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Soil Fertility Management for Sustainable Aquaculture Farming

Hariom Bohare[1], Sona Dubey[2], Mayur Bhadarka[3], Pooja Sahu[4], Soumya Rai[5*]

[1]ICAR-PhD Research Scholar, Department of Aquaculture, College of Fisheries Science, Kamdhenu University, Veraval 362265 (G.J) India.
[2]Assistant Professor, College of Fishery Science, Nanaji Deshmukh Veterinary Science University, Jabalpur 482004 (M.P) India.
[3]PG Scholar, Department of Aquatic Environment Management, College of Fisheries Science, Kamdhenu University, Veraval 362265 (G.J) India.
[4,5*]Undergraduate, College of Fishery Science, Nanaji Deshmukh Veterinary Science University, Jabalpur 482004 (M.P) India.

*Corresponding Author
Soumya Rai[*]

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INTRODUCTION

In pond aquaculture, soil fertility describes the ability of pond bottoms to sustain the growth of aquatic life, which plays a vital role in boosting fish yields. This fertility depends on nutrient levels, the use of organic and inorganic fertilizers, and the general condition of the pond environment. The physical and chemical characteristics of pond soils such as pH and texture greatly influence how nutrients are made available and how productive the pond can be (Boyd, 1995). Healthy pond sediments enhance the biological capacity of the system, fostering complex food webs that are crucial for fish development (Banerjee et al., 2010). Abundant organic matter and key nutrients such as nitrogen and phosphorus are vital for promoting phytoplankton development, which serves as the foundation of the aquatic food chain (Barua, 2022). Differences in soil texture for instance, the proportions of clay and silt can influence how well nutrients are retained and made accessible, thereby affecting fish growth and overall (Bhowmick et al., 2024). The quality of pond soil has a direct impact on the nutrients accessible to aquatic species. For example, Acid Sulphate Soils (ASS) can drastically reduce aquaculture yields by lowering water quality through heightened acidity and the leaching of nutrients (Tarunamulia et al., 2024). Proper management of nutrient runoff from ponds is crucial to avoid water quality decline, which could negatively impact surrounding aquatic ecosystems (Yang et al., 2019).

Role of Soil in Aquaculture Ponds

Soil is vital for retaining water, which greatly affects agricultural output and the well-being of ecosystems. To boost the soil's capacity to hold moisture, different soil conditioners and nutrient blends have been created, helping to support better plant growth and higher survival rates.

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In Moreton Bay, heavy rainfall events trigger sudden increases in nutrient levels, which notably boost phytoplankton growth, especially in nutrient-poor (oligotrophic) waters (Saeck et al., 2019). The availability and balance of nitrogen, phosphorus, and iron play a crucial role, with phosphorus commonly acting as the limiting factor in many marine environments. However, newer research indicates that nitrogen and iron can also restrict productivity (Hagstrom et al., 2016). Phytoplankton contribute to nearly 98% of oceanic primary production, capturing carbon dioxide and transforming it into organic matter (Pal & Choudhury, 2014). Studies show that pH levels influence how effectively macrophytes absorb nutrients in Floating Treatment Wetlands (FTWs). Elevated pH values (above 7.5) tend to decrease the efficiency of nitrogen and phosphorus removal. However, some species, such as the 'Rising Sun' Japanese iris, have demonstrated stable nutrient uptake regardless of pH fluctuations (Chance et al., 2019). Additionally, microbial processes play a vital role in nutrient recovery within wastewater treatment systems. These microorganisms break down organic matter, thereby improving nutrient cycling and overall water quality (Lahiri et al., 2018).

Factors Affecting Soil Fertility in Aquaculture

Soil health, fertility, and ecosystem functioning are largely determined by its texture, structure, and composition. Soil texture describes the proportions of sand, silt, and clay, which influence key properties like water retention, nutrient supply, and microbial diversity. The soil structure, or how these particles are organized into aggregates, is crucial for proper air circulation and water infiltration. These characteristics collectively impact the soil's ability to support plant growth and resist erosion.

Soil texture, structure, and composition:

Loamy soils, with higher water retention (35%) and porosity (50%) than sandy soils (10% water retention, 35% porosity), promote better aeration, thereby supporting root respiration and microbial activity (Zega, 2024). Additionally, soil composition especially levels of organic carbon and nutrients vary with texture, with finer soils typically holding more nutrients (Ding et al., 2021).

Organic matter content:

Research conducted in Riau Province reported organic matter concentrations in water between 17.38 and 49.3 mg/L, with sediment content ranging from 2.28% to 13.78% (Effendi et al., 2020). Elevated organic matter in water bodies often signals contamination from agricultural and industrial sources, which can negatively impact aquatic ecosystems (Lestari et al., 2023).

pH and salinity:

The interaction between pH and salinity plays a vital role in ecological and environmental systems, shaping chemical reactions and biological functions. Studies show that both parameters significantly influence organism toxicity and the behavior of heavy metals in aquatic habitats. Their combined effects can trigger diverse biological responses, which are key to understanding ecosystem behavior. For instance, in the case of Prymnesium parvum, higher pH levels increase its toxicity, while lower salinity can reduce this effect, though to a lesser extent (Caron et al., 2022). Additionally, there is an inverse relationship between soil pH and salinity, largely influenced by the presence of soluble calcium ions that affect both variables (Al-Busaidi & Cookson, 2003).

Soil Fertility Assessment

Evaluating soil fertility is essential for enhancing agricultural output and promoting sustainable land use. Both conventional soil testing and modern techniques, such as machine learning, are employed to assess soil health and nutrient availability, helping inform effective management strategies. The Extreme Learning Machine (ELM) model has demonstrated potential in predicting soil fertility by analysing key soil characteristics, using feature selection methods like Principal Component Analysis (PCA) and Recursive Feature Elimination (RFE) (Pant et al., 2024). Research indicates that cover crops can significantly boost organic carbon content, especially in the upper soil layers, thereby enhancing overall soil health (Sharma et

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al., 2018). Tracking nitrogen concentrations is important for understanding nutrient cycles in the soil and for refining fertilization practices (Raghavendra et al., 2020).

Soil Fertility Management Practices

Liming to correct pH:

Liming is a well-established agricultural method used to adjust acidic soil pH, promoting better crop yields and improved soil quality. This process involves applying materials such as calcium carbonate or dolomitic limestone to decrease soil acidity. By doing so, liming enhances nutrient availability and reduces the harmful effects of toxic elements like aluminium. It raises the soil pH toward neutral levels, thereby creating more favourable conditions for plant nutrient uptake and growth (Nyamaizi et al., 2022).

Use of organic and inorganic fertilizers:

The application of both organic and inorganic fertilizers is essential for boosting agricultural output and maintaining soil health. Using them in combination helps maximize nutrient availability, enhance crop productivity, and preserve soil fertility. This integrated nutrient management approach supports not only short-term plant growth but also the long-term sustainability of farming systems. Additionally, it enriches soil organic matter, fostering beneficial microbial communities that play a key role in nutrient cycling (Kumar et al., 2023).

Bottom soil drying and tilling between culture cycles:

Drying and tilling the bottom soil between cultivation cycles are key soil management practices that affect soil structure, nutrient behavior, and microbial activity. These techniques help improve soil aeration, minimize compaction, and enhance water absorption, thereby promoting healthier plant growth. The impact of repeated drying and wetting, along with tillage, is complex altering pore structure, aggregate stability, and carbon processes. Studies show that after 12 drying-wetting cycles, both conventional tillage (CT) and no-tillage (NT) systems experience about a 50% reduction in soil porosity. The largest pores contribute the most to total porosity, but pore connectivity generally declines with repeated cycles (Pires et al., 2024).

Addition of compost/manure to boost organic matter:

Incorporating compost and manure into soil significantly boosts soil organic matter (SOM), which is essential for enhancing soil quality and agricultural output. This practice not only enriches the soil with nutrients but also improves its physical and biological characteristics. Compost and manure, such as cow manure which increased soil organic carbon by 1.46%, improve soil structure by enhancing aggregation, porosity, air circulation, water absorption, and erosion prevention (Wardah et al., 2014).

Pond preparation: de-silting, removal of black soil:

Proper pond preparation, especially through de-silting and removing black soil, is essential for preserving water quality and overall ecosystem balance. Implementing effective techniques for these tasks can greatly improve pond performance and reduce excess nutrient buildup. Mechanical Excavation uses machinery to remove accumulated sediment, effectively eliminating layers rich in nutrients that degrade water quality. For example, a study showed that removing around 103,000 m^3 of phosphorus-rich sediment resulted in a significant drop in phosphorus levels from about 1000 µg/L to just 20 µg/L (Hassett & Steinman, 2022).

Sustainable Approaches

Integrated Nutrient Management (INM) is a comprehensive strategy that blends different nutrient sources to improve soil fertility and boost agricultural productivity while reducing environmental harm. This approach combines the use of organic and inorganic fertilizers, crop rotation, and soil cover to support sustainable farming practices. INM has been shown to deliver numerous advantages, such as higher crop yields, enhanced soil health, and lower greenhouse gas emissions. The application of biofertilizers and probiotics in agriculture offers an eco-friendly alternative to chemical fertilizers, delivering multiple advantages for soil quality, plant development, and environmental

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protection. Biofertilizers, composed of beneficial microorganisms, increase nutrient availability and support plant growth by forming symbiotic associations with crops. Plant probiotics further contribute by enhancing soil health and helping plants withstand environmental stresses. These sustainable methods are gaining popularity due to growing concerns over the negative impacts of chemical fertilizers on both ecosystems and human health. Biofertilizers, made up of organic substances and helpful microbes, improve soil fertility and boost plant productivity through their symbiotic interactions with plants (Zailani et al., 2024).

Challenges in Soil Fertility Management

Soil acidification in shrimp ponds is a major concern, largely resulting from the oxidation of pyrite-containing sediments, which leads to the development of acid sulphate soils (ASS). These soils exhibit extremely low pH levels and contain high concentrations of sulphates and harmful metals, all of which impair both water quality and shrimp health. The situation worsens due to the buildup of organic matter, which, under anaerobic conditions, promotes sulphide formation an element highly toxic to shrimp. Consequently, these conditions degrade pond environments and hinder shrimp growth and survival. Addressing this issue through proper management practices is vital for the sustainability of shrimp aquaculture (Sammut & Smith, 1999; Torun et al., 2023). Salinization impacts soil pH and alters its ionic balance, thereby influencing the availability of essential nutrients. Elevated salinity levels can reduce the availability of nitrogen and phosphorus, primarily due to co-precipitation and disruptions in nutrient mineralization processes (Dijk et al., 2019). Additionally, the presence of terminal electron acceptors under saline conditions can affect the rate of carbon mineralization, though these effects tend to vary depending on specific site conditions (Mazhar et al., 2022).In Northeast China, studies have found that soil organic carbon (SOC) levels in black soils tend to stabilize over time, with a large portion of the SOC present in slow and passive fractions, suggesting strong potential for long-term carbon storage (Gao et al., 2004)..Maintaining soil cover through this practice supports soil structure and minimizes runoff (Rashmi et al., 2017).

Case Studies / Best Practices

Successful pond farming operations implement diverse soil management strategies to boost both productivity and sustainability. Maintaining healthy soils is essential, as it directly influences yields in both aquaculture and agriculture. Tools like FARManalytics assist farmers in refining soil management techniques while optimizing profitability by incorporating soil health indicators and informed production choices (Kik et al., 2024). In Bangladesh, innovative practices like relay cropping have proven economically beneficial, enabling farmers to increase profits while lowering input expenses compared to traditional methods (Alam et al., 2010). Farmer-driven innovations often emphasize sustainable methods, such as organic matter use and water harvesting, which are especially important in areas vulnerable to climate stress (Critchley, 2000). However, many of these grassroots innovations remain undocumented and lack institutional support. To ensure broader adoption and impact, stronger frameworks are needed to recognize and scale up these practices (Baliwada et al., 2016).

Policy and Extension Support

Soil testing and effective management are vital for preserving soil quality, which underpins both environmental sustainability and agricultural productivity. By offering detailed information on soil fertility, soil testing enables farmers and land managers to make informed choices regarding fertilizer use and soil improvement measures. Sustainable soil management is supported by international frameworks like the The Voluntary Guidelines for Sustainable Soil Management (VGSSM) promote soil health and resilience through a holistic approach, but their widespread adoption remains limited due to insufficient political will and financial investment, highlighting the need for broader societal awareness and support (Baritz et al., 2018).Building farmers' capacity is vital for

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boosting agricultural productivity and promoting sustainable practices. This process involves providing farmers with the skills, knowledge, and tools needed to improve their methods and respond effectively to environmental changes. Strategies such as agricultural extension services, participatory training, and community involvement are key components. Rather than simply promoting new technologies, extension services encourage shared learning and collaboration among farmers (Ndlela & Worth, 2023). Initiatives like farmer field schools and community-based organizations strengthen farmers' negotiating power and encourage the adoption of improved practices, ultimately resulting in higher incomes (Iqbal, 2014).

CONCLUSION

Soil fertility plays a fundamental role in the success and sustainability of pond aquaculture. Healthy pond soils not only enhance nutrient availability and water quality but also support robust aquatic ecosystems and fish productivity. Factors such as soil texture, pH, organic matter content, and the presence of toxic substances significantly influence fertility levels. Effective management practices such as liming, integrated nutrient management, compost application, and proper pond preparation can greatly improve soil conditions. Technological tools and farmer-led innovations further strengthen these efforts. However, challenges like soil acidification and salinization persist, highlighting the need for continuous monitoring and policy support. Strengthening capacity building and institutional frameworks will be key to advancing sustainable soil management in aquaculture systems.

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