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SPATIAL DISTRIBUTION OF SOIL CHEMICAL PROPERTIES AND NUTRIENT AVAILABILITY ACROSS DIFFERENT LAND USE SYSTEMS IN *POKKALI* WETLANDS

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ABSTRACT

Coastal wetland ecosystems provide critical interfaces between terrestrial and marine environments, where distinctive biogeochemical conditions shape soil fertility and nutrient cycling. This study investigated the spatial distribution of soil chemical properties and primary nutrient availability across five representative land use systems in *Pokkali* wetlands of Kerala, India: rice monoculture, prawn monoculture, integrated rice-prawn systems, fallow lands, and mangrove stands. Surface soil samples were collected from each land use system during the pre-monsoon period and analyzed for pH, electrical conductivity, organic carbon and available nitrogen, phosphorus, and potassium. The results revealed substantial variation in soil chemical properties across land uses, with rice monoculture exhibiting extremely acidic conditions (pH 3.54) and exceptionally high nitrogen and phosphorus levels, while the rice-prawn integrated system demonstrated near-neutral pH (6.36) and the highest potassium content. Prawn monoculture showed elevated salinity and potassium accumulation but remarkably low phosphorus availability. Mangrove ecosystems maintained moderately acidic conditions with intermediate nutrient levels, reflecting inherent conservation mechanisms, whereas fallow lands displayed progressive nutrient depletion, particularly in potassium. Organic carbon content remained statistically uniform across all systems, suggesting resilient carbon dynamics in *Pokkali* ecosystems despite diverse management practices. These findings emphasize that different land uses create distinct biogeochemical environments with unique nutrient management requirements, and no single system simultaneously optimizes all soil fertility parameters. The study provides crucial insights for developing land use-specific nutrient management strategies to enhance productivity while maintaining long-term soil health in these valuable coastal agroecosystems.

***Keywords* :** Coastal wetlands, *Pokkali* lands, soil nutrients, land use systems, integrated farming, soil health

Introduction

Coastal wetland ecosystems represent critical interfaces between terrestrial and marine environments, where tidal inundation and seasonal rainfall create distinctive biogeochemical conditions (Vulliet *et al.*, 2024). Kerala's coastal plains, shaped by centuries of alluvial deposition, encompass a diverse and interconnected array of ecosystems, with the *Pokkali* lands found in the Thrissur, Ernakulam, and Alappuzha districts emerging as a quintessential model of integrated farming practices coexisting with ecological integrity. The *Pokkali* fields, a remarkable agricultural heritage of Kerala, exemplify a harmonious blend of rice cultivation and aquaculture uniquely adapted to the region's coastal environment, characterized by elevated salinity and periodic inundation (George *et al.*, 2017). These fields represent climate-resilient food production in tropical coastal zones, supporting saline-tolerant rice cultivation, brackish-water aquaculture, and natural ecosystems while providing essential services including biodiversity conservation, carbon sequestration, and coastal protection (Shaji *et al.*, 2024). For centuries, farmers have synchronized management with monsoon cycles: rice grows during the low-salinity monsoon phase, when freshwater dilutes salts, while prawn farming occurs during the dry-season high-salinity phase, when tidal exchange intensifies (Jose *et al.*, 2023). Clarifying how nutrients fluctuate across different land uses, such as rice monoculture, prawn monoculture, integrated rice-prawn systems, fallow lands, and mangrove stands, is essential for sustaining productivity while safeguarding ecosystem function under mounting environmental pressures.

Each *Pokkali* land use presents a distinct biogeochemical template. During monsoon rice cultivation, flooded low-salinity conditions favour reductive dissolution, potentially elevating ammonium-nitrogen and mobilizing phosphorus from iron and aluminium oxyhydroxides, while plant uptake and rhizosphere oxygenation locally re-oxidize surfaces (Jose *et al.*, 2023). Dry-season prawn ponds experience saline inflows, feed inputs, and organic matter accumulation that enrich nutrient pools but increase stratification and hypoxia risks (Hu *et al.*, 2022). Integrated rice-prawn systems may mediate between these extremes, with alternating hydrologies potentially enhancing the soil quality index (Sreelatha and Joseph, 2019), nutrient recycling and retention relative to monocultures (MSSRF, 2021). Fallow plots serve as reference conditions, where inundation and tidal exchange occur without cultivation or aquaculture inputs, thereby isolating the hydrologic effects on baseline nutrient pools (Zhao *et al.*, 2018). Mangrove stands function as biogeochemical hotspots that trap sediments, support high microbial activity through tannin-rich litter, and modulate salinity and nutrient export to adjacent plots (Shao *et al.*, 2015).

Essential plant nutrients, including nitrogen, phosphorus and potassium, respond sensitively to soil physicochemical conditions and environmental forcing (Ahmed *et al.*, 2020). Nutrient stocks and stoichiometric ratios serve as integrative biogeochemical indicators across various scales. Management practices, including crop choice, residue retention, and organic amendments, shape soil organic carbon accumulation over longer horizons (Zhang *et al.*, 2015). The magnitude and direction of changes should differ among land uses due to contrasting inundation patterns, redox conditions, and organic matter inputs, with long-term management practices superimposing persistent signals on seasonal fluctuations. This research investigates the distribution of chemical properties and availability of primary nutrients across five representative land uses rice monoculture, prawn monoculture, integrated rice-and-prawn systems, fallow lands, and mangrove stands in *Pokkali* lands using common sampling design. These measurements capture direction and the degree to which land use mediates change and elucidate fundamental drivers of nutrient availability and soil health in complex coastal agroecosystems.

Materials and Methods

Study area and site characteristics

The study was conducted in the *Pokkali* lands of Kerala, India (Figure 1), which are unique coastal wetlands characterized by their unique topography, tidal influence, and seasonal salinity fluctuations. The area traditionally follows an alternate rice and aquaculture practice under saline water influence. The region experiences a tropical monsoon climate with heavy rainfall during the southwest monsoon season (June–September) and a distinct dry season thereafter. The soils are hydromorphic in nature, influenced by tidal inundation and varying salinity levels. It is classified as coarse loamy over sandy, mixed, active, isohyperthermic typic Sulfaquepts (Nideesh, 2019). Five distinct land use systems traditionally practiced in the *Pokkali* ecosystem were selected from different *Pokkali* areas for the study:

1. Rice monoculture (seasonal *Pokkali* paddy cultivation): Rice Research Station, Vyttila, Ernakulam
2. Prawn monoculture (exclusive aquaculture system): Kodungallur, Thrissur
3. Rice–prawn integrated system (rice cultivation practised organically during the low saline phase of monsoon (April - October), followed by saline aquaculture (November - March) when salinity increases): Kumbalangi, Ernakulam
4. Fallow lands (uncultivated areas left idle for at least 5 years): Kadamkkudi, Ernakulam
5. Mangrove (natural mangrove vegetation adjacent to the farming lands): Vallarpadam, Ernakulam

Representative sites under each land use were identified based on an initial survey and the details collected from agricultural officers.

Soil Sampling

Soil samples were collected before the onset of the southwest monsoon during April- June (pre-monsoon) in the year 2023-24. From each land use system, representative lowland soil samples were collected from the surface layer (0–20 cm depth) using a soil auger. At least five random cores were taken from each land use system. The collected samples were analysed for different soil parameters.

Laboratory Analysis

The soil samples were analyzed for various chemical parameters, using standard laboratory methods. Soil pH was determined in a 1:2.5 soil-water suspension using a digital pH meter (Jackson, 1958). Electrical conductivity (EC) was measured in the same suspension using a conductivity bridge (Jackson, 1958). Organic carbon (OC) content was estimated by the Walkley and Black (1934) wet oxidation method, and available nitrogen (N) was determined by the alkaline permanganate method (Subbiah and Asija, 1956). Available phosphorus (P) was extracted using Bray I method (Bray and Kurtz, 1945) for acidic soils and the Olsen's method (Olsen *et al*, 1954) for basic soils, then determined colorimetrically by reduced molybdate ascorbic acid blue colour method (Watanabe and Olsen, 1965) using an ELICO SL177 spectrophotometer. Available potassium (K) was extracted with neutral normal ammonium acetate and estimated by ELICO CL378 flame photometry (Jackson, 1958).

Statistical Analysis

The data obtained were subjected to CRD experimental analysis to assess the effect of the land uses on chemical properties and soil nutrient distribution. Statistical analyses were performed using GRAPES and R, and significance was tested at 5% level ($p \leq 0.05$) (Gopinath *et al.*, 2021).

Results and Discussion

The distribution of soil chemical properties and available primary nutrient contents is given in Table 1.

Soil Chemical Properties

The analysis of soil pH revealed substantial variation across the five land use systems examined in this study, with pH ranging from extremely acidic to near neutral conditions. Rice monoculture exhibited extremely acidic soil conditions with a pH of 3.54, which was statistically distinct from all other land uses. In contrast, the rice-prawn integrated system demonstrated the highest pH value of 6.36, followed closely by prawn monoculture at 5.74 and mangroves at 5.50. Fallow lands were very strongly acidic (pH - 4.89). This progressive shift from acidic to near-neutral pH conditions represents a fundamental transformation in soil chemistry that has far-reaching implications for nutrient availability and biogeochemical processes. The extremely acidic conditions observed in rice monoculture systems can be attributed to several interconnected factors. Continuous submergence contributes to soil acidification through nitrification processes and the release of hydrogen ions during organic matter decomposition (Yang *et al.*, 2022). The marked increase in pH observed in prawn and rice-prawn systems reflects the distinctive biogeochemical environment created by aquaculture activities. Aquaculture operations modify soil pH through the accumulation of feed residues, fecal matter, and metabolic byproducts, which contain alkaline compounds that gradually neutralize soil acidity (Yang *et al.*, 2022). The pH values recorded in our study align closely with findings from similar integrated systems, where researchers have documented pH increases associated with aquaculture interventions. The near-neutral pH in rice-prawn systems creates optimal conditions for nutrient cycling and supports diverse microbial communities essential for maintaining soil health. Mangrove ecosystems, despite their exposure to saline conditions, maintained moderately acidic pH levels of 5.50. This finding corroborates research indicating that mangrove soils typically exhibit acidic to slightly alkaline pH depending on the degree of organic matter accumulation and the presence of sulphur-reducing bacteria (Sofawi *et al.*, 2017). The organic acids released during litterfall decomposition and the presence of sulphur compounds contribute to the acidic nature of mangrove soils, though tidal influences and seawater buffering capacity prevent extreme acidification.

Electrical conductivity measurements revealed significant difference among land uses, with mangrove systems exhibiting the highest EC value of 7.47 dSm^{-1}, substantially exceeding all other land uses. This elevated EC reflects the characteristic salinity associated with mangrove habitats, where regular tidal inundation introduces dissolved salts and maintains elevated ionic concentrations in the soil solution. The EC values for rice cultivation (3.89 dSm^{-1}) and prawn farming (6.74 dSm^{-1}) indicated non-saline to high salinity levels, while rice-prawn systems recorded an EC of 4.88 dSm^{-1}. Fallow lands demonstrated the lowest EC value of 3.26 dSm^{-1}, suggesting reduced salt accumulation in the absence of active cultivation or aquaculture operations. Electrical conductivity serves as an indirect indicator of nutrient availability, with strong correlations between EC and potassium content documented in agricultural soils (Mazur *et al.*, 2022). However, excessively high EC values, as observed in mangrove systems, can indicate salinity stress that may limit nutrient uptake and plant growth. The moderate

EC levels in rice-prawn systems indicate a balanced ionic environment that supports both crop production and the health of aquatic organisms without imposing severe osmotic stress. Research on coastal wetland soils has shown that variations in EC reflect not only salinity but also the concentration of dissolved nutrients and organic matter in the soil solution (Denre, 2025). The elevated EC in prawn monoculture compared to rice monoculture likely results from the accumulation of salts during the high saline summer season and buildup of nitrogenous compounds, phosphates, and other dissolved organic materials derived from feed inputs and metabolic waste products (Luo *et al*., 2023). These findings underscore the importance of monitoring EC as both a salinity indicator and a proxy for nutrient enrichment in intensive aquaculture systems.

Interestingly, organic carbon content exhibited no significant variation across the five land use systems, with values ranging narrowly from 1.62% in mangroves to 2.84% in prawn monoculture. This uniformity in organic carbon content suggests that the *Pokkali* ecosystem maintains inherent regulatory mechanisms that buffer against large-scale organic matter fluctuations, regardless of land use intensity. However, our results align with research indicating that coastal wetland soils can maintain relatively constant organic carbon levels due to high rates of both organic matter input and decomposition (Tam & Wong, 1998). The anaerobic conditions prevalent in flooded *Pokkali* lands may slow decomposition rates, while the continuous input of organic materials from crop residues, aquatic vegetation, and mangrove litter maintains carbon stocks at equilibrium levels. The moderate organic carbon content observed across all systems, ranging from 1.62% to 2.84%, falls within typical ranges reported for tropical wetland soils. The absence of significant variation implies that short-term land use changes have not yet profoundly altered the fundamental carbon dynamics of these soils, though longer-term monitoring would be necessary to detect gradual shifts in carbon sequestration capacity

The available nitrogen content in soil exhibited significant variation across land uses, representing one of the most distinctive soil parameters measured in this study (Figure 2). Rice monoculture demonstrated high available nitrogen levels in soil of 597.25 $kgha^{-1}$, significantly surpassing all other systems. Fallow lands and mangroves recorded low available nitrogen content of 230.99 and 205.86 $kgha^{-1}$, respectively, while prawn monoculture also exhibited the second-low nitrogen content of 173.82 $kgha^{-1}$. Most notably, rice-prawn integrated systems showed the lowest available nitrogen concentration of 158.04 $kgha^{-1}$, despite combining two production activities. The unexpectedly low available nitrogen content in rice-prawn systems' soil warrants careful consideration. Studies on integrated rice-aquaculture systems have documented that while total organic matter and total nitrogen may remain stable, available nitrogen forms can decrease due to enhanced uptake by both crops and aquatic organisms (Yang *et al*., 2022). The prawns in integrated systems actively consume available nitrogen through direct uptake and through their consumption of nitrogen-rich microorganisms and organic matter. Research on similar coastal farming systems has revealed that aquatic animals in rice paddies can help maintain soil nitrogen through nutrient recycling, though they may simultaneously reduce total nitrogen stocks through consumption and waste export (Victory *et al*., 2018). The low available nitrogen content in fallow lands suggests gradual nitrogen depletion in the absence of external inputs, though biological nitrogen fixation by free-living bacteria may partially compensate for this loss. Available N content in Mangrove soils, while low, reflects the unique nitrogen cycling characteristic of these ecosystems. Ammonium represents the primary nitrogen form in mangrove soils, and tree growth depends mainly on ammonium uptake due to anoxic soil conditions (Reef *et al*., 2010). Mangroves have evolved efficient nitrogen conservation mechanisms, including high nutrient resorption efficiency prior to leaf fall and the immobilization of nutrients in decomposing litter, which help maintain nitrogen stocks despite limited external inputs.

Phosphorus content demonstrated pronounced variation across land uses, with rice monoculture exhibiting the highest levels at 293.08 $kgha^{-1}$, followed by rice-prawn systems at 190.02 $kgha^{-1}$. Mangrove soils and fallow lands also recorded high available phosphorus content of 71.25 $kgha^{-1}$ and 70.55 $kgha^{-1}$ respectively. Prawn monoculture exhibited medium available phosphorus content in soil of 18.29 $kgha^{-1}$ (Figure 2), representing the most extreme variation observed among all nutrients measured. This striking disparity in phosphorus distribution reflects fundamental differences in phosphorus cycling and retention capacity across these diverse land use systems. In rice monoculture, unlike nitrogen which is subject to significant gaseous losses, phosphorus tends to accumulate in soils due to its low mobility and tendency to form stable complexes with soil minerals (Zhang *et al*., 2025). The high available phosphorus levels in soils of rice-prawn systems, while lower than rice monoculture, remain adequate to support both rice growth and aquaculture activities. Integrated rice-fish systems can regulate soil phosphorus fraction conversion and availability through the combined effects of organic carbon inputs and phosphatase enzyme activity (Wang *et al*., 2022). The presence of prawns may enhance phosphorus cycling through bioturbation, which physically mixes soil layers and increases the contact between phosphorus-containing compounds and soil microorganisms capable of mineralizing organic phosphorus forms. Aquaculture operations typically accumulate phosphorus from feed inputs, yet environmental discharge and removal of harvested biomass create significant phosphorus export pathways (Luo, 2023). In prawn farming, phosphorus-rich feed residues and faecal matter may accumulate initially, but frequent water exchange and the harvest of prawns remove substantial quantities of phosphorus from the system. The high available P content in soils of mangrove and fallow land, reflects the natural phosphorus cycling characteristic of these less intensively managed systems. Mangrove ecosystems are frequently limited by nitrogen and phosphorus availability, and nutrient-conserving mechanisms are well developed in these environments (Alongi *et al*., 1992). The similarity in phosphorus content between mangroves and fallow lands suggests that in the absence of external inputs, both systems equilibrate at comparable phosphorus concentrations determined by weathering rates, organic matter decomposition, and tidal inputs.

Available K distribution patterns revealed rice-prawn integrated systems as having the highest potassium content at 1650.81 $kgha^{-1}$, followed by prawn monoculture at 1339.70 $kgha^{-1}$ (Figure 2). Mangroves maintained elevated potassium levels of 1127.77 $kgha^{-1}$, while rice monoculture showed 1000.43 $kgha^{-1}$. Fallow lands exhibited the lowest potassium content at 506.09 $kgha^{-1}$. All the land use systems recorded high available K content in soil. This distribution pattern contrasts markedly with nitrogen and phosphorus trends, suggesting fundamentally different factors govern potassium accumulation and retention in *Pokkali* land use systems. The comparatively high potassium content in rice-prawn and prawn monoculture systems represents one of the most significant findings of this study. This accumulation likely results from the combination of saline water inputs, which naturally contain elevated potassium concentrations, and the biogeochemical processes associated with aquaculture operations. Potassium is essential for various plant functions and helps plants develop resistance to salinity stress and drought conditions (Constance *et al*., 2022). The elevated potassium in aquaculture systems may provide a competitive advantage for rice grown in integrated systems, enhancing osmotic regulation and improving salt tolerance. Studies on soil nutrient dynamics have shown that soil electrical conductivity demonstrates strong positive correlations with potassium content, reflecting the high mobility and solubility of potassium ions (Mazur *et al*., 2022). The pattern observed in our study supports this relationship, with systems showing higher EC values generally exhibiting elevated potassium concentrations. Unlike phosphorus, which accumulates in relatively immobile forms, potassium remains highly mobile in soil solutions and readily responds to water movement, cation exchange processes, and biological uptake. The moderate potassium levels in mangrove systems reflect the dynamic nature of these coastal ecosystems. Potassium is highly leachable under saline conditions, and lower concentrations at upper soil layers may result from this enhanced mobility (Sharif *et al*., 2025). However, the regular influx of potassium-rich tidal waters helps replenish potassium stocks, maintaining adequate levels to support mangrove growth and ecosystem function. The potassium concentrations measured in mangrove soils fall within ranges reported for similar tropical coastal wetland systems, indicating typical nutrient status for these environments. Without regular tidal inputs, potassium is gradually depleted through leaching, particularly given the high rainfall characteristic of tropical coastal regions (Mack *et al*., 2024).

Conclusion

The comprehensive analysis of soil chemical properties across *Pokkali* land uses reveals that each system creates distinct biogeochemical environments with unique nutrient management implications. Rice monoculture, despite being cultivated under completely organic management practices, exhibited extreme soil acidification coupled with substantial nitrogen and phosphorus accumulation, though these apparent nutrient advantages may be offset by reduced bioavailability under acidic conditions. The rice-prawn integrated system emerged as the most balanced land use, demonstrating near-neutral pH conditions that optimize nutrient cycling while maintaining the highest potassium levels among all systems, though careful attention to nitrogen supplementation appears necessary to sustain long-term productivity. Prawn monoculture created a distinctive high-salinity, alkaline environment characterized by exceptional potassium accumulation but marked phosphorus depletion, suggesting that this system requires targeted phosphorus management to maintain soil fertility. Mangrove ecosystems maintained moderately acidic conditions with intermediate nutrient levels, reflecting the inherent nutrient conservation mechanisms of these natural systems, while fallow lands showed progressive nutrient depletion across all major elements, particularly potassium, underscoring the consequences of removing land from active management without compensating inputs. The stability of organic carbon across all land uses suggests remarkable resilience in the fundamental carbon dynamics of *Pokkali* ecosystems, indicating that short-term land use transitions have not fundamentally disrupted carbon sequestration processes. However, the divergent patterns observed for primary nutrients highlight the complex trade-offs inherent in different land management strategies, where no single system simultaneously optimizes all soil fertility parameters. The findings emphasize that sustainable intensification of *Pokkali* landscapes requires land use-specific nutrient management approaches that account for the distinctive biogeochemical characteristics of each system. These results provide crucial insights for developing site-specific nutrient management that enhances productivity while maintaining the long-term soil health of these valuable coastal agroecosystems.

Table 1 : Distribution of soil chemical properties and primary nutrients across the land uses

Land Use	pH	EC (dSm^{-1})	OC (%)	N ($kgha^{-1}$)	P ($kgha^{-1}$)	K ($kgha^{-1}$)
Rice	3.54^{b}	3.89^{bc}	2.57	597.25^{a}	293.08^{a}	1000.43^{c}
Prawn	5.74^{a}	6.74^{a}	2.84	173.82^{b}	18.29^{c}	1339.7^{b}
Rice-Prawn	6.36^{a}	4.88^{b}	1.89	158.04^{b}	190.02^{b}	1650.81^{a}
Fallow	4.89^{ab}	3.26^{c}	2.71	230.99^{b}	70.55^{c}	506.09^{d}
Mangroves	5.50^{a}	7.47^{a}	1.62	205.86^{b}	71.25^{c}	1127.77^{bc}
LSD	1.70	1.12	ns	143.42	66.79	281.83

(Treatments with the same letters are not significantly different; ns: not significant)

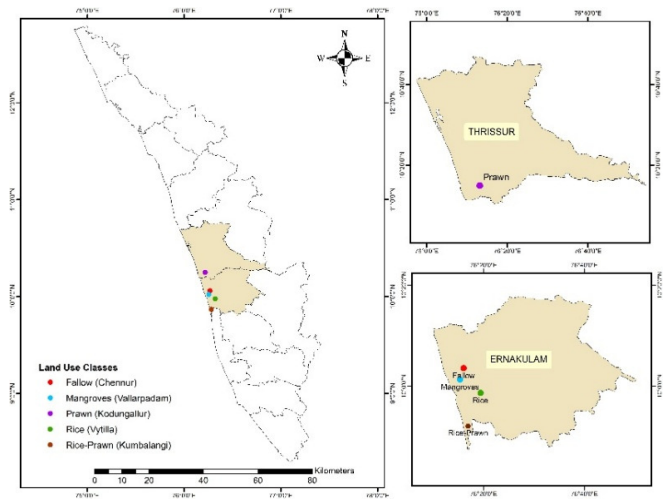

Fig. 1: Map showing the locations of five land uses selected across the *Pokkali* lands

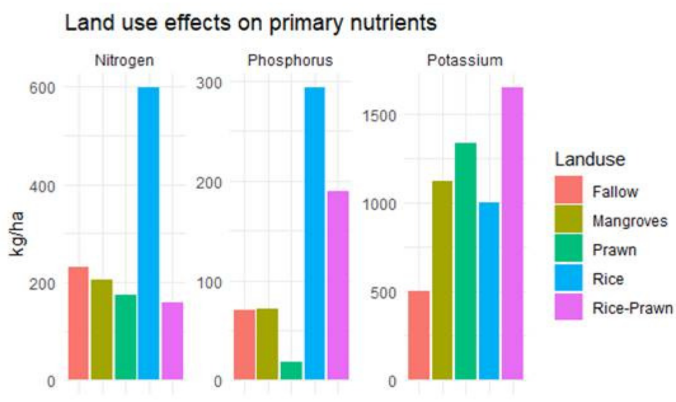

Fig. 2 : The distribution of available primary nutrients (N, P and K in $kgha^{-1}$) across the selected land use systems of *Pokkali* areas.

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