

Understanding and mitigating greenhouse gas emissions in aquaculture: a review of emission sources, regional trends and sustainability pathways

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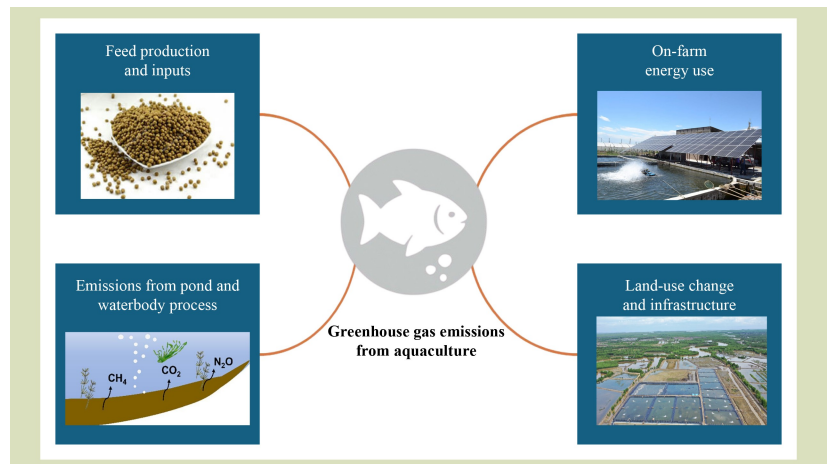
KEYWORDS

Aquaculture, greenhouse gas emissions, sustainability life cycle assessment, climate change mitigation

HIGHLIGHTS

- Identification of key GHG sources in marine and freshwater aquaculture systems.
- Emissions vary by region due to species, practices and energy use.
- Mitigation strategies such as feed efficiency and energy optimization are reviewed.
- Future research directions for emission reduction are presented and discussed.

GRAPHICAL ABSTRACT



ABSTRACT

Aquaculture is increasingly important in global food production; however, its environmental impacts, particularly greenhouse gas (GHG) emissions, are subject to increasing scrutiny. This literature review synthesizes current research on GHG emissions from aquaculture, identifying key emission sources, species-specific emission patterns, geographical research trends and mitigation approaches. A systematic search was performed using the Web of Science, using search terms associated with aquaculture and GHGs. The search yielded 1821 publications. Subsequent analysis indicated a marked rise in academic interest since 2000, reaching a peak of 222 publications in 2023. Geographically, China has dominated publication output, followed by the USA, Australia and Norway. Major themes have included quantifying emissions of CO₂, CH₄ and N₂O across species, such as mussels, salmon, shrimp, and tilapia. Seaweed and bivalves have often been identified as low-emission or carbon-sequestering organisms, whereas intensive production of shrimp and catfish tended to be associated with elevated emission levels. Notable mitigation measures included optimized feed composition, integrated multi-trophic

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aquaculture and adoption of renewable energy technologies. This review also highlights the lack of research in regions such as Africa and stresses the importance of adopting standardized methodologies for emission measurement and life cycle assessment. This work offers research-informed and policy-relevant guidance to advance low-carbon aquaculture systems in line with global climate objectives.

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1 Introduction

In response to growing global seafood and freshwater fish demand, aquaculture has expanded significantly in recent decades, yet this growth has prompted increasing concern over its environmental implications, particularly its contribution to greenhouse gas (GHG) emissions^[1]. Emissions of carbon dioxide, methane and nitrous oxide in aquaculture arise from multiple sources, including feed production, energy consumption and biological processes occurring within aquatic environments, postharvest processing and other contexts^[2,3]. Although aquaculture generally emits less GHG per unit of protein than land-based livestock systems^[4], its overall emissions remain substantial. Recent assessments indicate that global aquaculture, including mariculture, emits about 261 Mt of CO₂-equivalent (CO₂-eqv), accounting for about 0.5% of total anthropogenic GHG emissions. China is responsible for more than half of these emissions, with India and Indonesia also contributing significantly^[5]. These data highlight the importance of incorporating aquaculture into broader climate change mitigation efforts.

Although several reviews have assessed GHG emissions from aquaculture, most have focused on specific countries or regions, such as China^[6,7] or the Amazon Basin^[8,9], or have been limited to particular GHG types^[10,11] or methodological approaches^[12,13]. In contrast, research on mitigation strategies remains relatively underexamined^[8,14,15]. This review seeks to bridge this gap by synthesizing current literature across four key themes: (1) sources of GHG emissions in aquaculture systems, (2) variations in emissions by species and production systems, (3) spatial distribution and emission hotspots, and (4) available strategies for mitigating emissions.

2 Data collection and processing

To thoroughly examine the existing literature on GHG

emissions from aquaculture, a bibliometric analysis was performed using the Web of Science database. The search used the topic field (TS) with the following Boolean expression: TS = (“greenhouse gas” OR “GHG” OR “CO₂” OR “carbon dioxide” OR “carbon emission” OR “CH₄” OR “methane” OR “N₂O” OR “nitrous oxide”) AND TS = (“aquaculture” OR “mariculture” OR “fish farm” OR “aquafarm” OR “fish culture” OR “aquatic farm” OR “aquatic culture”). A total of 1821 records were retrieved through this query as of 2024.

The bibliographic information, comprising authors, titles, abstracts, keywords, sources and publication years, was exported in plain text format and analyzed using the R package “bibliometrix”^[16]. This package facilitated a quantitative examination of publication patterns, national contributions, and keyword co-occurrence. Key bibliometric metrics, including yearly publication counts and leading contributing countries, were illustrated using R (“ggplot2”) and Python (“matplotlib”). Analyses of keyword frequency and their temporal trends were conducted to reveal emerging research topics and changes in scholarly focus.

3 Trends and patterns in the literatures on aquaculture and greenhouse gas emissions

The body of scientific work addressing GHG emissions from aquaculture has grown substantially over recent decades (Fig. 1). From only four publications in 2000, this increased to 222 by 2023, reflecting a marked rise in scholarly interest in the intersection of aquaculture and GHG emissions. This upward trend became particularly pronounced after 2010, with annual publications exceeding 100 from 2016 onwards and reaching a peak in 2023. The sustained increase underscores a growing global awareness of the environmental implications of aquaculture in the context of climate change.

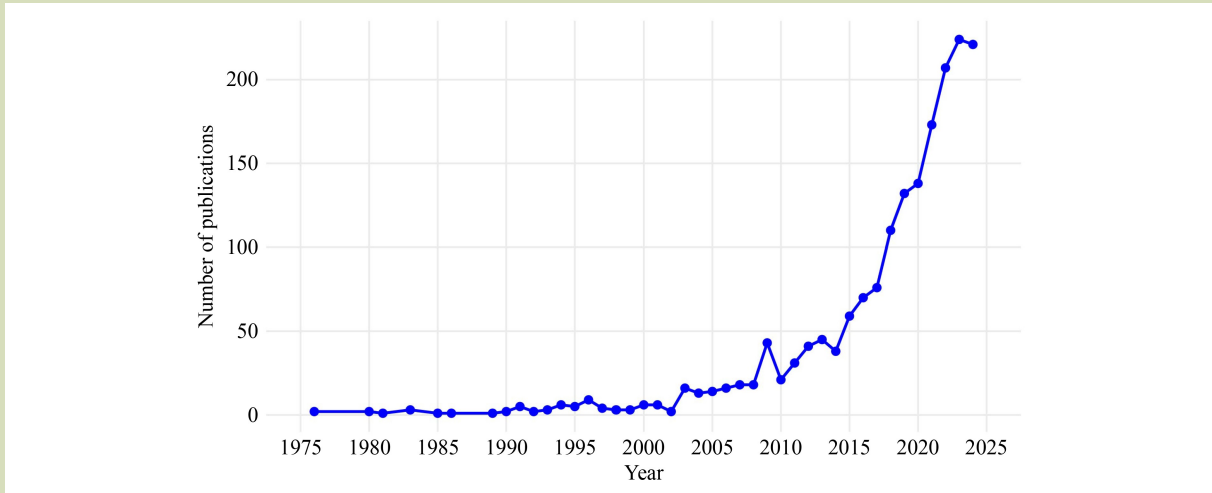


Fig. 1 Annual number of publications up to 2024, based on a Web of Science search yielding 1821 references related to aquaculture and greenhouse gas emissions.

China has emerged as the most prolific contributor to research on aquaculture and its environmental dimensions, accounting for 511 publications in recent decades (Fig. 2). The USA ranks second with 342 publications, reflecting its ongoing involvement in global environmental science discussions. Notable contributions also come from Australia (141

publications), England (110) and Norway (108), indicating robust research efforts in both developed countries and those with substantial aquaculture sectors. This distribution of scholarly output underscores the prominence of countries with well-established aquaculture industries and strong commitments to environmental research.

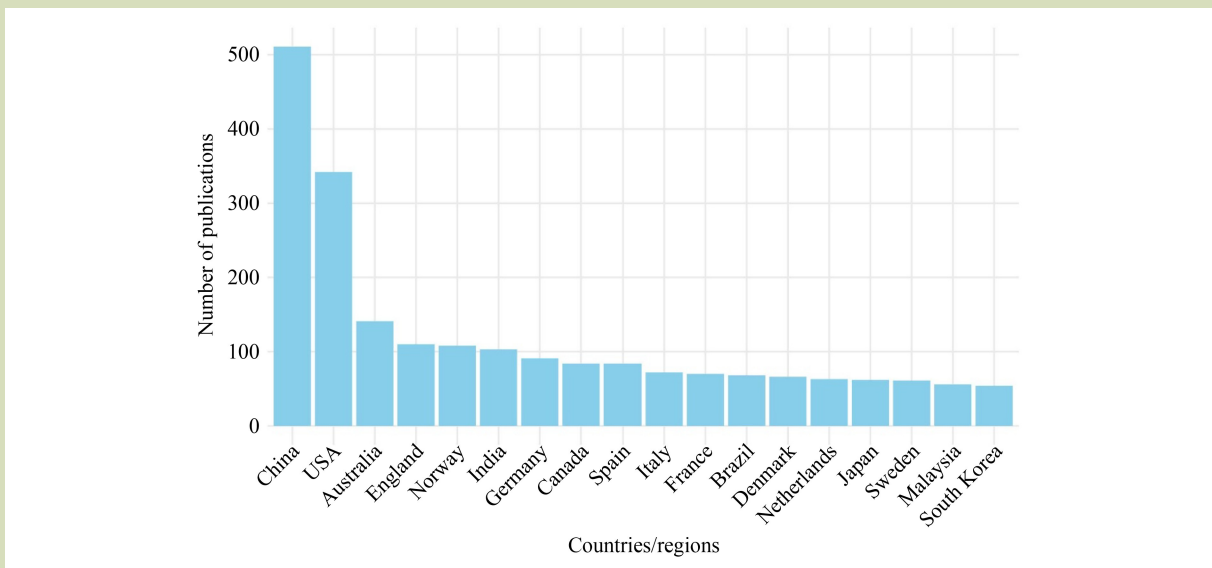


Fig. 2 Countries or regions with at least 50 publications, based on data from a Web of Science search of 1821 references related to aquaculture and greenhouse gas emissions.

The keyword frequency analysis reveals a pronounced focus on “Aquaculture,” which features in 315 publications, underscoring its prominence within the research landscape (Fig. 3). Notable recurring terms such as “Climate change” (104 instances) and “Ocean acidification” (82 instances) indicate growing scholarly attention to the environmental implications of aquaculture. Additionally, frequent references to “Carbon dioxide” (71 instances), “Methane” (60 instances) and “Nitrous oxide” (44 instances) demonstrate considerable academic interest in the GHG emissions associated with this sector.

4 Emission sources in aquaculture

Aquaculture systems have complex GHG dynamics, with potential for both net emissions and carbon uptake. Primary producers (e.g., algae and phytoplankton) in nutrient-enriched aquaculture ponds can assimilate significant CO₂, occasionally resulting in net CO₂ sinks under certain conditions. For example, Zhang et al.^[17] observed strong CO₂ assimilation by algae coupled with CH₄ oxidation in aquaculture ponds, leading to low net methane emissions and even net CO₂ uptake. Similarly, Liu et al.^[18] reported that certain aquaculture

ponds functioned as CO₂ sinks, depending on local metabolic balance and management practices. However, this carbon sink function is highly context-dependent. CH₄ can be released from aquaculture ponds via diffusion and ebullition (bubbling), particularly from sediments where anaerobic microbial activity occurs, accounting for about 85% of total CH₄ flux in some ecosystems^[19]. Continuous aeration can suppress CH₄ release by enhancing dissolved oxygen levels, which promotes methane oxidation in the water column and inhibits the activity of methanogens. Yang et al.^[20] found that fish ponds equipped with aerators had significantly lower CH₄, as well as N₂O, emission rates compared to non-aerated ponds.

Comprehending the sources of GHG emissions within aquaculture is essential for developing targeted mitigation strategies. These emissions stem from a multifaceted supply chain, with principal sources including feed production and utilization, energy use on farms, biogeochemical processes in aquatic environments (which generate CH₄ and N₂O), land use changes associated with the establishment of aquaculture infrastructure, and activities related to postharvest processing and transportation^[21]. The relative contribution of these sources depends on the species and farming system.

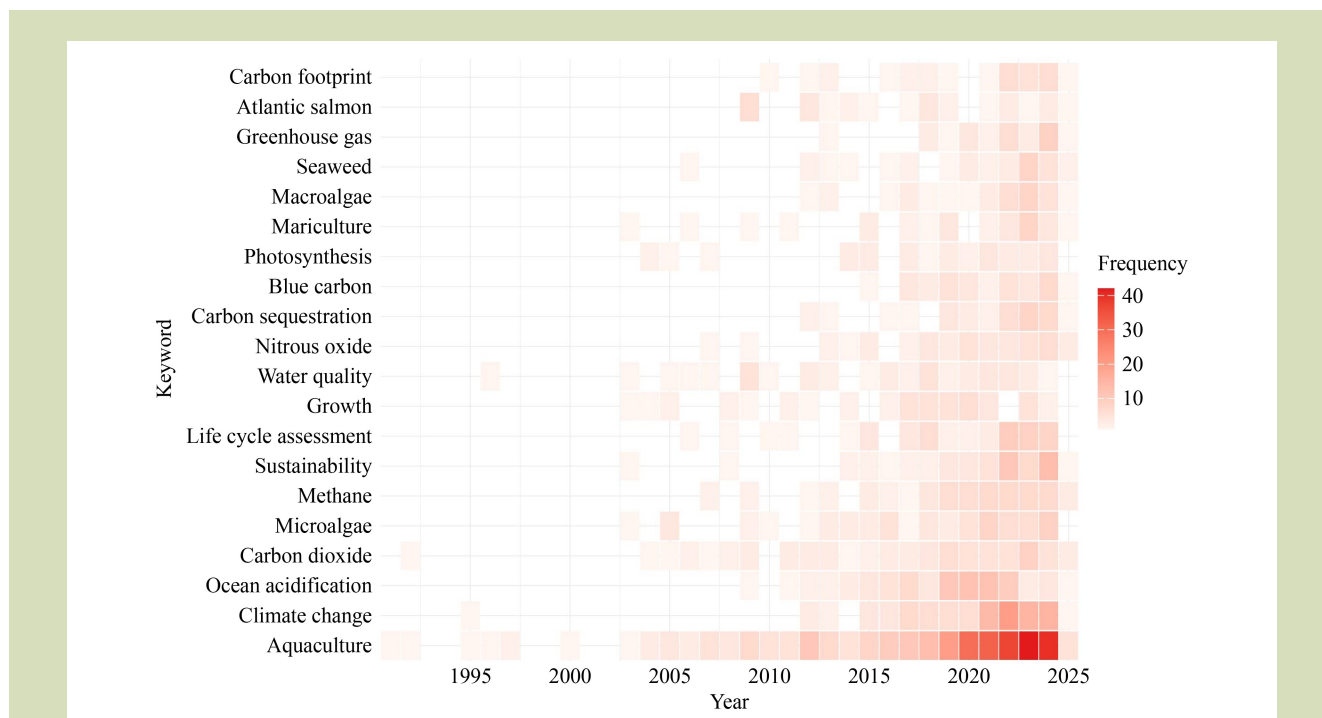


Fig. 3 Heatmap of keywords from 1821 references. Data were obtained from the Web of Science and analyzed using the R package “bibliometrix”.

4.1 Feed production and inputs

Feed provision is consistently recognized as one of principal sources of GHG emissions in many fed aquaculture systems^[22]. The aquafeed production chain involves growing raw materials (e.g., fish oil, fishmeal, maize, soy and wheat), processing these into feed, and subsequent transportation. Each stage is energy-intensive and contributes to CO₂ emissions. Additionally, ingredients derived from agriculture can emit N₂O due to fertilizer application^[23,24] and CO₂ as a result of land use change. A recent in-depth analysis of the Chinese aquaculture sector, the largest globally, revealed that the production of feed materials is the primary contributor to GHG emissions^[25]. Specifically, feed-related activities were responsible for 52% of total aquaculture emissions^[25]. In a similar vein, life-cycle assessments (LCAs) of salmon aquaculture in Canada and Norway showed that feed inputs, particularly fishmeal, fish oil, and crop-based ingredients, typically account for 50%–80% of the overall carbon footprint associated with farmed salmon^[26].

Feed-related emissions originate from various sources. These include the energy consumed in cultivating feed crops and harvesting feed fish, the industrial processes involved in feed production (e.g., extrusion and milling), as well as emissions resulting from fertilizer application and manure management. According to Xu et al.^[25], key contributors to feed-related emissions in China include energy use in crop farming, fertilizer manufacturing, N₂O emissions from cropland and CH₄ emissions from rice cultivation used for fish feed. For carnivorous species, the use of ingredients derived from wild-caught fish incorporates the emissions from fuel combustion in reduction fisheries into the overall GHG profile of aquaculture. More broadly, feed production consistently represents a significant GHG hotspot across species and regions, particularly in fed aquaculture systems such as those involving finfish and shrimp.

Beyond the production of feed itself, the efficiency with which it is used on farms significantly influences emission levels. Feed that fails to be converted into fish or shrimp biomass often becomes waste, which may decompose in sediments and emit CO₂, CH₄ or N₂O. Consequently, the feed conversion ratio plays a critical role in determining total emissions. In pond-based systems, for example, excessive feeding not only increases emissions associated with upstream feed production but also contributes to elevated CH₄ emissions within ponds due to the buildup of organic matter^[27]. Clearly, the feed supply chain, from the sourcing of crop and fishery inputs to

farm-level feed efficiency, represents the principal source of emissions in most aquaculture operations, highlighting its potential for targeted mitigation strategies, such as enhancing feed conversion efficiency and adopting lower-carbon feed alternatives.

4.2 On-farm energy use

A second significant contributor is the direct energy consumption associated with aquaculture activities, which predominantly generates CO₂ emissions through the combustion of fossil fuels or the use of electricity derived from fossil fuel sources. Energy demands vary considerably across aquaculture systems; some simple pond-based farms operate with minimal external energy input, whereas more intensive systems often depend on equipment such as aerators, pumps, temperature regulation systems and automated feeding devices. Additionally, fuel is consumed by fishing vessels and farm boats used for cage or pond maintenance and harvesting operations.

Research has indicated that in highly intensive systems, energy consumption can emerge as a principal source of emissions. Huang et al.^[28], for example, investigated Pacific white shrimp (*Litopenaeus vannamei*) aquaculture across varying levels of intensification. Their findings revealed that as operations transitioned from semi-intensive earthen ponds to super-intensive systems reliant on substantial aeration, water pumping and built infrastructure, CO₂ emissions from energy use increased sharply. Specifically, semi-intensive farms produced about 6.2 kg·kg⁻¹ CO₂-eqv of shrimp, whereas super-intensive systems emitted about 24 kg·kg⁻¹ CO₂-eqv, being an almost 4-fold increase. This escalation was mainly driven by a 24-times rise in energy consumption and a 160-times increase in infrastructure-related emissions. Essentially, the reliance on fossil-fuel-powered equipment such as blowers and pumps significantly amplified the carbon footprint of shrimp production. Between 2003 and 2022, GHG emissions from the Chinese shrimp farming sector tripled, largely due to both production intensification and coastal expansion, with energy use being a key factor in this rise^[28].

In Norwegian salmon aquaculture, energy consumption, primarily diesel used by well-boats and for farm operations, along with electricity for feed manufacturing and automated feeding systems, represents a significant source of emissions. According to Ziegler et al.^[29], GHG emissions linked to

Norwegian salmon delivered fresh to market are largely attributed to fuel burned by fishing and farm vessels, as well as electricity use. Additionally, refrigeration, often powered by diesel generators aboard vessels, was identified as another major contributor in wild-capture fisheries and may also influence emissions in farmed fish logistics.

The adoption of energy-demanding recirculating aquaculture systems (RAS) further exemplifies the environmental trade-offs within aquaculture. These systems, which recycle water and manage waste to prevent environmental degradation and habitat disruption, rely heavily on energy-intensive components such as pumps, filtration units and climate regulation technologies. As highlighted by Ahmed & Turchini^[30], although RAS are promoted for their ecological benefits, minimizing nutrient discharge, escapees, and habitat loss, their viability is constrained by high energy use and associated GHG emissions.

4.3 Emissions from pond and waterbody processes

A key distinction between aquaculture and terrestrial agriculture lies in the use of aquatic environments, such as ponds, lakes and coastal areas, where biological and chemical activities can directly release CH₄ and N₂O. CH₄ is generated through the anaerobic breakdown of organic matter within sediments, whereas N₂O arises from nitrification and denitrification processes acting on nitrogen-rich substances (including uneaten feed and fish waste) present in both water and sediments. These GHGs can be emitted into the atmosphere either via diffusion or through ebullition.

Studies have shown that CH₄ emissions from aquaculture ponds frequently constitute a substantial, and in some cases predominant, portion of on-site GHG outputs, particularly in freshwater systems. This is especially concerning because CH₄ possesses a global warming potential (GWP) about 27–30 times greater than that of CO₂ over a 100-year period^[31]. Feng and Zhuang^[32] reported that freshwater aquaculture in China, particularly in extensive and semi-intensive pond systems, contributed about 90.7% of total GHG emissions from Chinese aquaculture. This striking statistic underscores the prevalence of carp and other freshwater species in Chinese aquaculture, where fertilized, organic-rich ponds release considerable quantities of CH₄ from their sediments. Notably, Chinese aquaculture GHG profile stands out globally: despite intensive

feed and energy inputs, CH₄ emissions from ponds are the dominant warming contributor, surpassing N₂O and CO₂^[11].

Empirical investigations conducted in aquaculture ponds have enhanced understanding of GHG dynamics in these systems. Waldemer and Koschorreck^[33], for example, quantified GHG fluxes in temperate fish ponds in Germany and identified CH₄ as the dominant emission, far surpassing CO₂ and N₂O in terms of CO₂-eqv impact. Their findings indicated that feeding areas within the ponds served as key hotspots for CH₄ ebullition, with bubble fluxes near feeders reaching up to ten times those measured elsewhere in the pond. At these hotspots, ebullitive emissions reached 38 L·m⁻²·d⁻¹, with bubbles comprising about 79% CH₄, equating to a CH₄ flux of 1.24 mol·m⁻²·d⁻¹. CH₄ contributed roughly 90% of the total pond GWP, whereas CO₂ fluxes, although reaching as high as 242 mmol·m⁻²·d⁻¹ at feeding zones, had a comparatively lower impact^[33]. N₂O emissions were minimal, averaging about 5 ± 9 μmol·m⁻²·d⁻¹. That study also revealed marked spatial and temporal heterogeneity in emissions, with CH₄ ebullition declining sharply with increasing distance from feeding sites and having diurnal variability, peaking in the morning when benthic fish activity disturbed the sediments. These observations underscore the role of organic matter inputs, such as feed and fertilizers, in promoting CH₄ production in sediments, and suggest that GHG emissions could be mitigated through improved feed management strategies.

Although N₂O emissions from aquaculture are generally lower than those of CO₂ or CH₄, they are not insignificant due to the high GWP of N₂O, about 275–300 times greater than CO₂ over a 100-year timescale. The relatively low N₂O emissions in aquaculture can be attributed to the specific microbial pathways and environmental conditions required for its production^[10]. N₂O is generated through nitrification and denitrification processes, which rely on the presence of both oxygen and nitrogen substrates, particularly ammonium and nitrate, derived from excreta, uneaten feed or fertilizer inputs^[34]. However, these processes are often limited by suboptimal oxygen levels, nitrogen availability and spatial variability in pond sediments and water columns, thereby constraining N₂O production. Emissions arise from pond waters and sediments where microbial processes first oxidize ammonium, originating from fish excreta or fertilizer inputs, and then reduce it^[35]. For example, a study on Chinese catfish ponds reported that roughly 1.3% of the applied nitrogen was released as N₂O^[36]. Conditions such as low dissolved oxygen

levels and elevated feeding rates were associated with increased N₂O emissions. Nevertheless, in many systems, N₂O accounts for a smaller proportion of the total GWP compared to CH₄, for example, in German aquaculture ponds, N₂O emissions were found to be minimal^[33].

In the context of marine cage aquaculture, direct CH₄ emissions are typically negligible due to the oxygen-rich open-water environment, which is unfavorable for methanogenesis. Any N₂O produced from decomposing feed pellets is rapidly diluted. Therefore, GHG emissions from open-water systems such as salmon cages or oyster farms are usually minor at the site level, with the bulk of emissions stemming from feed production and fuel use rather than the aquatic environment itself. An important exception arises when aquaculture leads to land use changes, such as the transformation of coastal wetlands, where draining peat soils or converting mangroves can release large amounts of CO₂ and N₂O^[37].

4.4 Land use change and infrastructure

The development and expansion of aquaculture frequently entail substantial changes in land use, often leading to considerable GHG emissions, either as one-off events or ongoing contributions. A well-documented case is the conversion of mangrove forests into shrimp farming areas, a practice historically widespread in regions such as South-east Asia^[38] and Latin America^[39]. Mangrove ecosystems store large amounts of carbon in their soils, which, when disturbed through excavation or drainage for aquaculture, becomes oxidized and is released as CO₂, and potentially CH₄ under waterlogged conditions. The clearance of mangroves for aquaculture purposes results in significant carbon emissions; global studies indicate that GHG emissions from mangrove loss surpass those associated with the conversion of equivalent areas of upland tropical forests^[40]. In particular, Indonesia, having about 24% of global mangrove cover, has experienced high rates of mangrove deforestation, in part driven by aquaculture, leading to notable CO₂ emissions^[41].

Even in established farming operations, land-use-related emissions can arise intermittently. For example, when ponds are drained for harvesting or maintenance, the exposure of organic-rich sediments to air can lead to sudden releases of CO₂ and N₂O^[42]. These emissions, which result from specific management practices, are frequently neglected but nonetheless contribute to the overall life cycle emissions.

Another contributor in this category is the embodied carbon from infrastructure and input production. The construction of tanks, ponds, net pens or hatchery systems entails initial carbon emissions, for example, CO₂ emissions from cement used in raceways, an indirect source of carbon emissions in the aquaculture sector, as identified through life cycle assessment^[15]. Although these emissions are generally small in extensive systems compared to those from feed or energy, they can become substantial under more intensive production models. Huang et al.^[28] observed this in super-intensive shrimp farms in China, where the shift from traditional methods to high-density systems requiring concrete structures and greenhouses led to a dramatic rise of nearly 160 times in infrastructure-related emissions. This underscores the importance of accounting for the construction-related carbon footprint of capital-intensive aquaculture systems (e.g., fully indoor farms or large RAS facilities) by distributing it over the operational lifespan of the facility in carbon assessments.

In addition, postharvest stages such as processing, packaging, and transportation serve as additional sources of emissions. For example, the processing of aquaculture products in industrial facilities relies on electricity and packaging materials, each contributing to the overall environmental footprint^[43]. Research on packaging facilities for Greek sea bass and meagre highlights considerable energy consumption and GHG emissions linked to the use of materials like expanded polystyrene. However, the adoption of solar energy and recyclable alternatives offers potential for substantial reductions, possibly approaching net-zero emissions^[44]. Although packaging contributes relatively little to the total emissions across the value chain, transportation can have a far greater impact. Long-distance distribution, particularly air freight used for fresh seafood, can result in transport-related CO₂ emissions comparable to or exceeding those from on-farm activities. In the Norwegian salmon industry, the choice of transport was pivotal, airfreighting fresh gutted salmon to Asia resulted in a carbon footprint of about 14 kg·kg⁻¹ CO₂-eq, significantly higher than that of frozen products shipped by sea, such as herring exported to Europe, which accounted for only 0.7 kg·kg⁻¹ CO₂-eq^[45].

5 Species and system differences in emissions

Aquaculture involves the cultivation of a broad range of

species, including finfish (e.g., carp and salmon), crustaceans (e.g., prawns and shrimp), mollusks (including clams, mussels and oysters), and algae (notably seaweeds), within various production systems, such as ponds, cages, raceways and RAS. GHG emissions associated with these practices differ significantly depending on the species and production method used (Table 1). Recognizing these variations is essential for pinpointing key areas for emissions reduction and for informing both consumer choices and policy development.

5.1 Unfed aquaculture: bivalves and seaweeds (low emissions)

At the lower end of the GHG emissions scale in aquaculture are unfed systems, particularly those cultivating bivalve shellfish (e.g., clams, mussels and oysters) and seaweed (macroalgae)^[54]. These species do not depend on manufactured feed, bivalves obtain nutrients by filtering plankton, whereas seaweeds use sunlight and dissolved nutrients, thereby avoiding the substantial feed-related emissions associated with finfish and shrimp farming. Additionally, these systems generally require minimal energy inputs, limited to occasional boat operations

for maintenance and harvesting, and do not involve land use change, as they occupy existing water spaces. Consequently, the GHG emissions from bivalve and seaweed farming are significantly lower than those from fed aquaculture, often by an order of magnitude, and in certain instances may even be net negative due to their capacity for carbon sequestration^[55].

The Blue Food Assessment^[47], which provides an extensive evaluation of aquatic food systems, identified farmed bivalves and seaweeds as having the least environmental impact among all blue food categories, particularly in terms of GHG emissions. For example, cultivating mussels, oysters or kelp results in a very low direct carbon footprint, with emissions largely limited to CO₂ from small vessels or infrastructure used in aquaculture. In a study conducted in the Sacca di Goro lagoon in Italy, Tamburini et al.^[46] assessed the carbon dynamics of clam and mussel aquaculture and reported a noteworthy finding: harvesting 1 kg of clams results in the permanent sequestration of about 254 g of CO₂ in the form of calcium carbonate in their shells, whereas only about 22 g of CO₂ are emitted during the farming process. For mussels, the corresponding figures were 146 g sequestered and 55 g

Table 1 Greenhouse gas intensity for different aquaculture products

Aquaculture product & system	Approx. GHG intensity (kg.kg ⁻¹ CO ₂ -eqv edible product)	Country or region	Reference
Bivalves (mussels, clams); longline/raft, unfed	~0 or negative	Italy	[46]
Seaweed (kelp); rope farm, unfed	~0	Global	[47]
Carp (extensive polyculture); unfed/fertilized ponds	~1–2	Global	[47]
Carp (pond)	1.84	India	[48]
Tilapia (semi-intensive pond)	~2–4	Global	[47]
Nile tilapia (pond)	1.58	Bangladesh	[48]
Nile tilapia (pond)	2.10	Indonesia	[49]
Catfish (intensive ponds with aeration); e.g., channel catfish	~6–8	USA	[50]
Striped catfish (pond)	1.37	Vietnam	[48]
Striped catfish (pond)	2.85–8.93	Vietnam	[51]
Salmon (sea cage, processed)	~3.8	Norway	[29]
Salmon (air-freighted from Norway to Japan)	~14	Norway	[45]
Trout (cage farm)	~1.13	Turkey	[52]
Rainbow trout (flow through system)	1.78	Spain	[53]
Shrimp (semi-intensive pond)	~5–6	China	[28]
Shrimp (super-intensive)	~20+	China	[28]
Integrated aquaculture (fish + seaweed + shellfish)	Varies, generally lower than monoculture	China	[28]

emitted^[46]. These results indicate a net carbon removal of 232 g·kg⁻¹ CO₂ of clams and 91 g for mussels, suggesting that such farming systems function as net carbon sinks rather than sources.

Likewise, cultivating seaweed (macroalgae) is generally regarded as a low-carbon or carbon-neutral practice. As seaweeds grow, they absorb CO₂, consequently they are classification within the so-called blue carbon ecosystems. Although the carbon is released if the harvested biomass is consumed as food or feed, it can be sequestered if part of the biomass is allowed to sink or is incorporated into durable products. Even when all associated emissions are included, such as those from kelp rope farming and occasional boat use, the overall emissions remain low. According to Jones et al.^[56], seaweed mariculture often results in a smaller GHG footprint than equivalent land-based crops used for similar protein or product outputs.

In addition, both seaweed and bivalve aquaculture require neither fertilizers nor freshwater, which further reduces their environmental burden. From a protein yield perspective, bivalves are particularly climate efficient. Willer et al.^[57] demonstrated that shellfish and other low-trophic aquaculture systems have some of the lowest GHG and water use intensities per unit of protein produced.

5.2 Fed finfish and crustaceans: range from low to high emissions

Fed aquaculture species, particularly fish and shrimp that depend on externally supplied feed, tend to produce higher GHG emissions, though these emissions vary considerably depending on species and farming practices. Several critical factors influence this variability: feed conversion efficiency^[58], the dietary type (herbivorous versus carnivorous)^[4], the production system (intensive compared to extensive)^[7], and whether the species is ectothermic, since all fish are cold-blooded, they are generally more efficient in feed utilization than endothermic livestock^[4].

Commonly species such as Asian carp (including bighead, grass and silver carp), tilapia and milkfish are recognized as aquaculture finfish with comparatively lower GHG emissions. These species are generally cultivated in semi-intensive pond systems that involve moderate levels of feeding or fertilization. They are efficient in feed conversion and typically consume

food low on the trophic scale, such as plant-based matter or plankton. According to the Blue Food study^[47], farmed silver and bighead carps have low GHG emissions among both farmed finfish and crustaceans. This is partly due to their ability to grow well on plant-based feeds or even on the natural productivity of ponds, particularly within polyculture systems, thereby avoiding the need for resource-intensive feed inputs^[59]. Also, they demonstrate high feed efficiency when integrated into systems that exploit naturally occurring food sources. Nevertheless, the Blue Food assessment^[47] highlighted certain trade-offs: although carp farming results in relatively low GHG and nutrient emissions per unit mass of production, it is associated with comparatively higher water consumption.

Tilapia is frequently considered a climate-friendly species due to its omnivorous diet, rapid growth and high production efficiency^[56]. LCAs indicate that the carbon footprint of tilapia is comparable to, or marginally higher than, that of carp, yet lower than that of salmon or shrimp^[15]. However, when tilapia are reared on high-protein feed and subjected to intensive aeration, their emissions can increase significantly^[60]. One LCA conducted in Egypt estimated emissions at about 6.13 kg·kg⁻¹ CO₂-eqv of fish produced under semi-intensive tilapia farming conditions^[61]. Research on carp polyculture systems in Bangladesh and India demonstrates low energy consumption and input requirements, resulting in minimal carbon footprints, though values vary based on feed usage^[62]. Conversely, system intensification through increased feed and aeration tends to elevate emissions. In China, cyprinid species collectively accounted for the largest proportion of national aquaculture emissions, largely due to their high production volume (47%), although carp remain relatively low emitters on a per-unit basis^[25].

Catfish species such as Pangasius and Channel catfish represent a noteworthy case. Despite being primarily raised on plant-based diets and having relatively efficient feed conversion ratios (FCR), some catfish aquaculture systems are associated with high GHG emissions. A global assessment of protein sources by Hilborn et al.^[50] identified intensive channel catfish farming as among the most GHG-intensive methods of protein production, with emissions levels comparable to those of beef. This unexpected outcome is likely attributable to the substantial electricity demands for pond aeration in the channel catfish industry, a moderately elevated FCR (typically between 1.5 and 2), and the exclusive reliance on crop-based feeds, which contribute additional emissions through fertilizer-

derived N₂O. Notably, the application of synthetic fertilizers is a principal driver of N₂O emissions, primarily via microbial processes including nitrification and denitrification. Life cycle assessment confirm that feed ingredient production with high fertilizer input can account for up to 70% of the total GHG emissions^[63].

Salmonids are carnivorous species that require diets rich in protein and energy, traditionally comprising substantial amounts of fishmeal and fish oil^[64]. They are commonly reared in intensive systems such as net pens or RAS. These species demonstrate impressive FCRs, typically ranging between 1.1 and 1.3 for salmon. However, the environmental impact of their feed ingredients is significant, although this has been somewhat mitigated by the increasing inclusion of plant-based components^[29]. The carbon footprint of salmon aquaculture has been the focus of considerable research, owing to its economic relevance. Initial estimates indicated emissions of about 2–2.5 kg·kg⁻¹ CO₂-eqv of live weight, or roughly 3–4 kg·kg⁻¹ CO₂-eqv of edible fillet^[26]. Although enhancements in feed composition and energy efficiency may have reduced this figure, expansion in production and more intensive processing could offset such gains. Ziegler et al.^[45] presented a broad range: from 0.7 kg·kg⁻¹ CO₂-eqv for highly efficient cases (e.g., frozen herring) to 14 kg·kg⁻¹ CO₂-eqv for less efficient supply chains such as fresh salmon air-freighted to Tokyo. For more common scenarios, such as transporting fresh salmon to Europe by truck, emissions typically fall between 2 and 5 kg·kg⁻¹ CO₂-eqv of edible product. Feed production remains the primary contributor to overall emissions from salmon production, with transport, especially by air, also being a notable contributor. Trout, often cultivated in land-based raceway systems using formulated feed, has a comparable emissions profile. LCA of trout farming in concrete ponds in Turkey reported GHG emissions between 1.67 and 1.78 kg·kg⁻¹ CO₂-eqv of fish, primarily attributed to feed production and electricity consumption, mirroring values observed for salmon^[65].

Farmed shrimp species, such as whiteleg shrimp (*L. vannamei*) and giant tiger prawn (*Penaeus monodon*), typically have a high GHG footprint per unit mass, particularly under intensive farming conditions^[66]. This is primarily attributed to their relatively inefficient feed conversion ratios (FCRs, typically ranging from 1.3 to 2.5), reliance on high-protein feeds, and substantial energy demands for operations such as aeration in intensive systems^[67]. The GHG impact is further amplified

when shrimp farming involves mangrove deforestation, as the carbon emissions associated with land use change, although incurred once, are substantial when allocated across production years. Even when land use change is excluded, shrimp farming remains carbon-intensive. For example, Huang et al.^[28] found GHG emissions of about 6.2 kg·kg⁻¹ CO₂-eqv for semi-intensive and 24 kg·kg⁻¹ CO₂-eqv for super-intensive shrimp farming systems in China. Although the latter represents an outlier, it underscores the significant influence of energy consumption and infrastructure on emissions. According to the Blue Food assessment^[47], farmed crustaceans, including shrimp, generally rank among the highest in GHG emissions across aquaculture products, with only certain wild-caught species, such as trawl-caught shrimp, showing higher emissions. Additionally, shrimp ponds emit CH₄, especially in brackish environments where CH₄ production, though lower than in freshwater systems, still occurs. Consequently, shrimp are frequently characterized as a high-carbon luxury seafood.

Finfish, particularly herbivorous and omnivorous species, such as carp and tilapia, are generally associated with lower GHG emissions compared to crustaceans and carnivorous species. This is primarily due to their efficient FCRs and reliance on plant-based diets, which reduce the upstream emissions associated with feed production^[4]. For example, carps, widely farmed in Asia, can achieve FCRs to 1.03 using low-protein, locally sourced feeds, resulting in lower emissions^[68]. In contrast, carnivorous species such as salmon or shrimp often require high-protein feeds incorporating fishmeal, which are more carbon-intensive to produce^[4]. Also, finfish farming is often conducted in semi-intensive or extensive systems, such as cages or ponds, which demand less external energy for aeration, pumping or temperature control, further reducing direct on-farm CO₂ emissions. For example, tilapia farming emitted about 2.03 kg·kg⁻¹ CO₂-eqv of product^[69], significantly lower than emissions from shrimp farming of 13.5 kg·kg⁻¹ CO₂-eqv^[70].

Marine species such as amberjack, cobia, sea bass and sea bream typically require high-protein diets and have production intensities comparable to those of salmon. In contrast, sturgeon cultivated for caviar in RAS can have notably high environmental impacts due to substantial energy demands^[71]. At the lower end of the spectrum among fed fish, emerging species such as *Pangasius* and tilapia, particularly when reared in polyculture systems incorporating vegetation, tend to have reduced impacts^[72]. Additionally, integrated rice-fish farming

systems allow for partial attribution of emissions to rice production, which may result in a relatively low individual footprint for the fish component; however, accurately assessing emissions within such integrated systems remains methodologically complex^[73].

5.3 Influence of farming system intensity

Even within a single species, the intensity of the farming system can influence GHG emissions per unit of output. Shrimp farming provides a clear example, where semi-intensive and super-intensive systems differ markedly in their emission profiles^[28]. A similarly illustrative case is found in carp aquaculture: polyculture ponds with minimal inputs may have low emissions per fish but also generate low yields per unit area^[74]. In contrast, intensive monoculture systems produce significantly higher fish yields but are associated with greater emissions. This results in a nonlinear relationship between intensity and per unit mass emissions, as intensified systems often experience diminishing feed efficiency and increased energy demands, ultimately raising emissions per unit of production^[75].

Rice-fish integrated systems further highlight these complexities. In Vietnam, studies of integrated rice-shrimp farming have shown that the use of high-density polyethylene geomembrane liners in nursery ponds, combined with microbial additives, can substantially reduce CH₄ and N₂O emissions compared to conventional earthen ponds^[76]. Also, lined ponds may achieve lower GWP per unit area than unlined counterparts^[77]. However, such environmental benefits may facilitate greater intensification, such as increased cropping frequency or stocking densities, potentially offsetting gains made on a per-unit basis if not carefully managed.

6 Geographic patterns and hotspots

The spatial distribution of GHG emissions from aquaculture is primarily influenced by the locations where aquaculture production is most heavily concentrated and by the dominant farming methods used in the areas. Several countries, particularly China, along with Bangladesh, Chile, India, Indonesia, Norway and Vietnam, account for the majority of global aquaculture output and therefore are the principal contributors to emissions^[5]. Nevertheless, variations in emission intensities and production techniques mean that even

countries with lower output levels may represent significant emission hotspots if their practices are especially carbon-intensive.

6.1 Global distribution of aquaculture emissions

Global aquaculture activities generated about 261 Mt of CO₂-eqv emissions in 2018, accounting for energy use, water consumption and feed-related impacts^[5]. The sector is heavily concentrated in Asia, which leads in both production and associated emissions. Notably, China alone was responsible for more than half of global aquaculture GHG emissions, reflecting its dominant position in global aquaculture, with about 60% of the total production volume. India and Indonesia follow China as significant contributors, with India primarily engaged in freshwater fish farming (notably carp), and Indonesia producing both fish and shrimp through various systems, including extensive brackish water ponds. Other important contributors within Asia include Bangladesh, the Philippines, Thailand and Vietnam. Overall, tropical and subtropical Asian developing countries contribute the most to global aquaculture GHG emissions in absolute terms, primarily due to the large scale of their production. These countries commonly practice pond-based or coastal aquaculture, which is often associated with considerable CH₄ emissions in freshwater systems or with past mangrove deforestation for shrimp farming. In contrast, aquaculture producers in developed countries, such as Canada, EU member states, Japan, Norway and the USA, typically generate lower total emissions but have higher emissions per unit of output, largely due to energy-intensive operations and extensive international trade^[78].

6.2 China: the giant of aquaculture emissions

China is the leading producer of aquaculture globally, and its GHG emissions from the sector are correspondingly substantial. A number of studies have undertaken national-level evaluations for China. Xu et al.^[25] conducted a comprehensive analysis of the carbon footprint associated with both aquaculture and mariculture in the country. Their findings indicated that emissions from Chinese aquaculture, covering nine major species groups, totaled 112 Mt CO₂-eqv, a figure comparable to the annual emissions of a medium-sized national economy. Notably, emissions were found to be geographically concentrated, with about 46% originating from just four provinces: Guangdong, Jiangsu, Hubei and Shandong. These regions are among the most significant aquaculture

producers in China, with Guangdong and Jiangsu hosting intensive fish and shrimp farming, Hubei characterized by widespread carp polyculture, and Shandong supporting both mariculture and freshwater operations.

Significantly, freshwater aquaculture, primarily involving species such as carps and tilapia reared in ponds, accounts for the majority of Chinese aquaculture-related emissions, particularly in terms of feed use and CH₄ output^[32]. CH₄ emissions from freshwater ponds have been identified as the primary source of GHGs in aquaculture, contributing about 90% of total aquacultural emissions^[32]. Although coastal and marine aquaculture, including kelp, shellfish, and marine fish, are also substantial industries in China, they are associated with comparatively lower emissions. For example, seaweed cultivation, such as kelp farming, may provide a carbon sink, potentially offsetting some of the emissions from the sector^[79]. Within this broader context, shrimp aquaculture in southern China has notably expanded and intensified in recent years^[80].

China has started to recognize the environmental implications of its aquaculture sector, promoting measures such as improved feed formulations and advancements in farming systems to mitigate emissions^[62,81]. Nonetheless, considering that China accounts for over half of global aquaculture production, any effective international mitigation strategy for aquaculture-related GHG emissions must involve substantial engagement with China.

6.3 South Asia and South East Asia

Following China, South Asia and South East Asia together account for the majority of the remaining global aquaculture production, making them significant contributors to emissions. India ranks as the second-largest producer, primarily cultivating species such as catla, carp, rohu and some shrimp^[82]. As in China, Indian aquaculture is predominantly based on freshwater ponds, though typically with lower intensity. Nonetheless, the adoption of formulated feeds and aeration technologies is expanding in certain regions, which may lead to increased energy consumption.

Indonesia and Vietnam are also prominent in aquaculture, particularly in shrimp production. Indonesia has millions of hectares of shrimp ponds, including areas converted from mangroves, and also supports widespread seaweed cultivation, which contributes to carbon sequestration^[83]. Emissions from

Indonesian aquaculture are considerable, driven by both feed consumption, especially in tilapia and carp farming, and land use change^[84]. Research on Indonesian mangroves has revealed substantial GHG emissions from converted aquaculture ponds, but also highlights significant mitigation opportunities through ecological restoration^[85]. Vietnam, meanwhile, ranks among the leading exporters of shrimp and *Pangasius* catfish, with the Mekong Delta as a central production region^[86]. *Pangasius* is farmed relatively efficiently using riverine cages and pond systems with effective feed conversion ratios, leading to moderate emissions per unit mass of output, though the overall scale of production results in high total emissions. In shrimp farming, rice-shrimp rotation systems are commonly used in the Mekong Delta; enhancing these systems, for example, by pond lining, can lead to substantial reductions in emissions^[76].

Bangladesh and Myanmar operate large-scale aquaculture systems for fish and shrimp, characterized by relatively low input levels, which may result in lower emissions per unit area; however, the overall scale remains significant^[87,88]. Thailand and the Philippines are also notable contributors. Although the overall share of global aquaculture production in Thailand has somewhat decreased, its shrimp farming remains highly intensive^[89,90].

6.4 Europe and the Americas

Beyond Asia, substantial aquaculture production occurs in Europe, North America, and Latin America, with certain regions hosting high-value sectors, such as salmon and trout, that are associated with notable emissions per unit of output^[91]. As the leading global producer of salmon, Norway represents a key contributor to non-Asian aquaculture emissions. Although the total carbon emissions from Norwegian salmon farming, including those from its supply chain, remain relatively low on a global scale, the emissions intensity per unit places it in the midrange^[92].

In the EU, key aquaculture species include salmon (notably in Ireland), trout (cultivated in Denmark, France and Italy), sea bass and sea bream (prevalent in the Mediterranean Sea), and shellfish such as mussels and oysters (particularly in France and Spain)^[93]. GHG emissions vary across these types: shellfish aquaculture is generally low in carbon emissions and is even regarded as a potential method for carbon sequestration in some areas. Shellfish aquaculture, particularly the farming of

clams, mussels and oysters, is widely regarded as low in GHG emissions due to its unique biological and production characteristics. These bivalves are filter feeders, meaning they do not require externally produced feed, which eliminates one of the major sources of GHG emissions in aquaculture, the production, transport and use of formulated feed^[54]. In addition, shellfish farming requires less energy inputs and infrastructure, especially when grown in suspended or bottom culture systems, further reducing CO₂ emissions^[94]. Bivalves can also remove excess nutrients from the water column and contribute to water clarity, offering ancillary ecosystem services, although their capacity to sequester carbon needs more investigation^[95]. Catfish aquaculture, especially in large-scale operations, is associated with comparatively higher GHG emissions. This is primarily due to the high FCRs in some systems, energy-intensive aeration practices, and the accumulation of organic matter in pond sediments, which can promote CH₄ production under anaerobic conditions^[96]. Catfish are typically farmed in ponds that rely on formulated feeds rich in soybean and grain ingredients, inputs that carry significant upstream emissions, including CO₂ from fertilizer use and land use change^[97]. In contrast, the farming of sea bass and sea bream involves feed high in fishmeal content and the use of aeration during the hatchery phase, resulting in a moderate carbon footprint. Aligned with the objectives of the Green Deal, the EU is committed to promoting sustainable aquaculture by reducing GHG emissions through innovations in packaging and energy use^[98].

Catfish farming is primarily concentrated in the southern USA, whereas salmon aquaculture is more prevalent in Canada. As previously noted, the US channel catfish industry is among the highest in GHG emissions per unit of protein, which is significant given its prominence in Western aquaculture^[99]. In contrast, salmon farming in Canada, particularly in British Columbia and Atlantic regions, follows a model similar to that of Norway. A distinguishing feature of British Columbian operations is the extensive use of hydroelectric power in processing, which contributes to lower emissions^[100]. Both Canada and the USA also engage in shellfish aquaculture (e.g., oysters and clams) along their coastlines, a practice generally associated with low GHG emissions. In fact, the growth of shellfish farming in the USA is frequently supported on the grounds of its minimal environmental footprint. Chile ranks as the second-largest global producer of salmon after Norway^[101]. However, its operations are often located in remote areas reliant on diesel generators, and the use of fishmeal derived

from Peruvian anchoveta contributes additional emissions. In 2020, Chilean salmon farms were estimated to emit 244 kt CO₂-eqv^[102].

6.5 Oceania and Africa

The Australian aquaculture industry has undergone consistent growth, leading to heightened attention on its associated carbon emissions. A detailed investigation conducted by the Fisheries Research and Development Corporation highlighted the importance of thoroughly evaluating energy consumption and GHG emissions across Australian fisheries and aquaculture operations^[103]. LCA approaches have been used to quantify the carbon footprint of seafood consumed in Australia, revealing that imported products generally have higher emissions than those produced domestically, largely due to the impact of transportation^[104].

The African aquaculture sector remains relatively limited in scale. Egypt stands out as a major producer of tilapia, potentially the largest outside of Asia, primarily using pond systems in the Nile Delta, which are associated with moderate GHG emissions due to the use of palletted feed and some reliance on water pumping^[105]. In contrast, aquaculture in other African countries is still in its developmental stages. As the sector expands across the continent, current decisions, such as the adoption of renewable energy sources and the selection of locally sourced feed ingredients over imported soy, will have significant implications for its future emissions profile.

6.6 Regional initiatives and considerations

Variations in GHG emissions across regions are accompanied by distinct mitigation challenges and opportunities. In Europe, particularly Norway, strong regulatory frameworks and consumer expectations around sustainability have prompted companies to explore alternative low-carbon feed sources, such as using algae oil instead of fish oil or insect protein in place of soy, and to enhance logistical efficiency, for example by increasing maritime fish transport^[106]. The Norwegian government has also introduced the notion of achieving carbon-neutral aquaculture as a long-term objective, seeking to incorporate the aquaculture sector into broader climate policy discussions.

In parts of Asia, including China, governments are increasingly

promoting ecological aquaculture approaches such as integrated rice-fish farming, which are characterized by lower GHG emissions and closed-loop nutrient cycling^[107]. China has initiated pilot schemes aimed at developing low-carbon aquaculture systems. Nonetheless, relevant policy frameworks remain in the formative stage. Current initiatives largely focus on enhancing water quality, particularly in relation to eutrophication, and improving fish health. These objectives fortunately align with efforts to reduce GHG emissions, as measures such as improved feed efficiency contribute to both aims^[108].

Importantly, the global nature of aquaculture trade results in the transboundary transfer of emissions, with some being effectively exported or imported through international supply chains^[109]. For example, the carbon footprint associated with seafood consumption in Europe encompasses emissions originating from shrimp farming in Asia and salmon production in Chile and Canada. In contrast, domestic consumption of low-value fish in China leads to emissions that largely remain within its national boundaries. Consequently, effective global mitigation strategies may require consumer countries, such as the EU, Japan and USA, to offer support or enforce standards that promote low-carbon practices in producing countries.

7 Mitigation strategies for reducing emissions

Due to the wide range of emission sources associated with aquaculture, mitigating GHG emissions effectively necessitates a comprehensive, multifaceted strategy (Fig. 4). Various approaches have been assessed by researchers, including modifications to feed composition, advancements in farm management practices, and systemic redesigns^[62]. These interventions often enable emission reductions without compromising productivity, and several also offer additional advantages such as enhanced efficiency or long-term cost savings.

7.1 Improving feed efficiency and composition

As feed production represents a major source of emissions, enhancing feed utilization and composition is a key strategy for mitigation. Improving feed efficiency, specifically by lowering the feed conversion ratio (FCR) so that less feed is needed per unit of fish produced, can significantly reduce upstream emissions. Ziegler et al.^[29] found that even minor gains in feed conversion efficiency in Norwegian salmon aquaculture could lead to considerable reductions in overall GHG emissions. In

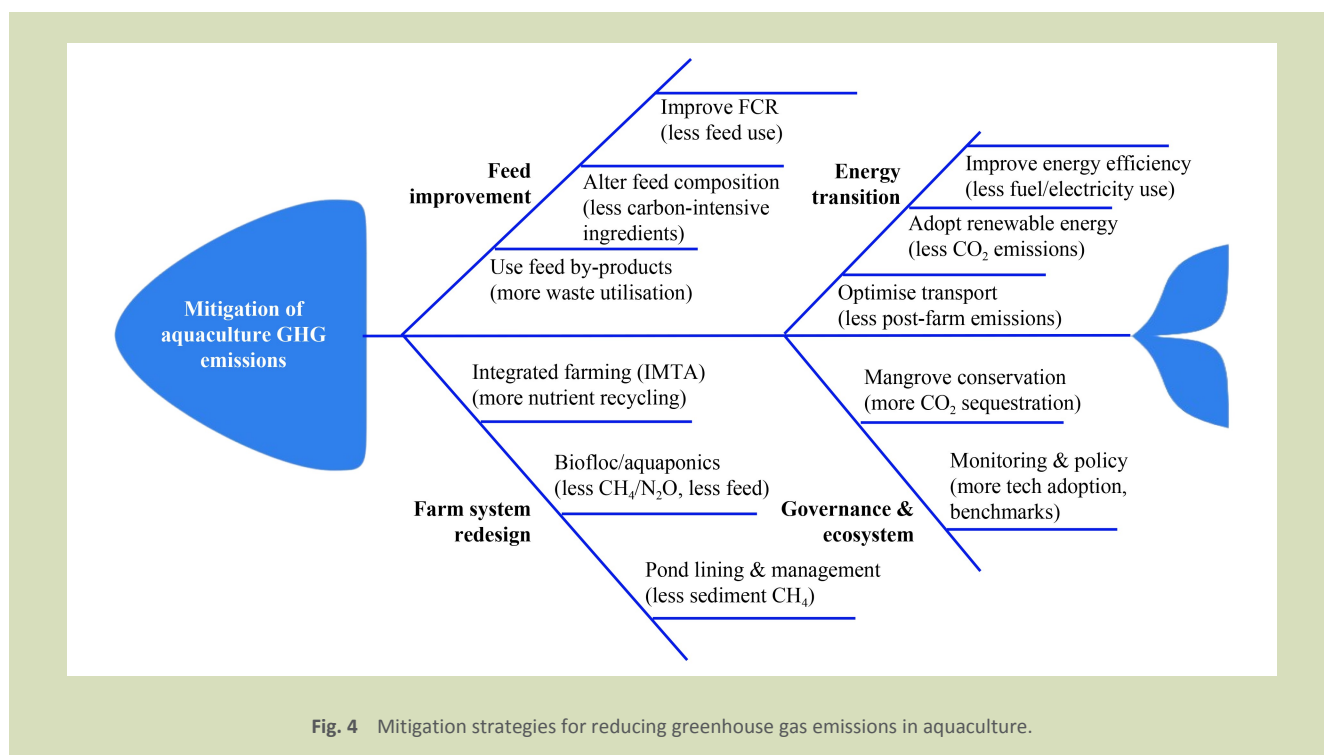


Fig. 4 Mitigation strategies for reducing greenhouse gas emissions in aquaculture.

their scenario analysis of the Norwegian salmon industry, a modest improvement in FCR emerged as the most impactful single intervention, contributing to a potential 60% reduction in emissions when combined with other strategies. Improved feed efficiency also leads to reduced feed residues in aquaculture systems, thereby indirectly lowering CH₄ and N₂O emissions arising from decomposing waste. A lower FCR means that a greater proportion of feed is assimilated into biomass, resulting in less uneaten feed and lower levels of fecal waste. This directly reduces the accumulation of organic matter in pond sediments, which under anaerobic conditions can be decomposed by methanogenic archaea to produce CH₄^[110]. Simultaneously, a reduction in nitrogenous waste from unassimilated dietary protein also limits the substrates available for microbial nitrification and denitrification processes, which are responsible for N₂O emissions in both water columns and sediment layers^[111]. Notably, Hu et al.^[10] highlighted that excessive nitrogen loading, often a consequence of inefficient feed use, enhances N₂O production via coupled nitrification-denitrification pathways. Strategies to enhance FCR include selective breeding for rapid growth and feed efficiency, fine-tuning feeding practices to avoid overfeeding, and promoting fish health and welfare, as illness and stress are known to cause feed inefficiencies^[112].

Altering feed formulations is an important mitigation strategy that involves incorporating ingredients with lower carbon footprints. Ziegler et al.^[29] identified changed feed composition as one of the five principal strategies for reducing emissions in salmon aquaculture. This approach typically entails reducing reliance on high-emission inputs. For example, some contemporary feeds partially substitute marine fishmeal and fish oil, derived from energy-intensive wild capture fisheries, with plant-based proteins or alternative sources such as insect meal and microbial protein. Nevertheless, crop-based ingredients may be associated with emissions from land use change, particularly in cases like soy cultivation in deforested regions^[62]. A promising solution lies in expanding the use of fishery byproducts and seafood processing waste in feed production. Repurposing trimmings that would otherwise be discarded not only diminishes the demand for targeted feed fisheries but also contributes to more effective waste management.

Also, novel feed sources such as insect meal, algae and single-cell proteins derived from fermentation processes typically

require less land and can be generated from waste streams, offering the potential to reduce GHG emissions per unit of feed protein. Although these alternatives are not yet widely adopted, they are under active investigation as environmentally sustainable feed options. For example, Quang Tran et al.^[113] reported that diets incorporating insect or mussel meal are associated with relatively low GHG emissions. It is essential that any modifications to feed composition continue to support optimal fish growth and health; however, with appropriate formulation, many species are capable of performing well on these alternative diets.

7.2 Energy efficiency and renewable energy

Lowering the carbon intensity of energy consumption in aquaculture represents a key component of mitigation efforts. Numerous studies emphasize enhancing energy efficiency on farms, such as adopting more efficient aerators, pumps, and equipment to deliver the same output with reduced electricity or fuel usage, as well as shifting toward cleaner energy alternatives^[114]. In the Norwegian salmon industry, improving energy efficiency and adopting low-carbon energy sources has been highlighted among the leading mitigation strategies^[29]. This includes the deployment of energy-saving technologies, streamlining operational practices to minimize fuel use (e.g., optimizing feed delivery to reduce the number of boat trips), and transitioning farm energy systems to renewables, such as solar, wind, or renewable diesel. A study of Mediterranean fish processing facilities demonstrated that integrating photovoltaic systems with enhanced materials management could result in near-zero GHG emissions during that phase of production^[44]. Likewise, energy-intensive recirculating aquaculture systems may be upgraded with renewable energy installations to substantially reduce their carbon emissions.

At a broader level, certain governments and corporations are investigating the use of hybrid energy systems in offshore aquaculture, incorporating technologies like wind turbines and wave energy converters into offshore fish farming operations to supply renewable power for lighting and feeding equipment^[115]. Such innovations have the potential to significantly decrease dependence on diesel generators. Additionally, replacing diesel-powered farm vessels and transport vehicles with electric alternatives or biofuels, where practicable, can contribute to emission reductions.

7.3 Optimize transportation and supply chains

Transport-related emissions in the seafood sector can be reduced by altering both the logistics and locations of product distribution. Researchers have highlighted the benefits of adopting more energy-efficient transport methods, for example, opting for sea freight or thermally insulated trucking over airfreight for fresh fish, such as salmon^[29]. Achieving this may involve shifts in market strategies such as encouraging the consumption of frozen or processed seafood in distant markets or relocating aquaculture operations nearer to consumer bases. An alternative strategy is to promote more local production and consumption in order to reduce supply chain length^[116], although this may be constrained in countries like Norway where production levels surpass domestic needs. Even so, measures such as shipment consolidation, enhancing cold-chain systems to allow for slower transport without compromising product quality, and processing seafood at the point of origin to limit transportation to edible components can contribute to lowering emissions associated with seafood logistics^[29].

7.4 Improved water and waste management

Mitigating CH₄ and N₂O emissions at the farm level requires effective management practices within ponds and tanks. A central approach involves limiting the buildup of organic matter in sediments, which serves as a primary source of CH₄ production^[117]. This can be achieved through practices such as maintaining moderate stocking and feeding levels to prevent excessive organic loading, routinely removing accumulated sludge using appropriate technologies, and introducing detritivorous benthic species that consume organic debris^[118].

Mitigating N₂O emissions necessitates minimizing surplus nitrogen within aquaculture systems. This is closely linked to feed efficiency, specifically, avoiding excessive protein feeding and selecting diets aligned with the nutritional requirements of fish to limit nitrogen excretion. Integrated aquaculture practices present viable mitigation strategies. For example, incorporating autotrophic organisms such as seaweeds or aquatic plants, which assimilate dissolved nutrients, can effectively remove nitrates from the water column, thereby potentially lowering N₂O generation^[119]. Empirical studies have demonstrated that cultivating vegetables, such as pak choi and water spinach, in conjunction with fish farming reduced N₂O emissions by more than 60%^[120]. Likewise, the integrated

multitrophic aquaculture model, where fish are farmed alongside nutrient-recycling species, such as shellfish and seaweeds, supports nutrient recovery. Seaweeds absorb dissolved inorganic nutrients that could otherwise contribute to N₂O emissions or eutrophication, whereas shellfish remove suspended organic matter through filtration^[121]. In addition to waste mitigation, seaweeds also absorb CO₂ during biomass accumulation, offering a potential contribution to carbon sequestration. The uptake of CO₂ is primarily driven by high primary production, a common feature of aquatic ecosystems^[122].

Biofloc technology represents a further innovative approach, whereby waste within the system is transformed into microbial biomass that can be directly consumed by fish^[123]. This process enhances feed efficiency and may help to minimize nutrient discharge. According to Huang et al.^[28], biofloc technology is identified as a mitigation strategy for shrimp aquaculture. By promoting a more closed nutrient cycle, it can reduce the frequency of water exchange, thereby limiting N₂O emissions associated with effluent discharge, and lessen dependence on externally sourced protein feed.

7.5 System design and new technologies

Re-evaluating the design of aquaculture systems presents opportunities for reducing emissions. RAS, though currently limited by energy demands, have the potential to produce fish with negligible direct emissions and without altering natural habitats, provided they are powered by renewable energy sources and optimized for energy efficiency. Ahmed and Turchini^[30] promote RAS as a climate adaptation measure, emphasizing the shift toward controlled environments to mitigate risks associated with climate-sensitive and high-emission practices, such as pond-based farming on converted land. The primary challenge lies in addressing the energy and financial constraints, which may be alleviated through renewable integration, such as installing solar panels on RAS facilities and implementing heat recovery systems.

An alternative strategy is precision aquaculture, which uses sensors and automated systems to enhance the efficiency of feeding, aeration, and other operational inputs, thereby minimizing waste^[124]. By aligning feed delivery with the real-time appetite of fish, overfeeding and the associated waste, can be avoided, potentially reducing emissions from both feed use and pond dynamics. Likewise, energy consumption can be

lowered by automating aeration to maintain optimal oxygen levels.

There is growing interest in carbon sequestration and offset initiatives associated with aquaculture. Seaweed cultivation has been identified as a potential method for carbon removal, particularly if a portion of the biomass is either deliberately sunk in the ocean or incorporated into durable products, thereby excluding the associated CO₂ from the carbon cycle^[79]. Similarly, shellfish farming has been proposed as a carbon sequestration strategy through the formation of calcium carbonate in shells. According to Tamburini et al.^[46], mussel and clam aquaculture can result in a net removal of CO₂, with sequestration in shells surpassing emissions from farming activities, potentially up to 0.233 kg CO₂ sequestered per kg of clams produced. Although concerns remain regarding the long-term stability of this sequestration, since shells may dissolve and re-emit CO₂ unless properly buried, these insights suggest the possibility of incorporating certain aquaculture practices into carbon credit frameworks^[55,125].

The conservation and rehabilitation of blue carbon ecosystems in proximity to aquaculture operations can contribute to emissions offsetting. For example, shrimp farmers may undertake mangrove restoration adjacent to their ponds as a means of compensating for emissions, given that healthy mangroves sequester CO₂ and, over time, may counterbalance a portion of the carbon emitted by aquaculture activities. Additionally, mangroves offer benefits such as coastal protection and habitat provision for wild fish^[126]. In Indonesia, the substantial mitigation potential of preventing further mangrove degradation has been quantified^[41]. In response, certain sustainable shrimp certification schemes have begun to promote or mandate the replanting of mangroves.

7.6 Policy and management measures

At a broader policy level, fostering the adoption of low-carbon technologies within the aquaculture sector is essential. Governments can make a pivotal contribution by offering incentives or subsidies that encourage the use of renewable energy sources, energy-efficient technologies and enhanced feed practices. Additionally, incorporating aquaculture into national GHG inventories and mitigation frameworks is important. Jiang et al.^[5] highlighted the need for integrated, cross-sectoral governance to enhance the sustainability of aquaculture, pointing out that no country currently achieves

high sustainability across the combined dimensions of food, energy, water and carbon. This underscores the necessity of targeted policy interventions to support comprehensive progress, including reductions in GHG emissions.

Also, incorporating GHG monitoring and reporting into aquaculture practices can enhance awareness and promote sector-wide advancements. Researchers advocate for the systematic acquisition of reliable emissions data to enable ongoing assessment of industry performance^[29]. Enhanced transparency may incentivize producers to differentiate themselves through low-carbon credentials and facilitate the evaluation of progress toward climate neutrality targets.

It is also crucial to account for potential trade-offs. An intervention that lowers GHG emissions may lead to other environmental consequences. For example, while RAS can reduce nutrient discharge, their use may elevate the overall carbon footprint; similarly, decreasing the protein content in feed could reduce N₂O emissions, but slower fish growth might prolong energy consumption. Effective mitigation should therefore prioritize synergistic outcomes or, at a minimum, manage trade-offs to avoid addressing one issue at the expense of another^[22]. For example, enhancing feed efficiency generally leads to both lower nutrient waste and emissions (a win-win), whereas relocating ponds to marginal wetlands may reduce feed demand through extensive practices, but risks triggering land-based emissions, an undesirable trade-off.

8 Future research

With the continued expansion of the aquaculture industry to satisfy the protein needs of a rising global population, it is crucial to confront its associated environmental impacts. Advancing research should prioritize the improvement of GHG assessment techniques, the formulation of effective mitigation measures and the investigation of sustainable policy frameworks to support the enduring sustainability of the sector.

8.1 Advancements in GHG quantification methods

Reliable quantification of GHG emissions is essential for implementing effective mitigation strategies. Commonly-used evaluation methods frequently fail to capture the complete range of emissions linked to aquaculture activities. The

integration of advanced technologies, such as eddy covariance systems, offers the potential to obtain detailed measurements of gas fluxes within aquaculture environments. The US Department of Agriculture has introduced standardized protocols for assessing GHG emissions in agricultural and forestry contexts^[127]. Nonetheless, these approaches require adaptation to reflect the distinct emission characteristics of various aquaculture systems. Advancing research in this area should focus on creating holistic, species-specific evaluation frameworks that include life cycle assessment, thereby facilitating more accurate assessments of environmental impact.

8.2 Comprehensive life cycle assessments (LCAs)

LCA serves as a critical method for assessing the environmental impacts linked to aquaculture systems. Standard LCAs have largely focused on direct emissions, frequently neglecting indirect sources such as those arising from feed production, energy consumption, and postharvest processing. To achieve a more comprehensive understanding of the carbon footprint of the sector, future research should work toward developing LCAs that account for the full value chain^[15]. For example, incorporating data on the sourcing and transportation of feed ingredients can uncover overlooked emission sources and highlight potential areas for mitigation.

8.3 Emerging technologies and data analytics

Harnessing technological innovations holds significant potential to transform GHG monitoring and mitigation within aquaculture. The integration of precision aquaculture technologies, including sensors and automated systems, allows continuous monitoring of parameters, such as water quality and energy consumption, thereby supporting more effective resource management^[128]. Also, the application of big data analytics and machine learning techniques can identify trends and forecast outcomes, enhancing decision-making processes focused on emission reduction^[129].

8.4 Innovative mitigation strategies

Feed production represents a major source of carbon emissions within the aquaculture sector. Shifting toward more sustainable feed options, such as those based on plant proteins or insect-derived meals, offers considerable potential for emission

reductions. The incorporation of seaweed into feed compositions has demonstrated effectiveness in mitigating CH₄ emissions in livestock and holds potential for similar application in aquaculture^[130]. Also, seaweed cultivation presents a dual advantage: it supplies an environmentally sustainable feed ingredient and functions as a carbon sink via photosynthetic activity^[131]. Nevertheless, further investigation in these areas remains essential.

8.5 Geographical considerations and policy development

Regional differences in aquaculture practices require context-specific investigations to determine the most effective mitigation approaches. In the case of South Africa, research has revealed a two-way interaction between aquaculture output and GHG emissions, emphasizing the importance of policies that support sustainable development^[132]. Coordinated action among governmental bodies, industry actors, and academic institutions is crucial for formulating regulations that align economic advancement with environmental responsibility.

9 Conclusions

The contribution of aquaculture to GHG emissions has increasingly come under scrutiny as a key component of its overall sustainability, reflected in the growing body of research and in-depth evaluations reviewed in this paper. This literature synthesis demonstrates that aquaculture presents both climate-related risks and opportunities. On one side, certain types of aquaculture, particularly those characterized by high input and feed dependency, can emit considerable GHGs through feed production, energy consumption, and CH₄ emissions from aquatic systems, sometimes equaling or surpassing the emissions associated with some forms of terrestrial livestock. On the other side, several aquaculture practices, notably those involving unfed species such as seaweeds and bivalves, have a negligible carbon footprint, with some integrated systems even offering potential for carbon sequestration. As such, aquaculture encompasses a continuum ranging from climate-detrimental to climate-beneficial food production.

Principal insights from this review include:

- **Sources of emissions.** In most fed aquaculture operations, feed production constitutes the largest source of GHGs,

followed by on-site energy consumption and CH₄ emissions from pond-based systems. Emissions may also be significantly heightened by air transport of products. Land use transformations, such as mangrove deforestation for shrimp farming, contribute to substantial, one-time CO₂ releases.

- **Species variation.** Emissions vary significantly by species. Unfed organisms like bivalves and seaweeds have the lowest emissions, often approaching zero or even resulting in net carbon removal. Semi-intensive farming of herbivorous fish such as carp and tilapia also yields comparatively low GHG outputs. Conversely, intensive farming of carnivorous fish (e.g., trout and salmon,) and shrimp tends to result in higher emissions due to substantial feed and energy demands. It is important to note that intensive aquaculture systems rank among the most GHG-intensive forms of protein production, underscoring that low-carbon outcomes are contingent on farming practices rather than being intrinsic to aquaculture.

- **Regional trends.** China accounts for the majority of global aquaculture-related GHG emissions, driven by its vast

production scale. Other Asian countries (including India, Indonesia and Vietnam) are also significant contributors, particularly in relation to CH₄ emissions from pond systems and ongoing sector expansion. Although European countries and the USA contribute less to absolute terms, their emissions per unit of production are often higher, particularly in energy-demanding systems like salmon aquaculture. Therefore, enhancing farming practices globally is essential for meaningful mitigation.

- **Reduction approaches.** There exists substantial scope for emission reduction through established interventions, such as optimizing feed use and formulation, transitioning to renewable energy sources, upgrading equipment efficiency, implementing species integration techniques (e.g., aquaponics and integrated multitrophic aquaculture) and improving farm-level practices to limit CH₄ and N₂O outputs. Advances in technology (e.g., energy-efficient RAS, alternative feeds) and supportive policy frameworks will be pivotal in achieving these mitigation objectives.

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Compliance with ethics guidelines

Hong Yang declare that he has no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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