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A REVIEW OF TECHNOLOGICAL DEVELOPMENTS IN SHRIMP AQUACULTURE PRODUCTION

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ABSTRACT

This review examines breakthrough technological developments in shrimp aquaculture, emphasizing key advances, remaining barriers, and policy implications for sustainable sector growth. Major technological innovations include biotechnology-driven improvements such as genetic selection, MAS and emerging CRISPR applications for disease-resistant stocks. AI-based monitoring and automation systems that optimize feeding and environmental control in real time; microbial approaches including probiotics and biofloc technology that enhance water quality and pond stability. Novel feeds incorporating insect, microbial and other alternative proteins to reduce dependence on fishmeal. These advances collectively improve productivity, animal health and environmental performance. However, adoption is hindered by high capital costs, technical complexity and limited farmer training. More so, uneven access to digital and genomic tools, particularly among small-scale producers. Addressing these barriers requires supportive policies that promote inclusive technology transfer, investment incentives, capacity building and regulatory frameworks for safe use of biotechnologies and data-driven systems. Overall, the review highlights how integrated biotechnological and AI-enabled innovations can transform shrimp aquaculture, provided that enabling policies ensure equitable, responsible and sustainable implementation.

KEYWORDS: Advanced technology; bioflocs; environmental sustainability; production systems; shrimp aquaculture

INTRODUCTION

Shrimp farming, which began more than a century ago in Southeast Asia, initially relied on simple pond-based practices (Quach, 2018). By the early 2000s, over 85% of global farmed shrimp originated from Asia, led by Thailand, China, Indonesia and India (FAO, 2020), and production has continued to expand toward a projected 5 million metric tonnes. The industry today operates through extensive, semi-intensive and intensive systems, each exerting different environmental pressures. Extensive systems, dependent on natural productivity, can degrade surrounding ecosystems (Schuur *et al*., 2020), while semi-intensive systems introduce moderate inputs that may contribute to pollution, habitat loss and fishmeal demand despite the use of biofilters and treatment units (Xiao *et al*., 2019; Tom *et al*., 2021). Intensive systems now account for roughly 55% of global output, supported by lined ponds, tanks and greenhouse-based operations that maintain high stocking densities (FAO, 2024).

Technological advances have significantly reduced reliance on wild seed resources. Modern hatcheries equipped with RAS, biofloc systems and genetic selection techniques now produce billions of robust post-larvae under controlled conditions (Hai *et al*., 2015; Ahmed & Turchini, 2021). Between 2017 and 2019, global market expansion reached 7.5%, dominated by *P. vannamei* and *P. monodon*, which represented 80% and 15% of production, respectively (FAO, 2020; Dao, 2019). Innovations in feed formulation including insect- and microbial-based proteins have also reduced dependence on fishmeal (Roccatello *et al*., 2024).

Despite this progress, the sector faces persistent challenges: disease outbreaks, resource inefficiency, rising production costs, and increasing pressure to meet sustainability standards. Emerging tools

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such as artificial intelligence, machine learning, precision feeding systems, and automated water-quality monitoring are increasingly essential for improving efficiency and reducing waste (Mustapha *et al.*, 2021; Lim, 2024). These pressures and technological shifts create a clear need for an updated review that synthesizes recent advances, identifies the remaining barriers to adoption, and assesses how innovation can support a more resilient and sustainable shrimp aquaculture industry.

METHODOLOGY

This review adopted a rigorous systematic methodology to comprehensively analyze technological advancements in shrimp aquaculture, ensuring transparency, reproducibility and academic rigor. The process followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to structure the literature search, selection and synthesis. To identify relevant studies, searches were conducted across multiple academic databases, including Scopus, Web of Science, PubMed and Google Scholar, ensuring broad coverage of interdisciplinary research. The search strategy employed a combination of keywords such as "shrimp aquaculture," "biofloc technology," "AI in aquaculture," "CRISPR shrimp breeding," and "sustainable shrimp farming," along with Boolean operators (AND, OR) to refine results. The initial search yielded 1,015 articles, which were then deduplicated, leaving 730 unique records for further screening.

Inclusion and exclusion criteria were strictly applied to maintain relevance and quality. Studies were included if they (1) focused on technological innovations in shrimp aquaculture, (2) were published between 2015–2024 to prioritize recent advancements, (3) provided empirical data or verifiable case studies, and (4) were peer-reviewed journal articles, conference proceedings or authoritative reports (e.g., FAO publications). Excluded studies were those that addressed non-penaeid shrimp species, lacked technical depth, or were opinion-based without supporting data.

To minimize bias, two independent reviewers conducted the screening and full-text assessment. Discrepancies were resolved through consensus. This double-screening procedure ensured consistency and

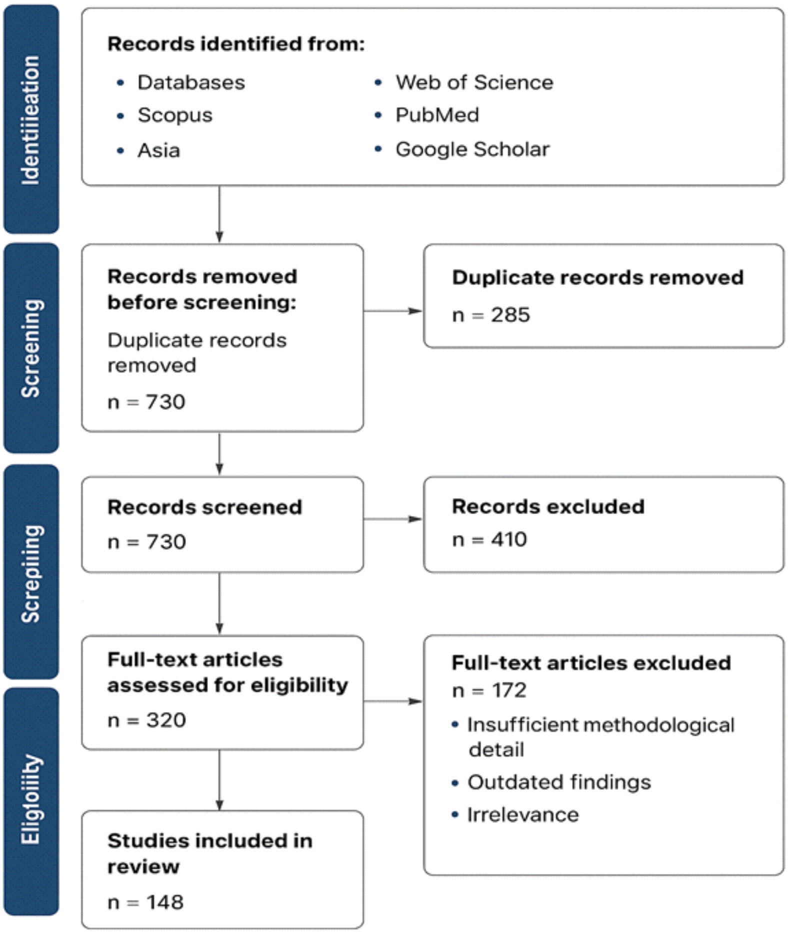

Figure 1. PRISMA flow diagram has been generated to visually summarize the identification, screening, eligibility and inclusion steps.

reduced selection bias. After title and abstract screening, 410 irrelevant studies were removed, and 320 full-text articles were assessed for eligibility. A further 172 studies were excluded due to insufficient methodological detail, outdated findings or irrelevance, resulting in a final selection of 148 high-quality studies for in-depth review.

A PRISMA flow diagram has been generated to visually summarize the identification, screening, eligibility and inclusion steps (Figure 1). Regarding geographic coverage, the review included studies from all shrimp-producing regions globally, including Asia, Latin America, the Middle East and Africa. Only English-language publications were included due to database limitations and to maintain consistency in methodological appraisal; non-English papers were therefore excluded.

ADVANCED TECHNOLOGY IN SHRIMP AQUACULTURE

Technological advances drive shrimp aquaculture growth (Figure 2). For instance, shrimp hatchery produced seed has contributed to the improvement of Shrimp aquaculture production worldwide (Figure 3). Despite a significant drop in marine farmed shrimp in 2020 (i.e., 15% lower than in 2019) due to the covid 19 pandemic, the global shrimp industry experienced a growth increase of 8.9% between 2020 to 2021,

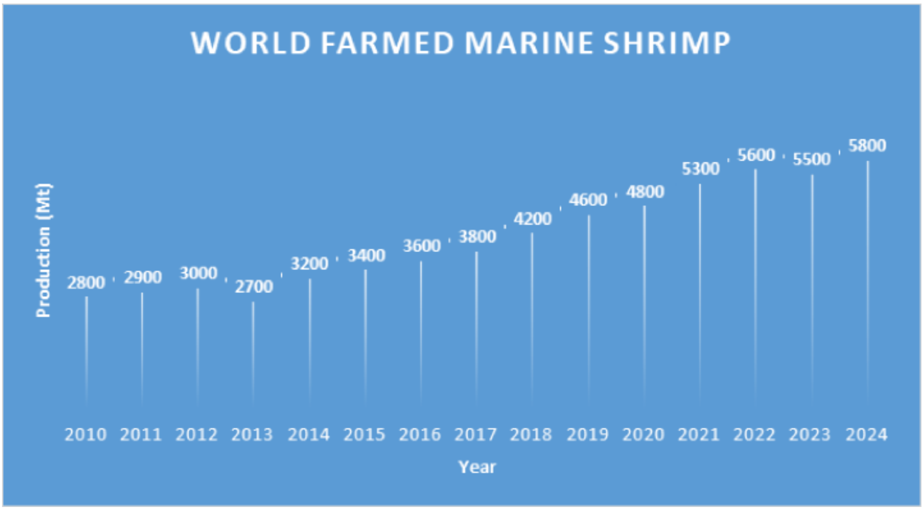

Figure 2. Global range of shrimp aquaculture production from 2010 to 2024. Data Source: Adapted from Jory, 2023 (Mt, million metric ton).

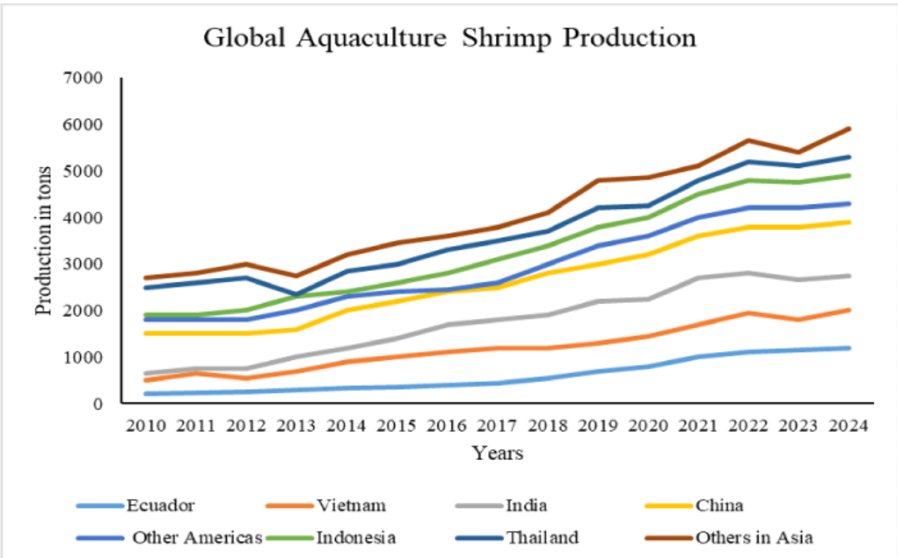

Figure 3. Shrimp aquaculture production by world region 2010-2022 with projections into 2023 and 2024. Data Source FAO (2022).

Note* Other Americas include: Mexico, Honduras, Peru, Venezuela, Brazil, Guatemala, Nicaragua, Colombia, Costa Rica, Cuba, Panama,

Note* Other Asia includeBangladesh, Myanmar, Brunei, Japan, South Korea, Taiwan, Philippines, Malaysia, Saudi Arabia and Iran.

with an additional 5% predicted for 2022 (FAO, 2022). The increase observed is due to the proliferation of modern infrastructures for intensive production that has placed farmed production higher above wild catch. Due to advancement in technology, the production of farmed shrimp is projected at 5.88 million metric tons, which constitutes the most valuable traded seafood commodity globally (Jory, 2023).

In addition, advanced technology systems of production are designed to increase profitability grounded on the advances in production techniques such as feed quality, skillful farm management, diseases management, etc. (Engle *et al*., 2017). Moreover, it enhances better environmental outcomes as farms strive to become more intensive and competitive while ensuring safe operating costs and environmental impacts.

Some of the technological advancements that have revolutionized shrimp aquaculture industries are discussed below:

Biotechnology

Shrimp aquaculture continues to experience recurrent disease outbreaks, which drive high antibiotic use and substantial economic losses. Bhassu *et al*. (2024) reported that disease pressure remains one of the main constraints on production, with outbreaks frequently disrupting farm operations. Among these diseases, white spot syndrome virus (WSSV) is identified as one of the most destructive. Duc *et al*. (2015) documented severe mortality events in black tiger shrimp linked to WSSV, while Schuur *et al.* (2020) highlighted its rapid transmission and major production losses in Peninsular Malaysia. Searchinger *et al*. (2019) estimated cumulative global losses from WSSV at approximately US$45 billion, underscoring its critical impact on the sector. Other pathogens including AHPND, EMS, TSV, and various *Vibrio* spp. were consistently identified across studies as major contributors to production decline (Table 1). Early management approaches reported in the literature largely focused on the use of specific-pathogen-free broodstock and strict biosecurity measures, yet these strategies were shown to be insufficient as new pathogens emerged (Duc *et al*., 2015). In response, several studies documented a shift toward biotechnological innovations. Flegel *et al*. (2008) demonstrated that genetic engineering applications can produce shrimp lines with improved tolerance to viral diseases. Similarly, studies by Yue (2014) and Zenger *et al*. (2019) reported that Marker-Assisted Selection (MAS) and genomic selection significantly improved breeding efficiency for disease resistance and growth performance.

Table 1. Common Shrimp Diseases identified in the literature

Disease	Causative Agent	Symptoms	Authors
Acute hepatopancreatic necrosis disease (AHPND)	*Vibrio parahaemolyticus*	Lethargy, anorexia, slow growth	(Boyd *et al*., 2018)
Enterocytozoon (EHP)	Microsporidian parasite	Hepatopancreatic microsporidiosis	
White Spot Syndrome Virus (WSSV)	White Spot Syndrome Virus (WSSV)	Lethargy, aggregation at pond edges, white spots on shell	(Duc *et al*., 2015)
Early Mortality Syndrome (EMS)	Multiple pathogens, mainly *Vibrio spp*.	High mortality in post-larvae, poor growth	(Prachumwat *et al*., 2019)
Taura Syndrome Virus (TSV)	Taura Syndrome Virus (TSV)	Lethargy, reduced feeding, high mortality	(Fadilah & Fasya, 2021)
Infectious Hypodermal and Hematopoietic Necrosis Virus (IHHNV)	Infectious Hypodermal and Hematopoietic Necrosis Virus (IHHNV)	Abnormal swimming, white or pale body coloration	(Dewangan *et al*., 2017)
Vibrio parahaemolyticus Infection	*Vibrio parahaemolyticus*	Softshell, dark discoloration, high mortality	(Navaneeth *et al*., 2020)
Vibrio anguillarum Infection	*Vibrio anguillarum*	Red discoloration, tissue necrosis	(Qiao *et* al., 2015)
Hematopoietic Necrosis Virus (HNV)	Hematopoietic Necrosis Virus (HNV)	Darkening of the body, reduced feeding	(Tang & Lightner, 2021)

Advances in hatchery biotechnology were also supported by empirical findings. Alfaro-Montoya *et al*. (2019) showed that molecular diagnostic tools increased the accuracy of early pathogen detection in broodstock, reducing the probability of disease transmission. Qian *et al*. (2018) further demonstrated that genetic techniques improved hatchery management by enabling screening for subclinical infections. Biotechnology-driven feed innovations were also evidence-based. Gonzalez (2025) reported that alternative protein formulations reduced reliance on fishmeal without compromising shrimp growth. Arnold *et al*. (2016) and Fry *et al*. (2018) found that bioengineered feed ingredients enhanced feed conversion efficiency in controlled trials. Biofloc technology (BFT), described by Emerenciano *et al.* (2017) and Abakari *et al*. (2022), was shown to mitigate nutrient waste by promoting microbial recycling, thereby improving water quality and reducing discharge. Emerging tools such as CRISPR remain mostly theoretical for shrimp, but Ferdous *et al*. (2022) provided early evidence from related aquaculture species showing potential for enhancing disease resistance. Giap *et al.* (2010) emphasized that coordinated research efforts and supportive policy frameworks are needed to scale such biotechnological applications. Finally, Shang *et al.* (1998) demonstrated that biotechnology adoption improves production efficiency and lowers disease-management costs, contributing to higher overall profitability.

Artificial intelligence

Artificial Intelligence (AI) has become an important tool in shrimp farming, mainly through its combination with IoT sensors and machine-learning models. Reviewed studies consistently report two major applications: disease prediction and feeding optimization. For disease prediction, studies show that AI can identify abnormal water conditions and shrimp behavior before clinical signs appear. Quach *et al*. (2020) demonstrated that algorithms analyzing pH, ammonia, dissolved oxygen, and behavioral patterns detected disease risks 7–10 days earlier than manual farm monitoring. Mustapha *et al*. (2021) reported a practical application of this approach through the AquaCloud system in Vietnam, which achieved a 60% reduction in Early Mortality Syndrome (EMS) across 42 commercial farms in the Mekong Delta. These findings highlight that early-warning detection is not only theoretical but functioning at scale under farm conditions. In feeding management, Biswas *et al*. (2023) documented that Ecuadorian farms using AI-based automated feeders achieved a 25% reduction in feed waste, attributed to real-time monitoring of consumption and algorithm-guided feeding intervals. Their study also noted improvements in consistency of feeding events compared to manual feeding. IoT applications covered in the reviewed literature emphasize real-time tracking of variables linked to production efficiency. Yoo *et al*. (2020) found that IoT-enabled monitoring improved decisions on feed conversion, harvest timing, and energy use, and that integrating robotics could further enhance these outcomes as datasets expand. Lal *et al*. (2024) showed that farms in Singapore, Japan, and the USA applying robotic systems for feeding and harvesting experienced reductions in labor demand and greater operational precision. Despite these benefits, most studies also highlighted persistent barriers to adoption. Taneja *et al*. (2023) documented high initial investment costs typically US$50,000–100,000 for medium-scale farms as a major constraint in low- and middle-income countries. Mohale *et al.* (2024) and Rastegari *et al*. (2023) reported that limited digital infrastructure and insufficient technical training frequently prevent effective use of AI and IoT systems. These challenges create uneven uptake, especially among smallholder farmers. Table 2 summarizes the AI and IoT technologies reported across the reviewed studies.

Table 2. Various AI and IoT technologies currently used in shrimp aquaculture, including their applications and potential benefits

Technology	Application	Potential Benefits	Authors
AI-Based Feed Management	Optimizing feed conversion rates	Improved feed efficiency and reduced waste	Biswas *et al*. (2023)
IoT Water Quality Monitoring	Real-time monitoring of water parameters	Early detection of issues and improved water management	Tsai *et al*. (2022)
Machine Learning for Disease Prediction	Predicting disease outbreaks in shrimp farms	Reduced mortality rates and timely interventions	Quach *et al*. (2020)
Automated Feeding Systems	Automated delivery of feed	Reduced labor costs and improved feed distribution	Reis *et al*. (2021)
Robotics for Harvesting	Automated harvesting processes	Increased efficiency and reduced operational costs	de Ávila *et al*. (2021)
Data Analytics Platforms	Analyzing large datasets for insights	Improved management strategies and operational efficiencies	Kajornkasirat *et al*. (2021)

Genetic applications

Genetic applications in shrimp farming have increasingly been shaped by empirical research demonstrating improvements in growth, disease resistance, reproductive performance, and environmental tolerance. Zhang *et al.* (2019) reported that selective breeding programs have successfully produced lines with enhanced growth rates and resilience to production stressors, supporting the shift toward more intensive and genetically optimized farming systems. Evidence from commercial breeding trials also shows that genetically improved lines perform more efficiently under controlled, high-density systems designed for mechanization and automation. A substantial body of research has examined reproductive manipulation techniques. Historically, eyestalk ablation was widely used to stimulate ovarian maturation. Experimental studies by Uawisetwathana *et al*. (2011) and Alfaro-Montoya *et al*. (2019) demonstrated that ablation induces physiological stress responses, disrupts normal behavior, and adversely affects welfare. These findings contributed to regulatory changes such as the European Commission's prohibition of ablation in organic shrimp production (Lembo *et al*., 2014). Comparative trials have further shown that non-ablated broodstock exhibit longer reproductive lifespans and require lower breeder replacement ratios (Zacarias *et al*., 2019), providing evidence-based support for the transition to non-ablated lines. Research has also documented the effects of genetic selection on product quality. Flegel (2019) and Emerenciano *et al*. (2022) reported that selective breeding contributes to observable variations in shrimp coloration and meat quality across different commercial lines. Industry statistics presented in these studies indicate that the number of domesticated broodstock used in breeding programs increased from approximately 100,000 in 2003 to 800,000 in 2015, reflecting the measurable expansion of genetically improved stocks.

Probiotics

Probiotics are beneficial microorganisms that enhance shrimp immune response and improve water quality by stabilizing microbial communities, as demonstrated in multiple empirical studies. Lu *et al*. (2019) showed that probiotic application significantly increased immune-related enzyme activity in shrimp, while also improving pond microbial balance. Environmental degradation in shrimp systems is strongly linked to pathogen dominance and toxin accumulation, and Ma *et al*. (2019) reported that routine antibiotic use in such systems not only accumulates residues but also promotes antibiotic-resistant bacterial strains. These findings highlight the need for alternative strategies supported by evidence rather than general practice. Several studies document measurable improvements in water quality and disease reduction when probiotics are applied. For instance, in biofloc technology (BFT) systems, Emerenciano *et al.* (2017) reported that *Bacillus* supplementation reduced toxic ammonia concentrations by 40–60% in Brazilian shrimp farms. Similarly, Kumar *et al*. (2016) recorded a 35% decline in *Vibrio* infections in Indian farms when shrimp were fed probiotic-enriched diets, confirming the disease-mitigating potential of these microorganisms. However, Butt *et al*. (2021) found that probiotic performance varied widely across strains and farming conditions, indicating that strain-specificity remains a major limitation for broad-scale application. Mechanistically, the reviewed evidence indicates that probiotics support shrimp health through several pathways. Knipe *et al*. (2021) demonstrated competitive exclusion of pathogens in controlled trials, while Jamal *et al*. (2019) showed increased production of immune-related molecules in shrimp exposed to selected probiotic strains. Studies by Butt *et al.* (2021) and Muthu *et al.* (2024) further confirmed that probiotics enhance nutrient absorption by breaking down complex feed components. Kakade *et al.* (2023) provided additional evidence that certain strains effectively detoxify ammonia and heavy metals in aquaculture systems. Delivery methods vary, with studies reporting positive results from both feed-based and water-based applications (Butt *et al*., 2021; Muthu *et al*., 2024). Recent work by Fenster *et al*. (2019) and Westfall *et al*. (2021) highlights the potential of automated dosing and precision strain formulations to improve consistency in commercial shrimp production.

Comparative Analysis of Technological Advancements in Shrimp Aquaculture

The reviewed studies reveal clear quantitative patterns in how key technologies influence shrimp survival and feed efficiency across regions (Table 3). Across all technologies, survival improvements range from 15% to 50%, while FCR reductions range from 0.3 to 0.4 units, indicating a consistent positive directional effect despite regional and infrastructural differences. When averaged across the reported studies, biofloc systems demonstrate a mean survival gain of ~32%, RAS systems ~40%, and AI-assisted monitoring ~20%, suggesting relatively higher effect sizes for RAS where capital investment is feasible. Biofloc technology (BFT) in Southeast Asia shows survival improvements of 25–40%, which corresponds to a relative increase of ~1.3× compared to traditional systems (Emerenciano *et al*., 2017). Feed conversion ratios improve from 1.2 to 0.9, a 25% reduction, representing one of the strongest FCR effect sizes among the technologies reviewed (Avnimelech, 2015). However, studies consistently note high-energy consumption as a limiting factor (Khanjani *et al.*, 2020). Recirculating Aquaculture Systems (RAS) in North America show the highest reported survival gains, 30–50%, translating to a relative improvement of ~1.4–1.5× (Xiao *et al.*, 2019). FCR improvements from 1.1 to 0.8 represent a 27% enhancement, similar in magnitude to BFT effects (Ahmed & Turchini, 2021). Capital requirements are the most frequently cited constraint (Boyd *et al.*, 2018), contributing to slower adoption outside high-income regions. Latin American farms implementing AI-based monitoring systems report survival gains of 15–25%, corresponding to a relative improvement of ~1.2× (Mustapha *et al.*, 2021). FCR improves from 1.3 to 1.0—a 23% reduction (Biswas *et al.*, 2023). Although the effect sizes are slightly lower than BFT and RAS, these systems offer comparatively lower operational disruption. Their main limitation is the need for skilled personnel and consistent sensor maintenance (Taneja *et al.*, 2023). Generally, the cross-regional synthesis indicates that while RAS exhibits the strongest biological performance effect sizes, adoption is limited by high capital costs. Biofloc offers moderately high effect sizes with lower capital barriers but higher energy requirements, making it more suitable for regions with reliable electricity. AI-assisted monitoring yields moderate improvements and is most scalable for medium-resource farms. These quantitative patterns reinforce the importance of matching technological complexity with regional infrastructure and economic capacity (Engle *et al.*, 2017; Giap *et al.*, 2010).

Table 3. Effectiveness of Key Technologies Across Regions

Technology	Region	Survival Rate Increase (%)	FCR Improvement	Key Limitations
Biofloc	Southeast Asia	25–40%	1.2 → 0.9	High energy costs
RAS	North America	30–50%	1.1 → 0.8	Initial capital
AI Monitoring	Latin America	15–25%	1.3 → 1.0	Technical training

APPLICATION OF ADVANCED TECHNOLOGY IN SHRIMP AQUACULTURE

Lined ponds

Shrimp farming is widely practiced in coastal zones where brackish water is available, but the physical and chemical properties of local soils often constrain pond performance. Organic soils tend to acidify over time, lowering pH and stressing shrimp, while sandy soils have poor water-retention capacity and destabilize pond embankments (Schuur *et al.*, 2020). In many low-slope coastal areas, these conditions make drainage and pond drying difficult, favoring anaerobic zones and increasing the risk of disease outbreaks such as Early Mortality Syndrome (EMS) (Engle *et al.*, 2017; Nguyen *et al.*, 2019). To mitigate these constraints, lined ponds have been adopted as a practical technological improvement to stabilize pond conditions. Plastic pond liners represent a significant advancement because they limit water seepage, reduce soil–water interactions, and help maintain consistent water quality. Commonly used materials include high-density polyethylene (HDPE), which offers high tensile strength for large ponds, and ethylene propylene diene monomer (EPDM), a flexible synthetic rubber suited to smaller systems (Figure 4). Geomembrane liners such as HDPE and PVC also provide strong UV resistance and long-term durability (Nguyen *et al.*, 2019). Evidence from recent studies shows that well-managed geomembrane-lined ponds can achieve up

Figure 4. Nirex lined ponds in southern region Cameroon.

to a 20% increase in survival rates, largely due to improved water stability and reduced exposure to sediment-associated pathogens (Hai *et al*., 2015). Lined systems also facilitate more effective removal of organic residues, thereby lowering the prevalence of bacterial infections, including Vibrio spp. (Nguyen *et al*., 2019).

The main advantages and limitations of lined ponds, particularly in relation to water management, production performance, and operational constraints, are summarised in Table 4.

Table 4. Merits and demerits associated with lined shrimp ponds

Merits	Demerits	Authors
Soil and Water Stability		
Prevents contact between pond water and acidic soils, reducing low pH stress during rainy seasons.	High purchase and installation costs.	Schuur *et al*. (2020)
Limits soil–water interactions, reducing acidity and preventing salinization from surrounding areas.	Requires high manual labour for thorough cleaning.	Nguyen *et al.* (2019)
Controls seepage of water in high-water-table areas.	Aeration failure (mechanical/electrical) may cause high mortality.	Schuur *et al*. (2020); Engle *et al*. (2017)
Improves water stability and reduces sediment-associated pathogens, increasing survival.	—	Hai *et al*. (2015); Nguyen *et al*. (2019)
Operational Efficiency		
Facilitates easy drainage of wastewater and removal of solids through central drains.	Requires skilled technical assistance for installation and management.	Hai *et al.* (2015); Engle *et al*. (2017)
Harvesting is easier, faster, and effective even during rainy seasons.	—	Schuur *et al.* (2020)
Prevents erosion of pond dikes.	—	Schuur *et al.* (2020)
Production Performance		
Supports high stocking density, increasing annual pond productivity and yield.	—	Nguyen *et al*. (2019)

Greenhouse technology

Greenhouse technology refers to shrimp production carried out inside enclosed structures made of plastic, metal, or glass. These enclosures typically cover lined ponds or culture tanks and are increasingly used in industrial shrimp operations in coastal regions (Nguyen *et al*., 2019). The controlled environment allows farmers to maintain temperature within the optimal range for shrimp growth throughout the year (Ma *et al*., 2013). This stability reduces seasonal fluctuations that commonly limit productivity in outdoor systems. Greenhouses also provide improved biosecurity by limiting exposure to external pathogens and vectors, which helps lower disease incidence one of the major constraints in shrimp aquaculture (Hine *et al*., 2010; de Almeida *et al*., 2021). The enclosed setup facilitates more consistent monitoring of water quality and supports efficient waste removal, contributing to stable culture conditions (Orozco-Lugo *et al*., 2022). However, greenhouse systems require substantial initial investment for construction and depend on a reliable energy supply to maintain internal conditions (Samocha, 2010). These cost and infrastructure demands remain barriers to adoption, particularly in regions with limited access to energy or financing. Despite these limitations, greenhouse-based operations have shown higher yields and improved disease management in countries such as Thailand, Vietnam, and India (Boyd *et al*., 2018; Orozco-Lugo *et al*., 2022). Table 5 summarizes the principal advantages and constraints associated with greenhouse farming systems.

Biofloc technology

Biofloc technology (BFT) is a microbial-based production method in shrimp aquaculture that relies on the formation of suspended aggregates composed of bacteria, microalgae, diatoms, faecal particles, and residual organic matter. These aggregates function as an additional protein source, reducing the dependence on formulated feeds because shrimp can directly consume the flocs. The system operates through continuous aeration, which keeps solids in suspension, supports aerobic microbial activity, and

Table 5. Merits and demerits of greenhouse technology according to Orozco-Lugo *et al.* (2022)

Merits	Demerits
• Allows for very high stocking density, with 45–60 shrimps/m² at a depth of 1.2m, and 200-250 shrimps/m² at a depth of 1.4m.	• The initial investment cost is very high, making it difficult for small farmers to engage, despite the economic and environmental benefits being significant.
• Provides critical data on factors like temperature, humidity, light exposure, and carbon dioxide, which helps regulate HVAC and lighting for optimal shrimp growth.	
• Stable yield, producing about four to five times greater than traditional intensive shrimp farming models.	
• Reduces the risk of disease outbreaks, as canvas ponds inhibit pathogen generation in the soil, making disease management easier during the farming process.	
• Enables year-round production, with the potential for three to four harvests per year, unlike traditional models with fewer cycles and shorter farming durations.	
• High-tech shrimp farming is independent of seasons and weather conditions, especially in areas prone to saline intrusion or heavy rain affecting water sources.	

Table 6. Merits and demerits of Biofloc technology according to Avnimelech (2015)

Merits	Demerits
Biosecurity & Environmental Performance	
• High biosecurity; no recorded outbreaks of white spot syndrome virus (WSSV) in well-managed systems.	• Biofloc ponds require lining to prevent soil contact, increasing installation costs.
• Zero water exchange reduces environmental impact and minimizes discharge into natural ecosystems.	—
Production Efficiency	
• Carrying capacity is typically 5–10% higher than in conventional systems.	—
• Faster growth rates with low FCR values (1.0–1.3).	—
• Production costs are 15–20% lower than pond or raceway systems.	—
Operational Constraints	
—	• High energy demand due to continuous aeration requirements.
—	• Power outages—even brief ones—can result in severe stock losses.
—	• Requires skilled technical personnel for consistent management.

facilitates the removal of excess solids through siphoning. Effective operation typically requires maintaining floc concentrations around 14 mg/L and regulating the carbon-to-nitrogen ratio near 14:1 using carbon sources such as molasses or grain-based inputs. Originally implemented in commercial settings such as Belize Aquaculture Ltd., BFT has been associated with high production yields, including reports of up to 13.5 metric tons per hectare (Avnimelech, 2015). The approach is also applied in super-intensive configurations, where stocking densities can exceed 9 kg/m³. Several studies report that BFT improves water quality stability and reduces the incidence of bacterial and viral outbreaks, including those linked to white spot syndrome virus (WSSV) (Khanjani *et al.*, 2020). Farmers have adopted the system for its potential to achieve low feed conversion ratios (FCRs) and stable survival rates. Large-scale projects, such as initiatives in Malaysia, illustrate ongoing interest in applying BFT within intensive commercial operations. Despite these advantages, BFT requires substantial aeration capacity, contributing to high energy demand and operational costs. Additional challenges include managing suspended solids, maintaining appropriate microbial community structure, and ensuring technical capacity for day-to-day monitoring. Research efforts continue to focus on optimizing energy efficiency and improving microbial control to support wider adoption of the technology. Table 6 summarizes the main benefits and constraints associated with BFT.

Recirculating Aquaculture Systems (RAS)

Recirculating Aquaculture Systems (RAS) are land-based production systems that continuously treat and reuse water through mechanical and biological filtration units (Xiao *et al.*, 2019). In these systems, water passes through sedimentation or mechanical filters to remove suspended solids, after which a pump transfers it to the biofilter for nitrification. Pump capacity determines the flow rate entering the biofilter, meaning that larger systems require higher-horsepower pumps to maintain adequate water movement. The biofilter is the central unit for ammonia oxidation, converting toxic nitrogen compounds into less harmful forms. After nitrification, water typically moves through a gas exchange unit, where carbon dioxide is removed and oxygen is replenished. Depending on system intensity, additional components may be incorporated, including ultraviolet or ozone disinfection units, pH regulation devices, temperature controls, and video monitoring systems for real-time observation (Xiao *et al.*, 2019). Culture tanks used in RAS vary in size and shape but must be watertight and suitable for the intended biomass. Common construction materials include plastics, concrete, and fiberglass. Plastic tanks offer low cost and ease of cleaning; concrete tanks provide a durable, fixed structure; and fiberglass tanks are highly durable but generally more expensive. Smooth internal surfaces are preferred because they reduce the risk of physical injury and subsequent infection in shrimp. Table 7 summarizes key advantages and limitations of RAS across these design and operational elements.

Table 7 Merits and demerits of Recirculating Aquaculture Systems Xiao *et al.* (2019)

Merits	Demerits
• Allows for high stocking density and very high yield.	• Very high cost of investment.
• The farm can be set up in locations close to the target market.	• The system requires trained professionals and technicians to install and operate.
• Reduces wastage of feed and improves environmental control.	• A breakage in power supply within a few minutes could be catastrophic due to depletion of oxygen supply and increased ammonia levels.
• Enables year-round production and a regular supply of fresh products to the market.	
• Easy to manage; water parameters can be controlled and monitored to provide an optimal growing environment for the fish and maximize profitability.	
• Requires less space and a low volume of water to operate.	
• Can be operated anywhere land exists.	

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SUSTAINABILITY OF TECHNOLOGY IN SHRIMP AQUACULTURE

Growing global demand for seafood continues to drive technological innovation in shrimp aquaculture. Advanced production systems such as biofloc, recirculating aquaculture systems (RAS), lined ponds, and automated monitoring offer improved traceability, resource efficiency, and environmental performance (Lu *et al.,* 2020). However, the sustainability of these technologies depends not only on their technical benefits but also on their economic accessibility and social feasibility (as seen in Figure 4).

Several technologies show strong potential for smallholder adoption, particularly those that improve water quality, reduce feed waste, and lower disease risks without requiring large capital investment. Biofloc systems, simple pond liners, and low-cost aeration technologies fall into this category. They allow farmers to improve productivity while maintaining flexibility in operations. These systems also enhance resilience by reducing reliance on external water sources and minimizing environmental discharge. However, even these "lower-cost" technologies require a degree of technical understanding and consistent management, which may limit uptake in regions with limited extension support.

In contrast, fully enclosed high-density systems, advanced RAS installations, and sensor-driven automated monitoring platforms remain largely restricted to commercial-scale operations. These systems demand high upfront investments, specialized technical staff, and reliable energy infrastructure. Evidence from Vietnam shows that farms adopting these intensive high-tech approaches achieve substantially higher yields and product quality than conventional ponds (Engle *et al.,* 2017). The case of Dang Thanh Tan illustrates how transitioning to high-tech farming insulated production from weather-related variability and improved disease control. Yet, such transitions are rarely feasible for small farmers without external financing or cooperative models. Thus, while high-tech farms demonstrate economic and biosecurity advantages, their scalability across the wider production landscape remains limited.

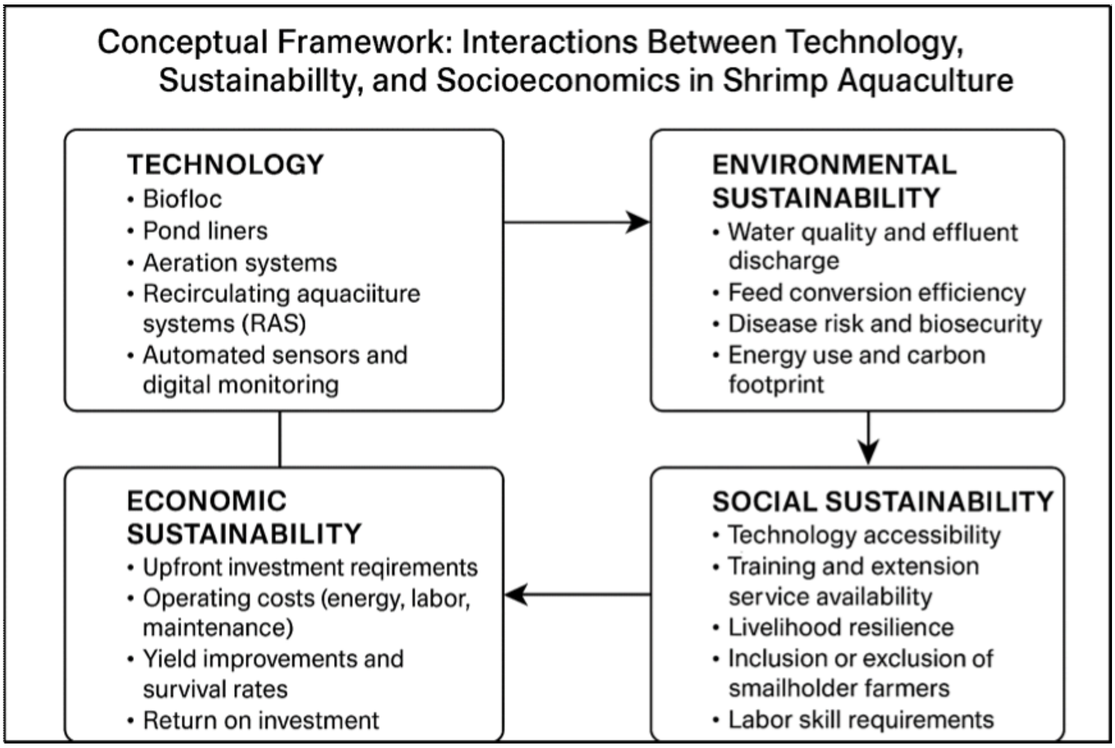

Figure 4. Interactions between technology, sustainability, and socioeconomic factors in shrimp aquaculture.

The diffusion of technology in shrimp aquaculture has created a dual production structure: highly capitalized farms pushing productivity frontiers and smallholders struggling to maintain competitiveness. This widening gap raises important sustainability considerations. Technological intensification can reduce environmental impacts per unit of production, but only if appropriate biosecurity, waste management, and energy efficiency measures are implemented. Moreover, unequal access to technology risks undermining social sustainability by marginalizing smallholders from high-value markets. Strengthening extension services, reducing technology costs, and promoting farmer cooperatives could help democratize access and enhance long-term sector resilience.

Several knowledge gaps remain. First, there is limited empirical evaluation of which technologies deliver the highest return on investment for smallholders under varying local conditions. Second, the long-term environmental performance of many high-tech systems, particularly their energy demands and waste output, requires more robust assessment. Third, socio-economic analyses are needed to understand adoption barriers, financing models, and the impacts of technological transitions on rural livelihoods. Finally, there is a lack of integrated frameworks that combine environmental, economic, and social dimensions to guide technology selection for different farm scales.

CONCLUSION

Shrimp aquaculture is expanding rapidly as global demand for high-quality seafood continues to rise. Ensuring the long-term sustainability of this growth requires a transition from conventional, resource-intensive practices toward more efficient, technology-integrated production systems. Recent advances including the use of probiotics and immunomodulators, IoT-based monitoring, automated control systems, and biotechnology-enhanced biosecurity demonstrate significant potential to improve production efficiency, strengthen disease prevention, and reduce environmental impacts. These tools collectively reinforce the need for high-tech farming strategies capable of supporting stable yields while minimizing ecological pressures. Nevertheless, substantial research and implementation gaps limit the equitable and effective adoption of these technologies. Current technological innovation is geographically uneven, with most AI-driven applications concentrated in Asia and limited empirical evidence available from Africa and other emerging regions. Long-term ecological assessments are scarce; only a small proportion of biofloc and intensive system studies evaluate environmental or ecosystem impacts beyond five years. Additionally, cost-benefit analyses for systems such as RAS, biofloc, and hybrid configurations remain limited in developing nations, constraining informed decision-making. Future research should therefore prioritize long-term environmental monitoring, region-specific economic evaluations, standardized welfare assessment frameworks, and context-appropriate digital and biotechnological tools that enhance both productivity and ecosystem resilience. Policymakers should establish supportive regulatory frameworks and incentive mechanisms to encourage responsible technology adoption, while farmers should implement scalable, data-informed practices suited to local ecological and socio-economic conditions. By integrating technological innovation with evidence-based governance and targeted capacity building, shrimp aquaculture can progress toward a more resilient, climate-smart, and socially equitable production model capable of meeting rising global demand sustainably.

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REFERENCES

Abakari, G., Wu, X., He, X., Fan, L., & Luo, G. (2022). Bacteria in biofloc technology aquaculture systems: Roles and mediating factors. *Reviews in Aquaculture, 14*(3), 1260–1284.

Adetunji, C. O., Anani, O. A., Olugbemi, O. T., Hefft, D. I., Wilson, N., & Olayinka, A. S. (2022). Toward the design of an intelligent system for enhancing saltwater shrimp production using fuzzy logic. In A. Abraham, S. Dash, J. J. P. C. Rodrigues, B. Acharya, & S. K. Pani (Eds.), *AI, edge and IoT-based smart agriculture* (pp. 533–541). Academic Press.

Ahmed, N., & Turchini, G. M. (2021). Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. *Journal of Cleaner Production, 297*, 126604.

Alfaro-Montoya, J., Braga, A., & Umaña-Castro, R. (2019). Research frontiers in penaeid shrimp reproduction: Future trends to improve commercial production. *Aquaculture, 503*, 70–87.

Amos, N. (2018). *The business of farm animal welfare*. In N. Amos & R. Sullivan (Eds.). Routledge.

Arnold, S., Smullen, R., Briggs, M., West, M., & Glencross, B. (2016). The combined effect of feed frequency and ration size of diets with and without microbial biomass on the growth and feed conversion of juvenile *Penaeus monodon*. *Aquaculture Nutrition, 22*(6), 1340–1347.

Avnimelech, Y. (2015). *Biofloc technology: A practical guidebook* (3rd ed.). World Aquaculture Society.

Bhassu, S., Shama, M., Tiruvayipati, S., Soo, T. C. C., Ahmed, N., & Yusoff, K. (2024). Microbes and pathogens associated with shrimps: Implications and review of possible control strategies. *Frontiers in Marine Science, 11*, 1397708.

Biswas, O., Biswas, S., Goswami, A., & Biswas, S. (2023). Artificial intelligence (AI): A prospective frontier area in the field of livestock and aquaculture. *Indian Journal of Animal Health, 62*(2), 145–150.

Boyd, C. E., McNevin, A. A., Davis, R. P., Godumala, R., & Mohan, A. B. C. (2018). Production methods and resource use at *Litopenaeus vannamei* and *Penaeus monodon* farms in India compared with previous findings from Thailand and Vietnam. *Journal of the World Aquaculture Society, 49*, 551–569. https://doi.org/10.1111/jwas.12524

Butt, U. D., Lin, N., Akhter, N., Siddiqui, T., Li, S., & Wu, B. (2021). Overview of the latest developments in the role of probiotics, prebiotics and synbiotics in shrimp aquaculture. *Fish & Shellfish Immunology, 114*, 263–281.

Dao, T. (2019). *Vietnam sets goals for shrimp industry through 2025*. Seafood Source. https://www.seafoodsource.com/news/supply-trade/vietnam-sets-goals-for-shrimp-industry-through-2025

de Almeida, M. S., Carrijo-Mauad, J. R., Gimenes, R. M. T., Gaona, C. A. P., Furtado, P. S., Poersch, L. H., ... & Fóes, G. K. (2021). Bioeconomic analysis of the production of marine shrimp in greenhouses using the biofloc technology system. *Aquaculture International, 29*(2), 723–741.

de Ávila, L. R., Botelho, S. S. D. C., Pias, M. R., de Vargas Guterres, B., & Junior, J. N. J. (2021, October). On aquaculture enhancements through robotic behaviour actuation. In *2021 Latin American Robotics Symposium (LARS), 2021 Brazilian Symposium on Robotics (SBR), and 2021 Workshop on Robotics in Education (WRE)* (pp. 294–299). IEEE.

Dewangan, N. K., Ayyaru, G., Kuzhanthaivel, R., Thirugnanasambandan, S. S., Martin, G. G., Daniel, K., & Ramakrishna, R. S. (2017). Incidence of simultaneous infection of infectious hypodermal and haematopoietic necrosis virus (IHHNV) and white spot syndrome virus (WSSV) in *Litopenaeus vannamei*. *Aquaculture, 471*, 1–7.

Duc, P. M., Hoa, T. T. T., Phuong, N. T., Bosma, R. H., Hien, H. V., & Tuan, T. N. (2015). Virus diseases risk factors associated with shrimp farming practices in rice–shrimp and intensive culture systems in the Mekong Delta, Vietnam. *International Journal of Science and Research, 5*, 2250–3153.

Emerenciano, M. G. C., Martínez-Córdova, L. R., Martínez-Porchas, M., & Miranda-Baeza, A. (2017). Biofloc technology (BFT): A tool for water quality management in aquaculture. *Water Quality, 5*, 92–109.

Emerenciano, M. G., Rombenso, A. N., Vieira, F. D. N., Martins, M. A., Coman, G. J., Truong, H. H., ... & Simon, C. J. (2022). Intensification of penaeid shrimp culture: An applied review of advances in production systems, nutrition and breeding. *Animals, 12*(3), 236.

Engle, C. R., Boyd, C. E., Paungkaew, D., Viriyatum, R., Tinh, H. Q., & Minh, H. N. (2017). Economics of sustainable intensification of aquaculture: Evidence from shrimp farms in Vietnam and Thailand. *Journal of the World Aquaculture Society, 48*, 227–239.

Fadilah, A. N., & Fasya, A. H. (2021, February). Examination of Taura Syndrome Virus (TSV) in white shrimp (*Litopenaeus vannamei*) and tiger prawn (*Penaeus monodon*) with Polymerase Chain Reaction (PCR) method. In *IOP Conference Series: Earth and Environmental Science, 679*(1), 012069.

Food and Agriculture Organization. (2020). *Regional review on status and trends in aquaculture development in Asia-Pacific 2020* (FAO Fisheries and Aquaculture Circular No. 1232/6). FAO. https://www.fao.org

Food and Agriculture Organization. (2022). *The state of world fisheries and aquaculture 2022: Towards blue transformation*. FAO. https://doi.org/10.4060/cc0461en

Food and Agriculture Organization. (2024). *The state of world fisheries and aquaculture 2024: Blue transformation in action*. FAO. https://doi.org/10.4060/cd0683en

Fenster, K., Freeburg, B., Hollard, C., Wong, C., Rønhave Laursen, R., & Ouwehand, A. C. (2019). The production and delivery of probiotics: A review of a practical approach. *Microorganisms, 7*(3), 83.

Ferdous, M. A., Islam, S. I., Habib, N., Almehmadi, M., Allahyani, M., Alsaiari, A. A., & Shafie, A. (2022). CRISPR-Cas genome editing technique for fish disease management: Current study and future perspective. *Microorganisms, 10*(10), 2012.

Flegel, T. W. (2019). A future vision for disease control in shrimp aquaculture. *Journal of the World Aquaculture Society, 50*(2), 249–266.

Flegel, T. W., Lightner, D. V., Lo, C. F., & Owens, L. (2008). Shrimp disease control: Past, present and future. In *Diseases in Asian Aquaculture VI* (pp. 355–378). Asian Fisheries Society.

Fry, J. P., Mailloux, N. A., Love, D. C., Milli, M. C., & Cao, L. (2018). Feed conversion efficiency in aquaculture: Do we measure it correctly? *Environmental Research Letters, 13*(2), 024017.

Giap, D. H., Garden, P., & Lebel, L. (2010). Enabling sustainable shrimp aquaculture: Narrowing the gaps between science and policy in Thailand. In *Sustainable Production Consumption Systems: Knowledge, Engagement and Practice* (pp. 123–144). Springer.

Gonzalez, T. J. (2025). Harmonizing animal health and welfare in modern aquaculture: Innovative practices for a sustainable seafood industry. *Fishes, 10*(4), 156.

Hai, T. N., Duc, P. M., Son, V. N., Minh, T. H., & Phuong, N. T. (2015). Innovation in seed production and farming of marine shrimp in Vietnam. *World Aquaculture, 46*(1), 32–37.

Hine, M., Adams, S., Arthur, J. R., Bartley, D., Bondad-Reantaso, M. G., Chávez, C., ... & Wardle, R. (2010). Improving biosecurity: A necessity for aquaculture sustainability. In *Farming the Waters for People and Food: Global Conference on Aquaculture* (pp. 22–25). FAO, NACA & Thai Department of Fisheries.

Jamal, M. T., Abdulrahman, I. A., Al Harbi, M., & Chithambaran, S. (2019). Probiotics as alternative control measures in shrimp aquaculture: A review. *Journal of Applied Biology & Biotechnology, 7*(3), 69–77.

Jory, D. (2023). Annual farmed shrimp production survey: A slight decrease in production reduction in 2023 with hopes for renewed growth in 2024. *Global Seafood Alliance*.

Kajornkasirat, S., Ruangsri, J., Sumat, C., & Intaramontri, P. (2021). Online analytics for shrimp farm management to control water quality parameters and growth performance. *Sustainability, 13*(11), 5839.

Kakade, A., Sharma, M., Salama, E. S., Zhang, P., Zhang, L., Xing, X., ... & Li, X. (2023). Heavy metals pollution in the aquatic environment: Role of probiotics and gut microbiota in remediation. *Environmental Research, 223*, 115186.

Khanjani, M. H., Alizadeh, M., & Sharifinia, M. (2020). Rearing of the Pacific white shrimp (*Litopenaeus vannamei*) in a biofloc system: The effects of different food sources and salinity levels. *Aquaculture Nutrition, 26*, 328–337.

Knipe, H., Temperton, B., Lange, A., Bass, D., & Tyler, C. R. (2021). Probiotics and competitive exclusion of pathogens in shrimp aquaculture. *Reviews in Aquaculture, 13*(1), 324–352.

Kumar, V., Roy, S., Meena, D. K., & Sarkar, U. K. (2016). Application of probiotics in shrimp aquaculture: Importance, mechanisms of action, and methods of administration. *Reviews in Fisheries Science & Aquaculture, 24*(4), 342–368.

Lal, S., Ahirwar, S. B., Kanojia, S., Rai, S., V., C. S., Gupta, S., … Nautiyal, P. (2024). Robot-assisted aquaculture and sustainable seafood production for enhanced food security. *International Journal of Environment and Climate Change, 14*(2), 215–220.

Lembo, G., Speiser, B., Casey, J., Garcia, A. E., Jokumsen, A., Papandroulakis, N., & Sorgeloos, P. (2014). *European Commission: Final report on aquaculture (Part B)*. EGTOP Annex II.

Lim, L. W. K. (2024). Implementation of artificial intelligence in aquaculture and fisheries: Deep learning, machine vision, big data, internet of things, robots and beyond. *Journal of Computational and Cognitive Engineering, 3*(2), 112–118.

Lu, C. L., Chen, S. N., & Hung, S. W. (2020). Application of novel technology in aquaculture. In Q. Lu & M. Serajuddin (Eds.), *Emerging technologies, environment and research for sustainable aquaculture* (pp. 2–15). IntechOpen.

Ma, Z., Wan, R., Song, X., & Gao, L. (2013). The effect of three culture methods on intensive culture system of Pacific white shrimp (*Litopenaeus vannamei*). *Journal of Ocean University of China, 12*, 434–440.

Mohale, H. P., Narsale, S. A., Kadam, R. V., Prakash, P., Sheikh, S., Mansukhbhai, C. R., … Baraiya, R. (2024). Artificial intelligence in fisheries and aquaculture: Enhancing sustainability and productivity. *Archives of Current Research International, 24*(3), 106–123.

Mustapha, U. F., Alhassan, A. W., Jiang, D. N., & Li, G. L. (2021). Sustainable aquaculture development: A review on the roles of cloud computing, internet of things and artificial intelligence (CIA). *Reviews in Aquaculture, 13*(4), 2076–2091.

Muthu, C. M., Vickram, A. S., Sowndharya, B. B., Saravanan, A., Kamalesh, R., & Dinakarkumar, Y. (2024). A comprehensive review on the utilization of probiotics in aquaculture towards sustainable shrimp farming. *Fish & Shellfish Immunology, 147*, 109459.

Navaneeth, K. A., Bhuvaneswari, T., Rajan, J. J. S., Alavandi, S. V., Vijayan, K. K., & Otta, S. K. (2020). Characterization of *Vibrio parahaemolyticus* isolates from shrimp farms of Southeast coast of India with special reference to acute hepatopancreatic necrosis disease (AHPND) status. *Aquaculture, 518*, 734813.

Nguyen, T. A. T., Nguyen, K. A. T., & Jolly, C. (2019). Is super-intensification the solution to shrimp production and export sustainability? *Sustainability, 11*(19), 5277.

Orozco-Lugo, A. G., McLernon, D. C., Lara, M., Zaidi, S. A. R., González, B. J., Illescas, O., … Rodríguez-Vázquez, R. (2022). Monitoring water quality in a shrimp farm using a FANET. *Internet of Things, 18*, 100170.

Prachumwat, A., Taengchaiyaphum, S., Mungkongwongsiri, N., Aldama Cano, D. J., Flegel, T. W., & Sritunyalucksana, K. (2019). Update on early mortality syndrome/acute hepatopancreatic necrosis disease by April 2018. *Journal of the World Aquaculture Society, 50*(1), 5–17.

Qian, C., Wang, R., Wu, C., Wang, L., Ye, Z., Wu, J., & Ji, F. (2018). A fast and visual method for duplex shrimp pathogens detection with high specificity using rapid PCR and molecular beacon. *Analytica Chimica Acta, 1040*, 105–111.

Qiao, G., Xu, D. H., Wang, Z., Jang, I. K., Qi, Z., Zhang, M., & Kim, S. K. (2015). Comparison of immune response of Pacific white shrimp (*Litopenaeus vannamei*) after multiple and single infections with WSSV and *Vibrio anguillarum*. *Fish & Shellfish Immunology, 44*(1), 257–264.

Quach, A. V. (2018). *Shrimp farming vulnerability and adaptation to climate change in Ca Mau, Vietnam* (Doctoral dissertation, Murdoch University).

Quach, L. D., Hoang, L. Q., Trung, N. D., & Nguyen, C. N. (2020). Towards machine learning approaches to identify shrimp diseases based on description. In *Proceedings of the 12th National Conference on Fundamental and Applied Information Technology Research (FAIR)* (pp. 494–501).

Rastegari, H., Nadi, F., Lam, S. S., Ikhwanuddin, M., Kasan, N. A., Rahmat, R. F., & Mahari, W. A. W. (2023). Internet of things in aquaculture: A review of the challenges and potential solutions based on current and future trends. *Smart Agricultural Technology, 4*, 100187.

Reis, J., Weldon, A., Ito, P., Stites, W., Rhodes, M., & Davis, D. A. (2021). Automated feeding systems for shrimp: Effects of feeding schedules and passive feedback feeding systems. *Aquaculture, 541*, 736800.

Roccatello, R., Endrizzi, I., Aprea, E., & Dabbou, S. (2024). Insect-based feed in aquaculture: A consumer attitudes study. *Aquaculture, 582*, 740512.

Samocha, T. M. (2010). Use of intensive and super-intensive nursery systems. In *The shrimp book* (pp. 247–280). CABI.

Schuur, A. M., Boyd, C. E., & McNevin, A. A. (2020). *Feasibility assessment for intensification of the small-holder extensive shrimp farm area*. [Report].

Searchinger, T., Waite, R., Hanson, C., & Ranganathan, J. (2019). *Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2050*. World Resources Report. https://wrr-food.wri.org

Shang, Y. C., Leung, P., & Ling, B. H. (1998). Comparative economics of shrimp farming in Asia. *Aquaculture, 164*(1–4), 183–200.

Taneja, A., Nair, G., Joshi, M., Sharma, S., Sharma, S., Jambrak, A. R., … Phimolsiripol, Y. (2023). Artificial intelligence: Implications for the agri-food sector. *Agronomy, 13*(5), 1397.

Tang, K. F., & Lightner, D. V. (2001). Detection and quantification of infectious hypodermal and hematopoietic necrosis virus in penaeid shrimp by real-time PCR. *Diseases of Aquatic Organisms, 44*(2), 79–85.

Tom, A. P., Jayakumar, J. S., Biju, M., Somarajan, J., & Ibrahim, M. A. (2021). Aquaculture wastewater treatment technologies and their sustainability: A review. *Energy Nexus, 4*, 100022.

Tsai, K. L., Chen, L. W., Yang, L. J., Shiu, H. J., & Chen, H. W. (2022). IoT-based smart aquaculture system with automatic aeration and water quality monitoring. *Journal of Internet Technology, 23*(1), 177–184.

Uawisetwathana, U., Leelatanawit, R., Klanchui, A., Prommoon, J., Klinbunga, S., & Karoonuthaisiri, N. (2011). Insights into eyestalk ablation mechanism to induce ovarian maturation in the black tiger shrimp. *PLoS ONE, 6*(9), e24427.

Westfall, S., Carracci, F., Estill, M., Zhao, D., Wu, Q. L., Shen, L., ... & Pasinetti, G. M. (2021). Optimization of probiotic therapeutics using machine learning in an artificial human gastrointestinal tract. *Scientific Reports, 11*(1), 1067.

Xiao, R., Wei, Y., An, D., Li, D., Ta, X., Wu, Y., & Ren, Q. (2019). A review on the research status and development trend of equipment in water treatment processes of recirculating aquaculture systems. *Reviews in Aquaculture, 11*(3), 863–895.

Yoo, S. H., Ju, Y. T., Kim, J. S., & Kim, E. K. (2020). Design and development of underwater drone for fish farm growth environment management. *The Journal of the Korea Institute of Electronic Communication Sciences, 15*, 959–966.

Yue, G. H. (2014). Recent advances of genome mapping and marker assisted selection in aquaculture. *Fish and Fisheries, 15*(3), 376–396.

Zacarias, S., Carboni, S., Davie, A., & Little, D. C. (2019). Reproductive performance and offspring quality of non-ablated Pacific white shrimp (*Litopenaeus vannamei*) under intensive commercial scale conditions. *Aquaculture, 503*, 460–466.

Zenger, K. R., Khatkar, M. S., Jones, D. B., Khalilisamani, N., Jerry, D. R., & Raadsma, H. W. (2019). Genomic selection in aquaculture: Application, limitations and opportunities with special reference to marine shrimp and pearl oysters. *Frontiers in Genetics, 9*, 693.

Zhang, X., Yuan, J., Sun, Y., Li, S., Gao, Y. I., Yu, Y., ... & Xiang, J. (2019). Penaeid shrimp genome provides insights into benthic adaptation and frequent moulting. *Nature Communications, 10*(1), 356.

