggregates in shrimp culture, modern biofloc systems have significantly advanced through improved aeration, carbon management and microbial regulation. Since then, commercial BFT operations have expanded globally, including in Asia, Latin and Central America, the United States, South Korea, Brazil, Italy, China and India, demonstrating the system's broad applicability and success (Tokrisna 2004).

The rising global demand for *L. vannamei* and environmental concerns associated with conventional shrimp farming have fuelled interest in sustainable alternatives such as aquamimicry and BFT. Figure 2 illustrates the annual number of publications indexed in Scopus and PubMed from 2013 to 2025 related to aquamimicry and BFT in *L. vannamei* culture, highlighting the growing focus on technological innovations that promote food security and environmentally sustainable shrimp aquaculture.

3.2 | Distinguishing Aquamimicry From BFT

Aquamimicry and BFT are two innovative approaches to sustainable shrimp aquaculture, yet they differ significantly in concept, mechanism and management (Table 1). Aquamimicry promotes the growth of beneficial microorganisms and zooplankton, such as copepods, through the fermentation of plant-based materials like rice bran or soybean meal (Ghosh and Hasanuzzaman 2025). This process not only recycles nutrients but also provides a continuous supply of natural live feed for shrimp (Deepti et al. 2024). It emphasizes ecological balance, low water exchange and lower aeration requirements, making it a more energy-efficient and nature-based approach (Deepti et al. 2024).

BFT relies on the proliferation of heterotrophic bacteria to convert waste nutrients, such as ammonia, into microbial protein that shrimp can consume (C. Li and Dai 2025). It typically requires high aeration to keep the bioflocs suspended and often uses simple carbon sources like molasses or glucose to maintain an appropriate C:N ratio (Minaz and Kubilay 2021). While BFT effectively improves water quality, reduces feed costs and enhances biosecurity, it demands high energy input and technical expertise for optimal management (Ogello et al. 2021).

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TABLE 1 | Differentiation between aquamimicry and BFT.

Characteristics	Aquamimicry	BFT
Definition	Ecosystem-based approach that stimulates heterotrophic bacteria and copepod blooms to provide natural feed and improve water quality. (Deepti et al. 2024).	Stimulates biofloc bacteria to convert organic waste and ammonia into microbial biomass, improving water quality and nutrient recycling (C. Li and Dai 2025).
Indoor or outdoor	Normally outdoor (Khanjani et al. 2023).	Both indoor/outdoor (Khanjani et al. 2023).
Stocking densities	Conservative (150–300 shrimp m^{-2}) (Khanjani et al. 2023).	Conservative to high (300 to > 450 shrimp m^{-2}) (Khanjani et al. 2023).
Carbon sources	External inputs such as rice bran or wheat bran (K. Catalani et al. 2023; Deepti et al. 2024; Cho and Yigit 2022).	Molasses, carbohydrate-rich materials or commercial carbon sources (Abakari et al. 2021b).
Microorganisms' addition	Probiotic use recommended.	Limited use of probiotics (Zeng, Khoruamkid, et al. 2020).
Water exchange	Minimum (Khanjani et al. 2023).	No (Khanjani et al. 2025).
Water quality management	Preserves water quality using natural ecosystem processes (Deepti et al. 2024).	Controls key nitrogen compounds through microbes and biofiltration (Khanjani et al. 2024).
Stoichiometric adjustment of the C:N ratio	No (Khanjani et al. 2023).	Often (Xu et al. 2016).
Intense zooplankton blooms	Yes (mandatory) (Khanjani et al. 2023).	Not expected (Yun et al. 2022).
Phytoplankton role	Major (TAN uptake and sustain zooplankton blooms) (Ghosh and Hasanuzzaman 2025).	Minor (Llario et al. 2019).
Disease Management	Enhance shrimp immunity and suppress pathogens through symbiotic action. (Deepti et al. 2024).	Enhances biosecurity by suppressing pathogens and minimizing chemical/antibiotic use (Butucel et al. 2022).
Economic	High setup cost; variable operations; manage excess sediments (Nisar et al. 2022).	High setup and operational costs (carbon, water treatment, electricity) (Khanjani et al. 2024).
Sustainability	Eco-friendly; enhances shrimp nutrition with natural feed sources (Deepti et al. 2024).	Improves nutrient recycling and lowers environmental footprint (C. Li et al. 2023).

3.3 | Mechanistic Nutrient Cycling of Aquamimicry Versus BFT Systems

Aquamimicry and BFT are intensive shrimp culture systems with distinct ecological mechanisms (Figure 3). In BFT, ammonia from shrimp metabolism is rapidly assimilated by heterotrophic bacteria into microbial biomass (bioflocs), supported by external carbon inputs, continuous aeration and mixing. In contrast, aquamimicry mimics natural estuarine ecosystems, recycling nitrogen through planktonic and detrital loops, relying on fermented plant substrates, moderate energy inputs and a complex plankton-based food web. Waste assimilation in BFT occurs via microbial biomass formation, whereas in aquamimicry wastes are recycled through detritus → plankton → shrimp pathways. Overall, while both systems enhance water quality and growth, BFT is a microbially-driven system with high external inputs, and aquamimicry functions as a plankton-based ecosystem, reflecting natural trophic dynamics.

3.4 | Aquaculture Species Suitable for Aquamimicry and BFT Systems

Aquamimicry systems replicate natural estuarine and mangrove ecosystems, promoting plankton, beneficial microbes and live feed organisms, which create a balanced environment for polyculture and multi-trophic aquaculture (Khanjani et al. 2023; Deepti et al. 2024). Shrimp species such as *L. vannamei*, *P. monodon*, *F. merguiensis* and *Metapenaeus ensis*, as well as finfish like *Oreochromis niloticus*, *Chanos chanos*, *Lates calcarifer* and *Mugil cephalus*, benefit from the stable water quality and natural productivity of these systems (Khanjani et al. 2022; Ambasankar et al. 2022; M. M. Lal et al. 2023). Co-cultured crustaceans (*Macrobrachium rosenbergii*) and mollusks (*Crassostrea madrasensis*, *Perna viridis*) enhance nutrient cycling and ecosystem stability (Alam et al. 2024). Overall, aquamimicry reduces feed dependency, enhances biodiversity and improves farm resilience.

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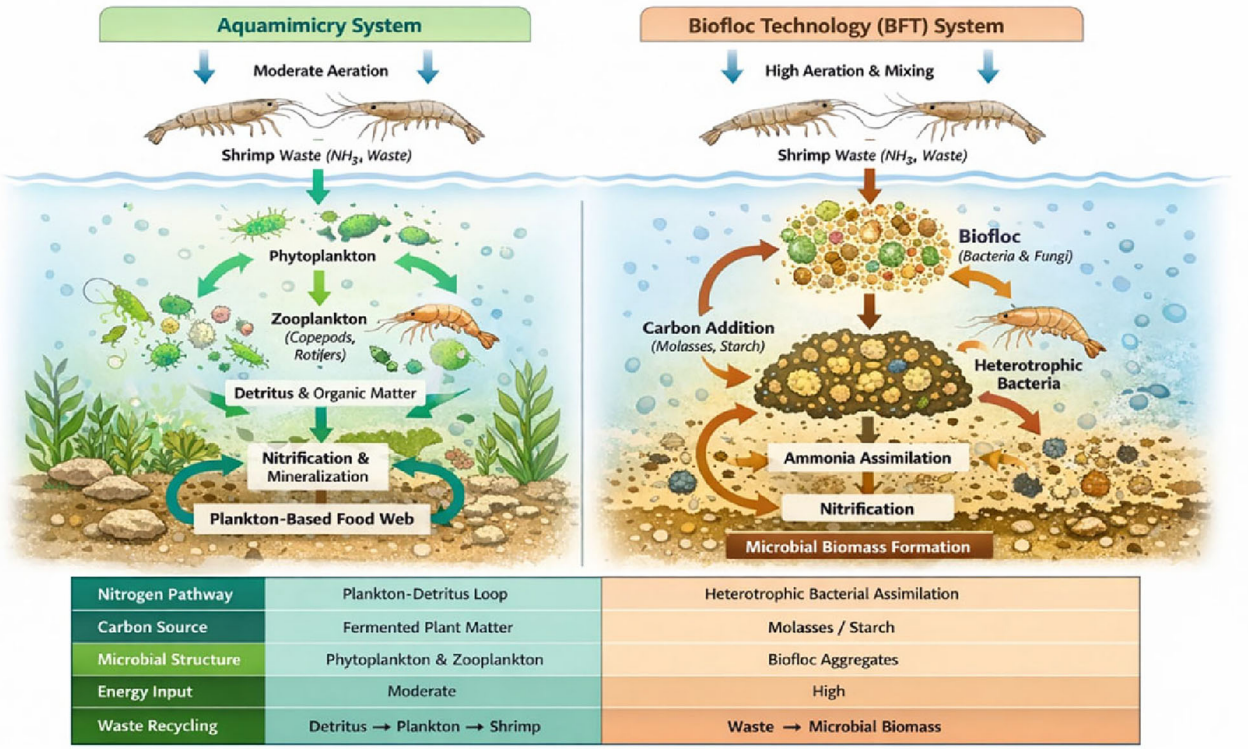


FIGURE 3 | Mechanistic nutrient cycling and system-level comparison between aquamimicry and biofloc technology (BFT) shrimp culture systems.

In contrast, BFT is designed for species tolerant to high suspended solids and variable water quality (Mugwanya et al. 2021). Air-breathing fish (*Heteropneustes fossilis*, *Clarias batrachus*, *Ompok pabda*, *Anabas testudineus*, *Pangasianodon hypophthalmus*) perform well under BFT conditions, while non-air-breathing species (*Cyprinus carpio*, *Labeo rohita*, *O. niloticus*, *C. chanos*) also show favourable growth (Mugwanya et al. 2021). Among crustaceans, *L. vannamei*, *P. monodon*, *Litopenaeus stylirostris*, *Farfantepenaeus paulensis* and *M. rosenbergii* thrive in biofloc systems (M. Emerenciano et al. 2011; Mugwanya et al. 2021; Cardona et al. 2016). Integrated culture studies indicate that co-culturing *L. vannamei* with mullet (*Mugil curema*) in BFT can increase total production (TP) by ~31% (Legarda et al. 2019).

While aquamimicry emphasizes ecological mimicry and polyculture for ecosystem stability and reduced feed inputs, BFT prioritizes high-density production of tolerant species with enhanced nutrient recycling and microbial management. Selection between these systems should consider species tolerance, production goals and sustainability objectives.

3.5 | Microorganisms in Aquamimicry and BFT

The use of probiotics in modern aquaculture has expanded considerably, as they help maintain a healthy gut microbiota (De et al. 2014) and improve the nutritional value of plant-based feed ingredients through fermentation (Van Nguyen et al. 2018). In aquamimicry systems, probiotics synergize with fermented carbon substrates, inhibiting pathogens via quorum-sensing pathways, enhancing shrimp immune responses, supporting in situ water bioremediation and increasing post-larval survival (Deepti et al. 2024). Notably, shrimp acquire only a minor portion of their gut microbiota from surrounding water; intestinal microbial community succession is largely driven by the host's developmental stage and age (V. Xiong et al. 2019; J. Xiong et al. 2020).

Liquid fermented rice bran (LFRB), produced by fermenting rice bran with *Bacillus subtilis* for 24 h under aeration, can alter hepatopancreas microbial composition and improve survival and growth in *L. vannamei* (Abdel-Tawwab et al. 2022; Liñan-Vidriales et al. 2021). In BFT systems, microbial dynamics involve floc-forming bacteria, saprophytes, nitrifiers, algal grazers and potential pathogens (Kumar et al. 2021). Bacterial densities typically range from 10^6 to 10^9 CFU mL^{-1} (Avnimelech 2007), regulated by C:N ratio, carbon source, species cultured, salinity and water quality parameters (Halim et al. 2025a, 2025b, 2025c, 2025d).

Recent metagenomic studies have revealed the functional potential of these microbial communities, identifying genes involved in nitrogen and carbon metabolism, antimicrobial compound production and immune modulation (J. Xiong et al. 2020). Quantitative ecological indices, such as the Shannon index and Simpson's index, are increasingly used to characterize microbial diversity and metagenomic monitoring, with higher diversity correlating with system stability, disease resistance and improved shrimp growth (Cardona et al. 2016). For example, BFT systems with Shannon indices > 3.5 demonstrate greater resilience against *Vibrio* outbreaks, while aquamimicry ponds with moderate Simpson indices indicate balanced dominance of beneficial species (Ghosh and Hasanuzzaman 2025).

Microbial communities interact through quorum sensing, competitive exclusion and production of antimicrobial compounds,

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which collectively suppress pathogens and stabilize water quality (Panigrahi et al. 2021). Co-culturing probiotics with heterotrophic bacteria can produce synbiotic effects, enhancing shrimp immune responses and supporting nutrient recycling (Ringø 2020; De et al. 2014). Incorporating metagenomic monitoring and diversity indices allows predictive management of system health, informing carbon supplementation, probiotic dosing and water exchange strategies. Table 2 summarizes microorganisms commonly associated with aquamimicry systems, while Table 3 lists beneficial microbes frequently observed in BFT environments.

3.6 | Total Haemocyte Counts of *L. vannamei* in Aquamimicry and BFT Systems

Total hemocyte count (THC) serves as a vital immunological parameter for assessing the health and immune capacity of *L. vannamei*, since haemocytes play critical roles in phagocytosis, encapsulation, coagulation and defence against pathogens (Tong et al. (2020). In the aquamimicry system, THCs are influenced by natural microbial communities, fermented rice bran and stable water quality, creating a probiotic-rich environment that promotes immune stimulation (Deepti et al. 2024). Shrimp reared under aquamimicry therefore tend to exhibit moderate to high THCs due to continuous exposure to beneficial bacteria and natural detritus (Khanjani et al. 2022). In contrast, the BFT system provides dense microbial flocs that function as both a biosecurity barrier and a nutritional supplement, supplying microbial proteins, essential fatty acids and immunostimulants that further enhance immune activity (Ogello et al. 2021). As a result, *L. vannamei* cultured in BFT typically shows higher THCs than those reared in aquamimicry, largely due to greater microbial diversity, continuous immunological stimulation and enriched bioactive compounds (Raza et al. 2024). Overall, both aquamimicry and BFT outperform traditional clear-water culture by supporting elevated THCs and stronger immune responses, which ultimately contribute to higher disease resistance, better survival and improved stress tolerance.

The comparative data presented (Table 4) for aquamimicry and BFT systems demonstrate clear differences in growth performance, feeding regimes, stocking duration and immune status of *L. vannamei*, as reflected by THCs. Under aquamimicry conditions, shrimp exhibited relatively higher final body weight (FW) and longer culture duration, with FW values of 10.71 ± 9.13 g at water temperatures of approximately 27.97 ± 0.62°C similar to Eissa et al. (2025). Feeding strategies based on formulated feed (FP) or feed combined with plankton-based carbon sources (FCPC) supported salinity at 19.99 ± 14.84% and were associated with elevated THCs ranging from 40.48×10^4 to 34.03×10^7 cells mL^{-1} (Eissa et al. 2025; Galkanda-Arachchige et al. 2021). These high THC values indicate enhanced immune competence, likely driven by stable water quality and the availability of natural biota in aquamimicry systems.

In contrast, shrimp reared in BFT systems generally showed lower final body weights but were cultured at comparable temperatures (27.95 ± 0.51°C) under controlled feeding conditions using commercial feeds (CF_1 and CF_2). Salinity in BFT ranged 17.00 ± 9.67, with THCs varying between 2.44×10^5 and 45.69

TABLE 2 | List of microorganisms with bacterial loads recorded in Aquaminicry system for *L. vannamei* aquaculture.

Microbial species names	Bacterial abundance	Cited literature
B. subtilis	2×10^7 CFU/g	Abdel-Tawwab et al. (2022)
Cyanobacteria	2.78×10^7 cells/L	K. Catalani et al. (2023)
Exiguobacterium, *Vibrio*, *Candidatus bacilloplasma*, *Pirellula*, *Pseudarthrobacter*, *Acinetobacter*, *Rhodopirellula* and *Photobacterium*	—	Zeng, Zhou, et al. (2020)
Aeromonas, *Phascolarctobacterium*, *Photobacterium*, *Vibrio*, *Candidatus Bacilloplasma*	—	Zeng, Khoruamkid, et al. (2020)
Bacillus subtilis, *Bacillus licheniformis*, *Bacillus coagulans*, *Lactobacillus acidophilus* and *Saccharomyces cerevisiae*.	4.0×10^9 CFU/mL	Liñan-Vidriales et al. (2021)
Lactobacillus acidophilus, *Aspergillus niger* and *Saccharomyces cerevisiae*	10^7 CFU/mL	Jannathulla et al. (2017)

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TABLE 3 | List of microorganisms with bacterial loads recorded in BFT system for *L. vannamei* aquaculture.

Microbial species names	Bacterial abundance	Cited literature
Cyanobacteria	3.86×10^7 cells/L	K. Catalani et al. (2023)
Lysinibacillus fusiformis, *Enterococcus hirae*	72.36×10^9 CFU/mL	Halim et al. (2025c)
	235.80×10^9 CFU/ mL	Halim et al. (2025d)
	131.76×10^9 CFU/mL	Halim et al. (2025b)
Gammaproteobacteria, Thiotrichaceae, Leucothrix, Alphaproteobacteria, Rhodobacteraceae, Bacteroidetes, and Saprospiraceae	—	Cardona et al. (2016)
Pseudomonas spp., including *Pseudomonas fluorescens*	10^5–10^8 CFU/mL	Dou et al. (2021)
Bacillus subtilis	10^6 CFU/mL	He et al. (2023)
Bacillus species	10.42×10^8 cells/g	Hostins et al. (2017)
Vibrio species	9.76×10^8 cells/g	
Heterotrophic microbial populations	5.93×10^5 CFU/mL	Khanjani et al. (2020)
Bacillus subtilis	10^9 CFU/L	K. F. Liu et al. (2010)
Vibrio fluvialis, *Vibrio alginolyticus*, *Aeromonas hydrophila*, *Aeromonas salmonicida* and *Pseudomonas aeruginosa*	10^5 CFU/mL	Manan et al. (2017)
Cobetia, *Exiguobacterium*, *Bacillus*, *Marinilactibacillus*, *Staphylococcus* and *Novosphingobium*	10^4 CFU/mL	Panigrahi et al. (2017)
Heterotrophic bacteria	6.12×10^4 CFU/mL	Panigrahi et al. (2020)
Heterotrophic bacteria	98.24×10^6 CFU/mL	Rajkumar et al. (2016)

$\times 10^5$ cells mL^{-1} (Halim et al. 2025b, 2025c, 2025d; Panigrahi et al. 2019). The observed variability in THCs under BFT reflects differences in culture intensity, biofloc density and feeding regimes, which can differentially stimulate the shrimp immune system. Overall, while aquamimicry systems tend to support higher growth and consistently elevated immune responses, BFT systems demonstrate greater flexibility in management and can also promote strong immunological performance when optimized, highlighting the influence of culture strategy on shrimp health and productivity.

3.7 | Proximate Composition (On a Dry Weight Basis) of *L. vannamei* in Aquamimicry and BFT Systems

The nutrient content and availability in feed are crucial determinants of the proximate composition of cultured aquatic species (Gunalan et al. 2013). In the present study, the proximate composition of *L. vannamei* was analysed on a dry-weight basis to evaluate the nutritional quality of shrimp cultivated under aquamimicry and BFT systems. Key biochemical components, including crude protein, crude lipid, ash and carbohydrates, were quantified following the standard procedures established by the Association of Official Analytical Chemists (AOAC). Noticeable differences in proximate composition were found between the two culture systems, reflecting variations in microbial activity, natural productivity and nutrient availability. Shrimp cultured in the BFT system generally exhibited higher protein and ash contents, likely due to continuous ingestion of biofloc particles that function as a natural supplemental feed (El-Sayed 2021). In contrast, aquamimicry-reared shrimp displayed relatively higher lipid levels and more stable carbohydrate concentrations, indicating efficient energy utilization and consistent nutrient assimilation from plankton-based natural feeds (Abdel-Tawwab et al. 2022). Overall, these findings demonstrate that culture environment significantly influences the nutritional profile of *L. vannamei*, offering valuable insights for optimizing feeding strategies and improving culture system efficiency (Y. Li et al. 2024).

As presented in Table 5, shrimp reared under aquamimicry showed consistently high protein content (71.35 ± 1.20%), indicating stable nutrient assimilation within the plankton-mimicking environment. Lipid content was comparatively higher (16.07 ± 11.08%), reflecting the availability of natural detritus and energy-rich particulates. Conversely, ash (6.20%) and carbohydrate (6.39%) levels remained relatively low, suggesting moderate mineral deposition and glycogen storage.

Shrimp cultured in the BFT system exhibited a more variable biochemical profile. Although average protein content was slightly lower (69.46 ± 9.30%), ash (14.28%) and carbohydrate (10.26%) contents were markedly higher, indicating enhanced mineral uptake and increased glycogen accumulation associated with continuous exposure to suspended microbial flocs. Lipid content was substantially lower (6.00 ± 3.26%), consistent with leaner tissue formation in biofloc-based systems. In summary, aquamimicry favours the development of lipid-rich, high-energy tissues, whereas BFT promotes greater mineralization and carbohydrate accumulation. These contrasting nutritional outcomes reflect the distinct ecological and trophic dynamics inherent to each culture strategy.

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TABLE 4 | Total hemocyte counts (THCs) in *L. vannamei* under aquamimicry and BFT.

System	FW (g)	WT (°C)	FC	ST (‰)	THCs (cells/mL)	Cited literature
Aquaminicry	17.16	27.53	FP	30.48	34.03×10^7	Eissa et al. (2025), Galkanda-Arachchige et al. (2021)
	4.25	28.4	FCPC	9.50	40.48×10^4	
Av.	**10.71**	**27.97**		**19.99**		
SD	**9.13**	**0.62**		**14.84**		
BFT	0.32	27.42	CF_1	7.50	2.44×10^5	Halim et al. (2025c)
	1.54	27.98	CF_1	15	29.94×10^5	Halim et al. (2025d)
	1.60	27.75	CF_1	15	45.69×10^5	Halim et al. (2025b)
	19.32	28.63	CF_2	30.50	17.50×10^6	Panigrahi et al. (2019)
Av.	**5.70**	**27.95**		**17.00**		
SD	**9.10**	**0.51**		**9.67**		

Note: FP denotes a combination of fermented prebiotic (mannanoligosaccharide, MOS) and probiotic (*Bacillus subtilis* WB60). The term CF1 refers to feed containing 40% crude protein with small pellets ranging from 0.25 to 1 mm in size, whereas CF2 represents feed formulated with 35% crude protein. ST indicates salinity in parts per thousand.
Abbreviations: FC, feed composition; FCPC, fermented corn protein concentrate; FW, final weight; WT, water temperature.

3.8 | Growth Parameters

Aquamimicry has been developed in shrimp aquaculture to replicate natural environmental conditions, fostering healthier and more sustainable shrimp production (Khanjani et al. 2023). This method is designed to improve feed efficiency, reduce disease incidence, limit the need for water exchange and enhance overall production quality (Zeng, Khoruamkid, et al. 2020). Research has shown that incorporating fermented carbohydrate substrates in culture ponds stimulates plankton growth, particularly copepods, by supporting heterotrophic microbial communities that mimic natural aquatic ecosystems (Deepak et al. 2020; Romano and Kumar 2017). In addition, Damayanti et al. (2020) reported that fermentation of rice bran significantly increased the production of live feed, such as *Moina macrocopa*, compared with unfermented treatments.

The summarized growth-performance data highlight clear contrasts between aquamimicry and BFT systems for *L. vannamei* culture under comparable thermal conditions (Table 6). In aquamimicry systems, water temperature remained within the optimal 27.54 ± 1.51°C, supporting moderate stocking durations of 58.33 ± 32.13 days and relatively low culture densities (1.35 ± 1.16 ind. L^{-1}). Shrimp in these systems exhibited steady growth, with an average FW of 10.93 ± 7.40 g and high survival rates (86.77 ± 13.83%). FCRs were generally favourable (1.63 ± 0.63), while specific growth rate (SGR) showed considerable variability (3.43 ± 2.37% day^{-1}), reflecting differences in feed type, stocking strategy and natural productivity across studies. Overall, aquamimicry promoted stable growth performance with efficient feed utilization and consistent survivability.

In contrast, BFT systems operated at slightly higher mean temperatures (28.18 ± 1.90°C) and shorter but more intensive culture cycles (52.82 ± 30.49 days), typically at higher stocking densities (0.90 ± 1.15 ind. L^{-1}) and with greater system inputs. Although average final weight (8.11 ± 7.95 g) and survival (83.62 ± 12.97%) were slightly lower than in aquamimicry. However, BFT systems showed higher variability in feed efficiency and growth dynamics, as reflected by a broader range of FCR values (mean 1.59 ± 0.46) and generally elevated SGR (5.13 ± 4.21% day^{-1}). TP tended to be higher in BFT due to intensified management and continuous nutrient recycling, despite the modest individual growth.

Overall, aquamimicry systems favour consistent individual growth, feed efficiency and survival under semi-natural conditions (Khanjani et al. 2023), whereas BFT systems emphasize intensified production with higher growth rates and greater variability in performance indicators (Ogello et al. 2021). These differences underscore the influence of culture strategy, feeding regime and stocking management on growth performance and productivity of *L. vannamei*, providing valuable guidance for selecting system-specific management approaches.

The comparative analysis indicated no statistically significant differences between aquamimicry and BFT for most performance indicators ($p > 0.05$) (Table S2). Aquamimicry showed slightly higher survival rate (86.77 ± 13.83%) and final weight (10.93 ± 7.40 g) than BFT (83.62 ± 12.97% and 8.11 ± 7.95 g, respectively), although the effect sizes were small (Cohen's $d = 0.24$ and

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TABLE 5 | Proximate composition (% dry weight) of *L. vannamei* reared under aquamimicry and biofloc (BFT) systems.

System	FW (g)	WT (°C)	FC	ST (‰)	Protein (%)	Lipid (%)	Ash (%)	CHO (%)	Cited literature
Aquaminicry	6.35	26.70	BFRB	18.33	70.50	23.90	1.90	3.70	Abdel-Tawwab et al. (2022)
	6.03	29.70	SDFB	2.80	72.20	8.23	10.5	9.07	Qiu and Davis (2018)
Av.	**6.19**	**28.2**		**10.57**	**71.35**	**16.07**	**6.20**	**6.39**	
SD	**0.23**	**2.12**		**10.98**	**1.20**	**11.08**	**6.08**	**3.80**	
BFT	13.27	29.05	DC_1	19.50	73.18	3.34	15.42	8.06	Jatobá et al. (2014)
	1.66	30.21	CF_1	32.95	75.67	7.27	11.19	5.87	Khanjani et al. (2017)
	2.56	30.25	CF_2	21	74.80	6.22	11.94	7.04	Khanjani, Alizadeh, et al. (2020)
	0.66	30.51	CFBF	21.01	74.72	6.84	11.47	6.97	Khanjani, Sharifinia, et al. (2020)
	7.43	26	ID	—	75.60	3.57	12.68	8.15	Hamidoghli et al. (2020)
	8.49	23.16	CP	25	44.24	14.18	22.87	18.71	Rajkumar et al. (2016)
	12.37	27.70	DC_2	32	72.97	3.91	14.07	9.05	Said and Ahmed (2022)
	15.67	27.10	DC_2	32	72.75	3.68	12.51	11.06	Said et al. (2024)
	8.83	27	DC_3	24	76.90	4.04	13.27	5.79	Tinh et al. (2021)
	0.32	27.42	CF_3	7.50	66.56	4.73	17.47	11.25	Halim et al. (2025c)
	1.54	27.98	CF_3	15	62.22	10	14.66	13.12	Halim et al. (2025d)
	1.60	27.75	CF_3	15	63.93	4.20	13.83	18.05	Halim et al. (2025b)
Av.	**6.20**	**27.84**		**22.27**	**69.46**	**6.00**	**14.28**	**10.26**	
SD	**5.51**	**2.06**		**8.05**	**9.30**	**3.26**	**3.24**	**4.40**	

Note: CF1 stands for commercial feed with 38% crude protein, 9% crude lipid, 3% crude fibre, 14% ash and 10% moisture; CF2 stands for feed with 36% crude protein, 8% crude lipid, 3% crude fibre, 14% ash and 10% moisture; CF3 stands for feed with 40% crude protein, with tiny crumbs sized 0.25–1 mm; CFBF stands for commercial shrimp feed containing 42% protein supplemented with moist bioflocs at 15% of body weight; CP stands for Charoen Pokph feed with 34.50% crude protein; DC1 stands for diets containing 24.30%, 30.30%, 32.90% and 36.7% crude protein; DC2 stands for diet containing 38% protein; DC3 stands for diet containing 33% protein; ID stands for isonitrogenous diets (360 g/kg crude protein) with varying lipid levels of 45, 60, 90, 120 and 150 g/kg.

Abbreviations: BFRB, *Bacillus subtilis*-fermented rice bran; CHO, carbohydrate; FC, feed composition; FW, final weight; SDFB, spray-dried fermented biomass (0, 25, 50 and 100 g/kg) used as a replacement for fish meal; ST, salinity; WT, water temperature.

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TABLE 6 | Comparison of growth performance of *L. vannamei* between aquamimicry and biofloc (BFT) systems.

System	WT (°C)	FC	ST (‰)	CD (days)	SD/L	IW (g)	FW (g)	SR (%)	FCR	SGR (% day^{-1})	TP (kg/m^3)	Cited literature
Aquaminicry	24.19	CF_1	11.42	120	0.60	1.44	11.73	53.3	1.75	1.75	0.10	K. Catalani et al. (2023)
	28.5	—	5	72	—	—	24.48	92	1.33	—	0.4	Zeng, Khoruamkid, et al. (2020)
	27	RB	37.50	28	—	6.50	12.25	98.25	2.23	2.24	0.18	Liñan-Vidriales et al. (2021)
	26.70	BS	18.33	84	1	0.51	6.35	88.70	—	2.80	4.80	Abdel-Tawwab et al. (2022)
	29.70	SD	2.80	30	—	0.59	6.03	100	1.60	7.75	0.60	Qiu and Davis (2018)
	28.85	SF	15.5	75	0.25	4.79	15.39	82.78	1.58	1.56	0.38	Van Nguyen et al. (2018)
	27.28	CF_2	28.18	30	2.62	—	0.76	83.15	0.52	—	1.43	Cho and Yigit (2022)
	27.53	DC_1	30.48	56	0.025	5.01	17.16	90.83	1.39	2.19	0.40	Eissa et al. (2025)
	28.40	CF_3	9.50	56	—	0.17	4.25	91.88	2.64	5.75	—	Galkanda-Arachchige et al. (2021)
Av.	**27.54**		**18.69**	**58.33**	**1.35**	**3.14**	**10.93**	**86.77**	**1.63**	**3.43**	**1.08**	
SD	**1.51**		**11.83**	**32.13**	**1.16**	**2.60**	**7.40**	**13.83**	**0.63**	**2.37**	**1.48**	
BFT	27.42	FNB	32.60	35	2.50	0.02	0.85	83.58	1.39	9.50	1.80	Brito et al. (2016)
	29.20	FG	30.78	47	0.50	7.81	13.42	79	—	1.15	1.06	de Morais et al. (2020)
	28	CF_4	16.50	42	4.88	0.09	0.44	89.88	1.50	8.60	0.04	Esparza-Leal et al. (2015)
	26.87	CD_1	26.87	42	1	1.30	5.22	83.64	2.61	3.31	0.44	Furtado et al. (2015)
	29.20	CF_5	34.71	119	0.35	0.18	11.58	98.14	1.24	3.50	4.54	Gaona et al. (2016)
	29.05	DC_2	19.50	49	0.25	4.70	13.27	86.92	—	2.12	2.88	Jatobá et al. (2014)
	28.73	CFS	5	63	0.27	0.81	11.81	90.67	1.26	4.18	2.87	Huang et al. (2022)
	27.50	LD	33.30	14	0.40	0.01	0.13	91.50	—	18.32	0.01	S. K. Kim et al. (2014)
	30.77	CF_6	32.95	32	1	0.10	1.66	87.49	1.30	8.81	0.15	Khanjani et al. (2017)
	30.63	CF_7	22.09	35	1	2.56	5.97	80.32	—	2.36	0.48	Khanjani, Alizadeh, et al. (2020)
	30.51	CFBF	21.01	27	1	0.07	0.66	83.93	—	6.73	0.06	Khanjani, Sharifinia, et al. (2020)
	28.63	CD_2	30.30	120	0.90	0.96	13.80	82.73	1.70	2.22	3.09	Krummenauer et al. (2011)
	26.66	BCF	33.14	30	0.31	3.50	8.08	92.94	1.17	1	2.34	Krummenauer et al. (2014)
	28.63	FD	30.30	112	0.10	1.34	19.32	88.22	1.18	2.41	1.70	Panigrahi et al. (2017)
	29.10	HI, EXP	29.64	77	0.29	4.70	28.01	88.24	1.66	2.32	8	Prangnell et al. (2022)
	23.32	CP	25	30	0.13	0.15	7.09	86.25	—	4.34	0.61	Rajkumar et al. (2016)
	30.70	HF	16.20	84	0.25	0.72	22.10	49.70	2.50	4.08	1.10	Ray et al. (2011)
	27.80	CFA	31.60	48	3	0.01	0.67	86.20	1.10	1.40	1.70	Tierney and Ray (2018)
	24	SF	32	30	0.19	7.41	10.83	89.53	—	1.25	0.97	Xu et al. (2013)
	27.42	CF_8	7.5	42	0.50	0.02	0.32	42.17	1.85	6.15	0.07	Halim et al. (2025c)

(Continues)

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TABLE 6 | (Continued)

System	WT (°C)	FC	ST (‰)	CD (days)	SD/L	IW (g)	FW (g)	SR (%)	FCR	SGR (% day^{-1})	TP (kg/m^3)	Cited literature
	27.98	CF_8	15	42	0.50	0.03	1.54	90	1.87	9.49	1.44	Halim et al. (2025d)
	27.75	CF_8	15	42	0.50	0.03	1.60	88.5	1.50	9.57	0.71	Halim et al. (2025b)
Av.	**28.18**		**24.59**	**52.82**	**0.90**	**1.66**	**8.11**	**83.62**	**1.59**	**5.13**	**1.64**	
SD	**1.90**		**8.90**	**30.49**	**1.15**	**2.43**	**7.95**	**12.97**	**0.46**	**4.21**	**1.86**	

Abbreviations: CD, culture duration; FC, feed composition; FCR, feed conversion ratio; FW, final body weight; IW, initial body weight; SD, stocking density; SGR, specific growth rate; SR, survival rate; ST, salinity; TP, total production; WT, water temperature.

0.36). FCR was nearly identical between the systems ($d = 0.07$), indicating negligible differences in feed efficiency. Conversely, BFT demonstrated somewhat higher SGR and biomass yield, but these differences were also small and statistically non-significant ($d = -0.46$ and -0.32). Overall, the results suggest that both systems produce comparable production performance, with only minor variations depending on the indicator.

A wide variety of feed types and formulations were applied across the experimental trials. CF_1 refers to a commercial Guabi feed containing 40% crude protein. RB denotes rice bran fermented using a consortium of *Bacillus* and *Lysinibacillus* species, while BS indicates rice bran fermented specifically with *B. subtilis*. SD represents spray-dried fermented biomass incorporated at inclusion levels of 0, 25, 50 and 100 g/kg as a partial substitute for fishmeal. SF consists of soybean meal fermented with *B. subtilis*, blended with locally sourced fishmeal (600 g/kg protein) and imported Chilean fishmeal (650 g/kg protein). CF_2 is a commercial feed containing 50% protein and 7% lipid.

DC_1 describes a formulated diet comprising fishmeal (72% protein), soybean meal (38%), corn gluten (63%), wheat bran, yellow corn, soybean oil, starch and a vitamin–mineral premix. CF_3 includes a commercial feed with protein ≥ 50%, fat ≥ 15% and fibre ≤ 1%. FNB is a formulated diet containing 40% protein and 8% lipid, enriched with *Navicula* spp. and *Brachionus plicatilis*. FG refers to Guabi commercial feed (1.60 mm pellet size) containing 40% protein. CF_4 and CD_1 are commercial feeds containing 40% and 38% protein, respectively, with CD_1 also providing 8% lipid. CF_5 contains 38% protein and 8% lipid, while DC_2 represents diets formulated with protein levels of 24.30%, 30.30%, 32.90% and 36.70%.

CFS denotes a commercial shrimp feed containing 40% protein, 5% lipid, 5% fibre, 15% ash and 12% moisture, whereas LD refers to a larval diet with 45% protein. CF_6 and CF_7 differ in protein and lipid composition but share similar ash and moisture contents. CFBF represents a commercial feed (42% protein) supplemented with moist biofloc at 15% of body weight. CD_2 is a commercial diet containing 38% protein. BCF refers to diets incorporating biofloc at graded levels (0%–100%) with a 40% protein commercial feed. FD denotes a formulated diet with 35% protein. HI and EXP feeds differ in proximate composition, while CP indicates Charoen Pokphand feed containing 34.50% protein. HF refers to a hyper-intensive feed formulation. CFA denotes commercial feed supplemented with *Artemia*, SF indicates shrimp feed with 40% protein and CF_8 refers to finely crumbled commercial feed (0.25–1 mm) containing 40% protein.

3.9 | Key Water Quality Indicators

Environmental conditions, including water temperature, salinity, dissolved oxygen (DO) and pH, play a pivotal role throughout the culture period of *L. vannamei* (Lara et al. 2017). Variations in these parameters can markedly influence shrimp physiological processes such as growth, metabolism, reproduction and molting (Nugraha et al. 2023). Critical water quality variables including temperature, alkalinity, salinity, pH, DO, concentrations of ammonia and nitrite and total suspended solids (TSS) also affect nitrification dynamics within the culture environment (Abakari et al. 2021a).

In this study, measured values were as follows: DO at 6.30 ± 0.50 ppm, temperature at 26.80 ± 1.20°C, pH at 7.90 ± 0.20, salinity at 16.50 ± 0.20 ‰, total ammonia-N at 0.42 ± 0.05 ppm, nitrite-N at 0.02 ± 0.05 ppm and nitrate-N at 31.06 ± 29.69 ppm. All observed parameters fell within the optimal ranges recommended for *L. vannamei* culture (Furtado et al. 2015). Furthermore, maintaining alkalinity above 100 mg $CaCO_3$ L^{-1} is essential for promoting stable biofloc formation and ensuring overall system stability (Furtado et al. 2015).

The compiled water-quality data clearly illustrate contrasting environmental characteristics between aquamimicry and BFT systems used for *L. vannamei* culture (Table 7). In aquamimicry systems, pH values generally ranged from slightly acidic to moderately alkaline, with an overall mean of 7.65 ± 0.53, reflecting relatively stable and buffered conditions. Water temperature remained within a narrow optimal 27.54 ± 1.51°C, while DO levels were consistently adequate for shrimp growth 6.28 ± 0.94 mg L^{-1}. Ammonia and nitrite concentrations were comparatively low on average (1.16 ± 1.06 and 1.15 ± 1.41 mg L^{-1}, respectively), indicating effective natural nitrification supported by plankton-based productivity. Salinity was relatively long 18.69 ± 11.83‰, and where reported, TSS and alkalinity values suggested moderate organic loading and sufficient buffering capacity, consistent with semi-natural, low-intensity culture conditions reported across multiple studies.

In contrast, BFT systems exhibited a more dynamic and nutrient-rich water quality profile. Mean pH (7.70 ± 0.34) and temperature (28.18 ± 1.90°C) were comparable to aquamimicry, but DO levels were slightly lower on average (5.99 ± 0.81 mg L^{-1}), reflecting higher microbial respiration associated with dense biofloc communities. Nitrate and nitrite concentrations were markedly more variable and generally higher (48.78 ± 77.85 and 2.50 ± 3.29 mg

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TABLE 7 | Comparison of water quality parameters in *L. vannamei* culture under aquamimicry and biofloc (BFT) systems.

System	FC	pH	AM (ppm)	WT (°C)	DO (ppm)	NA (ppm)	NI (ppm)	ST (‰)	TSS (ppm)	AL (ppm)	Cited literature
Aquamimicry	CF_1	8.44	0.25	24.19	7.85	2.82	0.12	11.42	165.71	232.57	K. Catalani et al. (2023)
	CF_2	7.65	2.48	27.28	6.96	13.95	3.09	28.18	—	150.25	Cho and Yigit (2022)
	—	6.75	1.75	28.5	5	0.80	0.25	5	—	—	Zeng, Khoruamkid, et al. (2020)
	RB	—	—	27	5	—	—	37.5	—	—	Liñan-Vidriales et al. (2021)
	BS	7.81	—	26.7	5.8	—	1.39	18.33	—	—	Abdel-Tawwab et al. (2022)
	SD	7.20	0.05	29.70	6.18	—	0.05	2.80	—	—	Qiu and Davis (2018)
	SF	—	—	28.85	—	—	—	15.5	—	—	Van Nguyen et al. (2018)
	DC_1	8.18	0.81	27.53	6.06	—	—	30.48	—	—	Eissa et al. (2025)
	CF_3	7.50	0.30	28.40	6.70	—	0.05	9.5	—	—	Galkanda-Arachchige et al. (2021)
AV.		**7.65**	**1.16**	**27.54**	**6.28**	**7.88**	**1.15**	**18.69**	**165.71**	**177.69**	
SD		**0.53**	**1.06**	**1.51**	**0.94**	**7.06**	**1.41**	**11.83**	**0.00**	**47.53**	
BFT	FNB	8.21	0.15	27.42	5.63	2.51	0.47	32.60	308.33	141.30	Brito et al. (2016)
	FG	7.56	0.98	29.20	5.14	56.79	5.87	30.78	325.68	142.28	de Morais et al. (2020)
	CF_4	7.50	1.50	28	6.50	85	0.10	16.50	711	60	Esparza-Leal et al. (2015)
	CD_1	7.10	0.04	26.87	6.10	280.37	0.05	23.03	934.42	69.99	Furtado et al. (2015)
	CF_5	7.5	0.26	29.20	5.60	44.11	3.98	34.71	550	118.84	Gaona et al. (2016)
	DC_2	8.02	0.18	29.05	5.50	43.55	0.18	19.50	—	—	Jatobá et al. (2014)
	CFS	7.40	0.03	28.73	5.41	32.10	12.63	5	327.40	104	Panigrahi et al. (2017)
	LD	8.15	0.22	30.77	5.78	6.45	4.85	32.95	—	—	Khanjani et al. (2017)
	CF_6	7.84	0.50	30.63	5.80	4.78	4.58	22.09	123.67	—	Khanjani, Alizadeh, et al. (2020)
	CF_7	8.17	0.37	30.51	6.19	2.81	2.61	21.01	141.7	—	Khanjani, Sharifinia, et al. (2020)
	CFBF	7.70	0.80	27.50	4.90	214.40	1.10	33.30	673.50	—	S. K. Kim et al. (2014)
	CD_2	8.16	0.78	28.63	5.48	0.26	0.35	30.30	196.37	136.12	Krummenauer et al. (2011)
	BCF	7.62	0.17	26.66	8.01	27.24	3.06	33.14	545.20	129.33	Krummenauer et al. (2014)

(Continues)

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TABLE 7 | (Continued)

System	FC	pH	AM (ppm)	WT (°C)	DO (ppm)	NA (ppm)	NI (ppm)	ST (‰)	TSS (ppm)	AL (ppm)	Cited literature
	FD	8.16	0.78	28.63	5.48	0.26	0.35	30.30	195.77	136.12	Panigrahi et al. (2017)
	HI, EXP	7.73	0.50	23.32	6.66	2.57	1.05	25	355.51	—	Rajkumar et al. (2016)
	CP	7.40	0.61	29.10	5	193.60	0.44	29.64	392.30	137	Prangnell et al. (2022)
	HF	7.40	1.80	30.70	6.20	0.35	2.30	16.20	147.45	298.40	Ray et al. (2011)
	CFA	8	1.50	27.80	5.90	21.40	9.20	31.60	—	—	Tierney and Ray (2018)
	SF	7.57	0.64	24	7.64	11	0.56	32	122.10	—	Xu et al. (2013)
	CF_8	7.56	0.30	27.42	7.30	3.19	0.08	7.5	—	—	Halim et al. (2025c)
	CF_8	7.31	0.62	27.98	5.51	19.66	0.56	15	—	—	Halim et al. (2025d)
	CF_8	7.26	0.33	27.75	6.08	20.84	0.53	15	—	—	Halim et al. (2025b)
AV.		**7.70**	**0.59**	**28.18**	**5.99**	**48.78**	**2.50**	**24.42**	**378.15**	**133.94**	
SD		**0.34**	**0.49**	**1.90**	**0.81**	**77.85**	**3.29**	**8.89**	**242.43**	**61.56**	

Abbreviations: AL, alkalinity; AM, ammonia; DO, dissolved oxygen; FC, feed composition; NA, nitrate; NI, nitrite; ST, salinity; TSS, total suspended solids; WT, water temperature.

L^{-1}, respectively), highlighting the intense nitrogen turnover typical of BFT systems. Salinity averaged 24.42 ± 8.89‰, while TSS levels were substantially elevated (mean 378.15 ± 242.43 mg L^{-1}), a defining feature of biofloc-based culture. Alkalinity values (133.94 ± 61.56 mg $CaCO_3$ L^{-1}) further emphasize the need for active buffering to sustain microbial activity and system stability.

Aquamimicry systems generally maintain more stable water quality, exhibit lower nutrient concentrations and contain moderate levels of organic matter, primarily supported by natural productivity (Ghosh and Hasanuzzaman 2025; Khanjani, Sharifinia, et al. 2020). In contrast, BFT systems are characterized by higher organic and microbial activity, increased suspended solids and greater variability in nitrogenous compounds (Abakari et al. 2021b; Khanjani et al. 2024). These differences in water-quality profiles highlight the distinct ecological dynamics of each culture method and emphasize the necessity of implementing management strategies tailored to the specific system to ensure optimal shrimp health and growth performance.

Climate resilience in aquamimicry and biofloc systems has been supported by studies reporting tolerance of cultured species to a wide range of environmental conditions. For instance, *L. vannamei* demonstrates optimal growth within a temperature range of approximately 26°C–32°C, while maintaining survival at slightly broader limits (≈22°C–35°C) (Halim et al. 2025c; Halim et al. 2025d). Similarly, this species tolerates salinity fluctuations from 5‰–35‰, with best performance typically observed between 10‰ and 25‰ (Y. Liu et al. 2023; Cho and Yigit 2022).

In biofloc systems, microbial activity contributes to buffering environmental fluctuations, allowing stable production even under moderate temperature and salinity shifts. Several studies report successful culture of shrimp and finfish under low-salinity (< 10‰) and high-density conditions, indicating system-level resilience (K. M. Catalani 2020; Abdel-Tawwab et al. 2022; Halim et al. 2025c).

However, the degree of resilience is species-specific and management-dependent, influenced by factors such as aeration, carbon source, stocking density and microbial community structure. Therefore, while both systems show adaptive capacity to environmental variability, their performance under climate stressors should be interpreted within defined operational ranges rather than generalized.

Water exchange requirements differ substantially between conventional, aquamimicry and biofloc systems. Conventional shrimp culture typically involves daily water exchange rates of 10%–30%, whereas aquamimicry systems operate with minimal exchange (generally < 5% per day), relying on natural ecosystem processes for water quality maintenance (Khanjani et al. 2022). In contrast, BFT systems are designed for near-zero or zero water exchange, with only periodic additions to compensate for evaporation and sludge removal (Khanjani et al. 2024).

In terms of water use efficiency, conventional systems may require 20,000–60,000 m^3 of water per tonne of shrimp produced, while aquamimicry systems can reduce this to approximately 5000–15,000 m^3 $tonne^{-1}$ (K. Catalani et al. 2023). BFT systems demonstrate the greatest efficiency, with water use often reported

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at 1000–5000 m^3 $tonne^{-1}$, depending on system design and management practices (M. Emerenciano et al. 2013). These reductions are primarily achieved through microbial nutrient recycling, reduced effluent discharge and improved internal water quality regulation.

A range of feed types and formulations were used in the experiments. CF_1 denotes a commercial Guabi feed containing 40% crude protein, while CF_2 provides 50% protein and 7% crude fat. RB represents rice bran fermented using a consortium of *Bacillus* and *Lysinibacillus* strains, and BS indicates rice bran fermented with *B. subtilis*. SD refers to spray-dried fermented biomass included at 0, 25, 50 and 100 g/kg as a partial fishmeal replacement. SF consists of soybean meal fermented with *B. subtilis*, blended with local fishmeal (600 g/kg protein) and Chilean fishmeal (650 g/kg protein).

DC_1 is a formulated diet made up of fishmeal (72% protein), soybean meal (38%), corn gluten (63%), wheat bran, yellow corn, soybean oil, starch and a vitamin–mineral premix. CF_3 includes feed with protein ≥ 50%, fat ≥ 15% and fibre ≤ 1%. FNB is a formulated feed with 40% protein and 8% lipid, enriched with *Navicula* spp. and *B. plicatilis*. FG represents Guabi 1.60 mm feed with 40% protein. CF_4 contains 40% protein, while CD_1 has 38% protein and 8% lipids. CF_5 provides 38% protein and 8% lipid. DC_2 represents diets formulated with 24.30%, 30.30%, 32.90% and 36.70% protein.

CFS is a commercial shrimp feed with 40% protein, 5% lipid, 5% fibre, 15% ash and 12% moisture. LD is a larval diet with 45% protein. CF_6 contains 38% protein, 9% lipid, 3% fibre, 14% ash and 10% moisture, while CF_7 includes 36% protein, 8% lipid, 3% fibre, 14% ash and 10% moisture. CFBF denotes commercial feed (42% protein) supplemented with moist bioflocs at 15% of body weight. CD_2 contains 38% protein. BCF represents biofloc applied at 0%, 25%, 50%, 75% and 100% with commercial feed containing 40% protein. FD is a formulated diet with 35% protein.

HI feed (% wet weight) contains 35.80% protein, 8.70% lipid, 1.90% fibre, 9.70% ash and 37.20% carbohydrate. EXP feed contains 39.50% protein, 9.20% lipid, 3% fibre, 12.30% ash and 31% carbohydrate. CP is Charoen Pokph feed with 34.50% protein. HF is a hyper-intensive feed with 33.40% protein, 10.40% fat, 8.60% moisture and 6.60% ash. CFA refers to commercial feed enriched with *Artemia*, SF is shrimp feed with 40% protein, and CF_8 is finely crumbled commercial feed (0.25–1 mm) containing 40% protein.

4 | Assessment of Advantages, Limitations, Expenses, and Applications of Aquamimicry and BFT Systems

Aquamimicry and BFT represent two ecologically driven yet operationally distinct approaches to intensive shrimp culture (Table 8). Aquamimicry is designed to simulate natural estuarine and mangrove food webs by promoting the growth of beneficial plankton, benthic organisms and probiotic microbial communities (Ghosh and Hasanuzzaman 2025). This approach offers several benefits, including high survival rates, reduced physiological stress, improved immune response and lower dependence on formulated feeds due to the availability of natural live food (Deepti et al. 2024). However, aquamimicry generally produces moderate growth rates and comparatively lower TP than highly intensive systems (Sangsayan et al. 2025). Performance may also vary with environmental conditions and the quality of fermented carbon and biological inputs used (Khanjani et al. 2022). In terms of costs, aquamimicry requires relatively low capital investment and modest operational expenses, as it relies on earthen ponds, limited aeration and reduced energy input (Nisar et al. 2022). Consequently, this system is well suited for small to medium-scale farmers, low-input sustainable aquaculture and regions with limited or unreliable electricity supply (Deepak et al. 2020).

In contrast, BFT is an intensive culture system driven by microbial activity, where dissolved nitrogenous compounds are converted into bioflocs through precise regulation of the C:N ratio and constant aeration (Khanjani et al. 2024). Its main advantage is the capacity to support high stocking densities, accelerate biomass growth, and maximize TP, all while reducing water exchange and environmental discharge (Ogello et al. 2021). Bioflocs also serve as a supplemental protein source, improving feed utilization and overall productivity (Khanjani and Sharifinia 2020). Despite these advantages, BFT is operationally complex and highly sensitive to management failures, particularly aeration disruption, excessive floc accumulation and imbalances in water quality (Khanjani et al. 2024). These factors can elevate stress and disease risks if not carefully controlled. BFT entails high capital and operational costs due to the need for lined ponds or tanks, continuous aeration, carbon source inputs and intensive monitoring (Ogello et al. 2021). As a result, this system is best suited for technically skilled operators, commercial-scale farms and settings where land is limited but energy and investment capacity are sufficient (Khanjani et al. 2024).

Overall, aquamimicry emphasizes system stability, animal welfare and cost-effectiveness, making it a lower-risk and environmentally harmonious option for sustainable shrimp farming (Islam et al. 2024). In contrast, BFT prioritizes maximum productivity and nutrient recycling efficiency, offering higher economic returns under optimal management but with greater technical demands and operational risk (M. G. C. Emerenciano et al. 2025). Both approaches show potential under controlled conditions but requires standardized validation across different species, environments and management practices. The choice between these systems should therefore be guided by farmer capacity, infrastructure availability, risk tolerance and production objectives.

5 | Challenges of Aquamimicry and BFT

The advancement of aquaculture technologies has greatly improved productivity and sustainability, yet many farmers continue to face limited access to modern tools, infrastructure and technical expertise necessary for effective management (Mustafa et al. 2021). Inadequate system maintenance further heightens the risk of disease outbreaks and the emergence of new pathogens (Subasinghe et al. 2023). Moreover, many sustainable culture systems require large treatment ponds and are difficult to implement in indoor environments. To mitigate these challenges, rigorous monitoring, proper treatment of used water, responsible effluent

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TABLE 8 | Comparison of aquamimicry and biofloc technology (BFT) in terms of benefits, limitations, costs and practical applications.

Aspect	Aquamimicry	Biofloc technology (BFT)
Core concept	Aquamimicry creates an aquatic system regulated by synbiotics (beneficial bacteria and prebiotics) (Khanjani et al. 2023).	Manipulates microbial communities through C:N ratio management to convert waste nutrients into bioflocs (Markou et al. 2024).
Main benefits	It ensures high survival through reduced stress and natural feeding behaviour, enhances shrimp health and immunity and lowers dependence on artificial feeds (Ghosh and Hasanuzzaman 2025).	Higher total production and biomass yield through efficient nutrient recycling, waste utilization and minimal water exchange, resulting in reduced environmental discharge (Nisar et al. 2022).
Growth performance	Moderate growth with stable size distribution (Cho and Yigit 2022).	Rapid growth and higher stocking density potential (Said et al. 2024).
Feed utilization	Natural live feed supplements reduce feed input and FCR (Khanjani et al. 2023).	Bioflocs act as supplemental protein source, improving feed efficiency (Panigrahi et al. 2019).
Water quality management	Relies on balanced ecological processes and moderate water exchange (Cho and Yigit 2022).	Requires strict control of aeration, C:N ratio and solids (Minaz and Kubilay 2021).
Disease resistance	Enhanced due to natural microbial diversity and probiotic dominance (Zeng, Khoruamkid, et al. 2020).	Improved immunity but risk of stress-related outbreaks if floc load is poorly managed (Said and Ahmed 2022).
Drawbacks	It delivers lower yields than BFT and relies on natural carbon inputs, with performance sensitive to environmental conditions (Deepti et al. 2024).	The system has high operational complexity, is highly sensitive to power failures and aeration breakdowns and carries a risk of water quality deterioration under poor management (Raza et al. 2024).
Capital cost	Low to moderate (earthen ponds, minimal infrastructure) (K. Catalani et al. 2023).	High (intensive aeration, liners, monitoring equipment) (Abakari et al. 2021b).
Operational cost	Relatively low due to reduced energy and feed use (Khanjani et al. 2022).	High due to continuous aeration, carbon source addition and monitoring (Abakari et al. 2021b).
Energy requirement	Low to moderate (Sangsayan et al. 2025).	Very high (24/7 aeration essential) (M. M. Lal et al. 2023).
Environmental impact	Environment-friendly, mimics natural ecosystems with moderate nutrient discharge (Deepti et al. 2024).	Highly eco-efficient with minimal discharge but energy intensive (Khanjani et al. 2024).
Skill requirement	Moderate technical knowledge sufficient (Ghosh and Hasanuzzaman 2025).	High technical expertise required for system stability (McCusker et al. 2023).
Risk level	Lower production risk; more resilient system (Khanjani et al. 2023).	Higher risk due to system sensitivity and dependence on management (Mugwanya et al. 2021).
Suitable applications	It is suitable for small- to medium-scale farmers, low-input sustainable shrimp farming and areas with limited electricity (Islam et al. 2024).	This approach is suited for intensive commercial shrimp farming, utilizing high-density cultures in biosecure indoor or lined pond systems, especially where land availability is limited (El-Sayed 2021).
Economic suitability	Best for risk-averse farmers seeking stable returns (Deepti et al. 2024).	Best for investors targeting maximum yield and profitability (Khanjani et al. 2024).

management and thorough soil preparation after each crop cycle are essential to maintain optimal pond conditions.

Among innovative approaches, the aquamimicry system has emerged as a promising method for sustainable shrimp farming. However, it still faces practical limitations such as its limited adaptability to indoor facilities, risk of new disease emergence and the requirement for extensive sediment management. Despite these challenges, aquamimicry aligns closely with the goals of sustainable aquaculture by enhancing production efficiency without substantial increases in water or land use. It is environmentally friendly, cost-effective and supports both economic and social sustainability (Santhanam et al. 2020).

The incorporation of fermented bran enriched with probiotics in aquamimicry systems has demonstrated notable success in shrimp culture by improving water quality and growth performance (Deepti et al. 2024). Shrimp produced under these systems

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are naturally fed, exhibiting higher immunocompetence and disease resistance (Ghosh and Hasanuzzaman 2025). Furthermore, the absence of harmful chemicals and antibiotics allows the production of organic, environmentally responsible seafood (Sheng and Wang 2021) However, the use of fermented carbon sources requires caution, as organic acids such as acetic and lactic acids can alter pH and inhibit beneficial microorganisms, including *Bacillus* species and zooplankton (Ng and Koh 2017). Elevated nutrient concentrations from these additives may also promote the growth of undesirable microbes or algae, emphasizing the need for careful nutrient management and sediment control (Hwang et al. 2024).

BFT contributes to sustainable aquaculture by facilitating microbial floc formation, which enhances both water quality and feed utilization. Successful operation, however, requires careful management of water parameters. Recommended TSS levels are 500–1000 ppm (Gaona et al. 2011), total ammonia nitrogen (TAN) should be kept below 0.50 ppm (Krummenauer et al. 2020) and DO must remain above 5 ppm (Lara et al. 2017). The optimal floc volume (FV) ranges between 5 and 10 mL/L and can be measured using Imhoff cones (Deng et al. 2018). Maintaining a C:N ratio of 20:1 has been shown to improve nitrification efficiency (Luo et al. 2020). Adequate aeration, for example 33.75 L/min in *L. vannamei* culture, supports the proliferation of nitrifying bacteria, while insufficient aeration can lead to microbial imbalance (Mugwanya et al. 2021; de Morais et al. 2020).

Despite its benefits, BFT presents certain challenges, including high energy requirements and susceptibility to power interruptions, which can lead to substantial production losses (Prates et al. 2023; Sun et al. 2023). The elevated electricity costs particularly restrict its adoption among small-scale farmers (Zhao et al. 2023). In addition, off-flavours such as geosmin and 2-methylisoborneol, produced by Actinomycetes and filamentous cyanobacteria, may reduce the market value of cultured fish and shrimp (Mugwanya et al. 2021).

Both aquamimicry and biofloc systems share the overarching goal of enhancing water quality, improving productivity and ensuring environmental sustainability (Nisar et al. 2022). While aquamimicry emphasizes ecological mimicry and natural feeding dynamics, biofloc focuses on microbial recycling and nutrient utilization (Khanjani et al. 2023). Integrating both systems could generate synergistic benefits strengthening resilience against environmental fluctuations, disease risks and market uncertainties (Khanjani et al. 2023). However, such integration requires careful system design, controlled experimentation and adaptive management. Collaborative efforts among researchers, practitioners and industry stakeholders will be essential to refine these hybrid approaches and advance their sustainable application in modern aquaculture.

6 | Future Prospects and Recommendations for Aquamimicry and BFT

Aquamimicry and BFT offer promising strategies for sustainable aquaculture, but both approaches encounter challenges such as high initial capital investment, considerable energy requirements and the need for skilled management (Laktuka et al. 2023; Gupta et al. 2024). Advances in technology are helping to address these limitations, making the implementation of these systems more practical and efficient (Gupta et al. 2024; Laktuka et al. 2023). Ensuring technical feasibility is crucial to attain economic sustainability (Khanjani et al. 2024). Given the high upfront costs, financial support from banks, donor agencies and NGOs is essential to encourage adoption among farmers (Khanjani et al. 2024). Future efforts in aquamimicry and BFT development should focus on optimizing both systems to enhance sustainable and efficient shrimp production (Nisar et al. 2022). Integrative strategies that combine the natural feed enhancement of aquamimicry with the nutrient recycling benefits of BFT may improve survival rates, growth performance and feed utilization efficiency (Deepak et al. 2020; Nisar et al. 2022).

Research is needed to fine-tune species-specific parameters such as salinity, temperature and C:N ratio, along with real-time water quality monitoring to prevent sudden deterioration, especially in BFT systems (Matishov et al. 2025). Innovations in low-cost carbon sources for BFT and fermented natural inputs for aquamimicry can enhance microbial activity and natural feed production (Nisar et al. 2022). Efforts should target small to medium-scale farmers through user-friendly system designs and practical training programs to improve management skills while minimizing environmental impact (W. Liu et al. 2025). Emphasis on reduced water exchange, effective waste utilization and integration with multi-trophic aquaculture can further support sustainability (Al-Saeedi and Massad 2025). Finally, economic viability studies and policy support, including technical guidelines and pilot projects, are essential to promote adoption and ensure long-term profitability under local conditions.

With the rapid development of artificial intelligence (AI), aquaculture is becoming increasingly technology-driven (Wu et al. 2022). AI-based systems can enhance production efficiency by enabling smart feeding practices and real-time monitoring of water quality and animal health (Alghamdi and Haraz 2025). The integration of Fourth Industrial Revolution technologies such as the Internet of Things (IoT), AI, big data analytics, cloud computing, 5G networks, automatic identification systems, high-resolution satellite imagery, machine learning, in situ sensor networks and robotics provides considerable opportunities to optimize productivity, processing and marketing in aquaculture (Zreikat et al. 2025).

These technologies help reduce reliance on manual labour, minimize risks and enable automation along with intelligent farm management. The integration of ICT and IoT with aquamimicry and BFT facilitates continuous monitoring of essential farming parameters through sensors, ensuring optimal growth and health of cultured species (Naz et al. 2025). Smart aquaculture, combining these advanced technologies with aquamimicry and BFT, can be divided into three key areas: (1) Real-time monitoring of physical and chemical environmental conditions, (2) proactive management of potential crises using prediction models, early warning systems and risk mitigation strategies and (3) health and disease surveillance by tracking behavioural and physiological indicators of cultured organisms in real time (Hu et al. 2020). Combining BFT with aquamimicry continues to be a critical strategy for improving sustainability and production efficiency.

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7 | Conclusion

Aquamimicry and BFT are two innovative and sustainable approaches for culturing whiteleg shrimp (*L. vannamei*). Aquamimicry enhances natural feed production through plankton-based food webs, supporting higher survival rates and more natural growth conditions, whereas BFT focuses on nutrient recycling via microbial floc formation, enabling high stocking densities, rapid biomass accumulation and efficient feed utilization. Both systems reduce environmental impacts by minimizing water exchange and improving waste management, though they face challenges such as energy requirements, technical complexity and initial investment costs. The choice between aquamimicry and BFT depends on production goals, available resources and managerial expertise. Future research should prioritize hybrid production models that combine the strengths of both systems, long-term economic and environmental assessments, co-culture strategies, integration of ICT/IoT and AI for smart aquaculture, pathogen control protocols, regulatory frameworks for commercial adoption and climate-resilient practices. Collectively, these advancements provide promising pathways toward sustainable, resilient and profitable *L. vannamei* aquaculture, supporting a more efficient and environmentally responsible shrimp farming sector. Performance advantages between aquamimicry and BFT appear to be context-dependent and influenced by key management variables.

Author Contributions

Md. Abdul Halim: resources, writing – original draft, formal analysis, data curation, conceptualization, software, formal analysis, writing – review and editing. **Dania Aziz**: methodology, project administration, supervision, validation, investigation. **Aziz Arshad**: conceptualization. **Nur Leena W. S. Wong**: visualization. **M. M. Nabi**: visualization, conceptualization. **Muhammad Hamidur Rahman**: data curation. **Md. Ariful Islam**: conceptualization. **Md. Saiful Islam**: conceptualization. **Debashis Kumar Mondal**: resources. **Md. Fakhrul Islam**: visualization. **Md. Eilious Hosain**: conceptualization.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the findings of this review study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary TableS1: aff270244-sup-0001-tableS1.docx **Supplementary TableS2**: aff270244-sup-0002-tableS2.docx **Supplementary TableS3**: aff270244-sup-0003-tableS3.docx

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