Physico-Chemical Characterization of Kole Wetland Soils in Thrissur District, Kerala: Implications for Paddy Cultivation and Wetland Management

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ABSTRACT

Kole wetlands of Thrissur District, Kerala, represent a unique low-lying rice-growing ecosystem of significant ecological and agricultural importance. This study investigated the physico-chemical properties of soils from nine representative sites across the Kole lands to assess their fertility status and redox characteristics. Soil samples were analyzed for moisture content, pH, electrical conductivity (EC), oxidation-reduction potential (ORP), total dissolved solids (TDS), salinity, specific gravity, and macronutrients (organic carbon, phosphorus, and potassium). Results revealed considerable spatial variability in soil properties. The pH ranged from 3.28 to 8.13, with most sites exhibiting near-neutral to slightly alkaline conditions favorable for rice cultivation. ORP values ranged from 250 to 393 mV, indicating predominantly oxidized conditions in the surface soils. EC values (0.00268–0.00730 dS/cm) and salinity (0.01–0.03%) were low, confirming the freshwater nature of these wetlands. Organic carbon content varied from 0.68 to 1.02%, while available phosphorus (16–17 kg/ha) and potassium (187–198 kg/ha) were within acceptable ranges for rice cultivation. One site (Pullazhi Wetland) exhibited anomalous characteristics with extremely low pH (3.28), high ORP (393 mV), and elevated EC (0.00730 dS/cm), suggesting localized acidification or contamination. The findings provide baseline data for sustainable management of Kole wetlands and highlight the need for site-specific soil betterment strategies to maintain soil health and agricultural productivity in this ecologically sensitive region.

Keywords: Kole wetlands; soil physico-chemical properties; oxidation-reduction potential; paddy soils; wetland management; soil fertility

INTRODUCTION

Wetlands are among the most productive ecosystems globally, providing critical ecosystem services including water purification, flood control, biodiversity conservation, and agricultural production [9]. In Kerala, India, the Kole wetlands represent a unique low-lying rice-growing ecosystem that has sustained agricultural livelihoods for centuries. The Kole lands of Thrissur District, covering approximately 13,632 hectares, are characterized by seasonal waterlogging and serve as important paddy cultivation areas during the dry season [1, 18].

The physico-chemical properties of wetland soils are fundamental determinants of their fertility, productivity, and ecological functions [9, 3]. Unlike upland soils, wetland soils undergo periodic or permanent waterlogging, which profoundly influences their redox chemistry, nutrient dynamics, and microbial processes [28]. The oxidation-reduction potential (ORP) is a master variable controlling numerous biogeochemical processes in wetland soils, including nutrient transformations, metal solubility, and organic matter decomposition [26, 36]. Understanding the redox status and associated chemical properties of Kole wetland soils is essential for developing appropriate management strategies to sustain their agricultural productivity while preserving their ecological integrity.

Previous studies on Kole wetlands have documented their unique hydrological characteristics [18], nutrient status [1, 2], and post-flood soil conditions [3]. However, comprehensive characterization of the physico-

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chemical properties, particularly the redox status and its spatial variability across different sites within the Kole ecosystem, remains limited. The relationship between soil pH, ORP, and nutrient availability in these seasonally flooded rice-growing systems requires systematic investigation to inform evidence-based management practices.

Rice cultivation in waterlogged conditions creates distinct soil chemical environments characterized by reduced oxygen availability, altered pH dynamics, and modified nutrient cycling [26, 40]. The submergence of rice soils triggers a cascade of redox reactions that influence the availability of essential nutrients such as nitrogen, phosphorus, and potassium, as well as the solubility of potentially toxic elements like iron and manganese [29]. The Kole wetlands, with their alternating flooding and drying cycles, present a particularly dynamic redox environment that warrants detailed investigation.

The objectives of this study were to: (1) characterize the physico-chemical properties of soils from representative sites across the Kole wetlands of Thrissur District, (2) assess the redox status and its spatial variability, (3) evaluate the fertility status in terms of organic carbon and macronutrient content, and (4) contextualize the findings within the broader understanding of wetland soil chemistry to provide recommendations for sustainable management of this ecologically and agriculturally important ecosystem.

Study Area

The study was conducted in the Kole wetlands of Thrissur District, Kerala, India, located in the central part of the state along the coastal plains. The Kole lands are low-lying areas situated below mean sea level, forming a unique wetland ecosystem that extends across Thrissur and Malappuram districts. The study area lies approximately between 10°30' to 10°40' N latitude and 75°55' to 76°10' E longitude.

The Kole wetlands serve a dual purpose as rice-growing areas during the dry season (December–May) and as water retention basins during the monsoon season (June–November). The area receives an average annual rainfall of approximately 3,000 mm, with the majority falling during the southwest monsoon. The wetlands are interconnected through a network of canals and sluice gates that regulate water levels and facilitate drainage for cultivation.

Nine sampling sites were selected to represent the spatial variability of the Kole ecosystem: (1) Monastery dry soil, (2) Monastery wet soil, (3) Thuruth far side, (4) Thuruth college side, (5) Manakkody Wetland, (6) Kannapuram, (7) Bridge Road, (8) Pullazhi Wetland, and (9) Pullazhi. These sites encompass different land use patterns, hydrological conditions, and management practices typical of the Kole lands. The selection included both actively cultivated paddy fields and wetland areas with varying degrees of waterlogging.

MATERIALS AND METHODS

Study Site and Sample Collection

Soil samples were collected from nine representative sites across the Kole wetlands of Thrissur District during the post-monsoon period (2021–2024). At each site, surface soil samples (0–15 cm depth) were collected using a stainless steel auger. Samples were collected in triplicate and composited to obtain representative samples for each location. The samples were transported to the laboratory in sealed polyethylene bags and stored at 4°C until analysis.

Sample Preparation

Soil samples were air-dried at room temperature, manually crushed, and passed through a 2-mm sieve to remove coarse particles and debris. A portion of each sample was further ground and passed through a 0.5-mm sieve for organic carbon and nutrient analyses. Subsamples were stored in labeled containers for subsequent analyses.

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Analytical Methods

Moisture Content: Gravimetric moisture content was determined by weighing approximately 10 g of fresh soil, drying in a hot air oven at 100°C for 24 hours, and reweighing. Moisture content was calculated as the percentage loss in weight.

Soil pH: Soil pH was determined in a 1:2 soil-to-water suspension using a calibrated pH meter (Equiptronics EQ-614, Eutech Instruments), after equilibration for 30 minutes. The electrode was calibrated with standard buffer solutions at pH 4.0, 7.0, and 9.2 before measurements.

Electrical Conductivity (EC), Oxidation-Reduction Potential (ORP), Total Dissolved Solids (TDS), Salinity, Specific Gravity, and Temperature: These parameters were measured simultaneously using a KERRO multi-parameter pen tester. Five grams of air-dried soil were mixed with 75 mL of distilled water in a beaker, stirred continuously for 30 minutes to achieve equilibrium, and the probe was immersed in the suspension for measurements. EC was expressed in dS/cm, ORP in mV, TDS in ppm, salinity in percentage, and temperature in °C.

Organic Carbon: Soil organic carbon was determined by the Walkley-Black wet oxidation method. One gram of soil was oxidized with potassium dichromate in the presence of concentrated sulfuric acid, and the excess dichromate was titrated against ferrous ammonium sulfate using diphenylamine indicator. Organic carbon content was calculated and expressed as percentage.

Available Phosphorus: Available phosphorus was extracted using the Olsen method. Five grams of soil were extracted with 0.5 M sodium bicarbonate solution (pH 8.5), and the phosphorus in the extract was determined colorimetrically using the molybdenum blue method at 660 nm wavelength. Results were expressed in kg/ha.

Available Potassium: Exchangeable potassium was extracted using neutral 1 N ammonium acetate solution. The potassium concentration in the extract was determined using a flame photometer, and results were expressed in kg/ha.

RESULTS

Moisture Content and PH

The moisture content of soil samples varied considerably across the nine sampling sites, ranging from 0.92% to 7.1% (Table 1). The highest moisture content was observed at Thuruth far side (7.1%), while the lowest was recorded at Pullazhi Wetland (0.92%). The Monastery dry soil, as expected, exhibited low moisture content (2.5%), whereas the Monastery wet soil showed higher moisture (4.2%).

Soil pH measured by pH meter ranged from 6.5 to 8.13 across most sites, indicating near-neutral to slightly alkaline conditions (Table 1). The Monastery dry soil exhibited the highest pH (8.13), while Monastery wet soil and Thuruth far side showed slightly acidic to neutral pH (6.5 and 6.55, respectively). Other sites displayed pH values between 6.75 and 7.64, which are generally favorable for rice cultivation.

Table 1. Moisture Content and pH of Kole Wetland Soils

Site	Sample Weight (g)	Moisture Content (%)	pH (pH meter)
Monastery dry soil	10.003	2.5	8.13
Monastery wet soil	10.0677	4.2	6.5
Thuruth far side	10.0174	7.1	6.55
Thuruth college side	10.1257	3.55	7.2

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Manakkody Wetland	10.1620	4.1	7.2
Kannapuram	10.0377	3.9	6.75
Bridge Road	10.0577	4.3	7.25
Pullazhi Wetland	10.0044	0.92	7.61
Pullazhi	10.0673	1.8	7.64

Multi-Parameter Measurements

The KERRO multi-parameter meter measurements revealed additional insights into the physico-chemical characteristics of the soils (Table 2). Specific gravity was uniform across all sites (1.002), indicating similar mineral composition and particle density.

Oxidation-reduction potential (ORP) ranged from 250 to 393 mV, with most sites exhibiting values between 250 and 290 mV. The Pullazhi Wetland site showed an exceptionally high ORP of 393 mV, coupled with an anomalously low pH of 3.28 measured by the multi-parameter meter, suggesting localized acidification or contamination at this site.

Electrical conductivity (EC) ranged from 0.00268 to 0.00730 dS/cm, with the highest value observed at Pullazhi Wetland. These low EC values indicate minimal salt accumulation and confirm the freshwater nature of the Kole wetlands. Correspondingly, salinity was very low across all sites (0.01–0.03%), with only Pullazhi Wetland showing slightly elevated salinity (0.03%). Total dissolved solids (TDS) ranged from 134 to 365 ppm, with Pullazhi Wetland again showing the highest value (365 ppm). Soil temperature during measurements ranged from 29.6°C to 30.0°C, reflecting the tropical climate of the region.

Table 2. Multi-Parameter Measurements of Kole Wetland Soils (KERRO Digital Meter)

Site	SG	ORP (mV)	pH	EC (dS/cm)	Salinity (%)	TDS (ppm)	Temp (°C)
Monastery dry soil	1.002	279	6.53	0.00316	0.01	157	29.6
Monastery wet soil	1.002	275	6.44	0.00287	0.01	145	29.9
Thuruth far side	1.002	286	5.53	0.00284	0.01	141	30.0
Thuruth college side	1.002	270	5.96	0.00304	0.01	152	30.0
Manakkody Wetland	1.002	255	6.81	0.00268	0.01	134	30.0
Kannapuram	1.002	250	6.97	0.00286	0.01	143	29.9
Bridge Road	1.002	290	4.83	0.00384	0.01	192	30.0
Pullazhi Wetland	1.002	393	3.28	0.00730	0.03	365	30.0
Pullazhi	1.002	280	7.61	0.00380	0.01	187	29.9

Organic Carbon and Macronutrients

Detailed organic carbon and macronutrient analyses were performed on two representative sites: Monastery wet soil and Thuruth far side (Table 3). Electrical conductance measured by conductometer was similar for both sites (1.3–1.4 µS/cm), confirming low ionic content.

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Organic carbon content was 1.02% in Monastery wet soil and 0.68% in Thuruth far side, indicating moderate organic matter levels. Available phosphorus was 17 kg/ha and 16 kg/ha for Monastery wet soil and Thuruth far side, respectively, which are within the low to medium range for rice cultivation. Available potassium was relatively high, with 198 kg/ha in Monastery wet soil and 187 kg/ha in Thuruth far side, indicating adequate potassium availability for crop growth.

Table 3. Organic Carbon and Macronutrient Status of Selected Sites

Site	Conductance (μS/cm)	Organic Carbon (%)	Phosphorus (kg/ha)	Potassium (kg/ha)
Monastery wet soil	1.4	1.02	17	198
Thuruth far side	1.3	0.68	16	187

DISCUSSION

PhD Dynamics and Soil Acidification

The relationship between pH and redox processes in wetland soils is well established [21, 25]. In submerged rice soils, pH tends to converge toward neutrality (6.3–7.5) regardless of initial values, due to the buffering effects of redox reactions and organic matter decomposition [25, 26]. The near-neutral pH observed at most Kole wetland sites suggests that these soils have reached a redox-pH equilibrium typical of periodically flooded rice-growing systems. This pH convergence phenomenon has important implications for nutrient availability and soil fertility management [26].

However, the extremely low pH (3.28) observed at Pullazhi Wetland represents a significant deviation from the typical Kole wetland soil characteristics and warrants special attention. Such acidic conditions may indicate the presence of acid sulfate soil characteristics, which are known to occur in some low-lying coastal areas of Kerala [10, 14, 16]. Acid sulfate soils develop when sulfide-rich sediments are exposed to oxidizing conditions, leading to the formation of sulfuric acid [17, 19]. The co-occurrence of low pH, high ORP (393 mV), and elevated EC (0.00730 dS/cm) at this site supports this interpretation. Similar acid sulfate soil conditions have been documented in the nearby Kuttanad wetlands of Kerala, where pH values as low as 2.5–4.0 have been reported [16, 17].There is a systematic drop in pH values measured by the KERRO digital meter (Table 2) compared to the standard pH meter (Table 1) across nearly all sites. This variation likely stems from differences in electrode calibration, soil-to-water ratio used during slurry preparation, or sensor reaction to dissolved solids. Diluting a soil solution with neutral distilled water generally raises the measured pH by 0.2 to 1.5 pH units. This explains why almost every site showed higher pH in Table 1 (distilled water suspension) than in Table 2 (direct moist soil).

The pH variability observed across the Kole wetlands reflects differences in hydrological regime, organic matter content, and land management practices. Sites with higher moisture content and more frequent waterlogging (e.g., Thuruth far side with 7.1% moisture and pH 6.55) tend to exhibit slightly lower pH values compared to drier sites (e.g., Monastery dry soil with 2.5% moisture and pH 8.13). This pattern is consistent with the acidifying effects of organic matter decomposition and CO_2 accumulation under waterlogged conditions [30, 21]. Wetland soils (like the Kole lands) are often in a reduced, low-oxygen state, containing reduced iron and sulfur compounds (e.g., iron sulfides or pyrite).

- Direct On-Site Measurement: Measures the soil in its native, reduced state.
- Lab Slurry Preparation: Drying, grinding, and stirring soil with distilled water exposes it to atmospheric oxygen. If acid sulfate soils are present, rapid oxidation generates free sulfuric acid and free H^+ ions, which drastically alters the pH.

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Redox Potential and Its Biogeochemical Significance

The ORP values observed in this study (250–393 mV) indicate predominantly oxidized to moderately reduced conditions in the surface soils of the Kole wetlands. These values fall within the range reported for wetland soils under various hydrological conditions [28, 34, 36]. The majority of sites exhibited ORP values between 250 and 290 mV, which are characteristic of soils with moderate oxygen availability and active aerobic microbial processes.

In wetland soils, ORP is a master variable controlling numerous biogeochemical processes, including nutrient transformations, metal solubility, and organic matter decomposition [26, 28, 36]. The ORP range observed in this study suggests conditions favorable for nitrification and aerobic decomposition processes, while being sufficiently reduced to limit excessive oxidation of organic matter. This redox status is typical of surface soils in seasonally flooded wetlands during the drained or partially drained phase [21, 34].

The exceptionally high ORP (393 mV) at Pullazhi Wetland, coupled with extremely low pH (3.28), indicates strongly oxidizing and acidic conditions that are atypical for wetland soils. Such conditions may result from the oxidation of sulfide minerals in acid sulfate soils [17, 24], or from anthropogenic contamination. High ORP values in wetland soils can have significant implications for nutrient dynamics, particularly for phosphorus availability and iron/manganese solubility [33, 37].

Electrical Conductivity and Salinity

The low EC values observed across the Kole wetlands (0.00268–0.00730 dS/cm) confirm the freshwater nature of these wetlands and indicate minimal salt accumulation. These values are well below the threshold for salinity concerns in rice cultivation (EC < 2 dS/cm for non-saline soils) and are consistent with previous reports on Kole wetland water quality [11, 18]. The low salinity (0.01–0.03%) further supports this interpretation.

The relationship between EC and TDS is well established, with TDS (in mg/L or ppm) typically approximating 640 × EC (in dS/cm) for most natural waters [13]. In the current study, the observed TDS values (134–365 ppm) are generally consistent with this relationship, confirming the reliability of the measurements. The slightly elevated EC (0.00730 dS/cm), salinity (0.03%), and TDS (365 ppm) at Pullazhi Wetland represent a notable deviation from other sites, further supporting the acid sulfate soil interpretation [17, 24, 46].

Organic Carbon and Nutrient Status

The organic carbon content observed in this study (0.68–1.02%) falls within the low to medium range for tropical wetland soils. Previous studies on Kole wetland soils have reported organic carbon values ranging from 0.28% to 3.47% [1, 7], indicating considerable spatial variability across the region. The moderate organic carbon content at both analyzed sites (Monastery wet soil: 1.02%; Thuruth far side: 0.68%) suggests adequate organic matter for supporting microbial processes and nutrient mineralization during rice cultivation [42].

The available phosphorus content observed in this study (16–17 kg/ha) falls within the low to medium range for rice cultivation. Phosphorus dynamics in wetland soils are strongly influenced by redox conditions [33, 37]. Upon flooding and reduction, iron oxides dissolve, releasing adsorbed phosphorus into the soil solution, thereby increasing phosphorus availability to plants [33, 37]. This redox-mediated phosphorus release is an important mechanism contributing to the fertility of submerged rice soils [26, 40]. The available potassium content (187–198 kg/ha) is within the medium to high range, reflecting the alluvial origin of these soils and their clay mineralogy, which provides a reservoir of exchangeable potassium [40].

Management Implications

The physico-chemical characterization of Kole wetland soils presented in this study has several important implications for sustainable management and rice cultivation. The predominantly neutral to slightly alkaline pH, low salinity, and adequate nutrient levels at most sites indicate that these wetlands are generally well-suited for

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rice cultivation. For sites with near-neutral pH and moderate ORP (250–290 mV), standard rice cultivation practices should be effective. The alternating flooding and drainage cycles typical of rice cultivation in these wetlands will induce dynamic redox changes that enhance nutrient availability, particularly for phosphorus and iron [26, 40].

The Pullazhi Wetland site, with its extremely low pH (3.28), high ORP (393 mV), and elevated EC, requires special management attention. If acid sulfate soil conditions are confirmed, lime application would be necessary to neutralize acidity and improve soil conditions for rice cultivation [16, 17]. Previous studies on acid sulfate soils in Kerala have demonstrated the effectiveness of lime amendments in raising pH and improving crop growth [14, 16]. Additionally, maintaining flooded conditions can help prevent further oxidation of sulfides and acidification [17, 19].

The moderate organic carbon content (0.68–1.02%) observed in the Kole wetlands suggests that organic matter management should be a priority for maintaining long-term soil fertility. Incorporation of crop residues, application of organic manures, and cultivation of green manures during fallow periods can help build soil organic matter and improve soil physical and chemical properties [7, 42].

Comparison with Other Kerala Wetland Systems

Comparing the Kole wetlands with the Kuttanad wetlands of Kerala reveals both similarities and important differences. Both systems are low-lying, seasonally flooded systems used for rice cultivation. However, Kuttanad wetlands are more severely affected by acid sulfate soil problems, with pH values as low as 2.5–4.0 reported in some areas [16, 17]. The Kole wetlands, as documented in this study, generally maintain near-neutral pH, although localized acidification (as observed at Pullazhi Wetland) can occur. This difference may reflect variations in sulfide content, hydrological regime, and management practices between the two systems.

Comparison with other wetland ecosystems globally reveals that the Kole wetlands exhibit physico-chemical properties typical of freshwater, rice-growing wetlands in tropical regions [3, 9]. The pH range (6.5–7.64 for most sites), ORP values (250–290 mV), and nutrient levels are comparable to those reported for rice-growing wetlands in other parts of Asia [26, 40]. However, the Kole wetlands appear to have lower organic carbon content compared to some permanently flooded wetlands and peatlands, which is appropriate for their use as rice cultivation systems [15, 42].

Limitations and Future Research Directions

This study provides baseline data on the physico-chemical properties of Kole wetland soils; however, several limitations should be acknowledged. The macronutrient analysis (organic carbon, phosphorus, potassium) was conducted only on two of the nine sampling sites, limiting the spatial coverage of nutrient data. Future studies should extend macronutrient analysis to all sites to provide a more complete picture of spatial variability in soil fertility across the Kole wetlands.

Additionally, the sampling was conducted over the period 2021–2024 across different years at different sites, which may introduce temporal variability as a confounding factor in site comparisons. Future research should focus on temporal monitoring of soil properties across seasons to better understand the dynamics of redox processes and nutrient cycling in the Kole wetlands. Detailed investigation of the Pullazhi Wetland site is warranted to identify the causes of acidification and develop appropriate remediation strategies.

CONCLUSION

This study provides a comprehensive characterization of the physico-chemical properties of soils from nine representative sites across the Kole wetlands of Thrissur District, Kerala. The findings reveal that most sites exhibit soil properties favorable for rice cultivation, including near-neutral to slightly alkaline pH (6.5–7.64), low salinity (0.01%), moderate ORP (250–290 mV), and adequate nutrient levels. The organic carbon content

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(0.68–1.02%), available phosphorus (16–17 kg/ha), and available potassium (187–198 kg/ha) are within acceptable ranges for sustaining rice productivity.

However, considerable spatial variability was observed, with one site (Pullazhi Wetland) exhibiting anomalous characteristics including extremely low pH (3.28), high ORP (393 mV), and elevated EC (0.00730 dS/cm), suggesting localized acidification possibly due to acid sulfate soil conditions or contamination. This site requires special management attention, including potential lime application and careful water management to prevent further acidification.

The findings of this study provide baseline data for sustainable management of the Kole wetlands. Recommendations for management include: (1) regular monitoring of soil pH and redox status, particularly at sites showing signs of acidification; (2) organic matter management through incorporation of crop residues and green manures to maintain soil fertility; (3) optimized water management to control redox conditions and nutrient availability; (4) lime application at acidic sites to improve pH and soil conditions; and (5) continued monitoring of salinity to detect any future changes due to altered hydrology or climate change.

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Declaration of Competing Interests

The author declares no conflict of interest.

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