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Integrasi Pengolahan Air Limbah Lanjutan dan Teknik Molekuler untuk Pengelolaan Kualitas Air Berkelanjutan pada Sistem Akuakultur Intensif

Integrating Advanced Wastewater Treatment and Molecular Tools for Sustainable Water Quality Management in Intensive Aquaculture Systems

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Abstrak

Akuakultur telah muncul sebagai salah satu sektor produksi pangan dengan pertumbuhan tercepat secara global, serta memainkan peran penting dalam ketahanan pangan, penyediaan mata pencaharian, dan pengurangan tekanan terhadap stok ikan liar. Meskipun memiliki kepentingan ekonomi dan gizi yang tinggi, intensifikasi akuakultur yang pesat telah menimbulkan berbagai tantangan signifikan yang berkaitan dengan penurunan kualitas air, produksi air limbah, wabah penyakit, penggunaan bahan kimia, dan keberlanjutan lingkungan.Tinjauan konseptual integratif ini mensintesis pengetahuan terkini mengenai pengelolaan air akuakultur yang berkelanjutan dengan mengaitkan praktik pengobatan, karakteristik air limbah, strategi bioremediasi, alat molekuler, dan teknologi digital. Tinjauan ini mengevaluasi dampak penggunaan agen pengobatan yang umum digunakan, termasuk florfenikol, formalin, dan hidrogen peroksida, dengan menyoroti efektivitasnya dalam pengendalian penyakit sekaligus risiko ekologis yang terkait dengan residu antibiotik dan gangguan mikroba.Perkembangan dalam pengolahan air limbah, seperti biofiltrasi, bioremediasi mikroalga dan mikroba, serta pendekatan fotodegradasi yang sedang berkembang, dianalisis berdasarkan potensinya dalam mengurangi pencemaran dan memulihkan nutrien. Selain itu, peran genomik dan transkriptomik dalam meningkatkan pemantauan kesehatan ikan, ketahanan terhadap penyakit, dan ketahanan lingkungan juga dibahas, seiring dengan meningkatnya penerapan sistem akuakultur digital untuk pemantauan kualitas air dan perilaku ikan secara real-time. Analisis ekonomi dan spasial dari wilayah penghasil akuakultur menunjukkan bagaimana skala produksi, komposisi spesies, dan praktik pengelolaan memengaruhi penggunaan air dan dinamika pasar. Tinjauan ini mengidentifikasi kesenjangan penting dalam integrasi strategi molekuler, teknologi, dan pengelolaan air limbah, serta menekankan perlunya kerangka kerja interdisipliner untuk mendukung sistem akuakultur yang bertanggung jawab secara lingkungan, tangguh, dan produktif.

Kata kunci: Akuakultur, Disrupsi Mikroba, Bioremediasi, Molekuler

Abstract

Aquaculture has emerged as one of the fastest-growing food production sectors globally, playing a critical role in food security, livelihood support, and the reduction of pressure on wild fish stocks. Despite its economic and nutritional importance, the rapid intensification of aquaculture has introduced significant challenges related to water quality deterioration, wastewater generation, disease outbreaks, chemical use, and environmental sustainability. This conceptual integrative review synthesises current knowledge on sustainable aquaculture water management by linking treatment practices, wastewater characteristics, biological remediation strategies, molecular tools, and digital technologies. The review examines the impacts of commonly used treatment agents, including florfenicol, formalin, and hydrogen peroxide, highlighting their effectiveness in disease control alongside ecological risks associated with antibiotic residues and microbial disruption. Advances in wastewater treatment, such as biofiltration, microalgal and microbial bioremediation, and emerging photodegradation approaches, are evaluated for their potential to reduce pollution and recover nutrients. Additionally, the role of genomics and transcriptomics in enhancing fish health monitoring, disease resistance, and environmental resilience is discussed, alongside the growing application of digital aquaculture systems for real-time water quality and behavioural monitoring. Economic and spatial analyses from aquaculture-producing regions illustrate how production scale, species composition, and management practices influence water use and market dynamics. The review identifies critical gaps in integrating molecular, technological, and wastewater management strategies and proposes the need for interdisciplinary frameworks to support environmentally responsible, resilient, and productive aquaculture systems.

Keywords: Aquaculture, Microbial Disruption, Bioremediation, Molecular

INTRODUCTION

Aquaculture is a fish farming that refers to the controlled cultivation of aquatic organisms, such as fish, crustaceans, mollusks, and aquatic plants. Aquaculture has become one of the promising economic activities to address the wild fish stocks. Then, it became one of the fastest-growing sectors in food production. It plays an increasingly crucial role in ensuring food security, supporting livelihoods, and reducing pressure on natural ecosystems. One of the primary benefits of aquaculture is the ability to provide a reliable and efficient source of protein. As the population grows, aquaculture offers a sustainable alternative to traditional capture fisheries due to overfishing, habitat degradation, and climate change.

Aquaculture also contributes significantly to economic development. From small-scale farmers in developing countries to large commercial operations in industrialised nations. Coastal and rural communities often rely on aquaculture for income and local food supply. There are also challenges raising environmental concerns, undermining conservation efforts. Aquaculture generates wastes using chemicals that pollute water and harm surrounding ecosystems (Tan et al., 2023). It threatens both productivity and ecosystem health (Tan et al., 2023). Disease outbreaks remain a serious risk, particularly in intensive aquaculture systems (Tan et al., 2023).

Aquaculture operations produce substantial wastewater containing high levels of organic materials, such as nitrogen and phosphorus, proteins, and other contaminants of concern (Kurniawan et al., 2021). These wastes can cause harmful effects to water quality (Kurniawan et al., 2021). If not properly treated, aquaculture may contribute to pollution of surrounding waters, which can lead to eutrophication, degraded aquatic systems, and broader water security challenges (Kurniawan et al., 2021). Therefore, there is a need for careful management through natural processes (microbial breakdown) or technologies (biochar and membranes) to recycle them.

Genomics uses the genomic data to identify genetic variation associated with desirable traits for a good health interpretation (Lau et al., 2025). Transcriptomics is for examining gene expressions to understand physiological responses of aquatic species under different environmental stressors for optimized feeding, health monitoring, and environmental resilience (Lau et al., 2205). The causes and consequences of water quality deterioration in aquaculture systems and what management strategies in terms of technological, regulatory, and operational to maintain or restore good water quality (Yusoff et al., 2024). If wastes are not properly managed, they can impose a serious environmental risk (Yusoff et al., 2024).

It reviews how wastewater (seawage), especially from domestic, industrial, or agricultural sources, can be treated and reused to support aquaculture safely and sustainably (Afia & Abasiubong, 2025). Then, it explores the risks and environmental impacts of discharging untreated wastewater into the environment and aquatic systems, such as oxygen depletion, pollution, and contamination, for proper wastewater treatment before reuse in fish culture (Afia & Abasiubong, 2025). It focuses on water quality and wastewater treatment needs in intensive aquaculture systems as it moves toward more intensive or recirculating operations that reuse water (Shingare et al., 2019). There is a solid removal and biological nitrification (biofiltration) as the most common and economically feasible approaches (Shingare et al., 2019).

Aquaculture produces nutrient-rich wastewater and chemical pollutants that degrade water quality, cause environmental harm, and increase disease risk, especially in intensive systems. Current treatment methods, such as sedimentation and biofiltration, are insufficient for modern aquaculture, and the unsafe use of untreated wastewater further threatens ecological and human health. Despite growing research, there is limited integration of advanced wastewater treatment technologies, insufficient linkage between molecular tools (genomics and transcriptomics) and water quality management, and a lack of comprehensive, sustainable frameworks for treating and reusing wastewater in intensive or recirculating aquaculture systems. The research objective is to investigate and develop sustainable strategies for improving water quality management and wastewater treatment in aquaculture systems, integrating advanced technologies and molecular tools to enhance environmental sustainability, fish health, and productivity.

LITERATURE REVIEW

Humanity faces escalating risks from climate change, biodiversity loss, and rising demand for food, especially protein (Becke et al., 2025). Aquaculture of fish, shellfish, and algae offers a promising path that is sure to continue to rise (Becke et al., 2025). There are more approaches suggested for the aquaculture systems, including ponds, tanks, and an integrated system to produce a high-quality protein with comparatively low pressure on wild ecosystems and less demand for land or water than terrestrial livestock (Becke et al., 2025). It is an overview of the use of vaccines to protect farmed fish from bacterial, viral, and parasitic diseases by reducing antibiotic resistance and improving animal health and production outcomes (Singh et al., 2025). There is a use for natural, plant-based immunostimulants to enhance the immune responses of aquatic species to be seen as a more eco-friendly alternative to chemical or antibiotic-based disease control (Singh et al., 2025).

It presented a comprehensive, up-to-date overview of global aquaculture, covering new technologies, sustainable feed alternatives, monitoring methods, genetic biomarkers, and

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digitalization, to reflect recent developments, challenges, and practical applications in aquaculture (Yalcin et al., 2025). Existing aquaculture monitoring systems often rely on underwater video analysis for fish motion and behavior, or water quality sensor data (Yalcin et al., 2025). Thus, the study aims to fill this gap by building an integrated system that monitors both the quality of water and fish motion, predicts water quality changes, and detects frantic stress or abnormal fish behaviour by supporting an intelligent aquaculture management system (Yalcin et al., 2025). They constructed an Integrated Multi-Trophic Aquaculture (IMTA) system in seawater ponds by combining multiple trophic levels, such as fish, shrimp, shellfish, and aquatic plants, to create a more sustainable, circular aquaculture model, where waste from one species can become a resource for others (Shreesha et al., 2023).

It is a review on challenges and opportunities arising from waste generated by aquaculture and fisheries, especially given global growth in seafood production (Pedziwiatr et al., 2017). By 2014, global fisheries and aquaculture output reached approximately 167.2 million tonnes (Pedziwiatr et al., 2017). There is also an intensive aquaculture and fish processing that produce large amounts of waste, including cut-offs (heads, bones, skin, viscera), unutilized byproducts, uneaten feed, and solid and dissolved organic or inorganic waste (Pedziwiatr et al., 2017). As one of the environmental challenges, nutrient-rich wastewater from aquaculture ponds, which are high in organic matter, such as nitrogen, phosphorus, and chemical oxygen demand (El-Hamid et al., 2025). By recognizing that conventional chemical or physical treatments can be costly and generate secondary pollution, the paper explores a biological (mycoremediation) approach using fungal biomass to aquaculture effluents, which offers a potentially low-cost, eco-friendly, and efficient solution (El-Hamid et al., 2025).

The review investigates the role of aquatic animals, particularly fish, as natural bioremediation agents (biofilters) in aquaculture (Sujadi et al., 2025). It was found that aquaculture often leads to water-quality issues (organic waste, nutrient build-up, excessive plankton, low oxygen, and pollutants), and using fish's natural behaviours might offer an environmentally friendly, sustainable alternative to chemical or mechanical treatments (Sujadi et al., 2025). The paper summarizes the bioremediation strategies for maintaining and balancing the pH value of water in the aquaculture remediating behaviour changes (Mukilan et al., 2024).

Microorganism-based treatment using bacteria, algae, and microbial consortia can metabolise or assimilate nutrients for nitrogen and phosphorus to degrade organic matter, and reduce pollution load (Mukilan et al., 2024). As mentioned before, algae uptake nutrients, such as nitrogen and phosphorus, to absorb pollutants to improve the water quality (Mukilan et al., 2024). The biological filters convert waste into microbial mass, which can be reused as feed or removed by reducing water exchange and pollutant discharge (Mukilan et al., 2024). The paper examines how aquaculture in developing countries can be made sustainable by balancing economic growth, environmental protection, and social equity (Oyeboade et al., 2024). It outlines aquaculture expansion as a component of food security, livelihoods, and national development, especially in regions where wild capture fisheries are overexploited or stagnating (Oyeboade et al., 2024).

The article argues that as fisheries and aquaculture develop, the core challenges have shifted, whereas early on the focus was on providing food and livelihoods, today the issues related to habitat conservation, human rights, property rights, fairness, and sustainability (He et al., 2021). Given this shift, they proposed that ethics as normative or superstructure should form the foundation of modern governance for fisheries and aquaculture, providing shared values, guiding principles, and a framework to balance ecological, social, and economic interests (He et al., 2021). The paper reviews the state of digital aquaculture using technology and data-driven methods in aquaculture, focusing simultaneously on tracking, counting, and behaviour analysis (Cui et al., 2025). This study adopts a unified and cross-modal perspective for covering vision-based, acoustic-based, and biosensor methods and maps out progress over time from 2000 to 2023 (Cui et al., 2025).

Aquaculture is increasingly positioned as a key solution to global challenges associated with climate change, biodiversity loss, and rising demand for sustainable protein. Compared with terrestrial livestock, aquaculture systems offer higher resource efficiency and reduced pressure on land and freshwater resources, making them essential for future food security. However, rapid sectoral expansion has intensified concerns related to environmental degradation, disease management, waste generation, and governance.

Recent studies emphasise a transition toward sustainable and integrated aquaculture systems**,** particularly Integrated Multi-Trophic Aquaculture (IMTA), which enhances nutrient recycling by combining species across trophic levels. Such systems reduce organic waste accumulation and mitigate nutrient-rich effluent discharge, a major contributor to water quality deterioration. Complementary to system design, biological remediation approaches using microorganisms, algae, fungi, and aquatic animals have emerged as cost-effective and eco-friendly alternatives to chemical treatments, improving water quality while reducing pollution loads.

Fish health management has also evolved, with vaccines and plant-based immunostimulants increasingly adopted to control infectious diseases and reduce reliance on antibiotics, thereby improving animal welfare and production sustainability. Alongside biological innovations, digital aquaculture technologies—including sensor networks, computer vision, and biosensors—enable real-time monitoring of water quality and fish behaviour. Nonetheless, existing monitoring systems remain fragmented, often failing to integrate behavioural and environmental data for predictive management.

Beyond technical solutions, the literature highlights growing ethical and governance challenges, underscoring the need to balance economic growth with environmental protection, social equity, and long-term sustainability. Collectively, these studies point toward the necessity of integrated, interdisciplinary aquaculture frameworks that align biological, technological, and governance innovations.

METHODOLOGY

This study adopts an integrative review methodology combined with secondary data analysis and conceptual modelling to evaluate sustainable aquaculture water management strategies. This methodology allows for a comprehensive evaluation of aquaculture systems, identifies areas requiring innovation, and supports the development of integrated strategies for enhancing both ecological and production outcomes. To achieve the stated objectives, this study applies a multi-faceted methodological approach that integrates literature review, experimental analysis, and technological evaluation to develop sustainable strategies for aquaculture wastewater management and water quality improvement. This methodology ensures that the study addresses both the technical and ecological aspects of wastewater treatment, links molecular insights to practical management, and develops actionable strategies for sustainable aquaculture.

This study employed a structured integrative synthesis methodology to summarise and integrate evidence from the Introduction, Methods, Results, and Discussion sections of selected aquaculture studies. Section-level summarization was conducted to extract core objectives, methodological approach, key findings, and interpretative insights, excluding redundant detail. A cross-sectional thematic synthesis was then applied to identify relationships between aquaculture intensification, wastewater generation, treatment technologies, fish health, and sustainability outcomes. Quantitative production and regression-based results were interpreted alongside qualitative findings to develop an integrated conceptual framework. Methodological rigor was ensured through systematic source verification and consistent analytical criteria. This approach supports a coherent, evidence-based understanding of sustainable water quality and wastewater management in aquaculture systems.

This study includes multi-source data capturing environmental, biological, and behavioural dimensions of aquaculture systems to enable an integrated analysis of system performance and sustainability. Key environmental variables include water quality parameters such as temperature, dissolved oxygen, pH, turbidity, salinity, ammonia, nitrate, and phosphate concentrations. Biological variables encompass fish growth performance, survival rate, feed conversion ratio, and health indicators, including stress-related behavioural responses and disease occurrence. Behavioural variables are derived from continuous monitoring of fish movement patterns, activity levels, and abnormal or frantic behaviour using vision-based and sensor-based systems. Operational variables, including feeding rates, stocking density, and water exchange frequency, are also incorporated to contextualise system dynamics. Only datasets with consistent temporal resolution, validated sensor

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calibration, and minimal missing values are included to ensure data reliability and comparability across experimental conditions.

RESULT AND DISCUSSION

Florfenicol, Formalin, and Hydrogen Peroxide are treatment protocols for fish and shrimp aquaculture. They are commonly used agents in aquaculture for fish health and water quality. Florfenicol is a broad-spectrum antibiotic used to treat bacterial infections in fish and shrimp by inhibiting protein synthesis, often medicated feed and water. However, there are ecological risks of using the antibiotic Florfenicol in aquaculture, specifically focusing on its effects on marine plankton communities rather than just target fish (Magiopolous et al., 2025). Given that antibiotics used in aquaculture may enter surrounding waters, to investigate whether exposure can disturb non-target organisms in the pelagic environment with cascading consequences for marine ecosystems (Magiopolous et al., 2025).

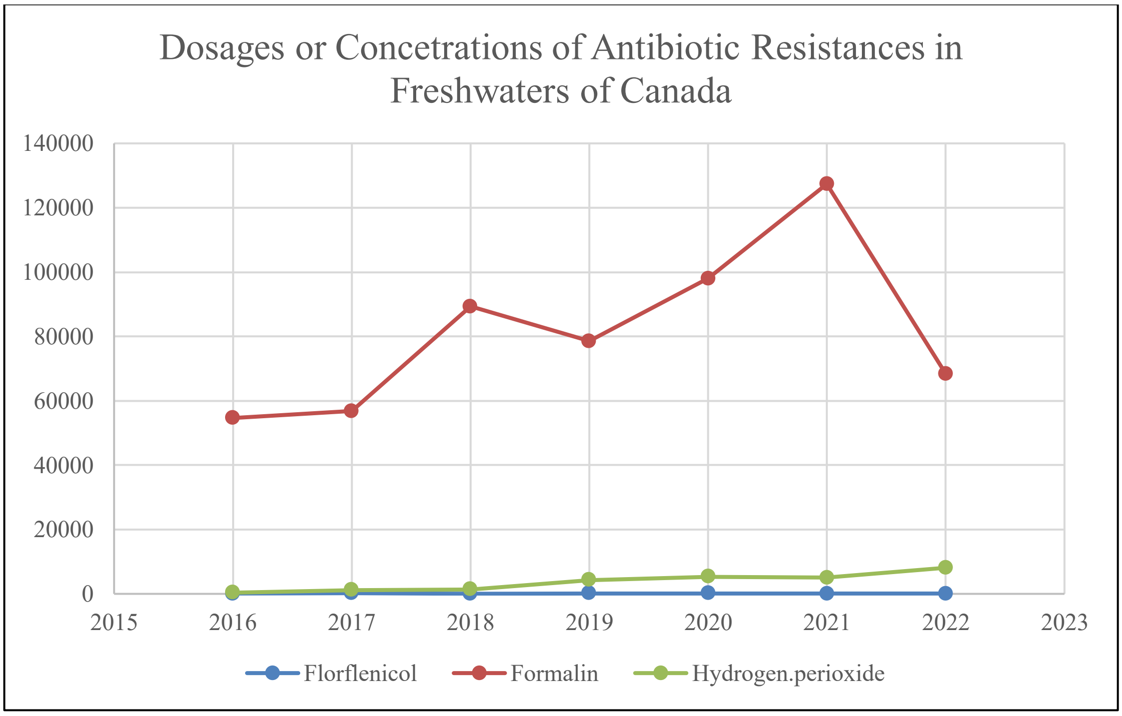

Figure 1: The Regulation Dosages of Antibiotic Resistance in Freshwaters of Canada.

In Canadian aquaculture, the approved in-feed dosage of Florfenicol is 10 mg per kg of fish body weight per day, for 10 consecutive days. After such treatment in finfish aquaculture, the antibiotic will eventually degrade in sediment under lab conditions, half life was found to be at 4.5 days. Formalin is an aqueous solution of formaldehyde, typically 37-40% used as a disinfectant, antifungal, and antiparasitic agent in aquaculture. It acts by denaturing proteins and disrupting the cell membranes of pathogens. Hydrogen peroxide is a strong oxidizing agent used as a disinfectant, antimicrobial, and antiparasitic in aquaculture. Their complementary roles in disease and water quality management for their mode of action, targets, and environmental impacts.

Canada's aquaculture operations, primarily freshwater fish, such as salmon, trout, tilapia, and catfish, rely on high-quality water to maintain fish health, growth, and ecosystem balance. Thus, the use of the antibiotic florfenicol in marine salmon aquaculture affects the microbial communities in the marine sediments beneath and around fish farms (Lynch et al., 2025). Sediments host diverse microbial communities that are crucial for biogeochemical cycles and may also act as reservoirs for antimicrobial resistance (Lynch et al., 2025). However, there is a major challenge in aquaculture wastewater: residues of the antibiotic Florfenicol (He et al., 2025). Therefore, the aim is to test a combined treatment strategy for photodegradation to reduce the florfenicol load in the water, then use a microalgal bioremediation to remove residual antibiotics and recover nutrients, such as nitrogen and phosphorus, for safer and more treatable water (He et al., 2025).

When freshwater quantity is regressed on the number of culturists and freshwater pricing, the coefficient for the number of culturists indicates how water usage responds to changes in farm workforce and operators. A positive and statistically significant coefficient would suggest that as more culturists are involved in a farm or region, freshwater consumption increases. This aligns with the expectation that larger or more intensively managed aquaculture operations require more water to support additional workers, tanks, or ponds. The magnitude of the coefficient represents the expected change in freshwater quantity for additional cultivators, holding freshwater price constant. Supportively, Canada and Malaysia utilize florfenicol, formalin, and hydrogen peroxide as key treatment agents in aquaculture, targeting bacterial, fungal, and parasitic pathogens to maintain fish and shrimp health.

The area for freshwater aquaculture refers to the total physical space allocated for farming fish or aquatic organisms in non-saline water, such as rivers, lakes, reservoirs, ponds, and man-made tanks. This area determines the production capacity of freshwater systems that commonly culture species, such as tilapia, carp, trout, and catfish. Therefore, larger freshwater farming areas typically support higher production volumes, greater water requirements, and more culturists, which often influences freshwater consumption and management practices. It examines sustainable health management strategies in freshwater aquaculture by integrating modern omics technologies, green therapeutics, and nanotechnology (Chandravanshi et al., 2025). These approaches support selective breeding for disease resistance and enhance monitoring of fish health under environmental stress (Chandravanshi et al., 2025).

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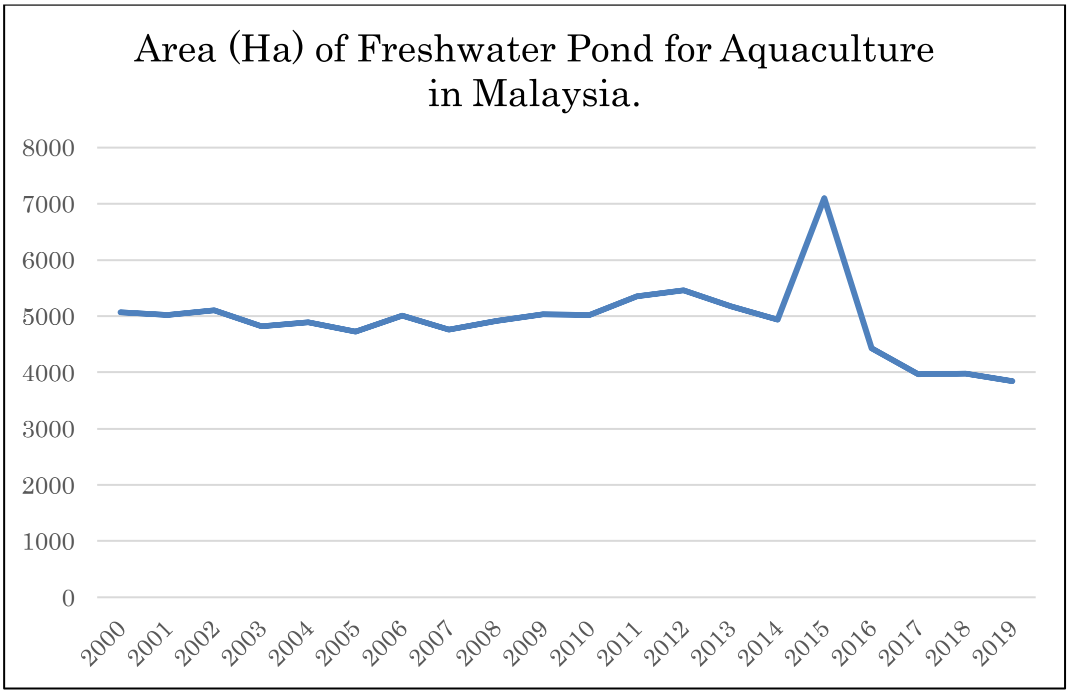

Figure 2: Area of Hectares for Aquaculture Ponds in Malaysia.

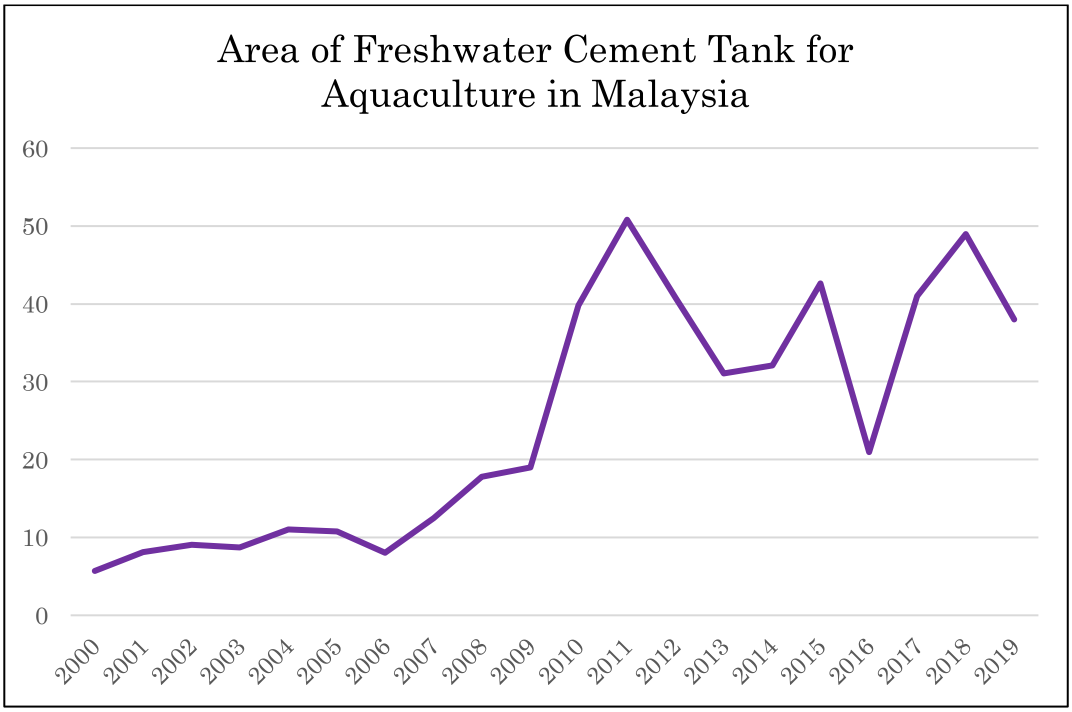

Figure 3: Area of Hectares for Aquaculture Cement Tanks in Malaysia.

At the turn of the century, Malaysia's aquaculture sector was still relatively small in spatial extent. According to data compiled up to 2009, the freshwater aquaculture area was recorded at about 7250 hectares. During this period, aquaculture largely consisted of ponds and smaller-scale operations, including earthen ponds and mining pools repurposed for fish farming. The modest reflects the early stage development, where aquaculture complemented capture fisheries rather than

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functioning as a leading contributor to the national fish supply.

From around 2010 onwards, the aquaculture area, especially for freshwater systems, saw further consolidation and modest growth. By 2015, government statistics show a total freshwater aquaculture area of approximately 9889 hectares. This increase suggests expansion of pond-based aquaculture, possibly due to an increase in demand, improved aquaculture policies, and investments in inland fish farming. According to national aquaculture statistics, in 2015, many culturists were working in freshwater aquaculture, reflecting a growing sector.

By 2019, data from the national Agrofood Statistics show the freshwater aquaculture area at about 6990 hectares. These numbers represent a slight reduction compared to the mid-2010s peak, indicating a consolidation phase, possible land-use changes, or shifts in aquaculture practices. Meanwhile, the total aquaculture area for all systems in Malaysia in 2019 was reported at 34,712 hectares.

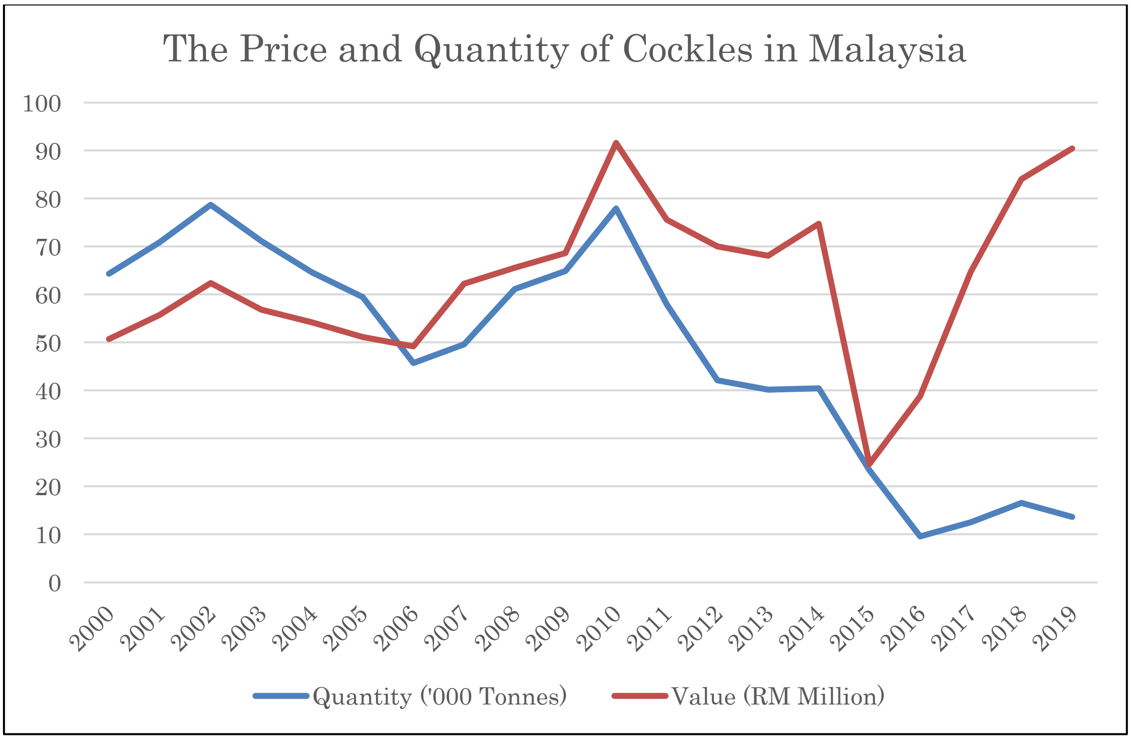

Figure 4: The Price and Quantity of Cockles in Malaysia from 2000 to 2019.

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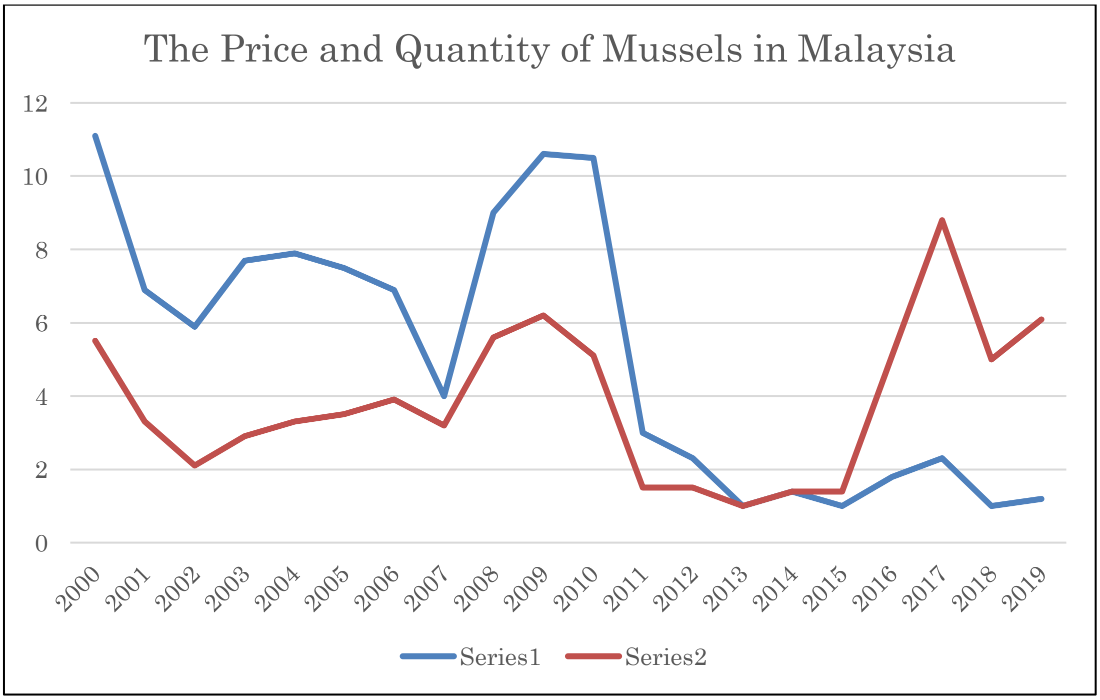

Figure 5: The Price and Quantity of Mussels in Malaysia from 2000 to 2019.

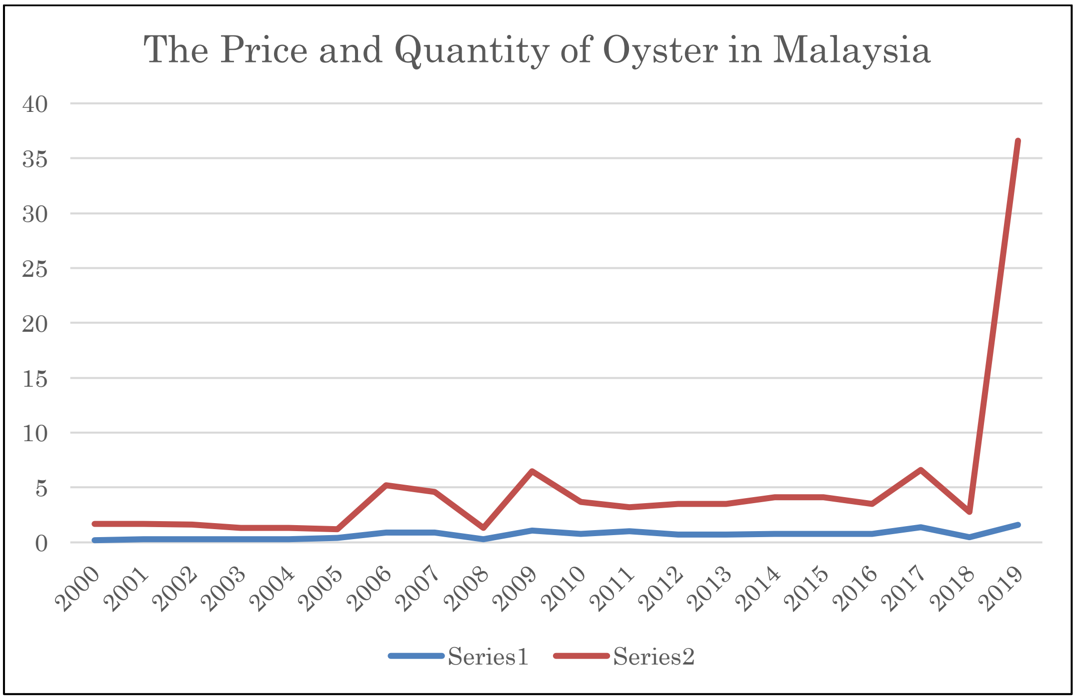

Figure 6: The Price and Quantity of Oyster in Malaysia from 2000 to 2019.

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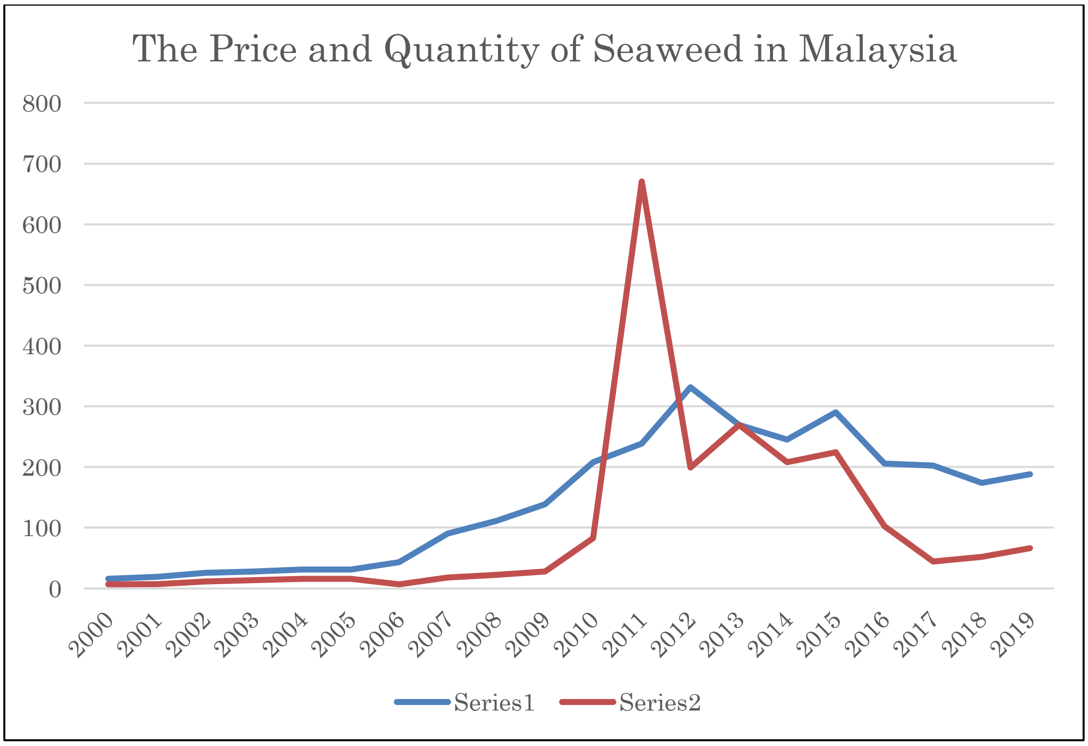

Figure 7: The Price and Quantity of Seaweed in Malaysia from 2000 to 2019.

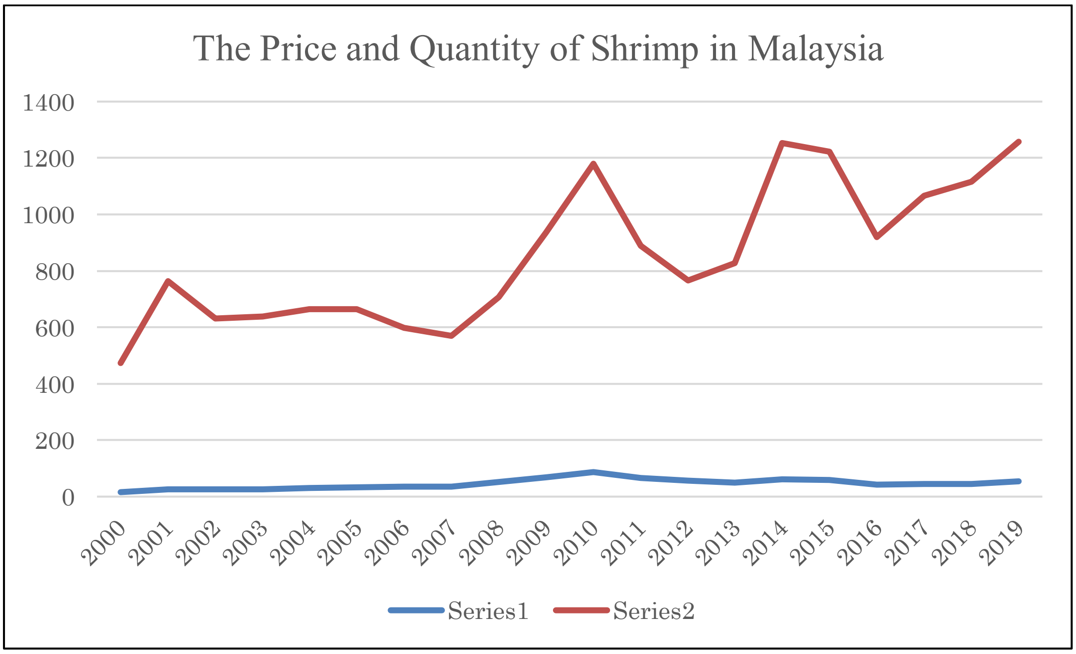

Figure 8: The Price and Quantity of Shrimp in Malaysia from 2000 to 2019.

From 2000 to around 2010, cockle production in Malaysia was relatively stable, with quantities fluctuating moderately due to seasonal variability and disease outbreaks. However, after 2012, cockle quantity declined significantly, largely attributed to habitat degradation, overharvesting, and rising mortality linked to sediment changes and pollution in mudflat areas. This sharp decline in quantity pushed cockle prices upward, especially between 2015 and 2019, when shortages became severe. As supply diminished, market prices rose faster than other bivalves, indicating that cockles became increasingly scarce relative to domestic demand. Thus, the price-quantity relationship during this period showed a clear inverse trend, when falling production volumes corresponded with consistently rising prices.

Mussels generally exhibit more stable production and pricing trends compared to cockles because they grow well in both wild and cultured systems and rely on simple farming techniques such as rope culture. Their quantity is influenced by water temperature, plankton abundance, and coastal water quality. When mussel farms experience high growth rates and good survival, the market is often well supplied, keeping prices moderate. However, harmful algal blooms, red tides, and red contamination events can temporarily halt harvesting, causing the prices to increase. Mussels are typically one of the most cost-efficient shellfish to produce, keeping their long-term prices relatively stable.

Oyster production is closely tied to hatchery success, seed availability, and the condition of farming waters. The quantity of oysters on the market increases when hatcheries produce strong seed cohorts, and farms can grow oysters to market size without major mortality events. Because oysters are a premium product in many markets, their price often remains higher compared to other shellfish. Prices also respond strongly to quality grading. Supply disruptions from diseases like Perkinsus marinus or environmental issues reduce market quantity and lead to price surges, reflecting the species' higher market sensitivity.

Seaweed production is generally high volume and price elastic. Seaweed farming requires relatively low input costs and can expand rapidly, leading to large quantities entering the market, especially in coastal Southeast Asia. However, seaweed prices are strongly influenced by global demand from the food industry. When demand from processors rises, prices increase even if quantity remains high; when demand weakens, prices fall sharply despite steady production. Quantities fluctuate depending on farm productivity, feed prices, disease outbreaks, and export demand. When production increases through intensification and improved disease control, shrimp quantities rise, and prices may decline. However, even minor disease outbreaks cause immediate supply shortages, quickly raising prices due to strong international demand. Shrimp remains the most economically sensitive species, reflecting the interplay between high production costs, global trade pressures, and environmental vulnerability.

The multiclass regression model was applied to classify seven fish species-Bream, Roach, Whitefish, Parkki, Perch, Pike, and Smelt-using morphological variables, such as width, height, and average length. In the context of aquaculture, this model explains how measurable body dimensions can reliably distinguish species that are often managed, monitored, or harvested together. By estimating the probability of each species based on physical traits, the model provides a data-driven

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method for species identification that supports stock assessment, grading, and production planning.

The results show clear morphological separation among species that aligns with their biological and production characteristics. Larger and deeper bodied species, such as Bream and Pike, are strongly associated with greater width and length, which increases their likelihood of classification and reflects their higher biomass yield and space requirements in culture systems. In contrast, smaller and more slender species, such as Smelt and Whitefish, are characterized by lower width and height values, making them more distinct in mixed-stock environments. Roach, Perch, and Parkki display intermediate body dimensions, with classification influenced by the balance of three measurements. This indicates that width and length are primary drivers of species separation, while height helps refine distinctions among mid-sized species.

Synthesising these results, the logistic regression demonstrates that body shape metrics can effectively differentiate fish species relevant to aquaculture operations. The flow of interpretation moves from identifying the model's role, to understanding how specific physical traits influence species probabilities and finally applying these insights in a production context. Practically, such findings can support automated species sorting, optimise tank or cage allocation, and improve growth monitoring and harvest decisions. Overall, the model reinforces the importance of integrating morphological data into aquaculture management to enhance efficiency, reduce misclassification, and support sustainable production practices.

CONCLUSION

Overall, the findings demonstrate that while florfenicol, formalin, and hydrogen peroxide remain essential treatment agents for maintaining fish and shrimp health in aquaculture, their use presents interconnected environmental, operational, and economic implications. Florfenicol is effective against bacterial infections but poses ecological risks through its persistence in sediments and impacts on non-target microbial and plankton communities, highlighting the challenge of antibiotic residues in aquaculture effluents. These concerns reinforce the need for integrated mitigation strategies, such as combined photodegradation and microalgal bioremediation, to reduce antibiotic loads while recovering nutrients and improving water quality. Spatial and economic analyses from Canada and Malaysia further show that expanding freshwater aquaculture areas, increasing numbers of culturists, and species-specific production dynamics directly influence water consumption, management practices, and market price–quantity relationships. Declines in sensitive species such as cockles contrast with the relative stability of mussels and the high economic sensitivity of shrimp, underscoring the role of environmental stress and disease in shaping supply and pricing. Finally, the application of morphological-based regression modelling demonstrates the value of data-driven tools for species identification and production planning. Collectively, these results highlight the importance of integrated health management, environmentally responsible treatment strategies, and advanced analytical approaches to support sustainable and resilient aquaculture systems.

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