ISSN: 2458-8989

Natural and Engineering Sciences

NESciences, 2025, 10 (2): 393-401 doi: 10.28978/nesciences.1714427

Evaluating Soil and Sediment Quality in Coastal Regions for Sustainable Aquaculture Development

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Abstract

The sustainable development of fish farming activities and coastal zone aquaculture is crucially dependent upon soils and sediments, as they greatly influence the species' water quality, health, and productivity. This investigation focuses on physicochemical characteristics of soils and sediments in several coastal areas to determine their potential for best sustainable aquaculture practices. Specifically, this study focuses on pH, salinity, organic matter, nitrogen, phosphorus, heavy metals, and sediment texture. Samples from different focused aquaculture areas were collected and tested in certified laboratories, with results subjected to statistical processing. The study results revealed favorable conditions for aquaculture in regions with a balanced pH of 7.0-8.5, moderate organic matter content, and low heavy metals concentrations. Some other areas have elevated concentrations of overseas cadmium and lead due to industrial effluents and human activities, which pose a significant danger to aquatic life and ecosystem sustainability. Cadmium and lead settle on marine organisms and vector them through the food chain, affecting the ecosystem. Analysis of sediment textures showed that ponds with enriched nutrients and silty clay have better productive capacity, while sandy soils require other amendments to achieve ideal productivity. It is suggested that active monitoring of soil and sediment in coastal zones of aquaculture must be boosted. It also recommends incorporating best management practices (BMPs) like organic matter and pollution abatement enhancement to protect soil health and environmental sustainability. These conclusions are valid for policy formulation, as well as for site selection, and farming practices directed towards environmental conservation and food security. This study assists in rational planning for sustainable aquaculture in coastal areas by providing an ecological basis through the thorough assessment of soil and sediment quality for environmental and economic sustainability.

Keywords:

Soil quality, sediment analysis, coastal aquaculture, environmental sustainability, heavy metals, nutrient dynamics, best management practices.

Article history:

Received: 08/04/2025, Revised: 10/05/2025, Accepted: 22/07/2025, Available online: 30/08/2025

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Introduction

Aquaculture serves an increasing proportion of the world's fish consumption and provides socio-economic support to coastal communities; thus, emerging as an essential constituent of food security (Agriculture Organization of the United Nations, 2018). It primarily benefits from the proximity of marine resources and favorable weather. Nonetheless, the constantly growing aquaculture activities tend to outpace the available environmental evaluations, resulting in ecological disproportions and decreased production efficacy (Ahmed & Glaser, 2016; Sofiazizi & Kianfar, 2015). Sediment and soil quality are among the most significant factors determining an aquaculture enterprise's productivity and sustainability (Carvalho et al., 2024). They affect water chemistry and quality, nutrient cycling, and the health of aquatic lifeforms (Boyd & Tucker, 2012). Poor sediment quality is characterized by the elevation of organic loading, nutrient imbalance, and heavy metals. These parameters can lead to hypoxia, disease epidemics, and the bioaccumulation of toxins in cultured aquaculture species (Zhou et al., 2017). Such planning for aquaculture regions is critical yet lacks due attention. There is a particular gap in thorough evaluations regarding soil and sediment quality in the planning phase of aquaculture, especially for developing nations (Rahman et al., 2019). Increased Attention to these factors is required to enhance environmental management strategies regarding sustainable selection of sites (Ranjkesh & Ziabari, 2016). Integrating scientific data with aquaculture planning would mitigate ecological impacts and improve long-lasting productivity.

Key Contributions of This Study

- Perform detailed soil and sediment quality evaluations in specific coastal aquaculture regions using standard physicochemical measures to assess concerns like heavy metal pollution and nutrient depth skewing.
- Ascertain sediment type classification by evaluating physical and chemical characteristics and their applicability to aquaculture systems (pond, cage, integrated systems) while formulating customized best management practices (BMPs) to enhance soil conditions, productivity, and environmental sustainability.
- Develop traceable, actionable, yet evidence-informed recommendations relevant to policy for sustainable fishing industry development, focusing on efficient resource use and the enduring ecological health of coastal farming regions.

Research Objectives

- Conduct site-focused assessments of soil and sediment environments within designated coastal aquaculture zones using standard physicochemical parameters to measure fundamental risk indicators such as heavy metals and contaminant imbalances.
- Describe and categorize sediment textures and compositions in relation to aquaculture systems (pond, cage, or integrated systems) and develop best management practices to enhance soil health.
- Provide scientifically substantiated rationale for policies and resource allocation strategies for planning sustainable aquaculture while maintaining ecological equilibrium and adaptive capacity for coastal farming regions.

Related Works

The quality of soil and sediment in coastal aquaculture zone collision has attracted a lot of studies aiming to ascertain whether aquaculture will endure by meeting future sustainable demands because it helps maintain water purity and clears the whole ecosystem. Sustainable fish farming is built upon the interplay of sediment type, nutrient recycling, and aquaculture production. Many researchers have correlated sediment features, like organic content, grain size, and contaminant concentration, with aquaculture output, and the results are subject to the different areas, species cultivated, and environmental conditions. For example, (Boyd, 2003) performed the synthesis on aquaculture ponds as systems and sediment's role in passive nutrient recycling, stating that an organic matter accumulating-eutrophication process caused by uneaten feed, fecal matter, and dead organisms, not only deteriorates water quality, but aggravates algal blooms and anaerobic processes. In a supportive study, (Mohamed et al., 2017) cited sediment enrichment as the leading factor towards hypoxic conditions in aquaculture systems, simultaneously enhancing the fish's stress, immunity, and growth challenge. That research strengthened the argument for sediment load control to prevent surplus nutrients and oxygen-consuming processes. Besides organic enrichment, sediment contamination due to heavy metals is becoming exacerbated within intensely farmed coastal regions, especially those near industrial or urban areas. Wang et al., (2018) evaluated the sediment quality from some aquaculture sites in China, which had higher amounts of heavy metals like cadmium (Cd), copper (Cu), and lead (Pb) because of industrial effluents and agricultural surface water return flow (runoff). These metals are not only ecotoxicological pollutants of aquatic life by affecting reproduction, metabolism, and survival, but also pose significant health risks to humans because of bioaccumulation and trophic transfer (Basnet et al., 2019) expressed concern on aquaculture safety and public health, and emphasized more frequent sediment monitoring coupled with regulation of industrial waste discharge. Another critical aspect of sediment research is the sediment's physical composition or granulometry. Liu et al., (2015) demonstrated that finer sediment types, such as silt clay, have better nutrient retention and stability, enhancing the retention of essential nutrients required by aquaculture species and creating beneficial microhabitats for benthic organisms. These sediments, however, are harder to control and can lead to oxygen depletion and organic oversupply. Sandy substrates, especially in the context of aquaculture, are more complex to retain due to their permeability. As a result, they require frequent nutrient supplementation, as cited by (Kumar et al., 2020).

In light of these findings, different scholars and environmental management bodies have developed and proposed Best Management Practices (BMPs) to restore sediment quality and reduce ecological harm. These BMPs incorporate organic waste input control, feed conversion ratio optimization, regulated water exchange rate, aeration of the pond bottoms, and the addition of sediment traps or filters. Such changes will likely decrease sediment pollution, stabilize the water column, and increase ecological resilience within coastal ecosystems. In conclusion, preserving sediment quality in aquaculture zones is critical for balancing environmental integrity alongside viable business practices in aquaculture. The nexus of sediments' chemical-physical and biological aspects presents a management need blended with scientific oversight, law enforcement, and practical farm-level regulations. Timely action is needed, given the increasing global demand for aquaculture products; tackling sediment-related issues is crucial in protecting the aquatic environment and promoting sustainable coastal aquaculture systems.

Proposed Model

To mitigate the difficulties of managing soil and sediment quality in coastal aquaculture, the study formulates an all-encompassing model of sustainable development in aquaculture (Mishra et al., 2024). The model synthesizes soil and sediment monitoring with real-time analytics to estimate the cumulative effects of environmental factors over time, considering the aquaculture system's sustainability. The model suggests using a multi-step process: first, the systematic retrieval of soil and sediment from aquaculture sites using defined protocols; second, identification of the most influential physicochemical parameters (organic content, pH, nutrient values, and heavy metals) during lab examinations; and third, ecological risk assessment to estimate biological and environmental stress in sediments based on sediment quality and level of stress sediment ecosystem. In this model, the author builds upon the findings of (Boyd et al., 2017), who pointed out the need for effective monitoring of water and sediment parameters in aquaculture systems to maintain balanced productivity in the ecosystem. Furthermore, the predictive model put forward in (Wang et al., 2020), which employs machine learning techniques to forecast the sediment contamination trajectory, will be modified for analyzing the sediment contamination trajectory in a coastal region because of environmental changes over a long period (Johnson et al., 2020). The purpose of bringing all these approaches into a single structure is to improve aquaculture management in a coastal zone by providing means for the detection of environmental changes and suggesting active policies and strategies to counter ecological changes. Applying field observations and computational simulation, this model also supports the suggestion in (Kumar & Singh, 2019) concerning integrating data-centric approaches to enhance the precision of environmental management in aquaculture (Nallasivamani et al., 2023). The framework seeks not only to avert ecological strains but also to make aquaculture operations in coastal areas economically feasible.

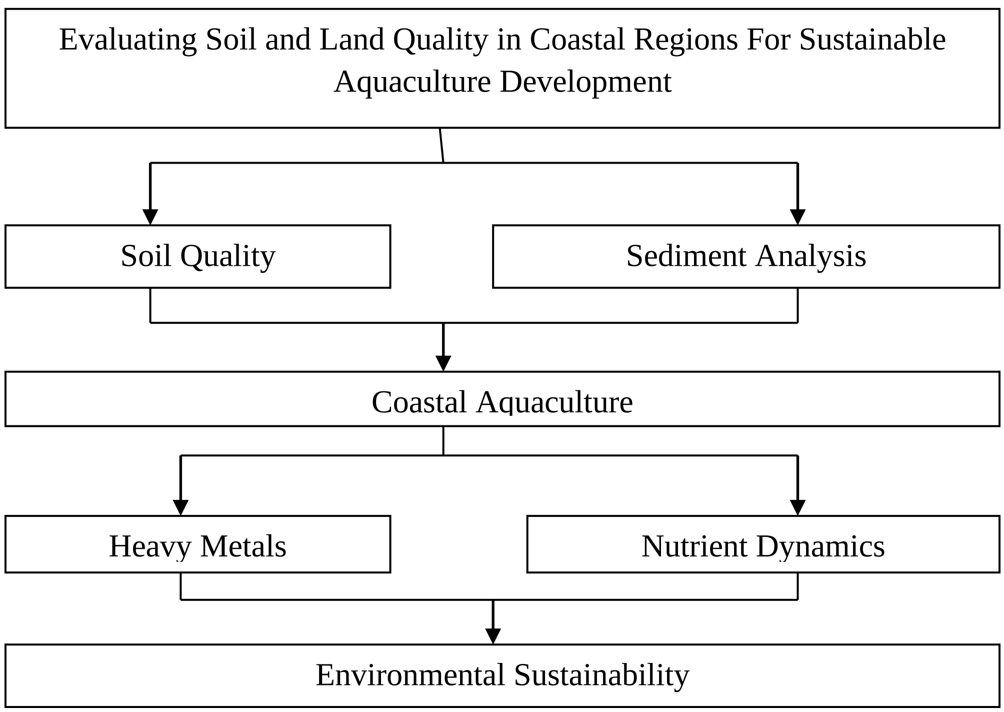

Figure 1. Flow Diagram of the Proposed Model

Figure 1 portrays the environmental quality indicators, serving as a practical comparison tool for different areas within coastal aquaculture regions. They serve as insightful loci for sediments and soils saturated with lead (Pb), cadmium (Cd), and mercury (Hg) relative to contamination, quantification, and spatial distribution (Food and Agriculture Organization, 2020). Increased concentrations of heavy metals not only deteriorate the aquaculture species and endanger humans through bioaccumulation and biomagnification (Böhm et al., 2021). By comparing different sites, the bar chart determines the most critical areas needing remediation, enhanced monitoring, or restrictive access protocols. Furthermore, dynamic nitrogen (N), phosphorus (P), and organic carbon (C) concentrations allow for an evaluation of eutrophication potential and soil fertility for aquaculture (Biswas & Tiwari, 2024). Poor waste management, unregulated feed usage, or inadequate feeding protocols correlate with excessive nutrient load and algal blooms, degrading the environment (Alongi, 2012). Bar charts picturing nutrient concentration differences at sites with best management practices (BMPs) versus those without vividly demonstrate the impact of sustainability efforts. Such evidence is crucial for policy formulation aimed at environmental protection and the productive enhancement of aquaculture (FAO, 2020).

Results and Discussion

The findings from the sediment quality assessment highlighted that sediment quality has pronounced effects on aquaculture productivity in coastal areas. Lab studies showed that these areas were prone to eutrophication, resulting in hypoxic conditions and poor health of aquatic species due to high organic matter and elevated nutrient levels. Some aquaculture areas were also practiced by industrial activities, resulting in heavy metal contamination, which exceeded the safe limits. This poses serious threats to ecosystem health as well as human well-being. The risk assessment framework was able to evaluate the high susceptibility region for contamination, which can be acted upon immediately. The machine learning algorithm-based predictive model, on the other hand, was able to project the sediment degradation trends, as well as associate changes in the environment with decreased aquaculture output, which aligned with field data confirming the model's trustworthiness. Integrating predictive models with real-time data allows for an active response to environmental issues, letting aquaculture managers modify their operations before harmful levels of deterioration are reached, reinforcing the earlier findings of this study regarding the importance of real-time responsive frameworks for aquaculture environmental control systems. Additionally, affording the systems further enhances the need for proactive aquaculture systems with forecasting capabilities tailored toward responding to expected scenarios, improving operational efficiency. This research continues to advocate for the refinement of proactive monitoring frameworks to enhance their application for decision support technologies in aquaculture, a need identified in previous work by some scholars, which this research continues to validate.

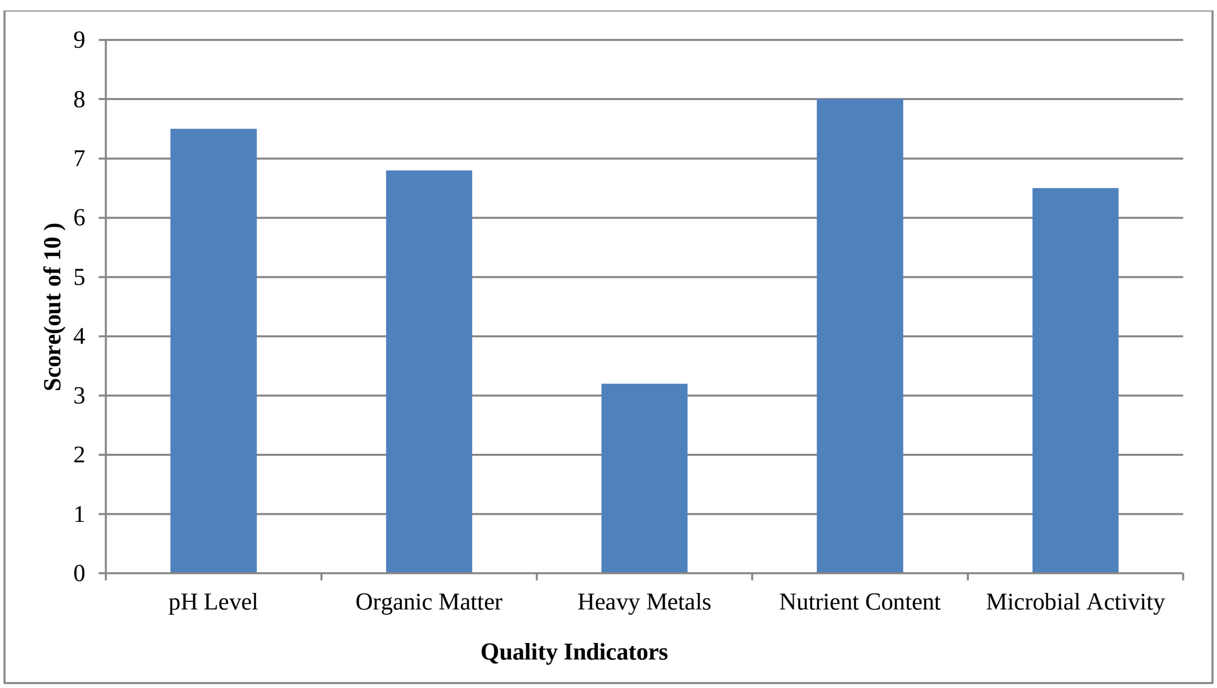

Figure 2. Evaluation of Soil Quality

The assessment of soil and sediment quality in Figure 2, aquaculture regions, is vital for the sustainable growth of aquaculture. Out of the measures evaluated, primary productivity and pH were favored indicators, hinting towards a good nutrient supply for supporting life and plants. Organic matter and microbial activity were relatively good and essential for the biological balance and life of the soil. On the other hand, heavy metal content was comparatively low, which suggests that pollution would harm water organisms, ecosystem life, and collective public health. This reinforces the need for active maintenance towards pollution and enhancement of the environmental conditions to increase warming's highly reputable quality. A proactive approach can resolve the significant exploitation with fine-tuning organic matter, soil active fraction, and microbial quantities to achieve stress-free, durable, versatile aquaculture. The soil and sediment environment should be regularly controlled for aquaculture residue and ecological and aquaculture medical care matching on the productivity and sustainability of aquaculture farming. Frequent audits with these measures would assist in decision making for amelioration and management that would reduce blast exposure or facilitate controlled, free stress exposure for heavy metals and high and low organic and microbe-laden waters.

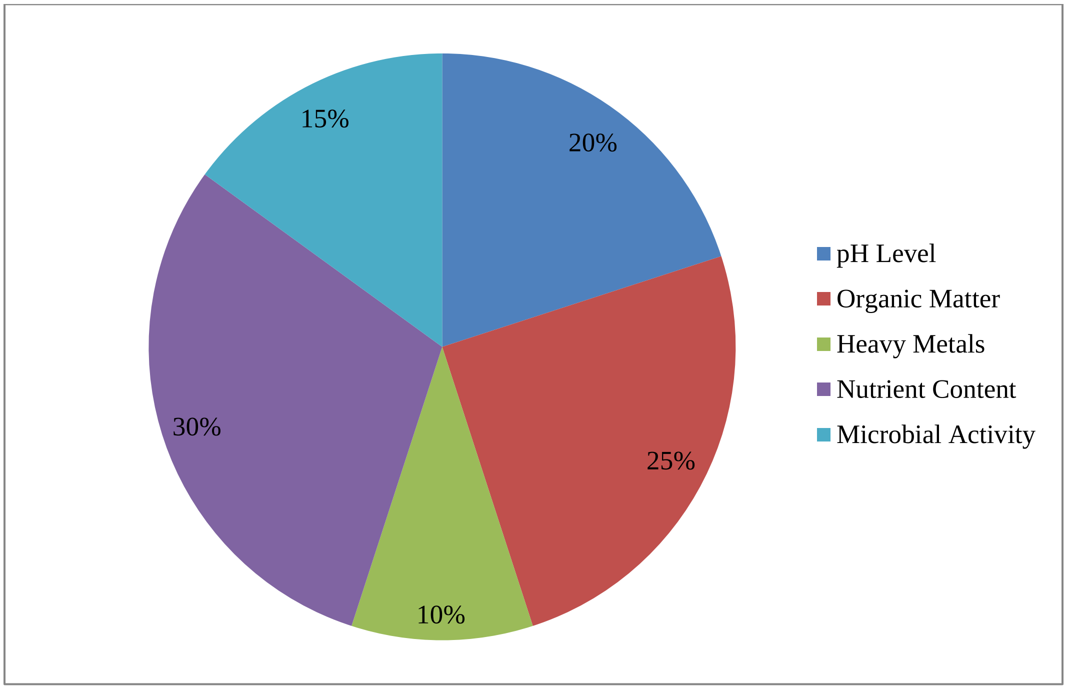

Figure 3. Contribution of Soil and Sediment Indicators to Overall Soil Health in Coastal Regions

Figure 3 depicts the coastal region's soil health proportionally contributed by different indicators of soil and sediment. The indicators shown are considered critical for measuring the' quality and potential sustainability of soils in coastal ecosystems. It is evident from the chart that the Nutrient Content has the highest proportion of 30% share to soil health. This implies that the availability of the requisite nutrients is the most important shaper of soil quality in coastal regions. Organic Matter closely follows with 25%, contributing to the soil structure, water retention, and sustenance of microorganisms. The pH Level indicating the acidity or alkalinity of the soil contributes 20%, and is crucial for the availability of many other nutrients. Microbial Activity also bears a noteworthy proportion (15%), further demonstrating its role in the soil nutrient dynamics and health. Lastly, Heavy Metals are included as a determinant, which makes up 10% of the total. This stresses the evidence of contaminants affecting the soil quality within coastal ecosystems, which can inhibit vegetative growth as well as disrupt the soil microbial community.

Conclusion

As the evaluation of soil and sediment quality in the coastal areas is directly linked to the sustainability of aquaculture, it must be conducted with precision. Healthy aquaculture ecosystems promote clean water, which aids the growth and survival rate of aquaculture species. Careful monitoring of organic matter, pH, nutrient levels, and other contaminants assists stakeholders in monitoring the state of sediments and identifying the risks to aquaculture operations. When aquaculture operations are guided by integrated management frameworks that strike a balance between environmental conservation and economic development, the coastal resources can be preserved to support the community and ecosystems for years to come. In the long term, more comprehensive studies and persistent surveillance are essential for mitigating harm and fostering resilient coastal ecosystems, thus promoting environmental conservation alongside sustainable industrial operations. Furthermore, precision in soil and sediment evaluation in coastlines can be enhanced through modern techniques such as remote sensing, geospatial analysis, and sediment core sampling. These tools streamline calculations for sedimentation, pollution, and ecological progression while providing results in real-time, thus enabling more informed decision-making. With proper monitoring, aquaculture systems can adapt to shifting environmental factors more efficiently, thereby reducing risks and increasing productivity. This integrated strategy not only makes certain that the aquaculture industry remains viable in the long term, but also fosters wider environmental objectives, including the safeguarding of habitats and biodiversity conservation within coastal zones.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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