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Research Paper

Linking Soil Physicochemical Characteristics to Taxonomic Classification across Lebak Swamp Typologies in South Sumatra

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Abstract

Lebak swamp areas in South Sumatra represent a strategic land resource for agricultural development and food security; however, their utilization remains constrained by variability in soil characteristics and hydrological conditions. This study aims to analyze soil physicochemical characteristics, classify soils based on Soil Taxonomy, and examine the relationship between soil taxonomy and lebak swamp typologies. The research was conducted through field surveys, soil profile description, soil sampling, and laboratory analyses. The results indicate that the total area of lebak swamp reaches approximately ±430,731 ha, which can be classified into five main typologies: shallow lebak, levee (pematang), middle lebak, deep lebak, and lebung. The soils are generally characterized by acidic conditions (pH 3.5-5.5), high organic carbon content (2.5-8.0%), moderate to high total nitrogen, and low available phosphorus (5-15 ppm). Based on Soil Taxonomy, the soils are classified into Entisols, Inceptisols, Histosols, and partly Gelisols, with distinct distributions across lebak typologies. Deep lebak and lebung areas are predominantly occupied by organic soils (Histosols), whereas shallow lebak and levee areas are dominated by young mineral soils (Entisols and Inceptisols). These findings demonstrate a clear relationship between hydrological typology and soil development, which can serve as a basis for zoning and sustainable management of lebak swamp land, particularly in determining suitable crops and soil amelioration strategies.

Keywords

Soil taxonomy; typology; lebak; soil physicochemical; agricultural potential

1. INTRODUCTION

Lebak swamp is a type of floodplain wetland ecosystem that plays a strategic role in supporting food security and sustainable agricultural development in tropical regions, particularly in Southeast Asia (FAO, 2021; Mulyani and Sarwani, 2021; Susilawati et al., 2021). This ecosystem develops in lowland areas influenced by river flooding and seasonal rainfall, resulting in periodic inundation that strongly controls soil formation processes and land use potential. In Indonesia, South Sumatra represents one of the largest areas of lebak swamp, which has been widely utilized for food crop cultivation, especially rice-based systems (Susilawati et al., 2021).

Based on inundation depth and duration, lebak swamp is commonly classified into several typologies, including shallow lebak, middle lebak, and deep lebak, each characterized by distinct hydrological and biophysical conditions. These hydrological variations significantly influence pedogenetic processes, leading to substantial variability in soil physical and chemical properties across typologies (Ritung et al., 2022; Liu et al., 2022). Consequently, understanding soil variability within these systems is essential for optimizing land use and improving agricultural productivity.

Despite its considerable potential, the utilization of lebak swamp for agriculture is constrained by complex biophysical limitations (FAO, 2021). Soils in these environments are typically characterized by high acidity, poor aeration due to prolonged waterlogging, and limited availability of essential nutrients (Husnain et al., 2020; Liu et al., 2022). In addition, fluctuations in groundwater levels induce alternating redox conditions, which strongly affect nutrient dynamics, organic matter decomposition, and microbial activity (Liu et al., 2022). These processes ultimately influence soil fertility and crop productivity, necessitating site-specific and soil-based management strategies.

Recent studies on lebak swamp have primarily focused on agronomic improvements, water management, and crop productivity enhancement (Susilawati et al., 2021; Mulyani and Sarwani, 2021). From a soil science perspective, wetland soils are generally classified into several major Soil Taxonomy orders, including Entisols, Inceptisols, and Histosols, depending on hydrological regimes and pedogenic development (Soil Survey Staff, 2022). Furthermore, recent findings highlight that variability in soil physicochemical properties plays a crucial role in regulating biogeochemical processes, particularly organic carbon dynamics and nutrient cycling in wetland ecosystems (Liu et al., 2022; Wang et al., 2023a).

However, existing studies remain largely fragmented, with limited efforts to systematically integrate soil characteristics with taxonomic classification across different lebak swamp typologies at a regional scale. In particular, the relationship between soil physicochemical variability and the distribution of soil taxa within each lebak typology has not been comprehensively examined. This gap limits the development of a robust scientific basis for land evaluation and sustainable management of lebak swamp ecosystems.

To address this gap, this study applies an integrated soil survey approach involving field observations, soil profile description, sampling, and laboratory analyses of soil physical and chemical properties. The collected data were used to classify soils according to Soil Taxonomy and to analyze their relationships with lebak swamp typologies in the study area. This approach enables a more systematic evaluation of how soil characteristics correspond to hydrological typologies within lebak ecosystems.

The novelty of this study lies in its integrative framework that explicitly links soil physicochemical characteristics with taxonomic classification across multiple lebak swamp typologies within a single analytical structure. This study provides one of the first comprehensive assessments of soil–typology relationships in lebak swamp systems at the regional scale of South Sumatra. The findings are expected to contribute to the advancement of soil science, particularly in wetland environments, and to support the development of more effective and sustainable management strategies for lebak swamp agriculture.

2. EXPERIMENTAL SECTION

Research Location, Biomaterial Use, and Cultivation Procedures

Study Area

This study was conducted in lebak swamp areas located in South Sumatra, Indonesia. The study sites were selected to represent the major lebak typologies, including shallow lebak, middle lebak, and deep lebak. Fieldwork involved soil surveys, soil profile observations, and soil sampling. Laboratory analyses were carried out to determine the physical and chemical properties of the soils.

Research Design

This study employed a soil survey method using a combined descriptive and analytical approach to characterize soil properties and classify soils across different lebak swamp typologies. Soil survey is a widely applied approach in pedological studies to obtain information on soil morphology, physicochemical properties, and spatial distribution of soil types within a given landscape (Soil Survey Staff, 2022).

Soil Survey and Profile Description

Field surveys were conducted to assess geomorphological conditions, topography, and lebak typologies. Observation points were determined using purposive sampling based on variations in land typology. At each observation point, a soil profile pit was excavated to describe soil morphological properties, including soil color, texture, structure, consistency, horizon boundaries, drainage conditions, and groundwater table depth. Soil profile descriptions followed standardized guidelines established by Soil Survey Staff (2022).

Soil Sampling

Soil samples were collected from each identified horizon within the soil profiles. Disturbed soil samples were taken for laboratory analysis of soil chemical properties and texture. The samples were air-dried, sieved through a 2 mm mesh, and stored in appropriate containers prior to analysis. The sampling procedures followed standard soil science protocols as described by Soil Survey Staff (2022).

Laboratory Analysis

Laboratory analyses were conducted to determine the physical and chemical characteristics of the soils. The parameters analyzed included soil pH, organic carbon content, total nitrogen, available phosphorus, and soil texture. Soil pH was measured using a pH meter in a soil-water suspension (1:2.5). Organic carbon content was determined using the Walkley-Black method, while total nitrogen was analyzed using the Kjeldahl method. Available phosphorus was measured using either the Bray or Olsen method, depending on soil conditions. Soil texture was determined using the hydrometer or pipette method to quantify sand, silt, and clay fractions. All analytical procedures followed standard soil laboratory methods commonly used in soil science research (Soil Survey Staff, 2022).

Soil Classification

Soil classification was carried out based on the Soil Taxonomy system by integrating field observations of soil morphology with laboratory data on physical and chemical properties, as well as environmental conditions of soil formation. Soils were classified up to the level of order, suborder, great group, and subgroup using the criteria outlined in the Keys to Soil Taxonomy (Soil Survey Staff, 2022).

Data Analysis

Data obtained from field surveys and laboratory analyses were analyzed descriptively to characterize soil properties across different lebak swamp typologies. In addition, relationships between soil physicochemical properties and soil taxonomic classification were examined to identify patterns of soil distribution. The results were further interpreted to assess the potential and limitations of soils in lebak swamp ecosystems for agricultural utilization and sustainable land management.

3. RESULTS AND DISCUSSION

3.1 Lebak Swamp Typologies

The results indicate that lebak swamp areas in South Sumatra cover approximately 430,731 ha and are distributed across several typologies. These typologies are primarily distinguished based on the depth and duration of inundation occurring annually (Ritung et al., 2022; Susilawati et al., 2021), which strongly influences soil conditions, hydrological regimes, and land-use potential.

Lebak swamp ecosystems in South Sumatra can be classified into several typologies based on the duration and depth of seasonal inundation. These typologies include shallow lebak, levee (pematang), middle lebak, deep lebak, and lebung. Shallow lebak areas experience inundation for less than three months with relatively shallow water depth. Levee areas are typically located along natural river embankments and are less frequently inundated. Middle lebak areas experience moderate flooding lasting approximately three to six months, while deep lebak areas are characterized by inundation periods exceeding six months. In contrast, lebung areas represent depressional zones where flooding occurs almost permanently throughout the year. These hydrological differences strongly influence soil formation processes, soil properties, and agricultural potential in lebak swamp ecosystems.

Table 1. Characteristics of lebak swamp typologies

Lebak Typology	Inundation Characteristics
Shallow lebak	Inundation < 3 months, relatively shallow water depth
Levee (Pematang)	Located around natural river levees
Middle lebak	Moderate inundation lasting 3-6 months
Deep lebak	Inundation > 6 months
Lebung	Nearly permanent inundation

Source: Wildayana and Armanto (2018)

Five main typologies were identified: shallow lebak, levee (pematang), middle lebak, deep lebak, and lebung. Shallow lebak areas experience inundation for less than three months, whereas middle lebak are flooded for approximately 3–6 months. Deep lebak are inundated for more than six months, while lebung areas are characterized by near-permanent flooding conditions. These variations clearly demonstrate that hydrological dynamics are the dominant factor controlling the characteristics of lebak swamp ecosystems.

The extent of each typology is not static but dynamic, influenced by climatic variability, river discharge fluctuations, and land-use changes. Variations in rainfall intensity and river water levels can alter inundation depth and duration, resulting in shifts in lebak typologies over time. Additionally, human activities such as agricultural expansion, settlement development, and infrastructure construction contribute to changes in the spatial distribution of lebak swamp areas.

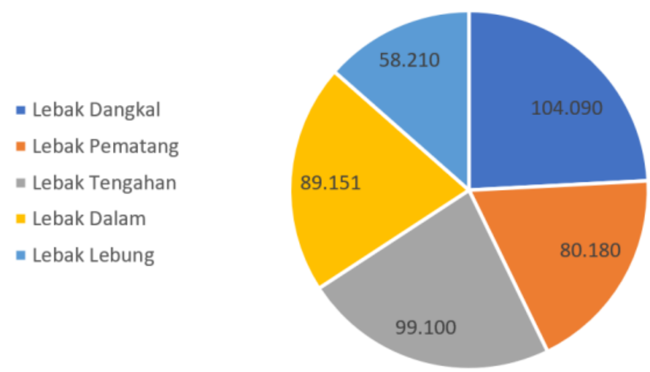

Figure 1. Lebak swamp typologies (ha)

3.2 Soil Morphological Characteristics

Field observations reveal that soils in lebak swamp areas are predominantly derived from alluvial parent materials deposited through fluvial processes. The soils generally exhibit fine textures, with dominant clay to clay loam compositions, reflecting sediment deposition under low-energy floodplain conditions.

The morphological characteristics of soils in lebak swamp areas reflect strong hydromorphic processes associated with prolonged water saturation. Soil colors generally range from grayish brown to very dark gray in the upper horizon, while lower horizons tend to show lighter gray to grayish brown colors. Soil texture varies from clay loam to clay in the upper horizons and from clay to silty clay loam in the lower horizons. Soil structure is generally weakly developed in the surface layer and moderately developed in the subsurface horizons. In terms of consistency, the soils are typically plastic and sticky, becoming very plastic in deeper layers due to high clay content and prolonged water saturation. Diagnostic horizons commonly observed include histic or ochric horizons in the upper layer and cambic or gleyic horizons in the subsurface layer.

Soil color ranges from gray to dark grayish brown, indicating strong reductive conditions associated with prolonged water saturation. The presence of gleyed horizons

Table 2. Morphological characteristics of lebak swamp soils

Parameter	Upper Horizon	Lower Horizon
Soil color	Grayish brown – very dark gray	Light gray – grayish brown
Soil texture	Clay loam – clay	Clay – silty clay loam
Soil structure	Weak blocky	Moderate blocky
Consistency	Plastic and sticky	Very plastic
Diagnostic horizon	Histic / Ochric	Cambic / Gleyic

Source: Wildayana and Armanto (2018)

Table 3. Physical properties of lebak swamp soils

Parameter	Value Range	Interpretation
Bulk density ($g\,cm^{-3}$)	0.9 – 1.3	Moderate
Porosity (%)	45 – 60	High
Water holding capacity (%)	40 – 65	High
Clay content (%)	40 – 65	Dominant fraction
Soil permeability ($cm\,hour^{-1}$)	0.2 – 1.5	Slow

Source: Wildayana and Armanto (2018)

confirms that these soils are subjected to anaerobic environments for extended periods (Soil Survey Staff, 2022; Wang et al., 2023b). Soil structure is generally weak to moderate, with plastic and sticky consistency, particularly in subsurface horizons. These morphological characteristics reflect hydromorphic soil development processes, where prolonged waterlogging limits oxidation and promotes the reduction of iron and manganese, resulting in characteristic gray colors and gley features.

These morphological characteristics indicate that lebak swamp soils are strongly influenced by periodic or permanent inundation, which promotes the formation of gleyic horizons and gray soil colors due to iron reduction processes under anaerobic conditions.

3.3 Soil Physical Properties

Soil physical properties play a critical role in determining the behavior of lebak swamp soils under fluctuating water conditions. These properties influence water retention, aeration, root penetration, and nutrient availability for crops cultivated in the area. The soils in lebak swamp environments generally exhibit high clay content, relatively high bulk density in deeper layers, and moderate to high water holding capacity due to the dominance of fine particles and organic matter accumulation.

Particle size distribution analysis indicates that clay fractions dominate the soil composition, reflecting the depositional nature of floodplain environments. Fine sediments transported by river flooding are gradually deposited in low-energy environments, resulting in soils with clayey textures.

The relatively high porosity and water holding capacity indicate that lebak swamp soils have the ability to store significant amounts of water, although slow permeability may lead to prolonged saturation during the rainy season.

3.4 Hydrological Characteristics

Hydrological conditions are the primary environmental factor controlling soil formation and agricultural suitability in lebak swamp ecosystems. Seasonal flooding, groundwater fluctuations, and drainage patterns determine the intensity of reduction processes that influence soil color, structure, and nutrient dynamics.

The duration of inundation varies across lebak typologies. Shallow lebak areas experience relatively short flooding periods, whereas deep lebak and lebung areas remain inundated for extended periods throughout the year. These hydrological differences strongly influence soil development and land use potential.

Table 4. Hydrological characteristics of lebak swamp areas

Typology	Flood duration	Water depth
Shallow lebak	< 3 months	20 – 50 cm
Middle lebak	3 – 6 months	50 – 100 cm
Deep lebak	> 6 months	100 – 150 cm
Lebung	Permanent	>150 cm

Source: Wildayana and Armanto (2018)

Prolonged inundation promotes anaerobic soil conditions, leading to reduction reactions that influence soil chemistry, particularly the availability of iron, manganese, and phosphorus.

3.5 Soil Chemical Properties

Laboratory analysis indicates that soils in lebak swamp ecosystems exhibit distinct chemical characteristics associated with wetland environments. The soils are generally acidic, with pH values ranging from 4.0 to 5.5. Organic carbon content is relatively high due to the accumulation of plant residues under anaerobic conditions. Total nitrogen content ranges from moderate to high levels, reflecting the contribution of organic matter to soil nutrient pools. However, the availability of essential nutrients such as phosphorus and potassium remains relatively low due to fixation processes and limited mineral weathering.

Table 5. Average chemical properties of lebak swamp soils

Parameter	Value	Criteria
Soil pH	4.0 – 5.5	Acidic
Organic C (%)	2.5 – 8.0	High
Total N (%)	0.2 – 0.6	Moderate – high
C/N ratio	5 – 49	Variable
CEC (cmol kg^{-1})	20 – 45	Moderate – high
Available P (ppm)	5 – 15	Low
Available K (cmol kg^{-1})	<0.5	Low

Source: Wildayana and Armanto (2018)

The relatively high organic carbon content contributes significantly to the cation exchange capacity of these soils, enhancing their nutrient retention capacity despite the generally low availability of phosphorus and potassium.

Cation exchange capacity (CEC) values range from 20 to 45 cmol kg^{-1}, suggesting moderate to high nutrient retention capacity. However, the availability of essential nutrients such as phosphorus (5–15 ppm) and potassium (<0.5 cmol kg^{-1}) is generally low, which may limit plant growth. The high organic carbon content is primarily attributed to the accumulation of plant residues under anaerobic conditions where decomposition rates are reduced (Liu et al., 2022; Wang et al., 2023a), where decomposition rates are significantly reduced. A strong relationship between organic carbon content and CEC was observed, indicating the imprtant role of organic matter in enhancing soil fertility through increased nutrient retention capacity. Low phosphorus availability is likely due to fixation by iron and aluminum under acidic conditions, which commonly occurs in wetland soils (Husnain et al., 2020; Liu et al., 2022), while low potassium availability may be associated with leaching and limited mineral weathering. These constraints highlight the importance of soil amelioration strategies, such as liming and organic matter addition, to improve soil fertility.

3.6 Soil Classification and Distribution

Based on morphological observations and laboratory analyses, lebak swamp Soils are classified into Entisols, Inceptisols, Histosols, and partly Gelisols according to the Soil Taxonomy classification system (Soil Survey Staff, 2022; Ritung et al., 2022). The distribution of these soil orders is closely related to lebak typology. Shallow lebak and levee areas are predominantly occupied by Entisols, reflecting young soils with minimal profile development due to continuous sediment deposition. Middle lebak areas are generally associated with Inceptisols, indicating moderate soil development under relatively more stable geomorphological conditions.

The distribution of soil orders in lebak swamp ecosystems varies according to hydrological typology. Shallow lebak areas are generally dominated by Entisols, which represent young soils with minimal profile development. Levee areas are characterized by Entisols and occasionally Gelisols due to periodic inundation. Middle lebak areas commonly contain Inceptisols or Entisols, indicating moderate soil development under relatively stable hydrological conditions. In contrast, deep lebak and lebung areas are dominated by Histosols, which are characterized by high organic matter accumulation resulting from prolonged waterlogging.

Table 6. Soil classification across lebak swamp typologies

Lebak Typology	Soil Order	Main Characteristics
Shallow lebak	Entisols	Young soils with minimal profile development
Levee (Pematang)	Entisols / Gelisols	Influenced by periodic inundation
Middle lebak	Inceptisols / Entisols	Moderate soil development
Deep lebak	Histosols	High organic matter content
Lebung	Histosols	Peat soils with permanent inundation

Source: Wildayana and Armanto (2018)

In contrast, deep lebak and lebung areas are dominated by Histosols, characterized by high organic matter accumulation resulting from prolonged waterlogging. These findings demonstrate that hydrological conditions play a fundamental role in controlling soil formation processes and taxonomic classification in lebak swamp ecosystems.

3.7 Hydrological Control on Soil Formation

Hydrological dynamics are the primary factors controlling pedogenesis in lebak swamp environments (Liu et al., 2022; Wang et al., 2023a). Prolonged flooding creates anaerobic conditions that inhibit organic matter decomposition and limit horizon development.

In shallow and levee typologies, periodic sedimentation from river flooding leads to the formation of young soils (Entisols), where soil horizons remain weakly developed. In contrast, more stable conditions in middle lebak areas allow for the development of Inceptisols with more distinct horizon differentiation.

In permanently inundated environments such as lebung, the accumulation of undecomposed organic material results in the formation of Histosols. These findings are consistent with previous studies indicating that hydrological regimes strongly influence soil development pathways in wetland ecosystems.

3.8 Implications for Agricultural Development

The characteristics of lebak swamp soils indicate substantial potential for agricultural development, particularly for rice cultivation with reported yields ranging from 4.0 to 6.8 t ha^{-1} under improved management practices (Susilawati et al., 2021; Mulyani and Sarwani, 2021) under appropriate management practices. However, successful utilization of these lands requires careful management of both soil fertility and water regimes. Soil acidity, low nutrient availability, and redox-related constraints necessitate site-specific management strategies, including soil amelioration (e.g., liming, organic amendments) and water control systems.

Proper water management is particularly critical to regulate groundwater levels, minimize iron toxicity, and prevent oxidation of pyritic layers that may lead to severe soil acidification. Therefore, integrating soil characteristics with hydrological typologies provides a scientific basis for developing sustainable and productive agricultural systems in lebak swamp environments.

3.9 Policy Implications for South Sumatra

The findings of this study provide a strong scientific basis for formulating targeted and adaptive land management policies for lebak swamp ecosystems in South Sumatra. Given the clear linkage between hydrological typology, soil characteristics, and soil taxonomic distribution, future policies should move beyond generalized land-use planning toward typology-based and soil-informed management frameworks.

1. Typology-Based Land Zoning for Agricultural Development

The differentiation of lebak typologies—shallow, levee (pematang), middle, deep, and lebung—should be explicitly incorporated into regional land-use planning. Each typology exhibits distinct soil characteristics and hydrological constraints, requiring tailored management strategies:

1) Shallow lebak and levee areas should be prioritized for intensive agricultural development, particularly rice cultivation, due to relatively better drainage and mineral soil dominance.
2) Middle lebak can be designated as adaptive agricultural zones, combining crop production with controlled water management.
3) Deep lebak and lebung areas should be classified as limited-use or conservation-sensitive zones, where agricultural activities must be carefully managed to avoid degradation of organic soils (Histosols). This zoning approach will enhance land-use efficiency while minimizing environmental risks.

2. Integration with Regional Planning and DAS Musi Management

Lebak swamp ecosystems are an integral part of the hydrological system of the DAS Musi. Therefore, policies for lebak management must be integrated into broader watershed management strategies.

1) Water regulation infrastructure (e.g., canals, gates) should be designed to maintain optimal groundwater levels across different lebak typologies.
2) Floodplain management should consider both upstream-downstream interactions and seasonal hydrological variability.
3) Coordination between agricultural, environmental, and water resource agencies is essential to ensure Integrated Water Resources Management (IWRM) at the basin scale.

3. Soil Fertility Management and Amelioration Programs

Given the acidic nature of lebak soils and the low availability of phosphorus and potassium, policy interventions should prioritize soil fertility enhancement programs, including:

1) Liming programs to increase soil pH and reduce aluminum and iron toxicity.
2) Subsidized fertilizers tailored to wetland soil conditions, particularly P and K inputs.
3) Promotion of organic amendments to improve soil structure and nutrient retention.
4) Government-supported extension services should disseminate site-specific recommendations based on lebak typology and soil classification.

4. Sustainable Water Management Strategies

Hydrological control is the key determinant of soil behavior and agricultural success in lebak ecosystems. Policies should emphasize:

1) Development of controlled drainage and irrigation systems adapted to each typology.
2) Prevention of excessive drainage in deep lebak and lebung areas to avoid oxidation of organic soils and potential subsidence.
3) Mitigation of iron toxicity and acid sulfate soil formation through proper water level management.
4) Community-based water management institutions should be strengthened to ensure long-term sustainability.

5. Protection of Organic-Rich Soils (Histosols)

Deep lebak and lebung areas dominated by Histosols require special protection due to their ecological and carbon storage functions. Policies should:

1) Limit land conversion and intensive drainage in these areas.
2) Promote low-impact land uses, such as paludiculture or wetland-compatible crops.
3) Integrate lebak management into climate change mitigation strategies, considering their role in carbon sequestration and greenhouse gas emissions.

6. Dynamic Mapping and Monitoring Systems

The study shows that lebak typologies are dynamic and can shift due to hydrological changes and land-use pressures. Therefore, policy frameworks should include:

1) Regular updating of lebak typology maps using remote sensing and field verification.
2) Development of digital soil and hydrology databases for decision support.
3) Integration of GIS-based tools into regional planning systems.
4) This will ensure that policies remain adaptive and responsive to environmental changes.

7. Strengthening Research–Policy Linkages
To support evidence-based policymaking, stronger collaboration is needed between: universities, government agencies, and local stakeholders. Research outputs such as soil classification, PCA-based analysis, and typology mapping should be translated into: technical guidelines, land evaluation tools, and policy briefs for decision-makers.

8. Toward a Lebak-Based Sustainable Agriculture Model
Ultimately, the findings support the development of a "Lebak-Based Agricultural Management Model", which integrates: soil taxonomy, hydrological typology, and adaptive farming practices. This model can serve as a prototype for: sustainable wetland agriculture in South Sumatra, and broader tropical floodplain systems in Southeast Asia.

4. CONCLUSION

This study provides a comprehensive assessment of soil characteristics, taxonomic classification, and their relationships with lebak swamp typologies in South Sumatra, Indonesia. By integrating field-based soil survey, laboratory analysis, and multivariate statistical approaches, this research offers a robust understanding of how hydrological variability shapes soil development and distribution in tropical floodplain wetland ecosystems (Liu et al., 2022; Wang et al., 2023a).

The results demonstrate that lebak swamp areas in South Sumatra, covering approximately 430,731 ha, exhibit clear typological differentiation driven primarily by the depth and duration of inundation. Five major typologies—shallow lebak, levee (pematang), middle lebak, deep lebak, and lebung—represent a hydrological continuum that strongly controls soil formation processes, physicochemical properties, and taxonomic distribution. This finding confirms that hydrology acts as the dominant ecological driver in lebak swamp systems, influencing both pedogenesis and land-use potential.

Soil morphological observations indicate that lebak swamp soils are predominantly derived from alluvial parent materials and exhibit hydromorphic features, including gleyed horizons and grayish soil colors, reflecting prolonged anaerobic conditions. These characteristics are consistent with floodplain environments where sedimentation and water saturation interact to regulate soil development. The presence of weak soil structure and high plasticity further emphasizes the influence of waterlogging on soil physical behavior.

From a chemical perspective, lebak swamp soils are generally acidic (pH 4.0–5.5), with relatively high organic carbon content (2.5–8.0%), moderate to high total nitrogen, and moderate to high cation exchange capacity. However, essential nutrients such as phosphorus and potassium are consistently low, indicating significant fertility constraints. The accumulation of organic matter under anaerobic conditions plays a critical role in enhancing nutrient retention capacity, as reflected by the strong association between organic carbon and cation exchange capacity. Nevertheless, nutrient availability remains limited due to fixation processes and reduced mineral weathering, highlighting the need for targeted soil fertility management.

The classification of soils into Entisols, Inceptisols, Histosols, and partially Gelisols further reinforces the strong linkage between hydrological typology and pedogenic processes. Shallow lebak and levee areas are dominated by Entisols, indicating young soils with minimal profile development due to continuous sediment deposition. Middle lebak areas are characterized by Inceptisols, reflecting moderate soil development under relatively stable conditions. In contrast, deep lebak and lebung areas are dominated by Histosols, which are formed through prolonged accumulation of organic matter under permanent or near-permanent waterlogging.

These findings have important implications for agricultural development and sustainable land management. Despite inherent constraints such as soil acidity, low nutrient availability, and redox-related limitations, lebak swamp soils possess significant potential for agricultural use, particularly for rice cultivation. However, successful utilization depends on the implementation of typology-specific management strategies. Shallow and levee areas, with better drainage and mineral soil characteristics, are more suitable for intensive agricultural practices. In contrast, deep lebak and lebung areas require careful water management and conservation-oriented approaches due to their high organic matter content and sensitivity to disturbance.

Soil amelioration practices, including liming to increase soil pH and the application of organic or inorganic fertilizers to address nutrient deficiencies, are essential for improving soil productivity. In addition, water management plays a critical role in regulating groundwater levels, preventing iron toxicity, and avoiding the oxidation of sulfide-bearing layers that could lead to severe soil acidification. Therefore, integrating soil characteristics with hydrological typologies provides a scientifically sound basis for designing site-specific and sustainable agricultural systems.

An important contribution of this study lies in its integrative framework, which combines soil survey, taxonomic classification, and multivariate analysis to reveal the underlying drivers of soil variability in lebak swamp environments. This approach moves beyond conventional descriptive studies by providing a systematic and quantitative understanding of soil–typology relationships. The results highlight the importance of incorporating hydrological variability into soil classification and land evaluation frameworks, particularly in wetland ecosystems where water dynamics play a central role. Furthermore, this study emphasizes that lebak swamp typologies and associated soil classifications are inherently dynamic, influenced by changes in hydrological regimes, climate variability, sedimentation processes, and land-use alterations. This dynamic nature underscores the need for periodic reassessment and adaptive management to ensure sustainable utilization of lebak swamp resources.

In conclusion, the strong linkage between hydrological typology, soil characteristics, and taxonomic classification demonstrated in this study provides a critical scientific foundation for improving land evaluation, agricultural planning, and sustainable management of lebak swamp ecosystems. Future research should focus on integrating soil–hydrology relationships with climate change scenarios, nutrient cycling dynamics, and advanced spatial modeling to further enhance the resilience and productivity of wetland-based agricultural systems in tropical regions.

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