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Impact of Aquaculture Intensification on Sediment Microbial Shifts and Greenhouse Gas Emissions in Coastal Earthen Ponds

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Abstract

Coastal aquaculture development has also exposed the earthen pond systems to greenhouse gases (GHG) and sediment degradation because increased production is brought about by the intensification of coastal aquaculture. The pond sediments serve as biogeochemical hotspots during which the feed and faecal-generated excessive organic loading changes the redox processes and remodels the community. These changes in the microbes have a very strong effect on carbon and nitrogen cycling and cause emission of carbon dioxide (CO 2), methane (CH 4) and nitrous oxide (N 2 O). This review summarises available data on the effect of aquaculture intensification on the remodelling of sediment microbiota and metabolic processes, focusing on the enrichment of anaerobic processes, including methanogens, sulphate-reducing, and denitrifiers, and the impoverishment of aerobic decomposers. We also attribute transitions in microbial functionality to manifest variability in GHG emissions and contrast the emissions made by aquaculture ponds and natural coastal ecosystems. Lastly, review covers sediment- and microbe-centred management strategies that would help to alleviate emissions and indicate significant research gaps that are necessary to enhance climate-sensitive and sustainable aquaculture.

Keywords:

Aquaculture intensification; sediment microbial communities; greenhouse gas emissions; coastal earthen ponds; biogeochemical cycling; climate-smart aquaculture.

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Introduction

The marine aquaculture has become a major rapidly developing food production industry globally and it has become instrumental in supporting the growing global demand of animal protein. Specifically, the earthen pond systems prevail in the farms of shrimp and finfish in the tropical and subtropical coastal areas because of its comparatively low cost of capital, flexibility in operations, and scalability (Poornimadarshini & Veerappan, 2023). In order to maximise productivity as well as economic returns, a number of aquaculture enterprises have tended to change into intensive and super-intensive forms of farm organization with high stocking rates, high rates of feed intake, continuous aeration and low water exchanges (Bao et al., 2023; Dinh et al., 2022). Though this intensification has greatly improved the yields, it has also increased the strain on the environment by the pond ecosystems, particularly in the sediment compartment. The coastal aquaculture ponds serve as dynamic water biogeochemical interfaces where uneats and feed are combined with faces and plankton debris, and they are transformed by microorganisms (Li et al., 2019). These organic inputs gradually modify physicochemical conditions of the sediment that results in the oxygen loss, redox stratification, enrichment of nutrients, and accumulation of sulphone. Consequently, microbial communities in the sediment experience significant structural and functional changes and become anaerobic and facultative anaerobic hosts (Baulch et al., 2012; Hu et al., 2020; Li et al., 2019). These microbial changes vigorously govern carbon, nitrogen, and Sulphur cycling and explicitly impact the generation of climate-relevant greenhouse gases (GHGs) and this comprises carbon dioxide (CO_2), methane (CH 4), and nitrous oxide (N 2 O) (Patel & Dusi, 2025). Increasingly, recent research has given reports of high GHG emission by aquaculture pond sediments, in instances, could in some cases compete with or surpass natural coastal wetlands fluxes (Sadulla, 2023). The three major pathways used by microbes that have been identified to stimulate these emissions under anoxic conditions, incomplete denitrification, and increased heterotrophic respiration have been noted, (Patil et al., 2021). Nevertheless, current studies still are in a piece meal fashion in different fields, and microbial ecology, aquaculture management, and climate science may be discussed separately, (Shrirao & Mishra, 2023). Besides, pond management practices, environmental environments, and methods all have yielded highly divergent and even contradictory estimates of microbial processes and GHG fluxes, (Urebe & Fatem, 2023). Although the evidence supporting the importance of aquaculture has been increasing over their geographical coverage as a potential source of greenhouse gases in the coastal environment, microbial processes that are dominated by sediments remain under oftended in climate management and blue carbon reporting (Dusi & Rahman., 2023) An integrated analysis that resort to a direct connexion between aquaculture intensification, sediment microbial restructuring, and GHG emissions is thus of high urgency to allow the development of climate-smart and sustainable aquaculture (David & Mdodo, 2025). Under this review, we critically analyse the effects of different levels of intensification on aquaculture with regard to the physical chemist conditions, microbial community structure, and functional processes, and the resulting changes in GHG emissions in earthen ponds situated along the coasts. We also specify the major feedback processes, mitigation possibilities and research needs that are necessary to balance productivity of aquaculture with environmental and climatic sustainability.

Enhanced fishing in Coastal in Earthen Pond

The intensive farming of earthen ponds along coastal zones is a developmental change of low-input, ecologically determined, production mechanisms towards highly intensive input elastic production systems. This change is mainly motivated by the necessity to raise productivity, feed ratios and makes it economically viable with rising land and resource limitations. The three systems of intensive, semi-intensive, and extensive and super-intensive are typically categorised based on unique approaches to management, the level of inputs, and the pressure they exert on the environment. Extensive and semi-intensive pond systems are commonly characterised by low to moderate level of stocking and depend in part on natural primaries productiveness to complements scheme feeds. These systems tend to have reduced rates of organic loading and keep relatively oxic sediment conditions which permits the dominance of aerobic microbial activity (Cheng, 2025). Contrarily, intensive and super-intensive systems utilise high stocking rates, high feeding ratios, mechanical aeration on a constant basis and in many cases, restrict water exchange (Arvinth, 2025). The result of such practices is massive deposit of organic matter and nutrients to pond sediments which are above the assimilative capacity of the benthic environment (Wu et al., 2018).

The sediment physicochemical properties of intensively managed ponds experience very sharp changes due to the accumulation of uneaten feed, faecal matter, and senescent plankton in the ponds (Velliangiri, 2025). High loading of organic carbon increases activity of microbes, resulting in fast consumption of oxygen and steep redox gradient in sediment profile (Yang et al., 2015). When oxygen is lost, other metabolic mechanisms which are anaerobic such as the sulphate reduction, methanogenesis and dissimulator nitrate reduction become more prominent (Zhang et al., 2024). These actions usually come with the build-up of sulphide, acidification of sediments and mobilization of reduced substances that spoil the cultured organisms and the overall health of the ponds (Yang et al., 2017). Management controls like mechanical aeration, sediment disturbance can reduce, to some degree, hypoxia in the surface sediments, but these decision-makings are no longer adequate to counteract over time the impact of continued organic enrichment (Kavitha, 2024). In turn, intensification essentially changes the environment of the sediments by establishing conditions, which are conducive to anaerobes and biogeochemical processes associated with the production of greenhouse gases (Yang et al., 2022). Table 1 will give a comparative summary of the level of aquaculture intensification, the management practices involved and the key sediment stressors, pointing out the mechanistic processes by which aquaculture intensification affects sediment functioning (Quick et al., 2019).

Table 1. Aquaculture intensification levels, management practices, and sediment stressors

Intensification Level	Typical Stocking Density	Feed Input & Management	Aeration & Water Exchange	Dominant Sediment Stressors
Extensive	Low	Natural productivity; minimal formulated feed	No aeration; high water exchange	Low organic loading; oxic sediments
Semi-intensive	Moderate	Supplementary feeding; moderate feed input	Limited aeration; periodic water exchange	Moderate organic accumulation; early redox stratification
Intensive	High	High feed input; frequent feeding	Continuous aeration; limited water exchange	High organic carbon loading; hypoxia; sulphide buildup
Super-intensive	Very high	Very high feed input; precision feeding	Intensive aeration; minimal water exchange	Severe organic enrichment; strong anoxia; acidification; reduced compounds

Sediment Benthic Community Generations and Greenhouse Gases

The main biological factor interconnecting the intensification of aquaculture with greenhouse gases (GHG) is the microbial community of sediment in coastal earthen ponds. The increase in the intensity of farming is associated with the progressive shift of the sediment physicochemical regime, resulting in the disappearance of oxygen, redox stratification, and increasing access to labile carbon and nitrogen substances. Such alterations cause strong changes in community structure and functional pathways of the microbial community and essentially redefine the sediment biogeochemical processes and the regulation of the carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) production. Aerobic and facultative aerobic heterotrophs are often preeminent in sediment microbial communities in aquaculture regimes of extensive and semi-intensive that mineralise organic matter and recycle nutrients. These systems may experience coupled nitrification-denitrification processes in the surface layers just above the sediment-water interface; the sulphate reduction processes and the methanogen processes are restricted to deeper, reduced layers of sediment. This kind of vertical microbial zonation restricts the buildup and discharge of reduced end products leading to a relatively low level of emissions of CH_4 and N_2O.

As it becomes more pronounced, a prolonged enrichment of the organics spurred up the respiration rate of microbes and quickly killed off the aerobes that favoured anaerobic and facultative anaerobic taxa. Methanogenic archaea are always enriched in intensive and super-intensive-managed ponds. (e.g., Methanobacteriales, Methanosarcinales), sulphate-reducing bacteria (e.g., Desulfovibrionales), fermentative bacteria (e.g., Clostridiales), and denitrifiers capable of incomplete nitrogen reduction. These community-level transitions are accompanied by increased abundance of functional genes associated with methanogenesis (mcrA), sulfate reduction (dsrB), and denitrification (nirS/nirK), alongside a decline in nitrification-related genes such as amoA. Table 2 gives a synthesis of the major microbial taxa and functional pathways across intensification gradients that show how the operation practices are controlling operational capabilities of the microbes in sediments.

A conceptual representation of the progressive restructuring of sediment microbial communities in intensification gradients is illustrated in Figure 1, within which the changes in carbon, nitrogen, and sulphur cycling pathways are represented by the transition of the sediment community, dominated by aerobes from aerobic to anaerobic conditions.

Table 2. Dominant Microbial Taxa and Functional Pathways across Intensification Gradients

Table 2. Dominant microbial taxa, biogeochemical pathways, and representative functional genes across aquaculture intensification gradients

Intensification Level	Dominant Microbial Groups	Key Biogeochemical Pathways	Representative Functional Genes (Markers)
Extensive	Aerobic heterotrophic bacteria; ammonia-oxidizing bacteria (AOB) and archaea (AOA); nitrite-oxidizing bacteria (NOB)	Aerobic organic matter oxidation; nitrification	amoA (ammonia oxidation); nxrB (nitrite oxidation)
Semi-intensive	Facultative anaerobes; denitrifying bacteria	Coupled nitrification–denitrification; partial denitrification	nirS, nirK (nitrite reduction); nosZ (N_2O reduction)
Intensive	Sulfate-reducing bacteria (SRB); fermentative bacteria	Sulfate reduction; anaerobic fermentation	dsrB (dissimilatory sulfate reduction); aprA (adenylylsulfate reduction)
Super-intensive	Methanogenic archaea; DNRA-associated bacteria	Methanogenesis; dissimilatory nitrate reduction to ammonium (DNRA)	mcrA (methane production); nrfA (DNRA pathway)

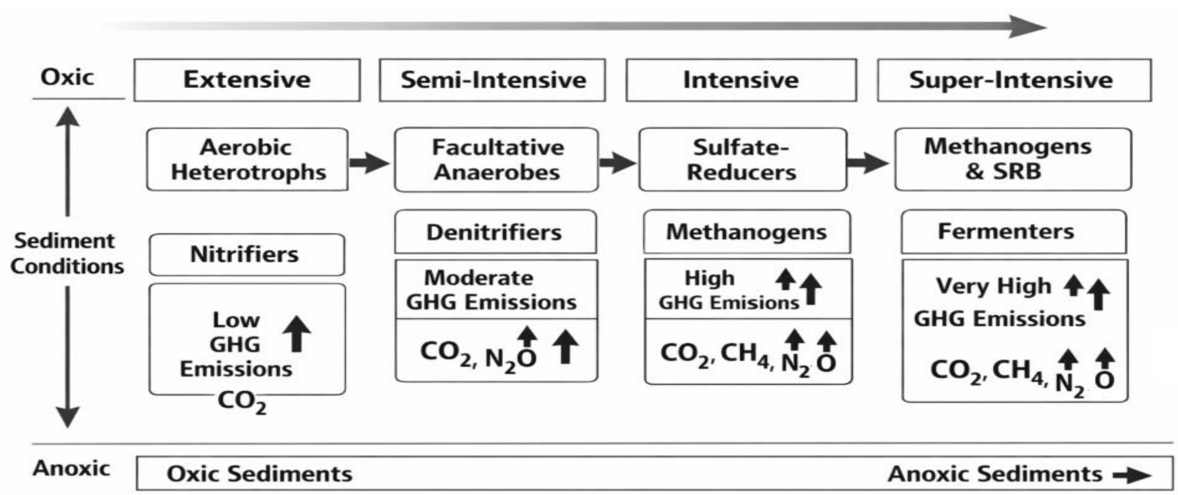

Figure 1. Conceptual model of sediment microbial community shifts along an intensification

These are microbial changes with direct implications on GHG production. High organic loading and enhanced heterotrophic respiration leads to increased CO 2 emissions by pond sediments. Constant anoxia enhances the consumption of acetoclastic and hydrogen trophic pathways to methanogenesis while restricted oxygen is deposited to inhibit the combustion of methane, which results in high levels of CH 4 diffusion and ebullition. The main factors that contribute to nitrous oxide emissions are due to nitrogen enrichment and varying redox conditions that prefer denitrification that is incomplete and in certain instances, dissimulator nitrate reduction to ammonium. Figure 2 presents the microbial and biogeochemical pathways between the processes occurring in sediments and the production of CO 2, CH 4, and N 2O schematically.

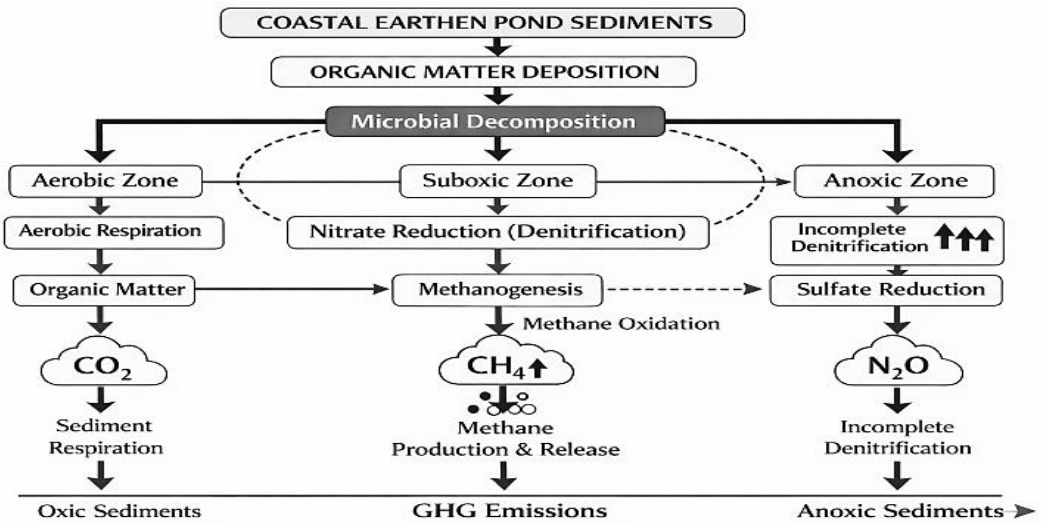

Figure 2. Microbial and biogeochemical pathways linking sediment processes to GHG emissions

The reported rate of GHG emission in the coastal earthen ponds is a variable phenomenon because of the species grown, sediment, intensive level, and methodology used. However, they all do exhibit a consistent trend wherein the intensive systems have a much greater CO 2 and CH 4 flux and sporadic N 2 O emissions than the large and semi-intensive pond. The significant range of reported emission of major GHGs is compared in Table 3 which highlights the possible role of aquaculture pond sediments in the greenhouse gas budgets of the coast.

Table 3. Reported ranges of CO_2, CH_4, and N_2O emissions from coastal earthen ponds

GHG	Emission Range	Dominant Microbial Source	Primary Drivers
CO_2	Moderate to high	Heterotrophic respiration	Organic carbon loading
CH_4	Low to very high	Methanogenesis	Anoxia, labile carbon
N_2O	Low to moderate	Incomplete denitrification	Nitrogen loading, redox fluctuation

Sediment MIC Climatic Feedback

The process of aquaculture intensification not only changes the community of microbes in sediments, as well as the occurrence of greenhouse gases (GHG), but also triggers a series of interdependent feedback pathways that make the pond management practises susceptible to the larger climate forcing. These are the feedbacks which occur due to the close interaction between organic matter loading, sediment redox interactions, functional dominance of the microbes and gas exchange processes which in turn increases the climatic footprint of intensively operated coastal earthen ponds. The high feeds and stocking densities raise the flux of the labile organic carbon and nitrogen to the pond sediments, activating the process of bacterial respiration and enhancing the rate of oxygen usage. These changes in anoxic, suboxic, and oxic surface sediments result in autotrophic metabolic activities predominating, which include the reduction of sulphates, methanogenesis, and incomplete denitrification. Not only do these pathways increase the production of CO 2, CH 4 and N 2O, but this reaction also results in minimised by-products (e.g. sulphides and ammonium) which further weakens aerobic microbial survival, which again strengthens anaerobic dominance. This leads to a positive biogeochemical feedback loop where microbial processes that maintain and go further to enhance anoxia conditions thrive in the favour of sediment anoxia. The pond management interventions also regulate the microbial feedbacks. Although mechanical aeration is also effective in raising the oxygen levels in the water column, it can very frequently fail to reach the deeper levels of sediment where anaerobic processes continue to occur. Incomplete denitrification can also be further amplified by intermittent aeration and varying redox conditions which can favour incomplete oxidation of nitrous oxide in some instances. Likewise, lower water exchange in intensive systems inhibit the elimination of end-products of metabolism that enable build-up of greenhouse gases and low concentrations of compounds in the pond ecosystem. On a larger scale, climate forcing gives two-way interactions with sediment microbial processes. Increased temperature promotes metabolism of microorganisms, which accelerates the decomposition of organic matter and methane generation, whereas increment of salinity and change of hydrological regimes affect the availability of sulphates and the composition of microbial communities. The resultant increase in emissions of CH4 and N2O as powerful greenhouse gases, in its turn, contributes to atmospheric warming, which, in its turn, may stimulate further activity of the microorganisms and turnover of organic matter in the aquaculture sediments. This microbe-climate nexus places aquaculture ponds that are intensively controlled in a microbial-based nexus as a changing and possibly self-reinforcing source of greenhouse gases in the coastal areas. This synergy between the mechanisms serves to explain why the changes in the conditions induced by intensification in aquaculture, in terms of sediment biogeochemistry, microbial ecology and climate processes, propagate via microbial processes in the creation of greenhouse gases and climate forcing (Figure 3). It is important to learn about these loop processes and break them to work out climate-smart strategies of aquaculture with both high productivity and environmental sustainability.

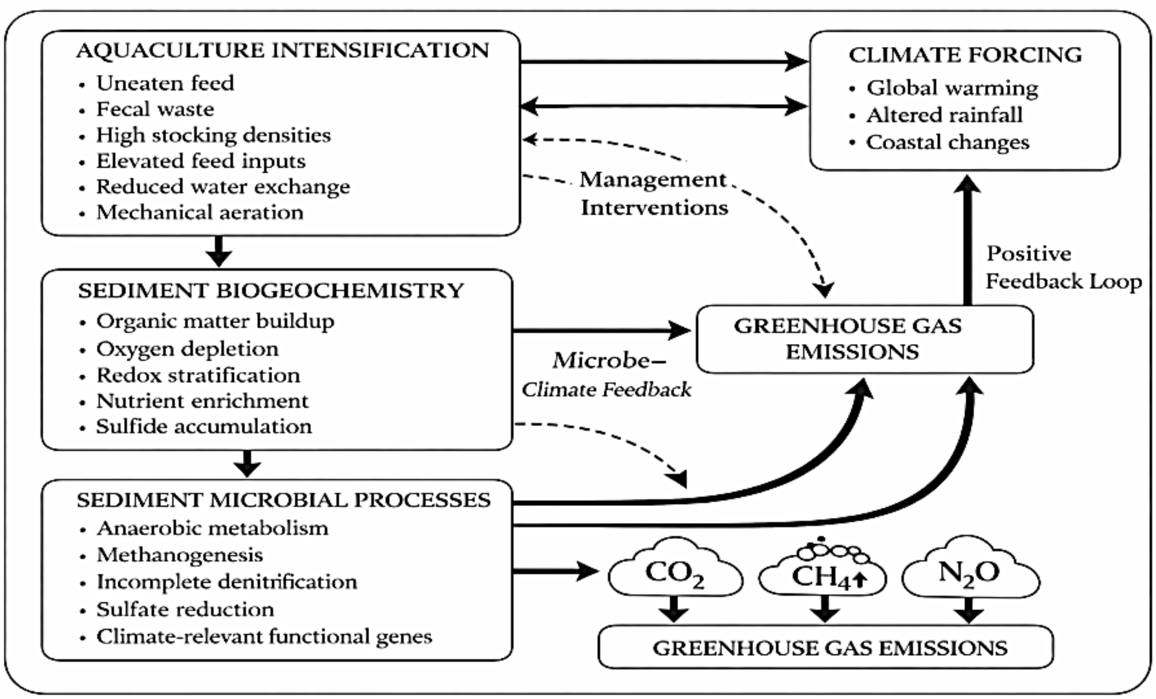

Figure 3. Integrated feedback framework linking aquaculture intensification, sediment microbial processes, and climate forcing

Climatic and Environmental Effects

The effects of the intensification of the coastal aquaculture are of an environmental and climatic capacity and cannot be limited to the single pond systems. The ability of increased management practises to essentially modify the biogeochemistry and microbial activity leads to increased carbon dioxide (CO 2), methane (CH 4) and nitrous oxide (N_2O) emissions in accordance with the previous sections. A combination of all of these emissions makes aquaculture pond sediments a new and little-known source of coastal greenhouse gases (GHG) budgets. Comparative studies show that GHG emissions in aquaculture ponds that are under intensive management can match, or even be higher, than the natural GHG emissions in coastal ecosystems like mangroves, salt marshlands and tidal flats. Compared with natural wetlands, however, the aquaculture pond is a highly-controlled regime, involving continuous organic loading, artificial aeration, and limited hydrological exchange, and can increase the anaerobic microbial activity and lowers the ability of the system to retain carbon. Consequently, the intensification can cause the community to change aquaculture ponds, which are unstable carbon systems or are almost neutral, to become sources of GHGs to the atmosphere.

Climatically, methane and nitrous oxide emissions are of special concern because their global warming potentials are high as compared to those of CO_2. To cause imbalance in radioactive forcing, even small contributions to CH_4 and N_2O fluxes of pond sediments can contribute in disproportional amounts to radioactive forcing. In addition, climate-related stressors, including temperature increase, changed precipitation levels, changes in sea level, and intrusion of saline waters, will probably increase the intensity of sediment anoxia and microbial metabolic rates, further affirming the positive feedbacks between aquaculture activities and climate forcing. However, with such implications, the GHG emissions associated with aquaculture are under-represented in the national greenhouse gas inventories and global climate assessment. Existing reporting systems tend to favour the land-based agricultural and natural wetlands and ignore the controlled aquatic food-production systems. This underrepresentation restricts the validity of the carbon budgets relating to coastal areas of interest as well as mitigation plans that ought to be based on evidence. It is of importance to appreciate the role of sediment microbial processes as key regulators of GHG emissions vehicles in aquaculture therefore in the incorporation of aquaculture within the blue carbon and climate mitigation models. To balance the two objectives of aquaculture productivity and climate sustainability, better quantification of the emissions, management manipulation, in tandem with sediment organic loading and microbial functioning, will be necessary.

Marginal Measures and Future Research

To reduce the threat of greenhouse gas (GHG) emissions generated in intensively managed coastal pond aquaculture, the combination of several strategies is needed to mitigate the challenges related to sediment organic loading, microbial functional preponderance, and systemic feedback. Due to the fact that the microbial processes of sediment directly control the generation of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), the best mitigation should be a combination of operational management and biogeochemical and microbiological intervention. The most direct way of mitigating emissions is to reduce the growth of organic matter in pond sediments. An increase in feed management, more precise feeding, and feed conversion efficiency can significantly reduce carbon and nitrogen to be added to the sediments. An annual removal, drying, or oxidation of the product in between production cycles may suppress anaerobic microbial activity and may recreate an oxic or suboxic sediment. Methanogenesis and incomplete denitrification may also be further limited by aeration interventions that increase oxygen penetration within the sediment and water interface (as opposed to just within the water column). System level advancements such as biofloc technology, and integrated multi-trophic aquaculture can be friendly in recycling of nutrients, and minimise the accumulation of organic wastes, where constructed wetlands or sedimentation basins can segment aquaculture discharge to the coastal waters.

New mitigation opportunities can also be provided by microbial and biogeochemical interventions. It is possible that the manipulation of microbial communities in sediments to achieve specific metabolic outcomes can be achieved through the use of probiotics or bio augmentation, to push the community towards metabolic processes that lead to reduced GHG generation, including increased aerobic degradation or complete denitrification. Carbon-to-nitrogen ratios can also be manipulated by feeding and managing sediments which can influence the choice of microbial pathways and intensity of emissions. Nevertheless, these solutions are mostly empiric and their cost-efficacy, environmental sustainability, and scalability have to be evaluated systematically. Although there is growing awareness on aquaculture-induced GHG emissions, there are still significant gaps in knowledge. There are also fewer studies that quantify sediment microbial activities and gaseous fluxes across multiple seasons that have sufficient duration to limit knowledge of temporal fluctuation and the accumulating climate effects. The deficiency of standardized methodologies in the quantification of GHG emissions in aquaculture ponds also does not facilitate cross-study comparison in addition to allowing regional upscaling. Further studies ought to focus on approaches that combine high-resolution microbial studies, including metagenomics and functional gene profiling with direct flux measurements. The creation of powerful upscaling strategies to capture aquaculture systems in regional and national stock of greenhouse gas emissions, always as a result of climate-driven stressors like warming, intrusion of salinity and severe weathers will be vital in enhancing climate-smart and sustainable aquaculture.

Conclusions

The growth in intensity of coastal aquaculture has come up to be a detrimental cause to sediment biogeochemical changes and greenhouse gas (GHG) emission in earthen pond systems. This review points out that the sediments are core and hotspots of biogeochemistry and microbial activities in which an overload of organic matter through enhanced agricultural activities has led to the loss of oxygen, redox stratification and radical reorganisation of microbial ecosystems. The presence of these microbial changes, in the form of an aerobic and nitrifying assemblage being replaced by an anaerobic consortium of methanogenic, sulphate-reducing, and denitrifiers, is key to controlling the generation of carbon dioxide (CO 2), methane (CH 4) and nitrous oxide (N 2 O). Combining evidence on intensification gradients, this review shows that intensive aquaculture ponds may serve as important and, in many cases, unrecognised carbon emitters of climate-relevant greenhouse gases, and the number of emissions can be as large or larger progressively than those of natural coastal ecosystems. Combination of microbial ecology and sediment biogeochemistry offers a mechanistic approach to comprehending the process by which management practises are transmitted across the sediment processes to affect climate forcing. Additionally, due to positive feedbacks among the anoxia of sediment, microbial metabolism, and the climate-imposed stressors, the effects on intensively managed systems due to future warming conditions have been emphasised. The response to the climate footprint of aquaculture needs a paradigm shift to climate-smart management practises which directly take into account sediment microbial processes. The key solution to the problem of reconciliation between aquaculture productivity and environmental and climate sustainability is to implement targeted interventions that would decrease organic loading, re-establish the redox balance of the sediment, and orientate microbial activity, in addition to enhancing monitoring and standardized assessment of emissions. Finally, integration of the aquaculture pond sediments in the carbon budgets and climate alleviation plans will be pivotal in the resilience and sustainability of the world aquaculture systems in the long term.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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