INITIATIVE ON
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Synthesis of baseline GHG emission data and estimation methods in aquatic food systems in Vietnam

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List of abbreviations

FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gas
NDC	National Determined Contribution
UNDP	United Nations Development Program
UNFCCC	United National Framework Convention on Climate Change
WB	World Bank
AD	Activity Data
EFsl	Emission Factors
SFs	Sequestration Factors
LCA	Life Cycle Assessment
FCR	Feed Conversion Ratios
IQF	Individually Quick Frozen (IQF)

1. Executive summary

Drawing data and information from desk-based reviews, key informant interviews, and group discussions with relevant stakeholders in Vietnam, this working paper compiled and analyzed emission baseline data of greenhouse gas (GHG) from Vietnamese aquatic food systems, focusing on key aquaculture systems of fish, crustaceans, mollusks, and seaweed, together with capture fisheries and post-harvesting and processing of aquatic foods. Vietnam's total aquatic food production in 2021 was about 8.79 million tons (4.86 million tons from aquaculture and 3.94 million tons from capture fisheries) and brought about USD 8.89 billion in export values to the country (D-Fish, 2022c). Of this total, pangasius catfish and brackish water shrimp (*P. monodon and white leg vannamei*) are key products nationally. In 2021, they contributed about 17.32% and 10.58% in total seafood production volume and about 18.22% and 43.87% in total seafood export value, respectively.

Besides contributing to local and national socio-economic development and supporting sustainable livelihoods, aquatic food systems also emit GHGs, contributing to global warming and climate change. IPCC has developed guidelines for calculating GHGs from the agriculture sector, including aquatic farming systems (IPCC, 1996, 2006, 2014, and 2019; WRI and WBCSD, 2013).[1] The IPCC methodological approach combines information on the extent to which human activity occurs, called activity data (AD) with coefficients that quantify the emissions or removals per unit activity, called emission factors (EFs). Following the IPCC guidelines, the basic equation is emissions = AD x EF.

According to the IPCC 1996 guideline, EFs are usually categorized into three tiers representing methodological complexity. Tier 1 is the basic method, and default factors are supplied. Tier 2 requires country-specific information. Tier 3 is the most demanding in terms of complexity and data requirements, usually involving detailed experiments and modeling. Tiers 2 and 3 are sometimes referred to as higher-tier methods and are generally considered to be more accurate and appropriate for computing and extrapolating GHG emissions to the national total. The default data or tier 1 methods for all categories are designed to use readily available national or international statistics combined with the default emission factors and additional provided parameters. Therefore, they should be feasible for all countries.

There is, however, a need to compute EFs with tiers 2 and 3 for various AD in the aquatic food sector in both global and national contexts. To date, EFs with tier 1 are mainly applied in calculating GHGs for aquatic systems. Still, tier 1 EFs for pellet feed use is not available for these calculations, and no reliable tier 3 EFs for aquatic food systems is available in the Vietnamese context. These shortcomings are because there are limited GHG emission studies done on Vietnam's aquatic food sector. Nonetheless, there were emission estimations of GHGs carried out disjointedly in several studies in Vietnam and other countries around the world. These provided a preliminary, scattered picture of GHG emissions in aquatic food systems, from production to post-harvesting, and mainly focused on key aquatic systems, like shrimp, tilapia, and catfish.

According to the GHG Protocol (Agricultural Guidance) (WRI and WBCSD, 2013), in the agricultural sector, including aquaculture, there are two main sources of GHG emissions: mechanical sources and non-mechanical sources. Mechanical sources include the use of equipment and machinery for aquaculture, such as excavators, pond diggers, water pumps, water paddlewheels, aeration, means of transporting inputs and raw shrimp and fish, etc. The amount of GHG emissions (N_2O, CH_4, CO_2, and others) from this mechanical source depends on the characteristics of the machinery and equipment and the energy input used (electricity or fuel). The main sources of non-mechanical emissions are related to biological and productive processes that take place on land and in water, as well as the growth and development of aquatic animals raised on farms and product harvesting processes, such as using food, chemicals, veterinary drugs, probiotic products in aquaculture farming, and emitting major gases of N_2O, CH_4, CO_2, etc.

Various studies conducted by Akvaplan-Niva (2010), Chang et al. (2017), Henriksson et al. (2014), Nguyen et al. (2019), and Natasha et al. (2017) show that emission estimations of GHGs from aquatic food systems still contain uncertainty and varied substantially based on the scope of GHG calculation, applied methods, and the nature of farming and fishing technologies. Concerning emission sources, feed production and on-farm electricity use are major drivers of aquatic farming systems' GHG emissions (Parker, 2012; Pathak et al., 2013; Akvaplan-Niva, 2010). This evidence was illustrated in shrimp farming (Nguyen et al., 2019) and catfish farming (Robb et al., 2017) in Vietnam and shrimp farming in China (Chang et al., 2017). In capture fisheries, fuel consumption during fishing also greatly contributed to GHG emissions from motorized fishing vessels (Parker, 2012). It is also noted that due to the issues of quantitative uncertainty estimates in GHG emissions from aquatic food systems, results of GHG emissions published by previous studies should be used to test hypotheses rather than to provide point value estimates or plain confidence intervals of products' environmental performance (Henriksson et al., 2015).

From the review findings, five key promising GHG emission mitigation studies in Vietnamese aquatic food systems are proposed:

1. Study and establish EFs for inputs used in aquatic farming, like feed and hatcheries, especially tier 2 and 3 EFs for compound pellet feed for key aquatic food production systems in Vietnam like shrimp, catfish, and tilapia. This will provide reliable EFs for GHG inventory of aquatic food systems at local and national scales.

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[1] Greenhouse Gas (GHG) Protocol provides standards, guidance, tools, and training for business and government to measure and manage climate-warming emissions.

2. Conduct a study to assess the effects of GHG mitigation interventions that focus on improving efficient uses of compound feed and electricity, such as improving feed management and optimizing the operation of aerators; in this case, technical interventions should be developed and piloted in demonstration sites representing different agro-ecological zones, particularly the Mekong Delta.
3. Conduct a study to understand and measure the GHG reduction potential of integrated aquaculture systems such as rice-shrimp, rice-fish, and shrimp-mangrove systems to generate EFs for both shrimp and rice products in these systems to inform the revision and implementation of targets for Nationally Determined Contributions (NDCs).
4. Conduct a study to understand carbon sequestration capacity and establish sequestration factors (SFs) of Vietnamese seaweed farming to contribute to the net-zero objective of the country toward 2050.
5. Conduct an inventory of GHGs for both non-motorized and motorized fishing vessels to provide evidence for GHG mitigation solutions and interventions in capture fisheries.

2. Introduction

Aquatic food value chains in Vietnam consist of aquaculture, capture fisheries, and seafood processing and their associated input suppliers like hatcheries, aquafeed production, and logistic supplying. They have all played important roles in the country's socioeconomic development. In 2021, the total production of Vietnam's fisheries sector was 8.79 million tons, of which capture fishing accounted for 3.94 million tons, and aquaculture accounted for 4.86 million tons. The total exported value of the sector in 2021 reached over USD 8.89 billion (D-Fish, 2022c).

Although the aquatic food industry in Vietnam contributes to food and protein supply, income, and job creation, the fisheries sector also creates negative environmental impacts, including GHG emissions contributing to global warming. There have been some studies relating to GHG emission calculation of aquatic food systems in Vietnam, such as Henriksson et al. (2014) for frozen peeled tail on shrimp farmed in the Mekong Delta; Nguyen et al. (2019) for intensive shrimp farming in Soc Trang, Bac Lieu, Ca Mau provinces; and Tran et al. (2018) for motorized and non-motorized capture vessels in Quang Tri province in coastal central Vietnam.

However, the inventory of GHG emissions[2] for aquaculture and capture fisheries commodities in Vietnam has not been done as per the IPCC Inventory Guidance. GHG Protocol Agricultural Guidance has not provided detailed guidance for conducting an inventory of GHG emissions in Vietnam's local aquatic food context. Globally and locally, there is still a lack of commonly accepted EFs for calculating GHG emissions for typical aquatic food systems like fish, crustaceans, mollusks, and capture fisheries. Due to data and methodology limitations, the fisheries sector has not been included in Vietnam's Nationally Determined Contributions (Vietnam NDCs), submitted to the United Nations Framework Convention on Climate Change (UNFCCC) biennially. Nonetheless, activities of aquatic food systems are integrated into the mitigation activities of other sectors in the Vietnam NDCs, such as agriculture (e.g., rice and shrimp land use change) and energy use (in agriculture and aquatic food production).

The context of an emerging trend in international markets toward low-carbon seafood products requires seafood exporting countries like Vietnam to prepare for their seafood GHG emission information provision, determine which stages of aquatic food systems emit the most, and implement proper interventions to mitigate GHG emissions throughout their seafood value chain.

This paper reviews baseline data and gaps related to GHG emissions from the Vietnamese fisheries sector. This study aims to address the following four primary research questions:

1. What GHG emission data exist from aquatic food systems (aquaculture, capture fisheries, post-harvest processing) for Vietnam?
2. Which existing data could be relevant for calculating the baseline of GHG emissions?
3. Which data gaps exist to carry out studies of GHG emissions in the coming years?
4. What are the existing tools and methods for measurement studies of GHGs in the aquatic foods sector?

Due to data and information limitations, this review is considered a preliminary step toward a GHG inventory of common aquatic food products in Vietnam and to recommend further studies toward developing and generating appropriate GHG calculation methods and reliable EFs for local aquatic food systems.

3. Methodology

We mainly used a desk-based review to collect relevant secondary data and documents for analysis and synthesis. Key literature and data sources collected for review are technical guidelines of the IPCC (2006, 2014, 2019), UNFCCC and World Business Council for Sustainable Development (UNFCCC carbon neutral[3]); and the GHG Protocol[4], EXACT (FAO)[5]; as well as published articles, reports, and related data/information from research institutes, academia, universities, management agencies, and international organizations.

In addition, we also arranged online meetings and/or telephone contacts with relevant agencies and stakeholders in Vietnam to discuss issues related to research themes related to this study's objectives. Several institutions were consulted to identify past and ongoing projects and data and information related to GHG emissions in the fisheries sector in Vietnam. They include the Research Institute for Aquaculture 1 and 2, Can Tho University, the Research Institute for Marine Products (RIMF), Nha Trang University, Agro-trade Vietnam, the Directorate of Fisheries, Department of Science Technology and Environment of the Ministry of Agriculture and Rural Development.

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[2] According to Decree 06/2022/ND-CP dated January 7, 2022, GHG inventory is the activity of collecting information and data on sources of GHG emissions, calculating the amount of GHG emissions and absorption within a specified range and a specific year in line with methods and procedures issued by competent authorities.

[3] https://unfccc.int/climate-action/climate-neutral-now/resources

[4] https://ghgprotocol.org/about-us

[5] https://www.fao.org/in-action/epic/ex-act-tool/suite-of-tools/ex-act/en/

4. Findings and discussions

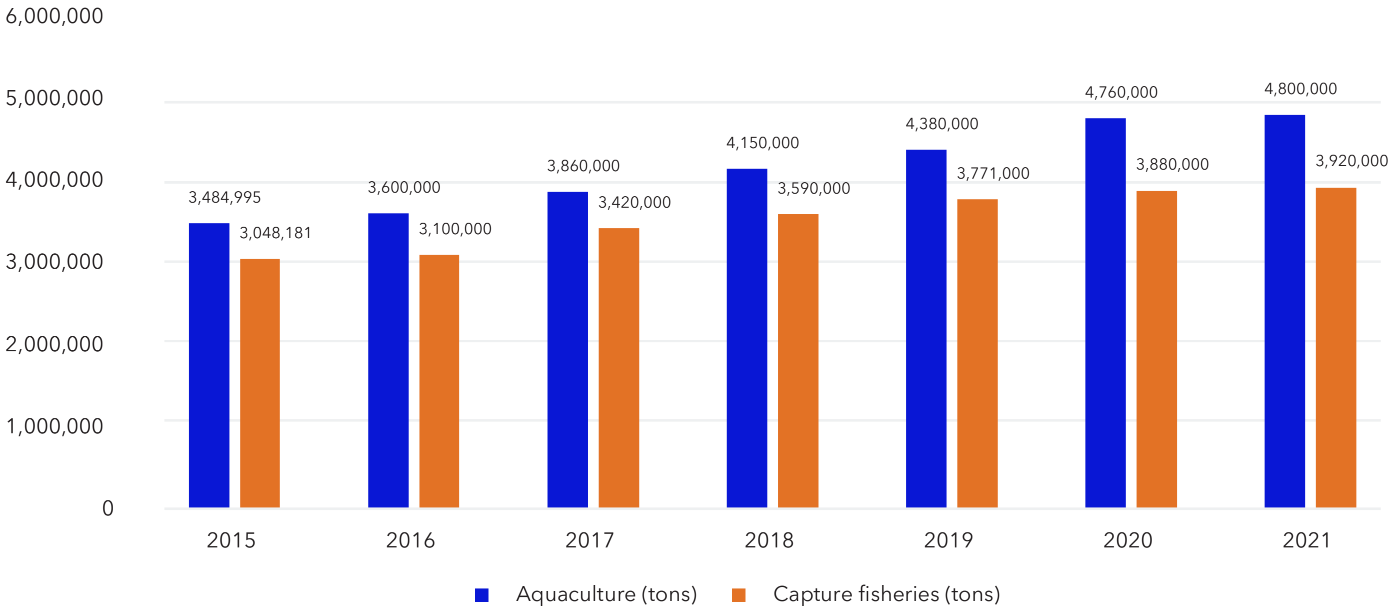
4.1. An overview of aquatic food systems in Vietnam

Aquatic food systems in Vietnam comprise aquatic farming systems (aquaculture) and capture fisheries, which provide most raw materials for post-harvest segments of aquatic seafood value chains, including seafood processing, distribution, marketing, and consumption in domestic and foreign markets.

The total annual gross value added of the fisheries sector is about 202,250–228,119 VND billion annually, contributing about 2.7%–3.4% of the total national GDP (MARD, 2020).

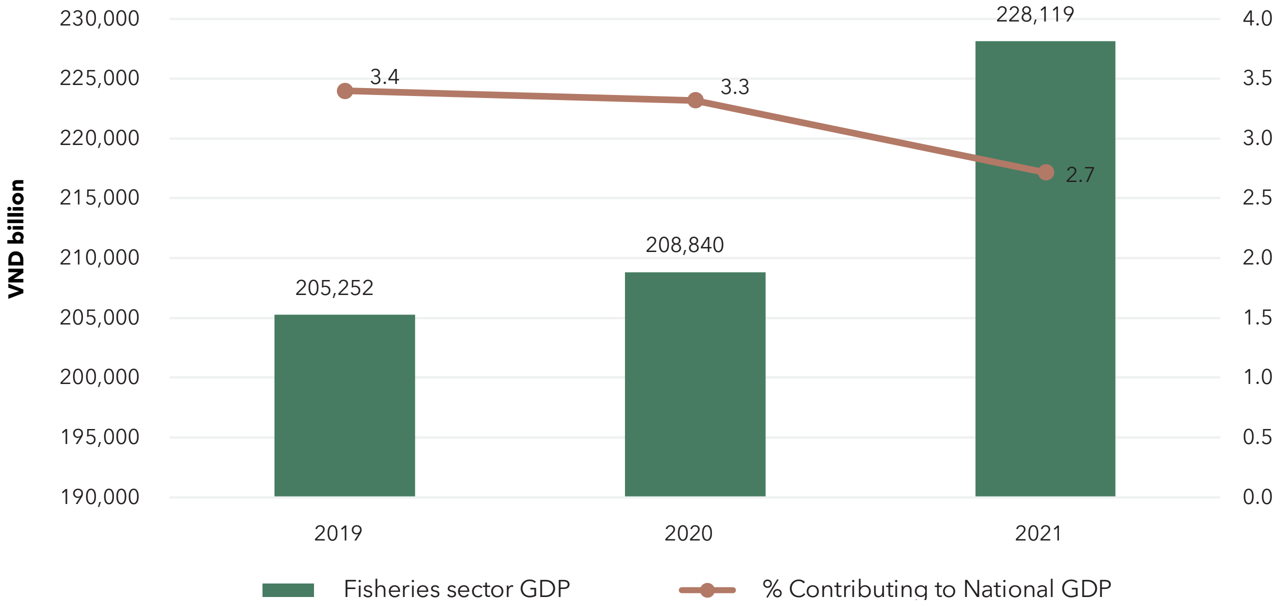
In total, the aquatic food sector's export value is about USD 8.6–8.9 billion per year, of which shrimp and catfish are two main export commodities, contributing about 39.3%–44.5% and 18.2%–23.3% per year, respectively (D-Fish, 2022c).

Figure 1. Aquaculture vs. capture fisheries productions in Vietnam.



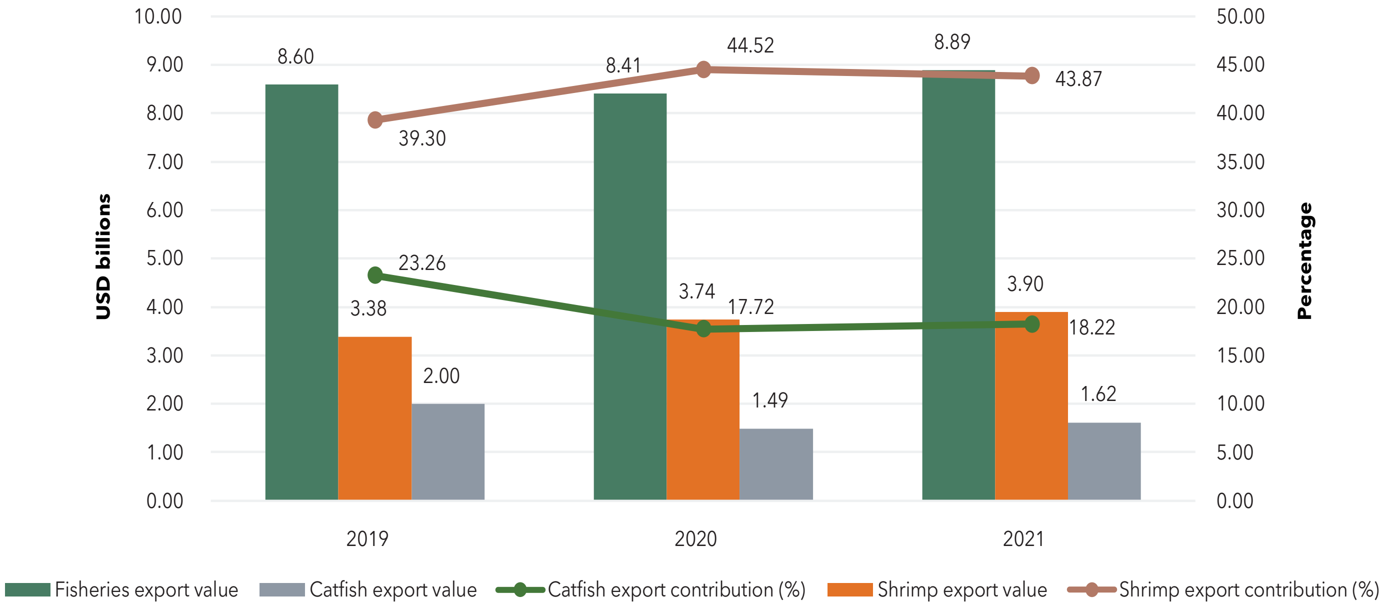
Source: *Compiled from annual sector reports of D-FISH*

Figure 2. The fisheries sector's total GDP and its contribution to national GDP.



Source: *Agrotrade Vietnam (2022) and D-Fish (2022c)*

Figure 3. Fisheries sector's export value and contributions of shrimp and catfish commodities.



Source: *Agrotrade Vietnam (2022) and D-Fish (2022a)*

Table 1. Sector's GDP, export value and contributions of shrimp and catfish.

No.	Item	Unit	2019	2020	2021	Last Annual growth rate (%)	Future annual growth rate for 2021–2025 (%)
1	National GDP (nominal price)	VND billions	6,037,348	6,293,145	8,398,606	17.95	
2	Fisheries sector GDP	VND billions	205,252	208,840	228,119	5.42	3.5
2.1	% contributing to national GDP	%	3.4	3.3	2.7		
2.2	% contributing to agriculture sector's GDP	%	24.4	22.3	22.0		
3	Fisheries export value	USD billions	8.60	8.41	8.89	1.67	3.5
3.1	Shrimp export value	USD billions	3.38	3.74	3.90	7.42	29.5
3.2	Shrimp export contribution	%	39.30	44.52	43.87		
3.3	Catfish export value	USD billions	2.00	1.49	1.62	-10.00	14.5
3.4	Catfish export contribution	%	23.26	17.72	18.22		
3.5	Main export markets	USA, Japan, Korea, China, EU, ASEAN					

Source: *Compiled from annual sector reports of D-FISH*

4.2. Emissions from aquatic food systems

4.2.1. Finfish farming system (catfish, tilapia, and marine fish)

Key finfish farming systems in Vietnam comprise catfish, tilapia, and marine fish. Among them, catfish (*Pangasius hypophthalmus*) is the most important, contributing a single production volume of 1,525,000 tons and using a total farming area of 5,856 ha (D-Fish, 2022c). Pangasius exports were valued at USD 1.6 billion in 2021 (VASEP, 2022), making Vietnam the world's largest catfish producer and exporter.

Pangasius catfish farming has developed dramatically since the 2000s, concentrating mainly in the Mekong Delta. Dong Thap, An Giang, Can Tho, and Ben Tre are key pangasius catfish-producing provinces with high intensive density and uses of seed and pellet feed. GHG emissions from catfish farming are obviously substantial. Several studies use a life cycle assessment (LCA) to estimate GHG emissions from pangasius catfish farming in Vietnam. One study showed that GHG emissions in pangasius farming in Vietnam were about 1,328 kg of CO_2e per ton of pangasius products (Akvaplan-Niva, 2010), such as the study results of Robb et al. (2017) at 1.37 kg of CO_2e/kg per live weight of fish. For pangasius fillets, small-scale pangasius farming emitted an average of 5,907 kg of CO_2e per ton of fillets, and this figure for large-scale farming is 6,730 kg of CO_2e per ton (Henriksson et al., 2015). Feed production was the largest source of GHG emissions for catfish farming, and high feed conversion ratios (FCRs) exacerbated the impact of feed on GHG emissions (Robb et al., 2017).

Tilapia farming is a potential species for meeting seafood exporting targets in Vietnam. However, production from this aquatic food system has been mainly for domestic consumption, with a reasonable annual production of about 250,000 tons on a total farming area of 30,000 ha (D-Fish, 2022c). GHG emissions from tilapia systems has been considered in a few studies in other countries, with an estimated emissions of about 1.58 kg of CO_2e per kilogram of live weight of Nile tilapia in Bangladesh (Robb et al., 2017) or about 1.5 kg of CO_2e per kilogram of fillets with tilapia farming in lake systems (Rosenberg et al., 2013). In addition, Dullah et al. (2020) applied an LCA and used tier 1 EFs[6] to estimate that about 1.69 kg of N_2O emitted from one ton of farmed tilapia produced in Malaysia was equivalent to 245.27 kg of CO_2e/ton of tilapia products.

Marine fish farming in Vietnam involves a diverse group of fish species., including grouper, snapper, cobia, seabass, and red drum. However, marine farming faces several difficulties in artificial seed breeding and low export market demand. Therefore, like tilapia, marine fish farming is considered a potential system for mass aquatic food production for export once these difficulties are resolved. Recent statistics suggested that marine fish is farmed in over 11,000 ha of sea cage cultured areas in Vietnam and produced about 65,000 tons of marine fish in 2021 (D-Fish, 2021). Feed used for marine fish farming combines trash fish and pellet fish. In terms of GHG estimations, no calculations of GHG emissions have been done for farmed marine fish in Vietnam and only a few in other countries. The highest GHG emission was estimated at 8 kg of CO_2e per kilogram of fresh fish in Panama, with five fish farms experimenting with cobia cage culture. This high GHG emission is due to the long distance of transporting feed and feed uses, which account for about 60% of total GHG emissions (Hagos, 2013). On the other hand, Asian sea bass recirculation farms had significantly lower emissions at 1.7 kg of CO_2e per kilogram of fresh fish. This difference is because feeds were delivered to the cobia farm in Panama from Chile and Peru, with an average transportation of 5,600 km, while feed for the Asian sea bass farm, on the other hand, averaged 880 km. In other research by García et al. (2019), GHG emissions from sea bass farming in Spain are estimated at 7.29 kg of CO_2e per kilogram live weight fish, while sea bass farming in Italia is 3.14 kg of CO_2e per kilogram (Zoli et al., 2023).

Another fish farming system in Vietnam is integrated rice and fish (carps) in freshwater environment, which used to be common in the country in over several decades. However, this system is in decline because of difficulties in marketing carp fish products. There have not been any studies to estimate GHG emissions from rice-fresh water fish farming in Vietnam. However, literature in the world shows that rice-fish systems could significantly mitigate water eutrophication by reducing nutrients nitrogen like total nitrogen (TN), NH_4^+, and NO_3^-, phosphors like total phosphorus and PO_4^{3-} and chemical and biochemical oxygen demands (COD and BOD) under the equivalent fish stocking density. Therefore, rice-fish systems significantly reduce N_2O by 56.2% without significant change in CH_4 (Hu et al., 2022).

For other freshwater fish farming, Robb et al. (2017) and Ghosh et al. (2020) identified the GHG emissions of various systems of Nile tilapia (*Oreochromis niloticus*) farming (from cradle to farm gate) in Bangladesh, major carps (*Catla catla, Cirrhinus cirrhosus, Labeo calbasu, Labeo rohita*) in India, and striped catfish *Pangasianodon hypophthalmus* in Vietnam is 1.58, 1.84 and 1.37 kg of CO_2e kg^{-1} live weight fish (excluding emissions arising from land-use change), respectively.

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[6] The Equation 4.10 in sub section 4.3.2.1 of 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands.

The above GHG emissions data on various aquatic food farming systems are summarized below.

Table 2. Summary of GHG emissions data in various aquatic systems.

Fish farming system	Location	CO_2e emissions per unit	Data source
Catfish	Mekong Delta, Vietnam	1.37kg/kg of live weight fish	Robb et al. (2017)
	Mekong Delta, Vietnam	5,907 kg/ton of fillets (small-scale)	Henriksson et al. (2015)
	Mekong Delta, Vietnam	6,730 kg/ton of fillets (large-scale)	Henriksson et al. (2015)
	Mekong Delta, Vietnam	1,327.90 kg/ton of pangasius products	Akvaplan-niva (2010)
Tilapia	Bangladesh	1.58 kg of CO_2e/kg of live weight fish	Robb et al. (2017)
	Malaysia	245.27 kg/ton of products	Dullah et al. (2020)
	NA	1.5 kg CO_2e/kg of fillets	Rasenberg et al. (2013)
Marine fish (Cobia)	Panama	8 kg/kg of fish output	Hagos (2012)
Asian sea bass	Asia	1.7 kg CO_2e/kg of fresh fish	Hagos (2012)
Seabass	Spain	7.29 kg CO_2e/kg of live weight fish	García et al. (2019)
	Italia	3,14 kg CO_2e/kg of live weight fish	Zoli et al. (2023)
Fresh mixed fish	China	513 kg/ha/year	Ma et al. (2018)
Indian major carps	India	1.84 CO_2e kg/live weight of fish	Robb et al. (2017)

4.2.2. Crustaceans farming (shrimp, mud crab)

The crustacean farming system in Vietnam includes mainly brackish water shrimp and mud crabs. Shrimp has been identified as a nationally key farmed species (Decision No 79/QĐ-TTg dated 18/01/20218). The shrimp farming industry has contributed significantly to the Vietnamese fisheries sector's total seafood production and export value for many years. A total of 1,014,900 tons of farmed shrimp produced in the farming area of 747,000 ha in 2022 gained USD 4.3 billion of export value, accounting for 39.1% of total seafood export value in 2022 (D-Fish, 2022a and 2022b).

The shrimp farming system in Vietnam is now highly diverse in terms of production systems, land uses, and intensification levels, including super-intensive, intensive, semi-intensive, improved extensive, shrimp-rice, shrimp-mangrove, and integrated systems. Common inputs include pellet feed, seed, bio-products, chemicals, vet drugs, and energy, but these vary between different farming systems. For intensive shrimp farms, pellet feed and energy use are considered the primary sources of GHG emissions, with pellet feed being associated with up to 75.5% of total GHG emissions in one kilogram of farmed shrimp in the Mekong Delta of Vietnam, according to Phung Nguyen et al. (2019). Still, Chang et al. (2017) reported that pellet feed is the second-largest emitter after energy use (29.39% of total GHG emissions in one kilogram of farmed shrimp) in Yijhu, Taiwan.

Several studies applied LCAs to estimate GHG emissions from shrimp farming systems in Vietnam with relatively diverse GHG emission outputs. Estimations from Nguyen et al. (2019) showed that intensive white-leg shrimp farming in Bac Lieu province in the Mekong Delta emitted about 10.2 kg of CO_2e per kilogram of fresh shrimp (Global Warming Potential), 69 kg of SO_2e per kilogram of fresh shrimp (acidification) and 55 kg of NO_3e per kilogram of fresh shrimp (eutrophication). Meanwhile, in Henriksson et al. (2014), GHG emissions from white-leg shrimp products in the Mekong Delta was 13,309 kg of CO_2e per ton of individually quick frozen (IQF) peeled tail-on shrimp.

Emissions from intensive and semi-intensive tiger shrimp products in the Mekong River Delta of Vietnam are higher than those for white leg shrimp, with 16,422–16,431 kg of CO_2e per ton of IQF peeled tail-on tiger shrimp (Henriksson et al., 2014) and 9.6 kg of CO_2e per kilogram of fresh farmed tiger shrimp (Jonell & Henriksson, 2014).

In the study of Chang et al. (2017), GHG emissions from an ecological shrimp farm in Yijhu, Taiwan, were lower at 6.94 kg of CO_2e per kilogram of fresh shrimp. The top-five sources of GHG emissions in shrimp culture were electricity (2.01 kg of CO_2e/kg, equal to 29.39%), feed (1.64 kg of CO_2e/kg, 23.98%), indirect raw materials (1.4782 kg of CO_2e/kg, 21.62%), waste treatment (0.78 kg of CO_2e/kg, 11.4%) and transportation and refrigerants (0.75 kg of CO_2e/kg, 11.0%) (Chang et al., 2017). Besides electricity and feed, wastewater treatment is one of the emission hotspots over the whole life cycle. Hence, attention should be paid to more efficient use of energy and feed or diverse energy sources for renewable energy and effluent management interventions to mitigate GHG emissions along the shrimp supply chain.

Between countries, GHG emissions from intensive white leg shrimp farming in Thailand are slightly higher than in Vietnam and higher than in China at 13,426–14,664 kg of CO_2e per ton of IQF peeled tail-on shrimp at European importers; 13,309 kg of CO_2e per ton of IQF peeled tail-on shrimp; and 8,510–8,893 kg of CO_2e per ton IQF peeled tail-on shrimp (Henriksson et al., 2014). For *Panaeus* monodon tiger shrimp, Henriksson et al. (2014) provided estimates for Bangladesh and Vietnam per ton of IQF peeled tail-on shrimp. The average emissions of Bangladesh were 5,641–6,863 kg of CO_2e for polyculture of improved-extensive shrimp products and 11,459 kg of CO_2e for a shrimp and prawn improved-extensive system. This was lower than intensive and semi-intensive tiger shrimp products in Vietnam, at 16,422–16,431 kg of CO$_2$e (Henriksson et al., 2014).

According to Akvaplan-Niva (2010), the GHG emissions from aquaculture products are mainly from the use of compound feed, which is calculated from both sources of feed production at the feed mill and feed use in aquaculture ponds as well as the use of electricity for aerators at the farm. Therefore, to reduce GHG emissions from aquaculture, efficient feed management, electricity-saving, and diversification towards renewable energy should be priorities.

Table 3. GHG emissions from shrimp farming in Vietnam and other countries.

Shrimp farming systems	Location	CO$_2$e emissions per unit	Source of data
White leg shrimp	Mekong Delta, Vietnam	13,309 kg of CO$_2$e/ton of IQF peeled tail-on tiger shrimp	Henriksson et al., 2014
		10.2 kg of CO$_2$e/kg of fresh shrimp	Nguyen et al., 2019
Black tiger shrimp (semi-intensive and intensive)	Mekong Delta, Vietnam	16,422–16,431 kg of CO$_2$e/ton of IQF peeled tail-on tiger shrimp	Henriksson et al., 2014
		9.6 kg of CO$_2$e/kg of fresh farmed tiger shrimp	Jonell & Henriksson, 2014
White leg shrimp	Thai Lan	13,426–14,664 kg of CO$_2$e/ton IQF peeled tail-on shrimp	Henriksson et al., 2014
White leg shrimp	China	8,510–8,893 kg of CO$_2$e/ton of IQF peeled tail-on tiger shrimp	Henriksson et al., 2014
Black tiger shrimp (improved-extensive)	Bangladesh (polyculture)	5,641–6,863 kg of CO$_2$e/ton of IQF peeled tail-on shrimp	Henriksson et al., 2014
	Bangladesh (shrimp and prawn system)	11,459 kg of CO$_2$e/ton of IQF peeled tail-on shrimp	Henriksson et al., 2014
Ecological shrimp farm	Yijhu, Taiwan	6.94 kg of CO$_2$e/kg of frozen shrimp	Chang et al., 2017

There are no available studies observed in Vietnam for estimating GHG emissions from local crab farming, given the real context that crab is normally integrated into brackish water shrimp farming ponds as a supplementary harvested product to shrimp. GHG emissions from crab farming are found in Ma et al. (2018) in "mixed-fish" and "crab" aquaculture ponds in southeast China. In this research, annual CH$_4$ and N$_2$O emissions were 64.4 kg of C ha^{-1} and 2.99 kg of N ha^{-1} in the "mixed-fish" ponds, respectively, and 51.6 kg of C ha^{-1} and 3.32 kg of N ha^{-1} in the "crab" ponds, respectively. Emissions of N$_2$O were estimated at 0.54% and 0.71% of the total nitrogen input (in the feed) for the "mixed- fish" and "crab" ponds, respectively.

4.2.3. Bivalve farming (clam, oysters)

Vietnam has a total area of over 200,000 ha potential for farming of bivalves, such as mussels, clams, and oysters. With its capacity to absorb organic residues, bivalves are considered to play an important role in water treatment (D-Fish, 2016). This characteristic may imply that bivalve farming has low GHG emission potential. In 2021, Vietnam's bivalve farming area and production were 54,500 ha and 375,000 tons, respectively (D-Fish, 2020, 2022b).

Meanwhile, several studies on the environmental impact of bivalve farming have been conducted, but few have been on GHG emissions. Recently, certain studies have applied direct measurement methods with GHG-Fluxes in laboratory incubations to quantify GHG emissions from mollusk farming. Ray et al. (2019) found that shellfish aquaculture may provide a low GHG alternative for future animal protein production compared to land-based sources. Oysters released no methane (CH$_4$) and only negligible amounts of nitrous oxide (0.00012 ± 0.00004 μmol N$_2$O gDW^{-1} hr^{-1}) and carbon dioxide (3.556 ± 0.471 μmol CO$_2$ gDW^{-1} hr^{-1}). Furthermore, sediment fluxes of N$_2$O and CH$_4$ were unchanged in the presence of oyster aquaculture, regardless of the length of time it had been in place. Oyster-mediated GHG- fluxes varied with changes in oyster physiology and behavior and with different ecosystem parameters (e.g., seasonal nutrient concentrations and phytoplankton assemblage (Gretchen et al., 2019). In their further study on GHG emissions of native oysters (*Crassostrea virginica)* and non-native oysters (*Ostrea edulis*) in Massachusetts, USA, Gretchen et al. (2019) identified that *C. virginica* was the higher GHG emitter and produced on average twice as much N$_2$O (0.39 nmol g-1 dry tissue weight hr^{-1}) and 20 times as much CH$_4$ (1.31 nmol g DTW^{-1} hr^{-1}) compared to *O. edulis* (0.16 nmol N$_2$O g DTW^{-1} hr^{-1} and 0.07 nmol CH$_4$ g DTW-1 hr^{-1}).

Generally, the collected secondary data in Table 4 shows that the GHG emissions from bivalve farming is generally low and varies depending on the farming species and scope of study.

Table 4. Summary of GHG emissions from bivalve farming.

Species	Location	Scope	Kg of CO_2e emissions per kg	Source
Oyster (*Crassostrea gigas*)	Scotland	Cradle-to-gate	1.281	Fry (2012)
Mussel (*Mytilus edulis*)	France	Cradle-to-gate	0.0404	Fontaine (2014)
Mussel (*Mytilus edulis*)	Scotland	Cradle-to-gate	0. 252	Fry (2012)
Bivalve (no specific species)	Norway	Cradle-to-dock	0.29	Schau et al.(2009)

4.2.4. Seaweed farming

Vietnam has high potential for seaweed farming with key species of *Sargassum, Gracilaria, Hypnea, Eucheuma, Kappaphycus* and *Caulerpa* (MARD, 2010). In 2020, with 10,150 ha of seaweed farming, Vietnam gained 120,000 tons of seaweed products. Extensive, semi-extensive, semi-intensive, and intensive are the main farming methods for growing seaweed in Vietnam (D-Fish, 2020).

Seaweed, also known as "marine macroalgae," "aquatic plants," or "sea vegetables," are autotrophic organisms that produce biomass using sunlight and extract elements from water-dissolved inorganic nutrients, including carbon. Several seaweed species are the most attractive of all CO_2 removal and biofuel aquatic crops. Seaweed can be viewed as miniature biochemical factories, photosynthetically efficient, and effective CO_2 fixers. Utilization of anthropogenic CO_2 as an industrial by-product for seaweed production holds great promise not only as a carbon sink but also as a source of food, fodder, fuel, and pharmaceutics. From an ecological point of view, the generation of biomass should not aim for a single application, treating the remainder as a "waste," but toward a comprehensive solution to several challenges, including biofuel, carbon sequestration, waste remediation, and natural production of food and bio-chemicals. CO_2 uptake by seaweeds can represent a considerable sink for anthropogenic CO_2 emissions, and harvesting and appropriate use of seaweed primary production is a commercially viable approach for GHG amelioration and biofuel production (Turan et al., 2011).

By capturing atmospheric CO_2 through photosynthesis, plants, including seaweed, can store large amounts of organic carbon in above- and below-ground biomass and can be used as bioenergy crops (Jansson et al., 2010). The percentage of carbon content in harvested seaweed dry weight varies among and within species. For example, in Kappaphycus, the range of carbon content is 20.7%–43.1% (Widowati et al., 2012). Muraoka (2004) reported carbon content to be 25%–31% in Saccharina, 32%–34% in Ecklonia, 33%–37% in Sargassum, and 36%–40% in Gelidium. In other studies, the percentage of carbon was reported as 23.6% in Saccharina and Undaria, 31.3% in Gracilaria (Fei 2004), and 27.3% in Pyropia (McVey et al., 2002).

According to Sondak et al. (2016), the use of seaweed aquaculture beds in potential carbon dioxide mitigation efforts has been proposed for commercial seaweed production in China, India, Indonesia, Japan, Malaysia, Philippines, Republic of Korea, Thailand, and Vietnam. It is in the nascent stage in Australia and New Zealand. We attempted to consider the total annual potential of seaweed aquaculture beds to draw down and fix anthropogenic CO_2. Seaweed production has increased tremendously in the Asian-Pacific region in the past decade. In 2014, the total annual production of Asian-Pacific seaweed aquaculture beds surpassed 2.61 million tons of dried weight seaweed. Total carbon accumulated annually in the Asian-Pacific region was more than 0.78 million tons, equivalent to over 2.88 million tons of CO_2 per year, and Vietnam contributed about 1,577 tons of potential sequestration of CO_2 per year (Calvyn & Sondak et al., 2016).

4.2.5. Capture fisheries

Capture fisheries play an important role in terms of proving livelihoods, income, and export value for Vietnam. In terms of production and fishing vessels, in 2020, the number of fishing capture production and fishing vessels in the country reached 3,632,500 tons and 94,572 vessels with a length of over 6 meters. Main fishing gear included purse seine, gillnet, trawl, long line, and gear net, and key species included marine fish, crustaceans, and mollusks (D-Fish, 2020).

Besides providing livelihoods and income benefits, capture fisheries consume fossil fuels to operate machines on fishing vessels, with subsequent GHG emissions. Other subordinate sources of GHG emissions could be ice/refrigeration, crew supplies, and mobilization inputs (FAO, 2012b).

GHG emissions from capture fisheries are mainly from motorized rather than non-motorized fishing vessels, as the former accounted for 97% and the latter 3% of overall emissions of capture fisheries globally, respectively (Parker et al. 2018). In the case of Vietnam, vessels without an engine did not emit any GHGs at all. Meanwhile, vessels with an engine under 40 CV and a group of vessels with an engine above 40 CV emitted 32 tons of CO_2e.y-1vessel-1 and 1,518 tons of CO_2e.y-1vessel-1 respectively (Tran et al., 2018).

Fuel use intensity in tuna fisheries has been found to fall between two broad classifications: those that primarily target skipjack and yellowfin tuna using purse seine and those that target albacore and bluefin tuna with longline, trawl, or pole and line gear (Tyedmers & Parker, 2012 and 2019). The former group, using purse seine gear, was found to, on average, use 368 L of fuel per ton of live weight landings, while the latter group was found to consume between 1,070 L (longline) and 1,490 L (pole and line) per ton. Based on these figures, GHG emissions in tuna fisheries in 2009 was accounted for as follows: the carbon footprint of purse seine-caught tuna was approximately 1,530 kg of CO2-e per ton of tuna landed, 75% of which was directly or indirectly (e.g., extraction, processing, and transportation) related to the consumption of fuel by the fishing vessel. In contrast, the carbon footprint of longline caught tuna was about 3,830 kg of CO2-e per ton of tuna landed, of which 87% was a direct result of fuel used by the vessel. Importantly, this latter estimate did not include inputs associated with bait provision (Tyedmers & Parker, 2012 and 2019). This species' long-distance fishing grounds could explain tuna fisheries' relatively high GHG emissions.

Sala et al. (2022) state that the fuel consumption rate varies widely according to gear type and vessel size. The amount of fuel burned from capture to landing is estimated at approximately 2.9 L of fuel per kilogram of landed fish, generating approximately 7.6 kg of CO2 per kilogram of fish on average for three typical Mediterranean trawl fisheries (mid-water pair trawl, bottom otter trawl, and rapido beam trawl).

A Korean study of offshore fisheries by Lee Jihoon et al. (2018) found that GHG emissions varied greatly by fishing methods and fishing grounds from 2009 to 2013. The total emissions reported were 1.99 kg CO_2 eq. per kilogram of fish landed for trawl, 1.36 for purse seine, 1.72 for gillnet, and 8.74 for longline.

Table 5. GHG emissions per unit production (kg CO_2 eq. per kilogram) by fishing method category in the Korean offshore fishery during the period 2009 to 2013.

No	Fishing method	2009	2010	2011	2012	2013	Average
1	**Average emission of trawl**						**1.99**
-	Large bottom pair trawl	3.70	3.81	3.16	3.22	3.52	3.48
-	Southwestern medium-size bottom pair trawl	2.24	1.84	1.56	1.27	1.74	1.73
-	Large trawl	2.52	2.53	1.79	1.34	1.76	1.99
-	Eastern area medium-size trawl	0.57	0.85	0.71	0.83	0.79	0.75
2	**Longline**	**8.72**	**9.38**	**8.32**	**8.49**	**8.81**	**8.74**
3	**Gillnet**	**1.87**	**1.81**	**1.45**	**1.78**	**1.67**	**1.72**
4	**Average emission of purse sein**						**1.36**
-	Large purse seine	1.25	1.71	1.27	1.58	1.73	1.51
-	Small purse seine	0.91	1.17	1.31	1.30	1.33	1.20

Source: *Lee Jihoon et al. (2018)*

The review shows that there have been certain studies on GHG emissions in capture fisheries, and almost all existing studies applied the LCA approach to measure GHGs. It is noted that in Vietnam, there has been a gap in studying GHG emissions in capture fisheries (by fishing gear and by fishing products).

4.2.6. Post-harvest processing

Seafood processing has developed into an important economic sector for Vietnam. The sector has contributed to agricultural and rural economic restructuring, as well as effectively contributing to Vietnam's objectives of hunger eradication, poverty reduction, income improvement, and job creation, with more than 435,000 workers directly working in seafood processing (MARD, 2020b) and contributions to over 4 million workers in the fisheries sector. The number and capacity of seafood exportation and processing establishments, as well as the value of seafood processing in Vietnam, increased rapidly from 2010 to 2019, with a growth rate of processed seafood production of 5.16% yr^{-1} by volume or 11.8% yr^{-1} by value (MARD, 2020a). In 2022, the value of seafood exports added up to USD 11 billion (D-FISH, 2022a).

GHG emissions from seafood processing, according to Quyen et al. (2022), originate from two sources: (1) transporting raw materials from farming areas to processing plants and (2) preliminary processing, processing in the factory (washing, sizing, sorting, weighing, washing, water filling, freezing, packaging, metal screening, putting into cartons, storage, etc.). These GHG emissions mainly come from energy use (gasoline, oil, electricity, coal/firewood, or other energies), refrigerant use (NH_3, CFCs, Freon 22, Freon 502, or other substances), and/or the use of additives, cleaning, and disinfecting chemicals (chlorin, P3 oxonia, compounds containing NH^{4+} and others).

Fresh products often result in lower environmental impacts than canned products and frozen products during processing (Almeida et al., 2015). Still, they are more reliant on chilled refrigeration and result in larger food waste and loss. Table 6 details the GHG emissions for different seafood processed products at the gate from a selection of LCA studies.

When comparing GHG emissions from shrimp processing and shrimp farming in Thailand, Mungkung et al. (2012) quantified that for IQF peeled tail-on breaded shrimp products, 53% of emissions were associated with the processing stage. During shrimp farming, electricity uses for aerators and feed was the major contributor, while for shrimp processing, most emissions were alleviated with the use of liquid CO_2 for freezing. This figure, however, differs from a case study on GHG emissions of frozen shrimp processing in Vietnam conducted by Quyen et al. (2022), in which 83% and 17% of GHG emissions were from shrimp farming and processing, respectively.

Table 6. GHG emissions in post-harvest processing by seafood processing products.

Product	Location	GHG emissions (kg of CO_2e/kg of product)	Scope of calculation	Source
Frozen cod fillet	Norway	2.5	Capture fishing and processing	Ziegler et al., 2016
Frozen salmon fillet	Norway	2.4	Aquaculture and processing	Ziegler et al., 2016
Canned fish	Iran	1.1	Processing	Asakereh et al., 2010
Canned tuna	USA	1.9	Processing	Hamerschlag & Venkat, 2011
Canned sardine	Portugal	7.6	Capture fishing and processing	Almeida et al., 2015
Frozen salmon	USA	2.9	Processing	Hamerschlag & Venkat, 2011
Mahi-mahi, snapper, and wahoo frozen fillet	Indonesia	0.6 g/kg	Processing	Sofiah et al., 2018
Frozen pangasius fillet (Vietnam)	Vietnam	0.9	Processing (only from electricity)	Rasenberg et al., 2013
Frozen pangasius fillet (Indonesia)	Indonesia	0.7b–1.0c	Processing (b: only from electricity; c: from gate to gate, including refrigerants)	Poernomo et al., 2019
IQF peeled tail-on breaded shrimp (Litopenaeus vannamei): processing stage 53%, farming stage 46%	Thailand	5.88	Farming and processing	Mungkung et al., 2012

Sources: *Compiled by authors*

4.3. Existing tools and methods for GHG measurement studies in the aquatic foods sector

4.3.1. Existing tools and methods for measuring GHGs in aquatic farming

The IPCC Guidelines for National Greenhouse Gas Inventories were first accepted in 1994 and published in 1995. UNFCCC COP3 held in 1997 in Kyoto, Japan, reaffirmed that the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories should be used as "methodologies for estimating anthropogenic emissions by sources and removals by sinks of greenhouse gases" in the calculation of legally binding targets during the first commitment period. In the 1996 guidelines, the chapter on agriculture discusses four GHG-emitting activities, including CH_4 and N_2O emissions from domestic livestock (enteric fermentation and manure management); CH_4 emissions from rice cultivation; CH_4, CO, N_2O, and NOX emissions from savanna and agricultural burning; CH_4, CO_2, and N_2O emissions from agricultural soils (https://www.ipcc-nggip.iges.or.jp/public/gl/guidelin/ch4ref1.pdf). The IPCC guidelines were further revised in 2006, 2014 and 2019.

Aquatic farming systems with high-intensive development levels have had major environmental impacts. Wastewater discharged from aquaculture contains nitrogenous compounds (ammonia, nitrite, and nitrate), phosphorus, and dissolved organic carbon (A Nora' aini et al., 2005). Ammonia (NH_3) is the product of fish respiration and decomposition of excess organic matter. Chemoautotrophic bacteria (Nitrosomonas and Nitrobacter) tend to oxidize ammonium ions (NH_4+) to nitrite (NO_2-) and nitrate (NO_3-) ions (Wei Tze et al., 2011). Therefore, the main principles for calculating N_2O emissions from agriculture in the 1996, 2006, 2014, and 2019 IPCC guidelines could be applied in discussing GHG emissions from aquatic farming systems, especially in the GHG Protocol Agricultural Guidance (WRI and WBCSD, 2013).

The IPCC guidelines and the GHG Protocol Agricultural Guidance exist for calculating GHGs from the agriculture sector, including aquatic farming systems (IPCC, 1996, 2006, 2014, and 2019; WRI and WBCSD, 2013).[7]. The IPCC's methodological approach combines information on the extent to which human activity occurs (called activity data) with EFs, which are coefficients that quantify the emissions or removals per unit activity. The basic equation is, therefore, Emissions = AD • EF.

According to the IPCC, 1996 EFs are usually categorized into three-level tiers representing methodological complexity. Tier 1 is the basic method, and default factors are supplied. Tier 2 requires country-specific information. Tier 3 is the most demanding in terms of complexity and data requirements, usually involving detailed modeling. Tiers 2 and 3 are sometimes referred to as higher-tier methods and are generally considered to be more accurate and appropriate for significant contributors to the national total. The default data

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[7] The GHG Protocol provides standards, guidance, tools, and training for business and government to measure and manage climate-warming emissions.

or tier 1 methods for all categories are designed to use readily available national or international statistics combined with the default emission factors and additional parameters provided and, therefore, should be feasible for all countries.

However, EFs with tiers 2 and 3 are needed for various activity data in the aquatic food sector in both global and national contexts. EFs with tier 1 are mainly used to calculate GHGs in aquatic systems. Still, tier 1 EFs for pellet feed use are not available for these calculations, and no tier 3 EFs are available either for the Vietnamese context. These shortcomings resulted in a limited number of GHG emission studies done in Vietnam's aquatic food sector.

GHG emission research was conducted disjointedly in several studies in Vietnam and other countries worldwide. It provided a preliminary, scattered picture of GHG emissions in aquatic food systems, from production to post-harvesting, and mainly focused on key aquatic systems like shrimp, tilapia, and catfish.

According to the GHG Protocol Agricultural Guidance (WRI and WBCSD, 2013), in the agricultural sector, including aquaculture, there are two main sources of GHG emissions: mechanical and non-mechanical. Mechanical sources include the use of equipment and machinery for aquaculture, such as excavators, pond diggers, water pumps, water paddy wheels, aeration, means of transporting inputs and raw shrimp, etc. The main types of GHG emissions from this mechanical source include CO_2, CH_4, and N_2O, and the quantity of emissions depends entirely on the characteristics of the machinery and equipment and the input energy used (electricity or fuel). The main sources of non-mechanical emissions are biological and productive processes that take place on land and in water, as well as the growth and development of aquatic animals raised on farms and product harvesting processes, such as using food, chemicals, veterinary drugs, probiotic products in aquaculture farming, and emitting major gases of N_2O, CH_4, CO_2.

In addition, several experimental methodologies measure GHG emissions from aquatic farming. Measuring instruments like air sampling pumps, Tedlar gas sampling bags, thermometers, silicon tubing, and floating chambers are designed to measure the amount of GHGs emitted in aquaculture ponds directly (from both water and soil). In the case of measuring CO2 emissions from soil, the alkali trap laboratory method (used during the culture period and harvested pond bottom soil) and the soda lime method (used for harvested pond bottom soil) have been applied. This sampling methodology is useful for tracking emission trends during the farming period. This method, also called the "closed-chamber method," has recently been implemented in certain countries (Muthuraman Vasanth et al., 2016).

Pathak at el. (2013) describe different direct methods of measuring GHGs in aquaculture, including (i) measuring gas on the water surface of the pond and (ii) measuring carbon dioxide emissions from soil in cultivated ponds and harvested pond bottoms. To measure GHGs from the ponds, a cylindrical acrylic chamber with a float can be used to trap the GHGs emanating from the water surface (Figure 1). The closed chamber system is constructed of chemically inert material. The chamber has an open-ended bottom that can penetrate water to a depth of 7 cm. It forms a seal between the water surface and the air within the chamber, thereby providing a completely enclosed system to measure gaseous fluxes. The floating chamber relates to the air sampling pump and Tedlar bag via three ways stop cock by silicon tubing. This method measures the gas accumulation in a closed compartment (chamber) floating at the water's surface. The chamber can float freely in the pond, and the samples will be collected in Tedlar bags at different intervals. The inlet and outlet of the chamber, air sampling pump, and Tedlar bag are connected by silicon tubing via a three-way stopcock. The air sampling pump sucks air from the inlet and discharges it into the outlet of the chamber, allowing the gas sample to mix effectively. The GHG sample is then discharged into the Tedlar bag by shifting the valves in the three-way stopcock (Figure. 1). The GHG fluxes are collected at different intervals in different Tedlar bags and transported to the laboratory in an ice box for analysis by a gas chromatography system with Headspace within 72 hours. The GHGs are quantified based on the standard GHG response in the chromatogram.

Figure 4. Sampler for collection of GHG samples from aquatic systems.

Source: *Pathak et al. (2013)*

The gas flux gradients are then calculated using the gas sample concentrations of the sampled air over a set period from the floating chamber on the aquaculture pond. Gas sampling time is determined by the rate of build-up of the gases in the chamber's headspace. The emissions of GHGs are calculated using the following equation: GHG flux (mg m^{-2} h^{-1}) = (DX × ECV (STP) × MW × 1000 × 60)/(106 × 22400 × T x A). Where DX = Difference in flux value between 60 min and 0 min (converted to ppm based on the standard CH_4 or CO_2 values and ppb based on the standard N_2O values), ECV (STP) = Effective chamber volume at standard temperature and pressure, MW = Molecular weight of the GHG, T = Flux time (min.), A = Area of chamber.

For measuring carbon dioxide emissions from pond sediments, Pathak et al. (2013) also applied the method introduced by Nakadai et al. (1993), which is called the "alkali trap laboratory method." The alkali trap (or soda lime) method was recommended for harvested pond sediments. These direct measurements require high technical skills to operate, are time-consuming and costly, and require a high level of measuring skill (Pathak et al., 2013).

An LCA approach is recommended to calculate GHG emissions from whole value chains. In an LCA, inputs and outputs are modeled and aggregated for each value chain process. LCAs rely on a mix of direct emission measurements and material flows. According to FAO (2012a), an LCA is used for many purposes (environmental impact assessment, product certification support, public policy support, GHG emission estimation, etc.). This could be applied to assess the GHG emissions of specific products, product groups, individual production units, corporations, and countries.

Recently, simplified models have been developed to support estimates of GHG emissions from aquaculture. For example, FAO (2017) developed an Excel-based model of an aquaculture LCA model v1.1, which summarized key input/output ratios for fish farms. These values were then used to calculate the defined production level's total inputs, outputs, emissions, and emissions intensities (kg of CO_2e/kg of output). This model could potentially be applied to Vietnam. Still, it may need to be revised to a Vietnamese context, as the activity dataset related to aquatic food production in Vietnam is insufficient.

In applying an LCA approach to measure GHG emissions in shrimp farming, Nguyen V. et al. (2019) used the CMLCA software developed by the Institute of Environmental Sciences of Leiden University and the "ecoinvent inventory database" (v2.2, https://www.ecoinvent.org/database/older-versions/ecoinvent-version-2/ecoinvent-version-2.html) to calculate the environmental impacts of shrimp farming. Using LCA software does, however, require certain background skills and cost money, which could limit its application in the M+ initiative. Another freely available platform that can be used to calculate GHG emissions from aquaculture is HESTIA. Various emissions estimates support this open-access platform and may better serve the needs of Mitigate+.

4.3.2. Existing tools and methods for measuring GHGs in capture fisheries

In the fishing sub-sector, the use of fossil fuel to propel the fishing vessel (direct fuel energy input; direct and indirect inputs to build and maintain fishing vessels; direct and indirect inputs to provide fishing gear "consumed" in the process of fishing; the energy required to preserve food) is the main source of GHG emissions, and therefore the main challenges are having fuel data to do a full estimate of GHG emissions from fishery operations (FAO, 2012a; Rosenberg, 2013; Sala et al., 2022). An equation for establishing fuel consumption per gear was also developed by FAO (2012b) and has been applied in many studies recently.

GHG emissions are calculated by vessel type, product type, species group, and region. However, in Vietnam, just a few studies have been done to measure GHG emissions by type of vessel. Tran et al. (2018) estimated GHG emissions from fishing vessels without an engine, vessels with an engine under 40 CV, and vessels with an engine above 40 CV in Quang Tri province, Vietnam. GHG emissions for other fishing vessel types in the rest of the 27 coastal provinces have not been found. This situation in Vietnam may result from a lack of statistical data on captured product type and vessel group, which might cause challenges in measuring GHG emissions in capture fisheries in Vietnam.

4.3.3. Existing tools and methods for measuring GHGs in seafood processing

Mungkung et al. (2012) estimated the carbon footprint of IQF peeled tail-on breaded shrimp in Thailand by applying the LCA technique as described in ISO 14040 and 14044 [using the PAS 2050 methodology as mentioned by BSI (2008)]. Another typical study, conducted by Poernomo et al. (2020), determined the carbon footprint of frozen pangasius fillets produced at PT. KMM, Purwakarta, West Java. In this study, the amount of CO_2 emitted from every activity in the system boundaries was estimated by using conversion factors based on electricity, fuel, and refrigerant use from farms, processing plants to market destination. Electricity used for office air conditioning units, office equipment, and lighting were calculated based on the daily average use. The carbon footprint was then expressed as kilograms of CO_2e per kilogram of edible product.

In Vietnam, there is a lack of GHG studies on seafood processing. Recently, Quyen et al. (2022) piloted a small study to establish a user-friendly tool for estimating GHG emissions from shrimp farming and processing that focuses on the main relevant factors. This is just the first step of establishing measuring tools and needs to be continuously supported by relevant stakeholders and agencies to improve tools and methods to generate reliable data and knowledge on GHG emissions at the processing stage of aquatic food systems in Vietnam.

4.4. Propose promising GHG emission mitigation studies, including GHG measurements

Aquatic food systems include different players, from the production of feed, seed, and input materials to farming, harvesting, processing, transportation, retail, exporting, consumption, and disposal. GHG emissions are observed at all production stages and should be studied throughout all aquatic food supply chains to determine which stage emits the most. However, it seems that recent GHG studies have focused mainly on the farming and processing stages, and Vietnam is a typical example of that. Therefore, GHG studies should be conducted at certain parts of LCAs, like feed mills, hatcheries, retailing, and consumption in domestic and export markets.

If the IPCC methodological approach combines information on how much the AD of aquatic farming is multiplied with EFs like the equation of Emissions = AD • EF, both kinds of data need to be collected, including AD and EFs. In this case, the EFs are usually used at three tiers, representing methodological complexity. Recent studies calculating GHG emissions from shrimp and catfish farming in Vietnam have mainly applied EF tier 1, which is a default emission factor readily available from statistical sources. EF tier 3 (sector-specific EF) has not been studied and established in Vietnamese aquaculture. Furthermore, EFs from compound pellet feed production and feed use in the farm are not available in either tier 1 or tier 2, though pellet feed production and feed use account for a significant part of GHG emissions from aqua-farming systems (Akvaplan-Niva, 2010; Nguyen et al., 2019; Henriksson et al., 2014). The application of tier 1 EF might lead to a high uncertainty level of GHG calculations with high errors. Therefore, tier 2 and tier 3 EFs should be studied and developed for key important aquatic food systems in Vietnam, like shrimp, catfish, tilapia, mollusks, and seaweed.

GHG emissions from pellet feed and electricity use accounted for 75% and 13% of total CO_2e emissions from intensive shrimp farming, respectively, in the three provinces of Ca Mau, Bac Lieu, and Soc Trang (Mekong Delta) (Nguyen et al., 2019). In pangasius farming, meanwhile, about 97% of GHG emissions are associated with feeds and 2% with electricity in the Mekong Delta (Akvaplan-Niva, 2010), while feed use for cobia cage farming in Panama is responsible for about 60% of GHG emissions in the system (Hagos, 2013). This suggests that GHG mitigation interventions should be focused on improving efficient uses of those two inputs of compound feed and electricity, such as feeding management and the optimal operation of aerators. In this case, technical interventions should be developed and piloted in typical demonstration sites.

According to Mai Van Trinh (2023), GHG emissions from the shrimp-rice farming system in the Mekong Delta are lower than both monoculture shrimp and mono-rice culture. Therefore, further GHG emission studies from shrimp-rice should be done to provide more concrete evidence for GHG mitigation potentials from this system.

GHG emission studies for capture fisheries in Vietnam are limited to both non-motorized and motorized fishing vessels. EFs for fishing vessels are not available for any vessel fleets in Vietnam. Therefore, GHG emission studies for both types of vessels should be implemented to provide evidence for GHG mitigation solutions and interventions in local capture fisheries.

The specific recommendations for further GHG emission studies are as follows:

1. Conduct more GHG studies to understand GHG emissions from the input supply for aquatic food production, such as feed mills, hatcheries, and demand sides, like retailing and consumption, in both domestic and export markets.
2. Study and establish tier 2 and tier 3 EFs of compound pellet feed for key aquatic food production systems in Vietnam, like shrimp, catfish, and tilapia, to provide acceptable EFs for GHG inventory of aquatic food systems at local and national scales.
3. Conduct a study to assess the effects of GHG mitigation interventions focusing on improving efficient uses of compound feed and electricity, such as improving feeding management and optimizing the operation of aerators. In this case, technical interventions should be developed and piloted in demonstration sites representing different agro-ecological zones, particularly the Mekong Delta.
4. Conduct a study to understand and measure the GHG reduction potential of integrated aquaculture systems such as rice shrimp, rice fish, and shrimp mangrove systems to generate EFs for both shrimp and rice products in these systems to inform NDC implementation.
5. Conduct a study to understand the carbon sequestration capacity and establish the SFs of Vietnamese seaweed farming to contribute to the net-zero objective of the country toward 2050.
6. Conduct GHG emission studies for both non-motorized and motorized fishing vessels to provide evidence for GHG mitigation solutions and interventions in capture fisheries.

5. General discussion and data gaps

Results of this review suggest that GHG emission studies for aquatic food systems in Vietnam are still at a preliminary stage compared with other agricultural food systems like crops, livestock, forests, and land use and land use changes. Aquatic food systems still lack standardized and commonly accepted GHG inventory methodologies at both the global and national levels. The most common methodology for measuring GHG emissions in aquatic food systems is the indirect method (life cycle assessment), which has been applied in GHG estimation for fish and shrimp farming. In contrast, direct GHG calculation methods with experimental equipment directly installed at aquaculture farms have been sparsely applied because of the highly complex nature of aquaculture systems and the high associated costs. Therefore, relevant GHG studies reviewed in this paper with indirect and direct methods are still considered in the research phase and have not been integrated into official documents or national policies like NDCs or mitigation plans.

Among the four reviewed aquatic farming systems, tiger and white leg shrimp have been paid the most attention in GHG emission studies at both the global and country level, especially in countries with high production of farmed shrimp, like China, Vietnam, Thailand, India, and some other countries in Southeast Asia and Latin America. The GHG emissions from shrimp culture systems vary substantially depending on the scope of GHG calculation, applied methods, farm management ways, and the intensification level of farming technologies. They may vary from the lowest level of 3.7 kg of CO2e per kilogram of fresh shrimp in India (Akvaplan-Niva et al., 2010) to 6.9 kg of CO2e per kilogram of frozen shrimp from an ecological shrimp farm in Yijhu, Taiwan (Chang et al. 2017), to 5.1-10 kg of CO_2e per kilogram of shrimp in China (Henriksson et al, 2014), to 9.96–16.3 kg per kilogram of shrimp in the Mekong Delta, Vietnam (Nguyen et al., 2019); 11–14 kg of CO2e per kilogram of shrimp in the Mekong Delta (Vietnam) (Henriksson et al., 2014); or 12.3-13 kg of CO2e per kilogram shrimp in Asia (Jarvio et al., 2017). Two common shortcomings exist among the reviewed GHG studies in the shrimp value chain. The first is the heterogeneous attribute in shaping the scope of GHG calculation, given the dynamic nature of shrimp farming systems with associated farming technologies in different countries. This leads to difficulties in comparing GHG emission levels between various shrimp farming systems. The second is the lack of tier 2 and tier 3 EFs specifically for pellet feed production and feed use in shrimp farming in Vietnam.

Available GHG emission research for shrimp systems has mainly focused on farming. Not many deep studies are conducted at pellet feed production mills and hatcheries, though they are parts of LCA studies. The main ingredient of fishmeal used for producing aquaculture pellet feed in Vietnam has mainly been imported from Peru, Ecuador, and other countries in Latin America. This is also why including GHG emissions from pellet feed production and supply in GHG calculation becomes more difficult.

LCA methods are also mainly applied in various studies to estimate GHG emissions of pangasius catfish farming in the Mekong Delta, Vietnam. The GHG emissions in catfish farming vary from about 1.3 kg of CO_2e kg^{-1} of pangasius products (Akvaplan-Niva, 2010) to 1.37 kg of CO_2e kg^{-1} live-weight fish (Robb et al., 2017), much lower than shrimp farming. The main source of GHG emissions is compound pellet feed production and uses (Robb et al., 2017), with a high FCR of 1.7–1.8 (Tran Dai N. et al., 2022). Like shrimp, GHG studies for catfish value chains have mainly focused on the farming phase but not at the feed mills and distribution, though they are parts of LCA studies, and tier 1 EFs have mainly been applied to calculate GHGs given the lack of tier 2 and 3 EFs.

Reviewed LCA studies for bivalve farming show that a few GHG studies have been conducted in some countries but not in Vietnam. This leads to challenges in establishing a GHG baseline for the aquatic farming system in Vietnam. In other countries, there are substantial variations in GHG emissions, arranged from the lowest emission of 0.0404 kg of CO2 per kilogram of mussel in France to the highest emission for oyster farming in Brazil.

There are also few GHG studies on both carbon emission and absorption in seaweed farming. Various studies have shown seaweed's absorption ability with tier 1 carbon SF. Seaweed production volume in Vietnam increased more than eight times from its 2014 amount of 14,327 tons up to 120,000 tons in 2020 (D-FISH, 2020). It is expected to increase again from 2021 to 2030, as mentioned in the Sector Strategy for Fisheries Development (Decision No 339/QD-TTg and Decision No. 985/QD-TTg). Once the carbon sequestration capacity and SFs for Vietnamese seaweed farming are established, it will contribute significantly to the Vietnamese objective of net-zero neutralization toward 2050. Therefore, studies to establish tier 2 and tier 3 SFs for Vietnamese seaweed farming should be done to support Vietnam in realizing its net-zero neutralization target.

6. Conclusions and recommendations

6.1. Conclusions

1. Aquatic food systems in Vietnam are diverse, with typical aquatic farming systems of fish, crustaceans, bivalves, and seaweed, together with capture fisheries and post-harvesting, processing, exporting, and domestic consumption. These contribute significantly to national and local economic development and job creation and emit GHGs to global warming and climate change.

2. There are two ways of estimating GHG emissions from aquatic farming systems: (1) inventory methodologies in line with IPCC and GHG Protocol Guidance, which require AD and EFs in three tiers of 1, 2, and 3, and (2) an LCA approach with indirect and direct calculation of experiment equipment on farms.

3. Various GHG emission studies for common aquatic food systems like fish, crustaceans, bivalves, seaweed, and capture fisheries have mainly been done with tier 1 and 2 EFs. Tier 3 EFs have not been established for Vietnamese aquatic food systems.

4. GHG emission studies have mainly focused on the farming phase of aquatic food chains. There are still gaps in GHG studies on feed mills, hatcheries, post-harvesting, processing, distributing, marketing, and consumption.

5. GHG emission levels from aquatic food systems vary substantially depending on the scope of GHG calculation, the method applied, and the nature of farming, capture, and seafood processing technologies.

6. Compound pellet feed and electricity energy use in finfish and crustacean farming are major GHG emission sources; diesel and gasoline use in capture fisheries is the major source of GHG emissions from motorized fishing vessels; and refrigerant use/leakage and electricity energy uses are the major sources of GHG emissions in seafood processing.

6.2. Recommendations

1. Further GHG studies should be done for input production and supply for aquatic food systems like feed mills and hatcheries.

2. Study and establish tier 3 FEFs for compound pellet feed for key important aquatic food systems in Vietnam like shrimp, catfish, and tilapia to provide acceptable EFs for aquatic farming system GHG inventory.

3. Focus GHG mitigation interventions on improving efficient uses of compound feed and electricity, such as feeding management and the optimal operation of aerators; in this case, technical interventions should be developed and piloted in typical demonstration sites.

4. Implement further studies for the shrimp-rice integrated system in terms of GHG emissions and develop EFs for both shrimp and rice products in this system.

5. Focus the carbon sequestration capacity and SF of Vietnamese seaweed farming on contributing to the net-zero objective of the country toward 2050.

6. Implement GHG emission studies for both non-motorized and motorized fishing vessels to provide evidence for GHG mitigation solutions and interventions in local capture fisheries.

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