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AQUATIC FOODS IN LOW-EMISSION FOOD SYSTEMS TRANSFORMATION IN VIETNAM:

OPPORTUNITIES, CHALLENGES AND FUTURE PATHWAYS

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TRANSFORMING AQUACULTURE IN VIETNAM: A REVIEW OF PROMISING LOW-EMISSION TECHNOLOGIES AND INNOVATIONS

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Abstract

Vietnam is one of the top aquaculture producers in the world. Over the past decades, the aquaculture industry has played an essential role in the country's socio-economic development. However, the expansion and rapid growth of the aquaculture sector also results in environmental issues, as aquaculture farming is associated with greenhouse gas emissions (GHG). There is thus an increasing concern about the environmental impacts of aquaculture operations. To reduce the detrimental impacts of aquaculture activities on the environment, applying technologies and innovations that can reduce GHG is necessary. This would promote sustainable aquaculture development in Vietnam and help Vietnam achieve net-zero emissions by 2050 Vietnam's government had committed. The main objective of this research is to review potential technologies and innovations used in the Vietnamese aquaculture sector that help reduce greenhouse gas emissions. To this end, a literature review was conducted. This review can provide critical information for aiming at sustainable aquaculture development and the low-carbon emission aquaculture industry by adopting potential low-carbon emission technologies in Vietnam. The research identifies several promising technologies that Vietnam's aquaculture industry can apply. Policy implications and recommendations are also presented in this study.

1. INTRODUCTION

It is undeniable that aquaculture makes an essential contribution to income, food, and nutrition security in many countries worldwide. While wild-caught fish tend to decrease, expanding aquaculture production is necessary to meet the increasing global demand for fish consumption. Over the past decades, global aquaculture production has increased dramatically, from about 20 million tons in 1991 to over 120 million tons in 2020 (FAO, 2022). However, as the aquaculture sector further expands and intensifies, there have been increasing environmental concerns, including water pollution, ecological degradation, and greenhouse gas emissions (GHG) that are associated with aquaculture activities (Ahmed & Turchini, 2021a; MacLeod et al., 2020).

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Vietnam was the world's fourth-largest aquaculture producer, with 4.6 million tons in 2020 (FAO, 2022). Aquaculture has emerged as an essential industry for socio-economic development, food security, and poverty alleviation in Vietnam, particularly in coastal and rural areas. In 2023, aquaculture production reached 5.4 million tons, and export value (including capture fisheries) was at 8.96 billion US dollar (VASEP, 2024a). The fisheries industry provides a million employments for people in the country, especially in rural and coastal areas. Annually, the fisheries sector, including aquaculture, contributes 4-5% to Vietnam's GDP. The year 2022 witnessed the first time when Vietnam's seafood exports reached a record of 10 billion USD (VASEP, 2024b).

There are diverse farmed species in Vietnam being farmed in freshwater and brackish water, and marine water environments. The farmed species can be classified into some main groups, including fish (catfish, tilapia, carps, snakehead fish, marine finfish such as cobia, seabass, and groupers), shrimp (white-leg shrimp, tiger shrimp), mollusk (oysters, clam), lobster, and seaweeds. However, catfish (*Pangasianodon hypophthalmus)* and shrimp are the most important aquaculture species in terms of production and value in Vietnam. Specifically, in 2023, total catfish production was about 1.7 million tons, earning 1.9 million US dollars from export while shrimp production was about 1.5 million tons with export value reaching 3.5 million US dollars (Directorate of Fisheries, 2023). Aquaculture activities have been practiced in almost all water areas in Vietnam. However, the Mekong Delta, a Southern part of Vietnam, is a well-known aquaculture area, especially for shrimp and catfish. It is estimated that about 95% of catfish farming and 80% of shrimp production are from this region (VASEP, 2024a).

The importance of the aquaculture sector to the socio-economic development of Vietnam, especially in rural and coastal areas, is undeniable. However, the expansion and rapid growth of aquaculture activities pose environmental challenges because some forms of aquaculture farming are associated with greenhouse gas emissions (GHG) (Nhu et al., 2016). There is thus an increasing concern about the environmental impacts of aquaculture practice. When aquaculture activities expand and intensify, there is also increasing pressure on the surrounding environment. To tackle environmental challenges, there is increasing interest in aquaculture technologies and innovations that can be applied to reduce GHGs in aquatic farming. The application of low-carbon technologies and strategies is essential for sustainable aquaculture development (Nazar et al., 2024). Moreover, the use of low-carbon production technologies in the aquaculture industry also would partly help Vietnam to achieve net-zero emissions by 2050 Vietnam's government has a commitment to net-zero emissions by 2050 at the 2021 United Nations Climate Change Conference (COP26) (Nguyen & Espagne, 2024).

The main objectives of this paper are to (i) identify potential technologies and innovations used in the Vietnamese aquaculture sector that help reduce greenhouse gas emissions; (ii) identify the constraints and challenges that influence the adoption of low-carbon emission technologies among aquaculture producers; and (iii) provides recommendations and implications for low carbon aquaculture production in Vietnam.

The remainder of this research is structured as follows: Section 2 presents the methodology used in this research. Section 3 analyzes research findings and discussions. Section 4 presents conclusions.

2. METHODOLOGY

This study applied various methods, including a literature review and focus group discussion. In the first stage, a literature review is conducted to identify potential technologies and literature relevant to the study topic. In the second stage, focus group discussions are held to examine the ability to scale up the potential technologies identified in the first stage for transforming aquaculture to low-emission production systems in the Vietnamese context.

A broad review of existing literature is important to provide a comprehensive overview of the study topic (Tranfield et al., 2003). The process of literature review used in this study includes searching and identifying relevant documents and existing literature using Google Scholar and journals. Several keywords were used to capture a wide range of literature that included Aquaculture, Greenhouse Gas Emission, Low Carbon, Green and Blue Economy, and Blue Ocean Economy, among others. Furthermore, the study also applied a focus group discussion approach to provide in-depth insights about potential technologies and innovations used in Vietnam's aquaculture sector. The workshop was held in Can Tho City, South Vietnam, on 26 December 2022 with 29 participants. The participants invited to the workshop came from different segments and actor groups of the aquaculture industry, including hatchery operators, fish/shrimp farmers, aquaculture cooperatives, University researchers/lecturers, research institutions, non-government organizations, and government bodies. In the workshop, a number of potential technologies identified in stage one were recommended, and then the participants evaluated the ability to scale up these technologies and their advantages and disadvantages when used for aquaculture in Vietnam.

3. POTENTIAL LOW-CARBON EMISSION TECHNOLOGIES USED IN AQUACULTURE

3.1. Renewable energy used in aquaculture

Energy used in aquaculture, including electricity and diesel, is essential for farming activities. Aquaculture activities need energy for their operations, including pond preparation, farm operating, water pumping, water and waste treatment, operating aerator systems, and other farming activities. It is estimated that the cost of energy use for aquaculture accounts for a significant amount of total production expenses, about 10% (Viet Nam Electricity Group, 2024). While aquaculture heavily relies on fossil fuels, a transition from using fossil fuels to renewable energy is necessary to reduce greenhouse gas emissions and lower operational costs (Robb et al., 2017; Scroggins et al., 2022; Tien et al., 2019). As the aquaculture sector continues to expand, driven by increasing domestic and international demand, the increase in energy used for aquaculture activities is inevitable. The aquaculture activities are associated with greenhouse gas emissions that are released into the surrounding environment. The need for reliable, green, and renewable energy sources becomes essential in aquatic farming for sustainable and green growth. It is admitted that renewable energy sources, such as solar and wind energy, are viable and environmentally friendly alternatives (Boston Consulting Group, 2019). The use of solar energy sources in the aquaculture sector can be found in many countries in the world, including China, America, Canada, Germany, and Korea (Vo et al., 2021).

Located in a tropical and sub-tropical country, Vietnam has great potential to develop renewable energy, including wind and solar, due to its favorable conditions. The country has an estimated capacity to generate approximately 2847 GW of electricity from solar photovoltaics (PV), with a levelized cost of electricity that remains competitive (Do et al., 2020). Since 2019, Vietnam has become the leader in solar and wind electricity adoption in the ASEAN area (Do et al., 2020, 2021). Noicetally, both solar PV and installed wind power capacity have experienced a dramatic expansion in recent years, rising from 4.7 TWh in 2019 to 9.5 TWh in 2020 (Do et al., 2020). The large potential solar and wind resources provide the country with great opportunities to significantly decarbonize its industries, including the aquaculture sector.

Regarding aquaculture, although grid-sourced energy is available for farming areas, aquaculture farms are also located in remote off-grid locations, and/or national electricity is sometimes not enough to supply all farms. Furthermore, in some farming regions with frequent energy outages, shrimp farmers must operate their cultural activities using expensive diesel power generation, partially or fully, to provide backup energy. With great potential solar and wind resources, the decline in the costs of solar PV modules, and enabling technologies would provide fish farmers to approach renewable power for their farming. Using renewable energy provides a viable solution to meet the energy demands of aquaculture while simultaneously addressing environmental concerns in the aquaculture industry. Aquaculture operations can significantly reduce their reliance on fossil fuels by using solar energy, lowering greenhouse gas emissions, and contributing to climate change mitigation efforts (Vo et al., 2021). Solar energy can be used in aquaculture for several purposes that include power generation, use for aerators, feeding dispensers, heating, pumping, household domestic use (Kim & Zhang, 2018; Vo et al., 2021; Zainal Alam et al., 2023).

Figure 1. Solar power used in aquaculture

The application of renewable technology, such as solar energy, has been practiced in several aquaculture regions in Vietnam. The use of renewable energy, especially solar power, seems to be suitable for both large-scale and small-scale farming activities, especially in shrimp farming. Compared to oil-powered oxygen aerators, shrimp farmers could reduce operating costs by 2-3 times if solar-powered oxygen aerators are used (Phu & Nguyen, 2022). A model that mixed wind turbines, solar panels, and a battery bank could be potential for shrimp farming. Using a mixed wind system and PV arrays are the suitable renewable energy sources for improving the dissolved oxygen (DO) concentration in a cultured pond, saving power costs, reducing operation costs, and decreasing the amount of CO2 emissions (Tien et al., 2019). The figure below shows a model of solar power used in aquaculture in Vietnam, proposed by the Fraunhofer Institute for Solar Energy System. The project is to support PV's potential to solve the energy demand issues of land-based aquaculture systems. The Fraunhofer Institute announced that a one-megawatt pilot plant may cut CO2 emissions by about 15,000 metric tons each year and cut water consumption by 75% compared to a conventional shrimp farm (Nestor, 2019).

Figure 2. A solar model used for shrimp farming in Vietnam

Source: Nestor, (2019)

However, the use of solar power in aquaculture has been limited due to several barriers and constraints. The barriers and obstacles that hinder farmers and businesses from using solar energy mainly include high initial investment costs (especially for large-scale farming), high level of uncertainties from policies (market mechanism, transmission grid system…), complex administrative procedures for installation, and a lack of appropriate support from the government (Do et al., 2020; Peter Makinde & Esther Obikoya, 2024).

3.2. Recirculating aquaculture systems (RAS)

With the expansion and development of the aquaculture industry, the traditional extensive aquaculture practices are suffering several challenges, such as high reliance on land and nature spaces, disease outbreaks, water and land pollution, and other uncontrollable factors, which are not conducive to the sustainable development of aquaculture (Li et al., 2023). Recirculating Aquaculture Systems (RAS) is an approach that can overcome these challenges by increasing the resources reused and minimizing waste discharged. RAS is based on a multidisciplinary engineering approach that combines biology, mechanical engineering, hydrochemistry, hydromechanics, electrical engineering, and aquaculture science sectors (Li et al., 2023). Recirculating Aquaculture Systems are seen to be eco-friendly, water efficient, highly productive intensive farming systems, which are not associated with adverse environmental impacts, such as habitat destruction, water pollution, eutrophication, ecological effects on biodiversity due to disease outbreaks, and parasite transmission (Ahmed & Turchini, 2021b). However, high energy consumption and then greenhouse gas emissions are the two most common limitations of Recirculating Aquaculture Systems. High energy requirements for water recycling and temperature controls increase operational costs and the potential impacts of using fossil fuels (Badiola et al., 2018; Zhang et al., 2023). To tackle these drawbacks, a possible solution is to use renewable energies as an alternative solution in RAS (Badiola et al., 2018). Moreover, RAS requires high investment of cost and complexity for system design, thus the application of RAS in a number of developing countries has been limited (Ahmed & Turchini, 2021c). Another drawback of RAS is that this technology seems to be suitable for large-scale production facilities (Frank, 2012). Since the first introduction in 1950s in Japan, RAS has been applied in many countries due to its unique advantages and supporting policies (Li et al., 2023). RAS has been used to rear various aquatic species, including 46 species of fish, 11 species of crustaceans, 7 species of mollusks, and 7 species of *Echinodermate* organisms (Li et al., 2023).

In Vietnam, several pilot projects in RAS were implemented and showed that RAS can offer a number of advantages compared to conventional farming practices. For instance, a white-leg shrimp RAS farming project was conducted in Hai Phong City, a Northern area in Vietnam, by the Institute of Resources and Marine Environment under the Vietnam Academy of Science and Technology. The results of this project proved that by using RAS shrimp farming, farmers can improve economic efficiency due to the chemicals and antibiotics used in this system, increasing crop per year, and stable production. Shrimp farming is considered to be a risky business and shrimp farmers are often at risk of losing their crops because of environmental pollution, natural disasters, and diseases (Joffre et al., 2018; Nguyen et al., 2021). However, with RAS shrimp, farmers can reduce the risk of disease infections as water environment factors are well-controlled. Furthermore, RAS farming can save space, water and then reduce production costs, shrimp farmers can increase high economic returns (Dinh, 2024). Another project was implemented in southern Vietnam, where RAS is used for tilapia farming. The results of this project showed that the productivity of tilapia increased nearly four times compared to traditional farming (Dao, 2019). RAS can also be applied in cities where space and land for farming are limited. For example, there are several projects that applied RAS for crab *(Scylla sp.)* farming in Hanoi and Ho Chi Minh cities where land for farming is limited (Diep, 2024). Using this model, farmers can produce 3 crops per year and can earn considerable profit (Diep, 2024).

It is worth noting that RAS technology has been applied in a number of projects in several areas in Vietnam, but the application of this technology in practice by fish farmers has been quite limited due to several constraints. RAS requires high initial investments (Ahmed & Turchini, 2021c) and high energy requirement (Badiola et al., 2018). It seems only to be suitable for large-scale farming operations with high-value species. Furthermore, RAS modes need skilled workers and technicians to operate the system, while most fish farmers in Vietnam have limited education levels and skills (Thị et al., 2022). Furthermore, most aquaculture farming in Vietnam is small-scale and operated at the household level. The high initial investment cost is a major constraint for farmers to adopt. The adoption of this technology also depended on the economic feasibility of this model (Ngoc et al., 2016). Other factors such as farm location, farmer's socio-demographics, and characteristics (e.g., age, gender, income), finance access, among others can be factors that might prevent aquaculture farmers from adopting RAS (Ngoc et al., 2016).

RAS technology requires high energy use, although renewable energy can tackle this drawback. To reduce the energy use for RAS, integrating renewable energy sources, such as solar power, can improve the financial and environmental feasibility of the RAS model (Clough et al., 2020; Vo et al., 2021). Existing literature shows that renewable energies are more cost-effective than fossil-based fuels (Badiola et al., 2018). While Vietnam has tremendous potential for renewable resources, including solar and wind power, integrating RAS and renewable energy sources would be a potential measure to reduce the operational cost of fish farming and greenhouse emissions in the aquaculture industry.

3.3. Integrated Aquaculture- Agriculture system

Integrated Agriculture-Aquaculture (IAA) systems combine aquaculture with broader farming practices to enhance productivity, resource efficiency, and environmental sustainability (Zajdband, 2011). In general, IAA systems include three main sub-systems: agriculture, aquaculture, and household activities (Lua, 2021). The IAA might combine systems with rice, fruit trees, vegetables, pigs, poultry, and fish/shrimp (Phong, Stoorvogel, et al., 2011). IAA system is an ecological agricultural model that both adapts to climate change and brings sustainable economic efficiency for households as the nutrients between farm components can be recycled (Prein, 2002). The IAA model is a promising approach to reducing the environmental impacts of farming while increasing farming output (Nhan et al., 2007). Livestock manure and other farm wastes could be used to fertilize fishponds, pond sediment, and aquaculture wastewater are also used to fertilize crops, and crop by-products are used to feed livestock and shrimp/fish (Prein, 2002). The Integrated agriculture–aquaculture (IAA) farming model has been widely applied in Asia including in Vietnam as a form of farming diversification (Phong, de Boer, et al., 2011; Phong, Stoorvogel, et al., 2011). Ponds within IAA farming systems sequester more carbon per unit area than conventional fishponds, natural lakes, and inland seas (Ahmed, Bunting, et al., 2017)

In Vietnam, the IAA farming system includes several combinations of fish, shrimp, livestock, cattle, gardening, and rice farming (Dang, 2020). The figure below presents an

IAA model in which catfish, cow, and gardening (i.e., grass planting and maize planting) are combined. Research results from the model show that the use of water Morning Glory helps to reduce water pollution. The authors indicated that an Integrated agricultural-aquaculture system not only helps improve the physical-chemical properties of cultivation soil and enriches the nutrients for the soil but also reduces the use of chemical fertilizer, leading to lower greenhouse emission (Tung, et al., 2021).

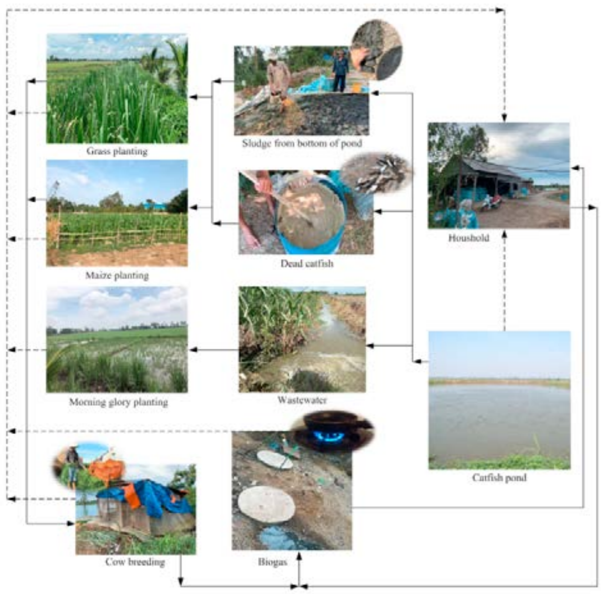

Figure 3. An integrated catfish-agriculture farming system

Source: Tung et al. (2021)

- **Rice-shrimp farming system**

The rice-shrimp/fish farming system is another IAA model that is considered to be an ecological agricultural model. This model can be seen as an economically effective and environmentally friendly system (Directorate of Fisheries, 2016). The rice-shrimp practice can limit pathogens arising in shrimp/fishponds while allowing rice plants to absorb organic substances in shrimp ponds. Moreover, rice shrimp systems also have the potential to improve livelihood, food security, and adaptation of coastal farmers (Dang, 2020). Thus, the rice-shrimp/fish farming system seems to be an adaptive model to climate change and offers sustainable economic efficiency for farmers (Pham et al., 2020; Thanh et al., 2019). This is important for farmers, especially in coastal areas where climate change (e.g., drought and salinity) might prevent them from rice monoculture farming. Rice farmers in coastal areas used to grow 2-3 crops of rice cultivation. However, due to prolonged salinity intrusion problems in recent years, rice farmers can only cultivate one rice crop per year (Directorate of Fisheries, 2016; Thanh et al., 2019). However, under the rice-shrimp/fish model, farmers can grow rice in the rainy season and can culture shrimp/fish in the dry season by allowing saline water into their fields (Directorate of Fisheries, 2016). Farmers can earn a diversification of income sources including rice and shrimp, about 4-5 tons of rice/ha/year and 0.3 - 0.5 tons of shrimp/ha/year (Directorate of Fisheries, 2016). Rice-shrimp fields also yield 15-30 percent higher profits than those where only rice and shrimp/fish are cultivated where saline water intrusion occurs in the dry season (Directorate of Fisheries, 2016). Furthermore, compared to rice and shrimp monoculture, the integrated rice-shrimp system can be seen as the most resilient to climate change by rice–shrimp farmers (Poelma et al., 2021). Under a rice-shrimp system, disease outbreaks are less likely to occur as rice farming can improve the soil, and shrimps are stocked at low density without feeding (Directorate of Fisheries, 2016). The rice-shrimp rotation model also provides social benefits such as employment creation, promotes the development of logistic activities, and reduces the use of chemicals and antibiotics (Thanh et al., 2019).

Over the past decades, the adoption of the rice-shrimp farming model has increased significantly, from 40.000 ha in 2000 to about 200.000 ha in 2019 (Directorate of Fisheries, 2024; Preston & Clayton, 2003). Due to its advantages, the model has been commonly practiced in the Mekong Delta area in Vietnam. Relevant stakeholders have paid attention to it as this can be seen as an effective approach for income diversification, food security, and adaptive measures to the climate change resilience of farmers.

Figure 4. Rice-shrimp model

Source: Dang (2020)

- **Mangrove-shrimp farming model**

Integrated mangrove-shrimp aquaculture has been a sustainable farming system and is used as one of the measures for mangrove rehabilitation and potentially sequestering blue carbon. This farming practice has become a part of the feasible measure for climate change and mitigating the anthropogenic footprints (Ahmed, Thompson, et al., 2017; Joffre et al., 2015). The environmental benefits of mangrove-shrimp aquaculture might include forest biodiversity conservation or coastal storm protection. Moreover, most of these ecological models are suitable for small-scale family farms, hence can minimize the effluent environmental impacts, such as water pollution from agrochemicals (Trang & Loc, 2021).

Over the past few years, mangrove shrimp farms have emerged in Mekong delta areas due to their favorable natural conditions. Traditionally, this integrated farming system depends on wild seeds entering the ponds through a sluice gate during spring tide. However, shrimp farmers have improved this practice by manually stocking shrimp in the ponds. Recently, ponds have also been stocked manually with mud crabs (*Scylla serrata*). Stocking of these species is all year round, and harvesting is usually conducted during spring tide for three to five days (Jonell & Henriksson, 2015). Under the mangrove-shrimp system, shrimp bred under extensive farming models eat primarily natural food in the mangrove forest. Although the profit is not as high as that from breeding shrimp under industrial farming, the model seems stable for shrimp farmers due to low operational costs and risks (e.g., disease and environment risks) (Binh et al., 1997). The mangrove-forest farming model is also a sustainable livelihood as it reduces the risk of shrimp disease while also maintaining forest coverage (Lua, 2021). Comparing traditional shrimp farming (without mangroves), intensive shrimp farming, and shrimp farming with mangroves, the mangrove-aquaculture system can provide a triple-win approach toward sustainable development (Nguyen et al., 2022) This is because the mangrove-aquaculture model provides the highest average benefit-cost ratio while demanding the least expensive investment costs, thereby being suitable for farmers with limited financial resources. Furthermore, the mangrove-aquaculture system can also bring other economic and environmental benefits such as carbon mitigation, low risk of shrimp farming model (Nguyen et al., 2022). Lai et al. (2022) showed that under the mangrove-shrimp approach, farmers with high forest cover would earn higher benefits than those with lower forest cover. This result implies that maintaining the cover of mangroves in farming systems would provide better economic and environmental benefits (e.g., reducing GHG emissions and playing an important role in coastal climate change adaptation) for farmers and society.

3.4. Aquaculture waste treatment and management

Sources of GHG emissions at on-farm activities come from different sources that include energy used, feeding, fertilizers, and domestic household activities (Robb et al., 2017; Xu et al., 2022). It is apparent that intensive aquaculture generates significant amounts of nutrient-rich sludge, representing a potential environmental threat (Tung, Thao, et al., 2021). Enriched organic molecules and nutrients in fish/shrimp pond sedimentation are thus a significant concern due to their effect on the intensification and management of ponds. Shrimp/Fishpond wastewater and sludge contain large quantities of solids, nitrogen, phosphorus, and algae. Several research shows that waste discharged from aquaculture practice is often regarded as the main factor responsible for potential detrimental impacts on the environment, primarily through the discharge of nitrogen and phosphorus as excreta and other metabolic products (De Silva et al., 2010a)Fish and shrimp farmers also face serious environmental problems from shrimp and fish pond waste, which mainly consists of shrimp feces, leftovers, peeled shrimp shells, and others. If such wastes are not properly treated, they pollute not only people's daily lives but also shrimp and fish ponds and the surrounding environment. Thus, reducing or reusing wastes from aquaculture would lead to lower GHG emissions at the farm level.

Regarding shrimp farming, it is notable that the feed conversion ratio in shrimp farming in Vietnam is around 1.3 (Anh et al., 2010), and then about 400gr-500gr waste would be discharged for a kilogram of shrimp production. Thus, effluent discharged from shrimp farming would contribute significant amount of waste into surrounding environment. Reducing or reusing shrimp's feces is possible way to reduce GHG in aquaculture. In Vietnam, shrimp's feces compressor has been used by shrimp farmers, especially intensive-shrimp farms. The potential advantages of using shrimp feces compressor are presented as follows:

Shrimp's feces compressor

- About 95-99% shrimp waste collected
- Reducing environmental impact: GHG, water pollution
- Reducing disease in aquaculture
- Reusing waste for agriculture and other aquaculture purposes (Artemia, tilapia farming)
- Low energy consumption 500W/h (100 VND/kg dried shrimp waste)
- Production cost: 200 VND/kg dried shrimp waste

Figure 5. Shrimp feces compressor information

In terms of fish farming, especially catfish, several studies in Vietnam have identified that catfish farming waste can be recycled as potential fertilizers for sustainable agricultural practices. Sludge from catfish ponds can be effectively used as organic fertilizer for rice, fruit tree, and maize cultivation, reducing the need for chemical fertilizers and improving crop yields (H. K. Nguyen et al., 2020). Moreover, catfish waste and sludge from catfish ponds can be utilized for soil cultivation and biogas production (Nhut et al., 2019; Tung, Tran, et al., 2021). It is estimated that a great amount of 50.364 tons of nitrogen and 15.766 tons of phosphorus were discharged in 2008 from catfish farming in the Mekong Delta region (De Silva et al., 2010b). Clearly, results from these findings indicate catfish waste and sludge can offer potential benefits in gardening and biogas production if the catfish waste and sludge can be treated and used for agricultural farming systems properly. Thus, when waste and sludge from shrimp and catfish, a major farmed species in Vietnam, can be properly used, it would contribute to more sustainable aquaculture and agricultural practices in Vietnam and help reduce the detrimental effects of aquaculture farming.

3.5. Feeding management

Existing literature shows that overfeeding can lead to disease outbreaks in cultured organisms, and uneaten feed residues can also pollute water bodies, which is neither economical nor beneficial to the health of aquatic organisms (Li et al., 2023). Research shows that feed is often regarded as the main factor responsible for potential detrimental impacts on the environment primarily through the discharge of nitrogen and phosphorus as excreta and other metabolic products (De Silva et al., 2010b). On the other hand, feed costs made up to 60% of total production costs (White, 2013). Thus, improving the efficient use of feed could help reduce GHG and production costs during farming practices while increasing the economic performance of fish farmers (Huysveld et al., 2013; Ton Nu Hai & Speelman, 2020).

The proposed measure for feeding management is to apply modern feeding and pond management technologies. Thanks to the advancement of the Internet, artificial intelligence (AI), and smart agriculture models, the application of the Internet of Things (IoT) and AI in aquaculture could be a feasible measure for aquaculture farming management (Aung et al., 2024; Mandal & Ghosh, 2024). An important application of AI in aquaculture is the development of smart monitoring systems that can help fish farmers adjust feeding schedules, modify water conditions, and administer treatment if needed (Mandal & Ghosh, 2024). A number of studies proved that deep learning models can be incorporated into feeding systems that can reduce the amount of leftover feed and the need for excessive use of antibiotics and chemicals (Chiu et al., 2022; Mandal & Ghosh, 2024)

It is undeniable that the application of advanced technologies in aquaculture could help improve the economic efficiency of fish farmers and reduce the negative impacts of farming on the environment by reducing uneaten feed and excessive use of chemicals and antibiotics. However, the adoption of these models requires high investment expenses, high skilled workforce, and support from the government while most of the fish/shrimp farms in Vietnam are small-scale and small-family farms (Boston Consulting Group, 2019).

3.6. Mariculture development

Viet Nam is a marine nation with enormous potential for mariculture development due to its favorable natural resources. Specifically, the country has a coastline of 3.260 km from the North to the South, a million square kilometers of Exclusive Economic Zone (EEZ), more than 3000 islands, a variety of bays, lagoons, and estuaries that are considered to be suitable for sea culture. It is noted that land-based aquaculture seems limited to expansion due to urbanization, soil and water degradation, climate changes (salinity intrusion, drought, a lack of suitable water sources), and others. Fish farming in freshwater and brackish water areas could result in a number of environmental externalities such as eutrophication, disease outbreaks, antibiotic pollution, ecosystem degradation, and mangrove deforestation, among others (Chen et al., 2023; Xu et al., 2022) while aquatic farming at sea has great potential for development. Furthermore, mariculture products could provide a climate-friendly, high-protein food source, because they often have lower greenhouse gas emission footprints than do the equivalent products farmed on land (Jones et al., 2022). Seaweed and bivalve farming are recommended for carbon sequestration (Song et al., 2024). Seaweed aquaculture, the fastest-growing component of global food production, can provide a slate of opportunities to mitigate and adapt to climate change (Duarte et al., 2017). Seaweed farming can release carbon, which is buried in sediments or exported to the deep sea, therefore acting as a CO2 sink. The crop can also be used, in total or part, for biofuel production which is environmentally friendly fuel (Duarte et al., 2017). Furthermore, additional benefits from seaweed farming might include potential reductions in agricultural emissions, shoreline protection, and local mitigation of ocean acidification (Duarte et al., 2017; Holgate & Ruddy, 2023).

Despite of huge potential of marine resources for marine aquaculture, the development of the industry has been far below its potential. While the expansion of land-based aquaculture in Vietnam seems limited, the development of mariculture is essential for the sustainable development of Vietnam's aquaculture sector. The development of mariculture would contribute to low-emission aquaculture production in Vietnam. However, there have been several constraints that hinder the development of the mariculture industry. For instance, mariculture production is mostly small-scale and uses traditional and outdated technology. Fish farmers often lack financial investment capacity, and they also face a variety of risks such as climate change, disease outbreaks, and markets. Mariculture zoning and maritime spatial planning, and allocation of sea areas to fish farmers and organizations are also considered to be barriers to the development of the sector (Quang et al., 2023). Thus, a number of measures should be promoted and carried out to promote the development of the mariculture industry.

3.7. Integrated multi-trophic aquaculture

Integrated Multitrophic Aquaculture (IMTA) is a system where aquaculture species from various trophic levels are integrated, leading to increased resource use efficiency (Chopin, 2010; Hossain et al., 2022). Through IMTA, some of the food, nutrients, and by-products from the fed component (e.g., uneaten foods, solid waste, and dissolved nutrients) are recaptured and turned into harvestable and healthy seafood of commercial value. In this way, IMTA promotes economic and environmental sustainability by converting byproducts and uneaten feed from fed organisms into harvestable crops, thereby reducing environmental effects and increasing economic diversification (Chopin, 2010; Lal et al., 2023). Furthermore, the Integrated Multi-Trophic Aquaculture system is also known as a promising model to reduce greenhouse gas emissions and enhance carbon sequestration in coastal ecosystems. IMTA can sequester more blue carbon in comparison with conventional aquaculture. This is because the translocation of shrimp farming from mangrove swamps to offshore areas IMTA could reduce mangrove loss, reverse blue carbon emissions, and in turn, increase storage of blue carbon through restoration of mangroves (Ahmed, Bunting, et al., 2017).

In general, the potential of IMTA to address environmental challenges while promoting sustainable aquaculture practices has been well documented in existing literature.

IMTA system has great success potential in various types of waters, with a variety of aquatic-fed species of fish and seaweeds in some countries worldwide. Existing literature has demonstrated that IMTA outperforms conventional polyculture in terms of environmental remediation, productivity, and economic returns (Biswas et al., 2020), and has the potential to boost the blue revolution in the near future (Lal et al., 2023). Wang et al., (2012) examine nutrient waste from Norwegian salmon farms in 2009. The results showed that IMTA can utilize excess nitrogen and phosphorus, thus reducing environmental impacts. Chopin (2010) also emphasizes that IMTA not only recaptures nutrients but also improves the sustainability and profitability of aquaculture by integrating fed and extractive species. Hossain et al., (2022) reviewed the application of IMTA and showed that IMTA can minimize the detrimental effects of aquaculture, assist local economies, and boost competitiveness and long-term economic viability.

In Vietnam, Tran et al., (2020) surveyed 80 aquaculture farmers in Central Vietnam, and the results indicated that the integrated shrimp-tilapia polyculture model yielded higher economic, lower feed and pond preparation costs than those using non-integrative practices. The results implied that the shrimp-tilapia polyculture model helps increase farmer's welfare and enhance the climate change resilience of farmers.

Although IMTA can be seen as a promising approach to sustainable aquaculture development, this practice has not been widely applied in Vietnam. Most IMTA systems are ongoing projects, initiatives, or trial experiments (Anh et al., 2024; Nguyen et al., 2023; Thuy et al., 2024). To move research from the pilot scale to the commercial scale and scale-up stage, regulations and support from relevant stakeholders are needed. Investment to strengthen institutional capacity to help farmers access markets and financial services is required (Tran et al., 2020). Furthermore, supporting industries such as cages and materials for marine aquaculture, logistic services, infrastructure, breeding technology, policies and regulations (e.g., marine area allocation, marine spatial planning), and a lack of skilled workforce are also limitations to the adoption of IMTA in Vietnam.

4. CONCLUSIONS

Over the past decades, the Vietnamese aquaculture sector has made a significant contribution to the socioeconomic development of the country. However, the expansion of aquaculture could lead to increasing environmental issues, especially greenhouse gas emissions. Vietnam's government has committed to achieve net-zero emissions by 2050 at the 2021 United Nations Climate Change Conference (COP26). Thus, transformation to a low-carbon emission aquaculture industry would not only boost the sustainable development of the aquaculture industry but partly help Vietnam reach its commitment.

There have been a number of potential technologies and models that can be applied and scaled up in aquaculture sector to reduce GHG emission in Vietnam. These include switching from fossil fuel use to renewable energy use, adopting RAS, IAA and IMTA modes, aquaculture waste farming management, feed management, and expansion and development of mariculture. Each of this technology and model has its own advantages and requires certain conditions to adopt it by fish farmers. The application of these technologies and models in practice in Vietnam has been limited for a number of reasons, thus policies and support from government and stakeholders play an important role to promote the application of these technologies and modes in reality. Policies and support from government such as capital investment, funding for research and technology development, technical training and education programs, among others should be provided. Market, production and consumption mechanism that are relevant to green products should also be promoted. Strategies, polices and master plans for green growth and low-carbon emission in aquaculture need to be paid attention by stakeholders.

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