Optimization of Soil Sampling for Layered Amelioration Trials Through Homogeneous Land Unit Mapping in Sandy Agricultural Landscapes

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Abstract. Improving soil quality in sandy farming areas needs more than just adding amendments. It requires careful planning, structure, and adapting to the specific conditions of each site. This study presents an integrated approach to optimize soil sampling for layered amelioration trials, using representative soils from sandy agriculturally areas in Cilacap Regency, Indonesia. The proposed experiment applies an engineered soil layering model, incorporating waste-derived silica-cellulose ameliorants such as rice husk ash, cocopeat, coffee husk and bentonite, to enhance moisture retention and minimize nutrient leaching. To ensure the study is relevant and can be repeated, the soil sampling was based on Homogeneous Land Unit (HLU) mapping. This divided the land into 8 groups based on soil type, slope, and land use. From these, 8 purposively selected soil samples were collected, representing diverse field conditions. These samples are used in lab experiments that mimic real underground soil processes. By matching the experiment to the variety in the landscape, this study makes the soil layering method more accurate and useful. The results aim to offer a flexible and sustainable way to manage damaged sandy soils in tropical farming areas.

1. Introduction

Sandy agricultural soils, particularly those in coastal regions such as Cilacap Regency, Indonesia, are characterized by low water retention [1, 2], weak nutrient-holding capacity[3], and fragile structure [4]. These limitations restrict crop productivity and make such soils highly vulnerable to degradation, nutrient leaching [3, 5] and drought stress. Improving the performance of sandy soils therefore requires more than conventional amendment practices; it demands site specific [6], structured approaches that address the heterogeneity soil and landscape condition.

Soil amelioration strategies have traditionally been implemented through bulk application of organic [7] or inorganic amendments. While these approaches can improve soil condition, the effectiveness if often inconsistent due to variability in soil properties [8] and land management practices. Recent studies highlight the importance of developing engineered systems, such as soil layering techniques [9, 10, 11], which strategically place ameliorants within soil profiles to enhance water storage, reduce nutrient leaching and strengthen soil structure. However, a persistent challenge in advancing such techniques lies in designing experiments that adequately represent the variability of field condition. Without representative sampling, laboratory trials may not reflect real world outcomes, limiting scalability and practical application. To address this challenge, Homogeneous Land Unit (HLU) mapping provides a methodological basis for identifying spatially consistent units based on soil type, topography, and land use. By integrating HLU mapping with purposive sampling, representative soil can be selected to capture landscape variability more effectively than conventional random sampling. This framework ensures that subsequent experimental trials, such as soil layering with waste derived ameliorant, are grounded in real field conditions rather than homogenized assumption.

In this study, the methodological framework focuses on sandy agricultural areas of Cilacap Regency. Representative soil were identified through HLU mapping [12], which provides the spatial basis for selecting sampling site. These soils form the foundation for laboratory based column experiments, in which composted silica-cellulose ameliorants [13] derived from rice husk ash [7], cocopeat [14], coffee husk [15] and bentonite will be tested. As the laboratory trials are still ongoing, this paper emphasized the establishment of an HLU-based sampling framework as the core methodological achievement, ensuring that sub-sequent soil layering experiments are both representative and scalable. Ultimately, this study not only advances a systematic approach for soil sampling but also lays the groundwork for precision amelioration strategies tailored to tropical coastal agroecosystems.

2. Materials dan Methods

2.1 Study Area

The research was conducted in sandy agricultural landscapes of Adipala, Binangun, and Nusawungu Sub-districts, Cilacap Regency, Central Java, Indonesia. Field survey, soil sampling and HLU identification were conducted beginning in August 2025, and the subsequent laboratory column experiments are currently in progress. This coastal lowland is dominated by Regosol, characterized by coarse texture, low water-holding capacity, and high nutrient leaching risk. Slopes range between 0-8 %, with diverse land uses including irrigated rice field, rainfed fields, mixed gardens, plantations and settlements. These characteristics make the area representative of tropical sandy agroecosystems under intensifying land use pressure.

2.2 Homogeneous Land Unit (HLU) Mapping and Soil Sampling

The study employed Geographic Information System (GIS) software tools to integrate multiple spatial datasets including soil type maps, Digital Elevation Models (DEM), topographic slope maps, land use maps and satellite imagery. These data sources enabled the delineation of Homogeneous Land Units (HLUs) (Fig. 1) based on consistent soil, slope and land use characteristics. Field sampling coordinates were precisely recorded using a Garmin Global Navigation Satellite System (GNSS) device.

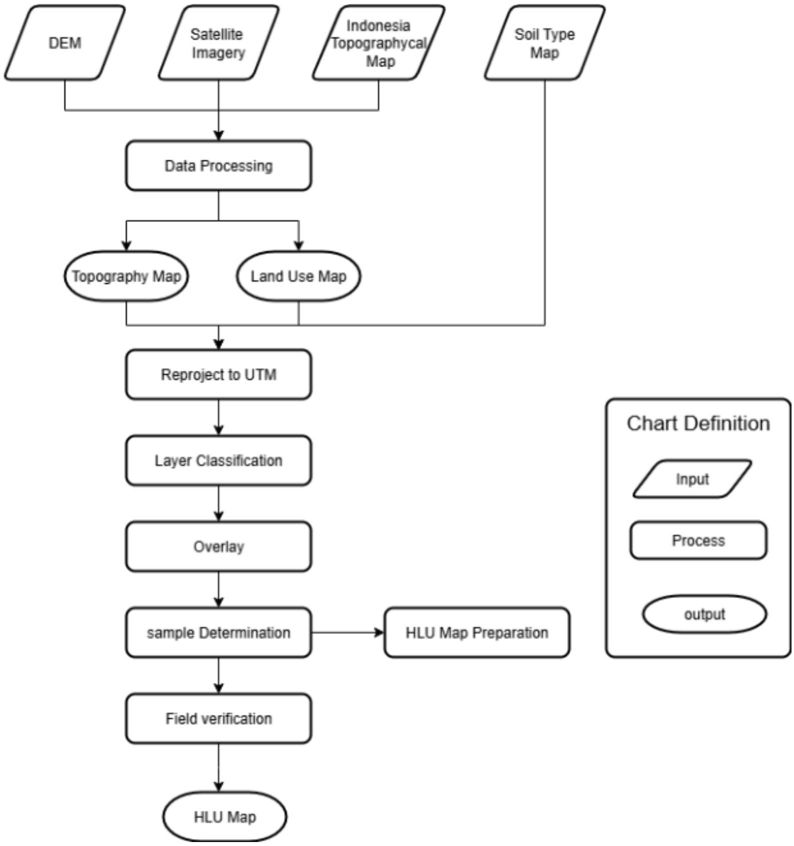

Fig. 1. Workflow of HLU mapping

Soil samples for the laboratory experiments were collected from 20-30 cm depth, chosen as it corresponds to the A horizon where root activity and cultivation occur, making it the most relevant layer for amelioration trials. The stratification into eight HLUs was justified to capture the spatial variability typical of the study area, ensuring representative sampling across diverse field conditions in improving experimental relevance and scalability.

2.3 Experimental Framework

The collected soil samples will serve as the basis for controlled column experiments in the laboratory. The experiments are designed to test the effect of layered amelioration using four amendments: rice husk ash, cocopeat, coffee husk, and bentonite.

The ameliorant was prepared by composting a blend of these materials. Rice husk ash was selected for its high silica content [7], cocopeat and coffee husk provided organic matter and cellulose-rich fibres while bentonite contributes to improving cation exchange capacity (CEC) and water retention. Through the composting process, the organic components were partially decomposed, stabilizing nutrient availability and enhancing the synergistic properties of the formulation. Columns of 30 cm will be packed with sandy soil and alternating amendment layers to simulate soil layering techniques, aiming to enhance water retention and reduce nutrient leaching.

Although laboratory analysis in ongoing, the present paper emphasizes the methodological framework that links landscape-scale variability (HLUs) to experimental design, ensuring that results will be representative and scalable.

3. Result and Discussion

3.1 Spatial Distribution of HLUs

The integration of soil, slope and land use maps resulted in the delineation of eight HLUs in the study area. Figure 2 present the distribution of the eight HLUs in Cilacap coastal lowlands, while Figure 3 provide satellite imagery of the same area for contextual visualization. Together, these figures demonstrate how spatially stratified HLUs capture the diversity of land use system across the coastal sandy landscape.

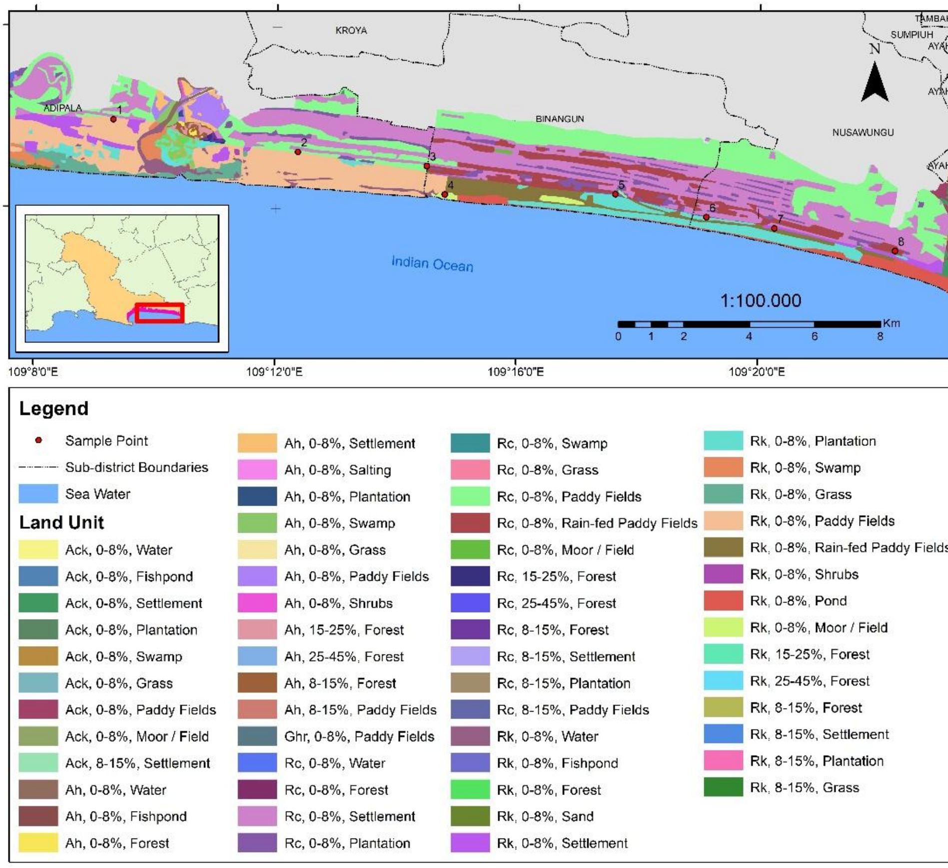

Fig. 2. The spatial distribution of eight HLUs in Cilacap coastal lowlands

Figure 2 illustrates the HLU thematic map, showing the spatial extent and distribution of eight HLUs. Each HLU reflects unique combinations of soil type, slope and land use, which are critical for understanding soil behaviour in sandy agroecosystems. The map demonstrates that the study area is dominated by flat to nearly flat terrain (0-8 %) with sandy soil textures, but differentiated by land utilization such as irrigated rice fields, rainfed fields, settlements, plantations, and mixed gardens.

To complement this classification, Figure 3 presents satellite imagery of the same area, providing a visual reference of the land surface. This imagery highlights the mosaic of agricultural and settlement pattern, showing how HLUs correspond with visible features such as paddy fields, vegetation cover, and proximity to the coastline. The integration of GIS-based HLU mapping and satellite imagery provides for understanding land-soil interaction.

This is crucial for designing amelioration strategies, as soil response may differ depending on land use intensity and proximity to the coast.

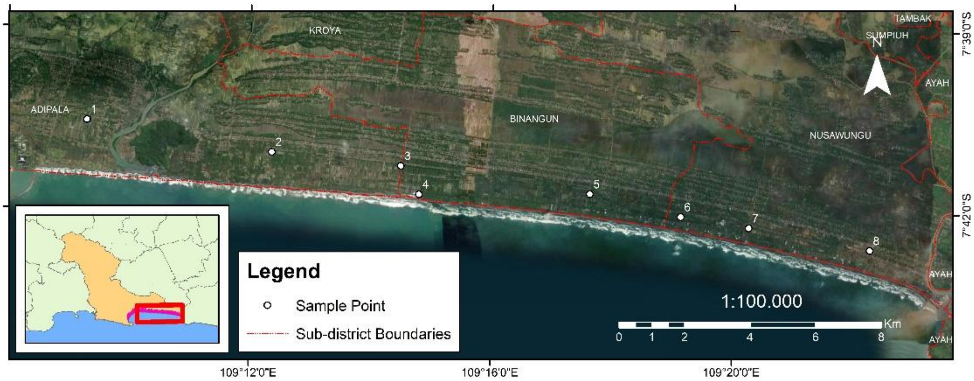

Fig. 3. Soil sampling point distribution in Cilacap Coastal Area

3.2 Soil Profile Characteristics from Mini-pit Observation

Field verification was carried out through mini-pit excavation (50 cm depth) at each HLU, from which soil samples were collected at the 20-30 cm depth to represent the cultivation horizon (A horizon). The photographs of soil profiles from the eight HLUs are shown in Figure 4. Visual examination indicates noticeable differences across the units:

- HLUs 1-4 (Adipala and Western Binangun): The soils are predominantly dark grey to brownish regosols with a loose sandy texture. Observations from several mini-pits revealed the presence of shallow groundwater, particularly in irrigated and rainfed rice fields, indicate fluctuating water tables that may exacerbate nutrient leaching. To mitigate this risk, incorporating amendment layers with high CEC, such as bentonite is recommended.
- HLUs 5-6 (Central Binangun): The soils exhibit a coarse matrix with lighter coloration, reflecting low organic matter content and limited water retention. Such condition requires the incorporation of organic rich amendment, such as cocopeat and coffee husk, to enchance moisture retention. Field observations further indicated the absence of visible water table within 50 cm depth, a condition typical of mixed garden area.
- HLUs 7-8 (Eastern Nusawungu): In the same subdistrict, soil profiles from HLU 7 and HLU 8 exhibited contrasting hydrological conditions. In HLU 7, a shallow water table was encountered at a depth of about 50 cm, with gradational colour pattern from grey in the upper horizon to brownish in the lower layers. In contrast, HLU 8 showed no visible water table within the same depth range. Despite this difference, both profiles appeared darker dan denser than those observed in central HLUs, suggesting a slightly higher clay fraction and improved aggregation. Although still classified as sandy regosols, their marginally greater structural stability may offer improved resilience and potential for diversified land use.

The variability in soil profiles confirms the heterogeneity of regosols across the coastal strip. While all soils share sandy dominance, subtle differences in texture, colour, and water table presence reflect differences in hydrology and land use. These observations validate the need for HLU-based stratification prior to laboratory experimentation, as soil responses to ameliorants will likely differ among units.

Fig. 4. Soil Profile from Mini-pit Sampling across Eight HLUs

3.3 Identification of HLUs

The spatial stratification resulted in eight HLUs, each defines by its soil type, slope, land use, and hydrological characteristics. Field coordinates were recorded using GNSS, and mini-pit observation confirmed the representativeness of each unit. Table 1. Demonstrates how land use system shape soil-water dynamics within the same regosol group. Irrigated HLUs exhibited shallow water tables, while rainfed and coastal system showed no visible groundwater up to 50 cm. This structures classification highlights the diversity of agroecosystem conditions within the same soil group, underscoring the importance of a stratified sampling approach.

Table 1. Identification of HLUs in Cilacap Regency

HLU	Soil Type	Slope (%)	Land Use	Water Table (0-50 cm)	Texture	Organic C (%)	Coordinates (X,Y)
1	Grey Regosol	0-8	Irrigated horticulture	45	Loamy sand	0.31	109,154808, -7,675826
2	Brown Regosol	0-8	Irrigated Rice	40	sand	0.08	109,205858, - 7,684348
3	Brown Regosol	8-15	Irrigated Rice	40	Loamy sand	0.98	109,241488, - 7,687876
4	Grey Regosol	0-8	Irrigated Rice	33	sand	0.54	109,246543, - 7,695633
5	Brown Regosol	0-8	Mixed Garden	-	Loamy sand	1.20	109,293699, - 7,695137
6	Grey Regosol	0-8	Mixed Garden	-	Loamy sand	1.37	109,318864, - 7,701208
7	Grey Regosol	0-8	Rainfed Rice	50	Loamy sand	0.80	109,337674, - 7,704085
8	Brown Regosol	0-8	Rainfed Rice	-	Loamy sand	0.54	109,371077, - 7,70999

Note: -: Not observed.

Variation among HLUs directly guide tailored amendment strategies by revealing specific soil and landscape needs. HLUs with shallow water tables indicate a higher risk of nutrient leaching, suggesting the use of amendments with high cation exchange capacity (CEC) such as bentonite to retain nutrients effectively. While HLUs with coarse sandy texture and low organic matter content require organic-rich amendments like cocopeat and coffee husk to enhance moisture retention and improve soil structure. Additionally, proximity to coastal zones identified through mapping highlights potential salinity constraints, guiding the selection of amendments that improve ionic balance and soil resilience. These insights from spatially stratified HLUs ensure the design of precise, site-adapted amelioration interventions that address heterogeneity, optimizing soil health and sustainability across the landscape.

3.4 Implication for the Experimental Framework

The mini-pit observations support the decision to collect samples from the 20-30 cm cultivation horizon, which represents the most actively managed soil layer in local farming systems. By focusing on this layer, the upcoming column experiments will more accurately simulate the real constrains faced by farmers, namely low water holding capacity, rapid nutrient loss, and weak soil aggregation.

The confirmed heterogeneity among HLUs strengthens the arguments that amelioration trials must be designed to capture landscape-level variability. For example, HLUs with shallow water tables may require amendments that reduce nutrient leaching, while coarser-textured HLUs may benefit more organic-based materials that improve moisture retention.

This framework underlines the strategic value of integrating field mapping, satellite imagery, and soil profile observation before conducting laboratory-based amelioration trials. The approach ensures not only scientific reproducibility but also practical relevance, enabling the eventual development of site-specific soil management recommendations for coastal sandy agroecosystem.

Although laboratory results are not yet available, the current framework ensures that experiments will be conducted on soils that truly represent the complexity of the Cilacap sandy landscape. This strengthens the potential contribution of the study to developing sustainable soil management strategies in tropical coastal agroecosystem.

4. Conclusion

The study demonstrates the importance of integrating spatial analysis with experimental design to address soil degradation in sandy agroecosystems. Through homogeneous land unit (HLU) mapping, the Cilacap coastal lowland was stratified into eight representative units, ensuring that soil sampling captures the variability of soil type, topography and land use. Mini-pit observations and soil sampling at the 20-30 cm cultivation horizon provided a strong empirical foundation for subsequent ameliorant trials.

Although laboratory trials are ongoing, this study confirms that integrating spatial analysis with targeted soil sampling significantly improves representativeness in amelioration trials within tropical sandy agroecosystems. The integration of HLU-based sampling with innovative soil layering approaches has the potential to generate site-specific and sustainable solution for improving soil performance in tropical sandy agroecosystem. The flexible HLU-based framework can be adapted for future studies across diverse agroecosystem types, ensuring site-specific soil variability is effectively captured. Its practical applicability supports scalable and precise soil management interventions designed to enhance soil health, productivity, and sustainability under heterogeneous landscape conditions

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