JPPIPA 12(4) (2026)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

Random Forest-Based Soil Mapping to Support Sustainable Watershed Management and SDG 15 (Life on Land): A Case Study of the Curahkemadu Micro Watershed

Ridho Maulana Ihsan[1], Kurniawan Sigit Wicaksono[2], Reni Ustiatik[2,3]*, Soemarno[2]

[1] Master Program of Soil and Water Management, Faculty of Agriculture, Universitas Brawijaya, Malang, Indonesia.
[2] Soil Science Department, Faculty of Agriculture, Universitas Brawijaya, Malang, Indonesia.
[3] International Research Centre for the Management of Degraded and Mining Lands, Universitas Brawijaya, Malang, Indonesia.

Received: January 30, 2026
Revised: February 20, 2026
Accepted: April 25, 2026
Published: April 30, 2026

Corresponding Author:
Reni Ustiatik
reni.ustiatik@ub.ac.id

DOI: 10.29303/jppipa.v12i4.14469

Abstract: Soil characteristics in the Curahkemadu Micro Watershed are influenced by volcanic parent material and other soil-forming factors, including organisms, topography, climate, and time. This study aims to analyze the spatial distribution of soil up to the subgroup level and identify the dominant factors that shape it using a machine learning approach with the Random Forest (RF) algorithm. Field surveys were conducted at 14 Land Mapping Units (LMU) in the Bocek and Donowarih villages, followed by laboratory analysis of the physical and chemical properties of the soil. Soil classification followed the United States Department of Agriculture (2022) system, utilizing Geographic Information Systems (GIS) and ArcGIS Pro for spatial mapping. The classification results showed the existence of two main subgroups: Andic Humudepts (172.73 ha) and Typic Humudepts (577.73 ha). The spatial distribution of soil was strongly influenced by slope, sub-landform, and elevation, with variable importance values of 40%, 35.7%, and 24.3%, respectively. The RF model showed high performance with good accuracy (overall accuracy = 85.7% and Cohen's Kappa = 0.69). This research provides an important basis for the optimal and sustainable management of watershed areas.

Keywords: Geographic information system; Humudept; Soil classification; Soil forming; Topograph

Introduction

Soil plays an important role in watershed systems, where soil characteristics in river basins can directly affect the quantity, quality and sustainability of water sources (Fahriati et al., 2022). One of the river basins in Karangploso Subdistrict, Malang Regency, is the Curahkemadu Micro Watershed. The soil characteristics in this area are influenced by parent material originating from Mount Arjuno-Welirang with the geological code Qvaw, which consists of volcanic breccia, lava, tuff breccia, and tuff (Reza & Syah, 2020). Petrological analysis of Arjuno-Welirang volcanic rocks shows that these rocks are intermediate-mafic in type, dominated by andesitic-basaltic and basaltic rocks (Fajrina & Lestari, 2016). The influence of volcanic parent material causes the formation of Andisol and Inceptisol soil (Yuliana et al., 2017; Wahyuni et al., 2023). Soil-forming factors cause the formation of different soil characteristics, which consist of climate, organisms, topography, parent material, and time (Herdiansyah et al., 2020; Utomo, 2024). Climate factors are influenced by rainfall and temperature, where the wet and dry seasons greatly affect the rate of weathering and leaching (Rusdaling et al., 2021; Fitriani et al., 2022). Organism factors influence the process of organic materials decomposition and the formation of humus, the type of vegetation, and topographical factors that influence the thickness or thinness of the soil layer (Asril et al., 2022). Parent material factors influence soil chemical

How to Cite:
Ihsan, R. M., Wicaksono, K. S., Ustiatik, R., & Soemarno. Random Forest-Based Soil Mapping to Support Sustainable Watershed Management and SDG 15 (Life on Land): A Case Study of the Curahkemadu Micro Watershed. *Jurnal Penelitian Pendidikan IPA*, *12*(4), 18-30. https://doi.org/10.29303/jppipa.v12i4.14469

composition and soil nutrient availability (Da Silva et al., 2022). The time factor influences the process of soil horizon formation (Ladjinga et al., 2020).

Understanding the characteristics of the soil in the Curahkemadu Micro Watershed can be done through more detailed soil classification (Dawson, 2023). Soil classification is a branch of science that studies how to distinguish soil properties and group them based on their similarities. Classification is carried out using the latest system from the United States Department of Agriculture (USDA) based on the 2022 Key Soil Taxonomy book up to the Subgroup level developed by soil survey and classification experts in the United States (Soil Survey Staff). The results of soil classification provide an overview of soil properties that can later be used as a basis for management (Kurniawan & Marpaung, 2018).

The development of machine learning-based Geographic Information Systems (GIS) using the Random Forest method provides opportunities to improve the efficiency and accuracy of land mapping (Putra et al., 2025). GIS enable visual mapping and representation of geographic data (Bahari et al., 2025). Machine learning-based mapping using the Random Forest (RF) method is used to improve classification accuracy (Purwanto et al., 2022). Machine learning is a technology that enables machines to learn and adapt quickly (Dasmadi, 2023). The use of the RF method in the spatial distribution of soil types can produce more detailed models, as this method performs classification using a machine learning algorithm that combines a set of decision trees to classify data into specific classes (Amaliah et al., 2022; Mahmuda, 2024; Putri et al., 2025; Sahyudi et al., 2025). The RF method can accurately make a models and reveal complex of non-linear interaction between soil-forming factors (climate, topography, organism, parent material, and time) in mapping soil subgroups and has been proven to produce accurate spatial soil classifications (Zeraatpisheh et al., 2017; Simon et al., 2023; Liu et al., 2024; Subangkit et al., 2026). In addition, this method has the advantage of evaluating variable importance, so that the dominant factors shaping the soil can be identified quantitatively. Variable importance is necessary to determine the level of importance of the factors that make up the soil. The RF method produces good scoring accuracy (Liu & Zhao, 2017). Detailed soil classification at the sub-group level in micro-watersheds is still limited. This study addresses this gap by applying the RF method to map soil sub-groups and identify dominant soil-forming factors in the Curahkemadu Micro-Watershed, providing accurate spatial information to support efficient watershed management. This study aims to analyse soil types at the sub-group level and their spatial distribution in order to facilitate planning and management by providing accurate soil type distribution data.

Method

Study Area

This study was conducted in the Curahkemadu Micro Watershed, which is administratively located in Bocek and Donowarih Villages, Karangploso Subdistrict, Malang Regency, East Java (Figure 1). The study area covers 750.46 hectares that located between 112°37'–112°40' East Longitude and 8°02'–8°15' South Latitude. The climate in this region is characterized by annual rainfall of approximately 2,023 mm and relatively stable temperatures between 22.5 °C and 25 °C. Soil laboratory analysis was conducted at the Soil Chemistry and Soil Physics Laboratory, Faculty of Agriculture, Brawijaya University. The research flowchart is presented in Figure 3.

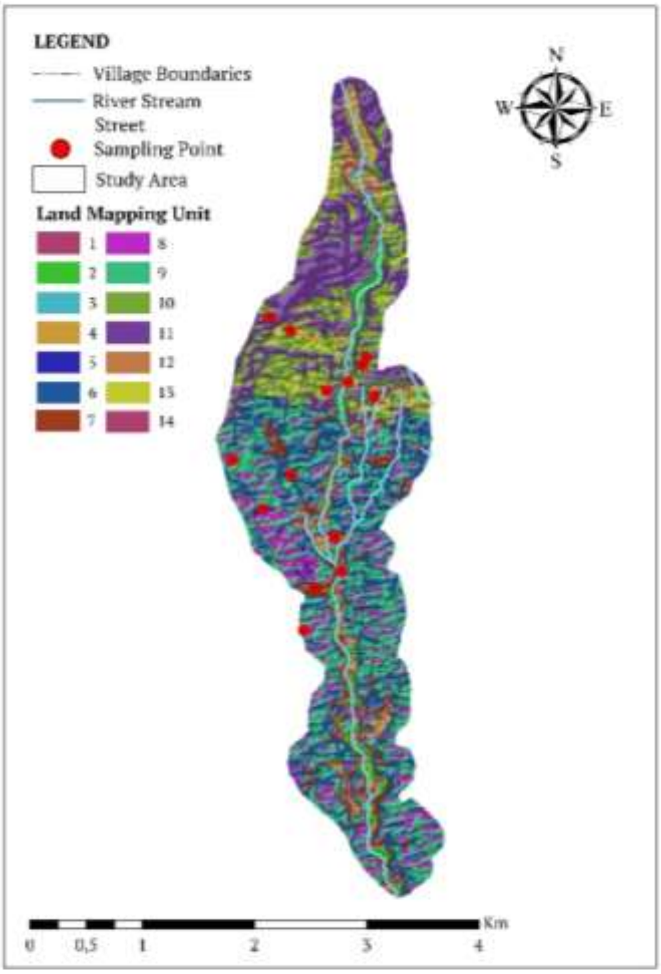


Figure 1. Map of land mapping unit in Curahkemadu Micro Watershed

Data Collection

The preparatory stage was carried out by preparing tools and materials in the form of topographic base map

(Rupa Bumi Indonesia, scale 1:25,000), 10 m resolution DEM data from ALOS PALSAR, computers, and ArcGIS Pro and Google Earth Pro software to compile basic research maps, including slope, sub-landform, and elevation maps. The pre-survey stage aimed to check the actual conditions of the research location, access to observation points, and permits from landowners. The main survey included field observations and soil sampling through the creation of 2 m deep profiles, 50 cm minipits, and drilling up to 150 cm, with observations of physiography and soil morphology as well as whole and crushed samples taken at each horizon. The research location was divided into 14 Land Map Units (LMUs). Laboratory analyses were conducted to obtain the physical and chemical properties of the soil, which were then combined with the results of soil descriptions in the field as the basis for soil classification. Soil classification was classified according to the 2022 USDA Key to Soil Taxonomy and was carried out in stages from the order level to the subgroup based on soil properties and characteristics.

Random Forest for Spatial Distribution and Variable Importance to Determine the Dominant Factors of Soil Types

Spatial distribution analysis of soil types was performed using the RF method with ArcGIS Pro, utilizing sub-landform, slope, and elevation maps as basic variables, as well as soil type data from the classification. Data processing was performed using the Spatial Analyst Tool with the forest-based classification and regression method. Map validation was carried out by internal validation based on observation points using overall accuracy and Kappa coefficient. Map prediction values were extracted at 14 LMUs and compared with field data. RF consists of a set of decision trees used to classify data into classes (Figure 2) (Amaliah et al., 2022).

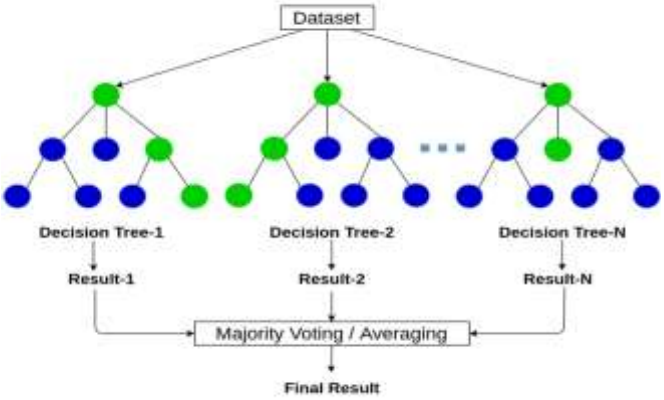


Figure 2. Random forest decision tree (Fatimah et al., 2024)

Variable importance is determined using two methods, namely Permutation Variable Importance and Gini Variable Importance. In classification, the importance of permutations is calculated based on the decrease in Out-of-Bag (OOB) classification accuracy after the predictor variable values are randomly shuffled. A greater decrease in accuracy indicates the importance of that variable in determining soil class, while Gini Variable Importance measures how much impurity (e.g., Gini index) is reduced each time a variable is used in node separation (split) in a decision tree, by calculating the total reduction in impurity across all nodes and the entire tree in the model (Aldrich, 2020). The following are the algorithms for both methods (Equation 1).

$$VI_{perm}^{(k)(x_j)} = Acc_{OOB}^{k} - Acc_{OOB}, perm(x_j)^{k} \tag{1}$$

$$VI_{gini}^{(k)}(x_j) = \sum_{t \in T_k : v(s_t) = x_j} p(t)\,\Delta I(s_t, t)$$

$$VI_{perm}(x_j) = \frac{1}{K}\sum_{k=1}^{K} VI_{perm}^{(k)}(x_j), VI_{gini}(x_j) = \frac{1}{K}\sum_{k=1}^{K} VI_{gini}^{(k)}(x_j)$$

where $VI_{perm}^{(k)}(x_j)$is the Permutation Variable Importance value for variable $x_j$in the k-th tree, Acc_{OOB}^{k} is the out-of-bag (OOB) classification accuracy of the k-th tree before permutation, $Acc_{OOB}, perm(x_j)^{k}$ is the OOB classification accuracy after permuting variable x_j, $T_k$is the set of all nodes in the k-th tree, $v(s_t)$is the variable used for splitting at node t, $p(t)$is the proportion of samples reaching node t, $\Delta I(s,t)$is the decrease in impurity due to splitting at node t, $VI_{gini}^{(k)}(x_j)$is the Gini Importance value for variable $x_j$in the k-th tree, and $K$is the Random Forest model.

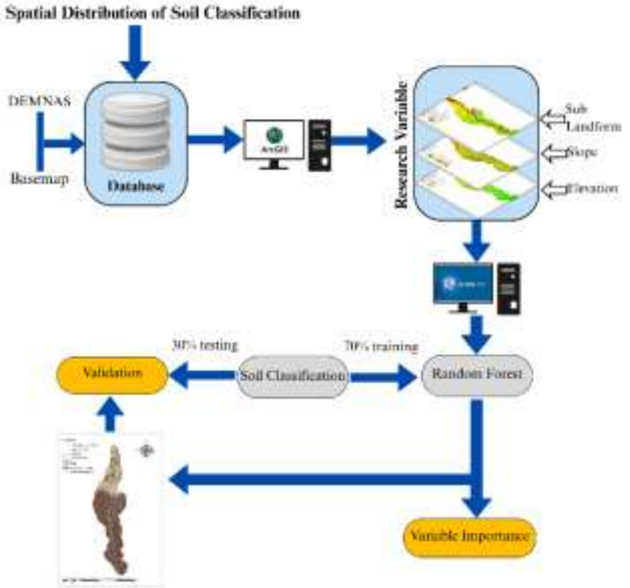


Figure 3. Flowchart of data preparation, collection, and interpretation for spatial distribution of soil types using Random forest

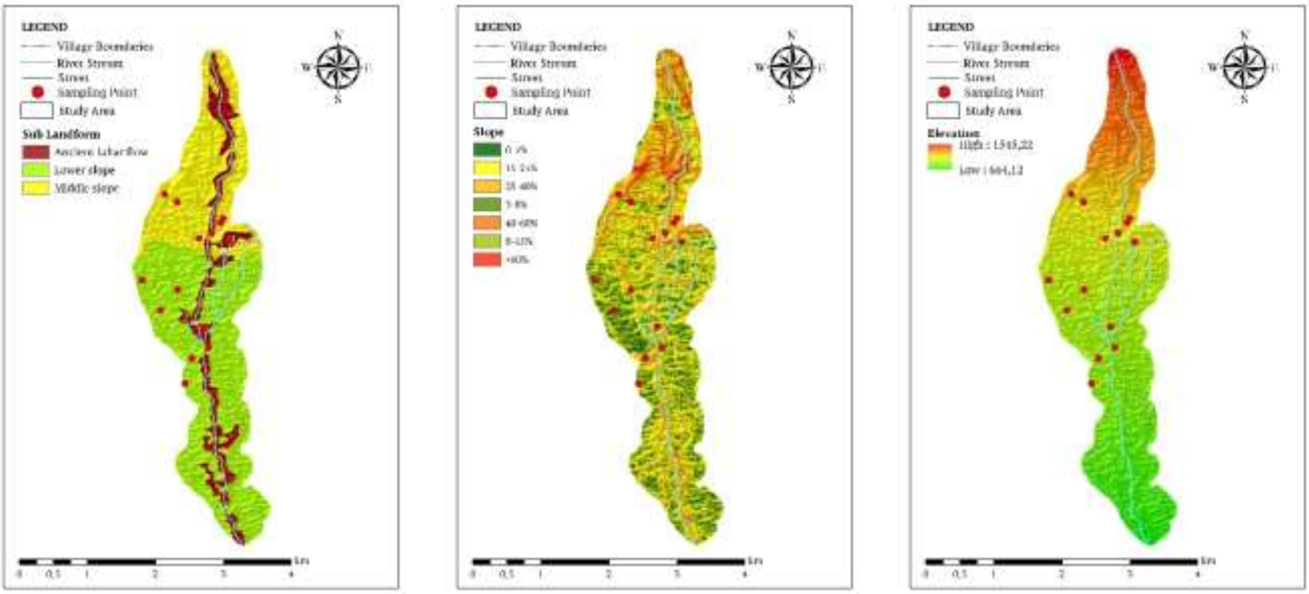
Result and Discussion

General conditions of the Curahkemadu Micro Watershed area

The research location consisted of three sub-landforms (Figure 4), namely old lava flows, middle slopes, and lower slopes with areas of 118.77 ha, 229.16 ha, and 402.53 ha, respectively. These sub-landform differences were include different types of Earth's surface features which formed as a result of volcanic processes with diverse material compositions, resulting in topographical variations from steep to gentle slopes (Diva et al., 2018; Virgiawan, 2020; Fadillah et al., 2024). These variations in landform affect the morphological, physical, and chemical properties of the soil, where the soil on the upper slopes tends to be shallower due to erosion, while the lower slopes have deeper solum due to material accumulation (Nugroho, 2016; Sitinjak et al., 2019).

The slope gradient at the study site (Figure 4) varied greatly as a result of volcanic activity that has shaped the complex surface morphology. Slopes were classified into seven gradient classes, ranging from flat to very steep, with the moderate slope class (15–25%) being the most dominant (Virgota et al., 2024). This variation in slope inclination affects soil formation processes and characteristics, particularly through erosion mechanisms and differences in slope position and configuration (Putri et al., 2017; Delfianto et al., 2021; Arrasyid et al., 2023).

The elevation at the study site (Figure 4) ranged from 664.12 to 1545.22 metres above sea level (m asl), showed variation in height. Elevation differences are related to variations in slope inclination and affect drainage, infiltration, and surface runoff processes that impact soil properties (Purwanto & Paiman, 2023). In addition, elevation also affects soil temperature and moisture, which play a role in biota activity and organic matter decomposition, thereby influencing soil classification results (Gilang et al., 2024).



(a) (b) (c)

Figure 4. Map of sub landform (a); slope (b); elevation (c) of the Curahkemadu micro-watershed

Soil Morphology in the Curahkemadu Micro Watershed

Field observations (Figure 5 and Table 1) indicated good soil horizon development, characterised by the presence of horizon A (with the suffix p for topsoil) and horizon B (with the suffix w for subsoil) as well as horizon R as rock at certain points (Rahayu et al., 2022; Wildan et al., 2023). Horizon A contained a mixture of organic and mineral materials, while horizon B showed colour or structural development. The horizon structure was observed up to 150 cm with the number of horizons varying between 3–7, depending on the location. This difference is influenced by the level of soil development and the addition of materials, i.e. more developed soils tend to have more horizons.

Soil colour at different LMUs varied but was generally uniform, determined based on hue, value, and chroma using the Munsell Soil Colour Chart. This variation reflects the influence of organic matter content, aeration, drainage, iron oxide, and local physiographic conditions (Utomo, 2016; Salam, 2020). Colour determination is important in identifying epipedons, and the observations showed that the epipedon formed was umbric because it had a value and chroma ≤3, a thickness ≥18 cm, and a base saturation (BS) <50%.

The observed soil structure showed two levels of development, namely weak and moderate, which were determined based on the stability of the structure against pressure (Meli et al., 2018). The structural forms found include granular, subangular blocky and angular blocky with sizes varying from very fine to coarse. Stable soil structure is important for improving water infiltration and the soil's ability to retain water, especially in spring recharge areas.

Soil consistency was observed in moist and wet conditions (sticky and plasticity), which reflect the water capacity and soil response to water content (Ma'shum et al., 2022). This consistency is influenced by the fine fraction of the soil, the type of clay minerals, organic matter, and soil texture.

Physical Characteristics of Soil in the Curahkemadu Micro Watershed

The physical characteristics of soil profile (Table 1) observed in this study were bulk density (BD) and soil texture (Palloan et al., 2023). The BD at the research site varies, reflecting differences in soil characteristics influenced by organic matter content, texture, depth, moisture content, soil biota, and anthropogenic activity (Yendani et al., 2024). BD is closely related to soil density, root penetration, drainage, and aeration. BD values are also an indicator of the properties of Andic properties, which require a BD of <0.90 g/cm^3. The lowest value of 0.70 g/cm^3 was found at LMU 12 of the Bw2 horizon on minimally managed agroforestry land, while the highest value of 1.40 g/cm^3 at LMU 9 of the Bw2 horizon occurred on intensively cultivated farmland.

The soil texture (Table 1) at the study site showed diversity from clay to sandy loam, reflecting the influence of factors such as climate, organisms, parent material, time, and soil cultivation (Rahayu et al., 2022). Soil texture affects the soil's ability to retain water, permeability, and fertility (Agustin et al., 2016). The subsoil horizon generally had a clay texture due to the process of illuviation. In the context of spring recharge areas, soil texture greatly determines infiltration capacity. Based on the Hydrologic Soil Group (HSG) classification, most LMUs included into categories B (good infiltration) and D (low infiltration), where category B supports hydrological balance and water conservation, while category D is more prone to surface runoff (Zeng et al., 2017).

Chemical Characteristics of Soil in the Curahkemadu Micro Watershed

Chemical characteristics (Table 2) are one of the analyses required in the soil classification process. Soil acidity at the study site showed no significant variation, with H_2O pH values ranging from 4.22 to 5.67 and KCl pH values ranging from 4.10 to 5.42. The pH value reflects the balance of H^+ and OH^- ions in the soil and is influenced by parent material, organic matter, base leaching, and mineral oxidation (Kautsar et al., 2018; Stefanie et al., 2022). The pH H_2O measurement describes the ions on the soil surface, while the pH KCl indicates the ions bound in the soil. These pH values indicate that the soil tends to be acidic, which can affect nutrient availability and BS at the study site.

The organic carbon content of the soil at the research site varied greatly and was an important indicator of soil quality. The highest value, 5.21%, was found at LMU 10 in horizon A (agroforestry land), and the lowest value, 0.84%, was found at LMU 4 in horizon Bw1 (farmland). Organic carbon content affects soil structure, nutrient availability, water retention capacity, and microorganism activity (Kamisah & Kartika, 2024). External factors such as soil type, climate, organic matter input, and soil management also play a role in determining organic carbon content (Farrasati et al., 2019).

Soil cation exchange capacity (CEC) showed variation at each LMU, influenced by organic matter, texture pH, and clay mineral type (Muhlisin et al., 2022). The highest CEC value of 59.21 me/100g was found at LMU 10 of horizon Bw1, while the lowest value of 24.36 me/100g was found at LMU 10 of horizon A.

Basic cations such as K-dd, Na-dd, Ca-dd, and Mg-dd also showed variations, reflecting the influence of CEC values, pH, and environmental conditions such as water runoff that leached soil bases (Mautuka et al., 2022; Ningsih et al., 2024). The highest K-dd value was found at LMU 11 of the Bw1 horizon at 3.86 me/100g, while the lowest value was found at LMU 1 of the Bw3 horizon at 0.06 me/100g. The highest Na-dd value was recorded at LMU 11 of horizon A at 1.92 me/100g, and the lowest value was at LMU 1 of horizon Bw2 at 0.21 me/100g. The highest Ca-dd value was found at LMU 13 of horizon A at 8.22 me/100g, while the lowest value was found at LMU 12 of horizon 1 at 3.61 me/100g. The highest Mg-dd value was found at LMU 11 of horizon A at 3.83 me/100g and the lowest value at LMU 12 of horizon Bw3 at 0.21 me/100g.

The BS value is the percentage of total CEC occupied by K, Na, Ca, and Mg (Aspan et al., 2021). The highest BS was 50.65% (LMU 9 Bw1), while the lowest was 14.12% (LMU 1 Bw2), with the majority showing values <50%, consistent with acidic soil conditions and the dominance of acidic cations such as Al-dd and H^+ (Karnilawati et al., 2022).

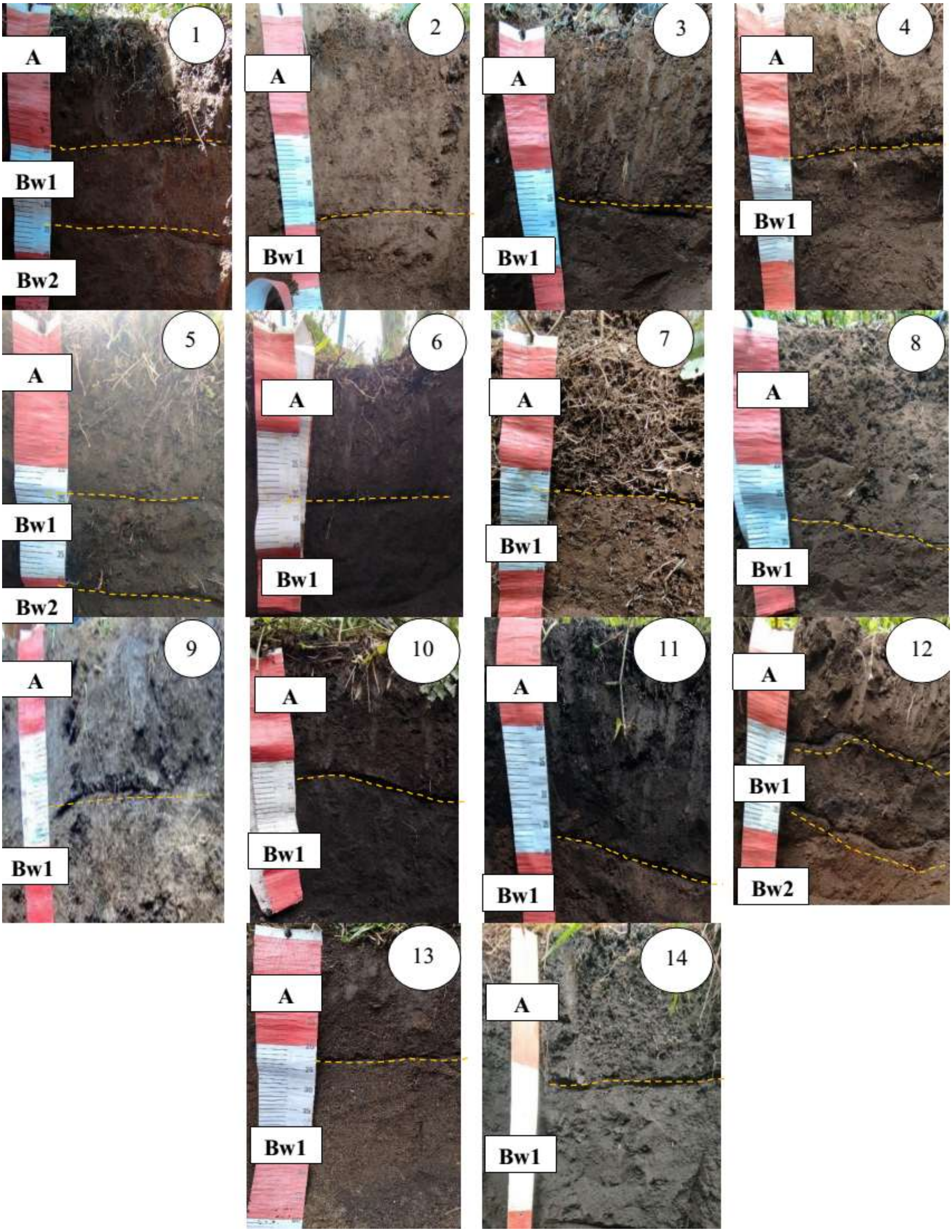


Figure 5. Soil profile in Curahkemadu Micro Watershed

Table 1. Soil Morphology and Physical Characteristic in Curahkemadu Micro Watershed

Pedon	Horizon	Depth (cm)	Morphology						Texture	BD
			Colour	Structure	Consistency	Sand (%)	Silt (%)	Clay (%)	Class	g/cm^3
1	A	0 – 19	10 YR 2/2	fi, g	f, ss, sp	28.43	52.13	19.44	SiL	0.92
	Bw1	19 – 34	10 YR 3/3	fi, g	f, ss, sp	17.76	58.04	24.20	SiL	0.80
	Bw2	34 – 71	10 YR 3/4	m, g	t, ss, sp	23.26	53.13	23.61	SiL	0.82
2	Ap	0 – 37/38	10 YR 3/3	m, g	f, ss, sp	34.40	46.10	19.50	L	0.98
	Bw1	37/38 – 74	10 YR 3/4	c, sb	t, ss, sp	37.30	35.44	27.26	L	0.74
3	Ap	0 – 25	10 YR 2/2	m, sb	t, ss, sp	9.98	52.51	37.51	SiCL	1.02
	Bw1	25 – 81	10 YR 2/1	m, ab	t, s, p	13.54	24.02	62.44	C	1.15
4	Ap	0 – 19	10 YR 3/3	fi, g	f, ss, sp	45.89	36.89	17.22	L	1.15
	Bw1	19 – 63	10 YR 2/1	m, sb	t, s, sp	40.31	35.27	24.42	L	0.86
5	Ap	0 – 24	7,5 YR 3/1	fi, sb	t, ss, sp	19.64	47.71	32.65	SiCL	1.19
	Bw1	24 – 42	10 YR 3/1	fi, sb	t, ss, sp	22.37	41.24	36.39	CL	1.14
	Bw2	42 – 83	10 YR 3/3	c, ab	st, s, sp	19.18	25.08	55.47	C	1.14
6	Ap	0 – 28	10 YR 2/2	m, sb	f, ss, sp	19.72	40.83	39.45	SiCL	1.36
	Bw1	28 – 55	10 YR 2/1	fi, sb	f, ss, sp	19.96	42.37	37.66	SiCL	1.15
7	A	0 – 22	10 YR 3/1	fi, g	f, ss, sp	20.08	53.95	25.97	SiL	0.96
	B	22 – 80	10 YR 3/3	m, g	t, ss, sp	19.84	42.59	37.58	SiCL	1.06
8	Ap	0 – 29/33	10 YR 3/3	m, sb	t, s, sp	19.73	49.20	31.07	SiCL	1.27
	Bw1	29/33 – 96	7,5 YR 2,5/2	m, sb	st, s, sp	6.17	27.16	66.67	C	0.94
9	Ap	0 – 34	10 YR 3/1	m, sb	f, ss, sp	25.91	44.90	29.19	CL	1.32
	Bw1	34 – 57	10 YR 3/2	m, sb	t, s, p	17.56	37.88	44.56	C	1.36
10	A	0 – 22/26	10 YR 2/2	vfi, g	f, ss, sp	28.47	49.33	22.20	SiL	0.96
	Bw1	22/26 – 76	10 YR 2/1	vfi, g	f, ss, sp	30.29	48.26	21.45	SiL	0.78
11	A	0 – 36/38	10 YR 2/1	fi, g	f, ss, sp	7.34	6177	30.89	SiCL	1.01
	Bw1	36/38 – 70	10 YR 3/3	m, g	f, ss, sp	10.95	41.05	49.00	SiCL	0.86
12	A	0 – 18/20	10 YR 2/2	fi, g	f, ss, sp	23.52	60.79	15.68	SiL	0.96
	Bw1	18/20 – 31/36	10 YR 2/1	fi, g	f, ss, sp	35.02	53.30	11.68	SiL	0.86
	Bw2	31/36 – 77	10 YR 3/3	m, sb	t, ss, sp	21.95	55.59	22.46	SiL	0.70
13	Ap	0 – 24	10 YR 2/2	m, sb	f, ss, sp	39.29	41.28	19.43	L	1.17
	Bw1	24 – 58	10 YR 3/2	c, sb	t, ss, sp	30.44	50.59	18.97	SiL	0.83
14	A	0 – 20	10 YR 2/1	fi, g	f, ss, sp	26.81	51.14	22.05	SiL	0.86
	Bw1	20 - 61	10 YR 2/2	c, g	f, ss, sp	20.22	53.32	26.46	SiL	0.82

*Note: vfi = very fine, fi = fine, m = medium, c = coarse; g = granular, sb = subangular blocky, ab = angular blocky; f = friable, t = firm; ss = slightly sticky, s = sticky; sp = slightly plastic, p = plastic, Si = silt, L = loam, C = clay, L = loam

Table 2. Soil chemical characteristic in Curahkemadu Micro Watershed

Pedon	Horizon	Depth(cm)	Exchange Kation					BS	pH		Organic C
			K-Exc	Na-Exc	Ca-Exc	Mg-Exc	CEC				
			....me/100g....................................					%	H_2O	KCl	%
1	A	0 – 19	0.54	0.36	3.96	2.52	31.06	23.75	4.50	4.32	1.87
	Bw1	19 – 34	0.32	0.23	4.38	0.99	37.13	15.92	4.52	4.35	1.64
	Bw2	34 – 71	0.06	0.21	5.17	0.32	40.78	14.12	4.64	4.44	1.61
2	Ap	0 – 37/38	2.64	1.03	5.59	2.31	38.40	30.12	4.65	4.42	2.08
	Bw1	37/38 – 74	2.71	0.94	6.40	0.53	41.47	25.51	5.17	4.81	2.11
3	Ap	0 – 25	1.68	1.22	4.94	1.59	26.94	34.98	4.55	4.32	1.48
	Bw1	25 – 81	2.88	1.07	5.55	1.09	37.98	27.90	4.58	4.33	1.31
4	Ap	0 – 19	1.98	0.72	5.51	2.93	26.32	42.32	4.94	4.22	2.69
	Bw1	19 – 63	0.58	0.31	5.92	0.97	38.64	20.14	5.01	4.65	0.84
5	Ap	0 – 24	1.30	0.79	6.64	1.66	30.90	33.63	4.80	4.52	2.79
	Bw1	24 – 42	1.35	0.72	6.55	0.90	48.46	19.67	4.83	4.66	2.85
	Bw2	42 – 83	1.31	0.77	6.76	1.07	35.32	28.09	5.02	4.74	2.25
6	Ap	0 – 28	1.01	0.72	4.61	0.99	28.44	25.76	4.92	4.78	2.24
	Bw1	28 – 55	1.48	0.80	8.16	0.99	50.61	22.59	4.97	4.61	2.85
7	A	0 – 22	0.85	0.74	7.09	2.08	28.74	37.43	4.70	4.60	4.84
	B	22 – 80	0.07	0.22	6.69	1.97	32.79	27.27	5.21	4.85	2.43
8	Ap	0 – 29/33	1.20	1.01	6.06	2.29	31.54	33.48	5.18	4.88	2.16
	Bw1	29/33 – 96	2.22	1.10	7.03	1.30	32.38	35.97	5.13	4.85	1.10
9	Ap	0 – 34	1.24	1.04	4.89	0.49	34.65	22.09	5.21	4.97	2.48

Pedon	Horizon	Depth(cm)	Exchange Kation					BS	pH		Organic C
			K-Exc	Na-Exc	Ca-Exc	Mg-Exc	CEC				
			....me/100g......................................					%	H_2O	KCl	%
	Bw1	34 – 57	1.81	0.99	6.04	1.51	20.45	50.65	5.33	4.97	1.62
10	A	0 – 22/26	0.61	0.93	4.50	1.17	24.36	29.60	5.23	4.92	5.21
	Bw1	22/26 – 76	1.00	0.86	8.05	1.27	59.21	18.88	5.67	5.42	4.93
11	A	0 – 36/38	2.01	1.92	5.29	3.83	37.62	34.72	4.52	4.38	4.09
	Bw1	36/38 – 70	3.86	1.56	5.53	0.98	30.30	39.39	4.75	4.39	1.50
12	A	0 – 18/20	0.84	0.85	3.61	0.86	27.40	22.48	4.22	4.10	2.82
	Bw1	18/20 – 31/36	1.28	0.98	6.55	0.66	51.19	18.50	4.63	4.45	4.19
	Bw2	31/36 – 77	1.78	1.14	6.67	0.21	40.10	24.44	4.80	4.53	2.22
13	Ap	0 – 24	1.01	1.22	8.22	1.48	37.12	32.12	4.88	4.62	2.63
	Bw1	24 – 58	1.54	1.12	5.96	0.66	50.65	18.34	4.92	4.73	1.72
14	A	0 – 20	0.59	0.28	6.73	0.33	37.13	21.36	5.01	4.94	4.47
	Bw1	20 – 61	1.04	0.94	5.17	1.45	31.12	27.65	4.96	4.72	3.81

*Note: K-Exc = Exchangeable K; Na-Exc = Exchangeable Na; Ca-Exc = Exchangeable Ca; Mg-Exc = Exchangeable Mg; CEC = Cation Exchange Capacity; BS = Base Saturation

Soil Classification and Pedogenesis in the Curahkemadu Micro Watershed

The results of soil classification (Table 3) at all LMUs showed similarities in the epipedon and endopedon. The epipedon formed was umbric, characterised by a depth of ≥18 cm, soil colour with value and chroma ≤3, and BS ≤50%. The identified endopedon was cambic, as the subsoil layer had a thickness ≥15 cm, had undergone alteration, but did not meet the other endopedon criteria like the presence of a clay coating. According to Keys to Soil Taxonomy (2022), the soil at the study site was classified as Inceptisols, as it did not meet the criteria for Andisols (BD >0.9 g/cm^3) and still showed development with the presence of a cambic horizon and umbric epipedon. The suborder identified was Udepts, as it was in an upland soil regime. Based on the umbric epipedon and other characteristics, the soil group was classified as Humudepts. Furthermore, two classifications were found in the subgroup, namely Andic Humudepts (points 1, 2, 10, 12, and 14), because meet the requirement “Humudepts that have, in one or more horizons with a total thickness of 18 cm or more within 75 cm of the mineral soil surface, a fine-earth fraction with both a BD of 1.0 g/cm^3 or less”, and Typic Humudepts (points 3, 4, 5, 6, 7, 8, 9, 11, and 13), because it did not meet the additional requirements to be included in the Andic subgroup.

The process of pedogenesis at the research site was influenced by soil-forming factors such as topography, parent material, and climate. Topographical variations, including landform and slope, greatly affect soil horizon thickness (Herdiansyah et al., 2022). On flat land, the thickness of the horizon tended to be greater, while on steep slopes, thinning occurs due to leaching and enrichment processes triggered by erosion and surface runoff. The soil at the study site develops from volcanic parent material from Mount Arjuno-Welirang in the form of breccia, lava, tuff, and tuff breccia that has undergone advanced weathering (Reza & Syah, 2020). This weathering process resulted in the transformation of rock into mature soil. One of the dominant processes is melanisation, which is the formation of a dark-coloured surface horizon due to the accumulation of organic matter (Riry, 2023). In addition, high rainfall accelerates the processes of eluviation (removal of material from the upper horizon) and illuviation (deposition of material in the lower horizon) which also accelerate soil profile development at the study site (Zakia et al., 2022).

Table 3. Soil classification in Curahkemadu Micro Watershed

Pedon	Epipedon	Endopedon	Sub Group
1	Umbric	Cambic	Andic Humudepts
2	Umbric	Cambic	Andic Humudepts
3	Umbric	Cambic	Typic Humudepts
4	Umbric	Cambic	Typic Humudepts
5	Umbric	Cambic	Typic Humudepts
6	Umbric	Cambic	Typic Humudepts
7	Umbric	Cambic	Typic Humudepts
8	Umbric	Cambic	Typic Humudepts
9	Umbric	Cambic	Typic Humudepts
10	Umbric	Cambic	Andic Humudepts
11	Umbric	Cambic	Typic Humudepts
12	Umbric	Cambic	Andic Humudepts
13	Umbric	Cambic	Typic Humudepts
14	Umbric	Cambic	Andic Humudepts

Spatial Distribution and Dominant Factor of Soil Types in Curahkemadu Micro Watershed

Spatial distribution of soil using RF method (Figure 6) with slope, sub-landform, and elevation variables results showed an area of 172.73 ha of Andic Humudepts and 577.73 ha of Typic Humudepts. Random Forest pays close attention to the variable importance values obtained by each variable (Putra et al., 2025). The variables to be included in the model can be sorted based on their level of importance, where the variable importance index takes into account the interaction between variables, making it a powerful method for finding important variables (Nyongesa, 2020). Variable importance is considered important if its absence in the model causes a significant decrease in prediction quality (Mahmuda, 2024). In the resulting model, each variable used to generate the model had a variable importance value that was not much different, namely slope contributing 40%, sub-landform 35.7%, and elevation 24.3%.

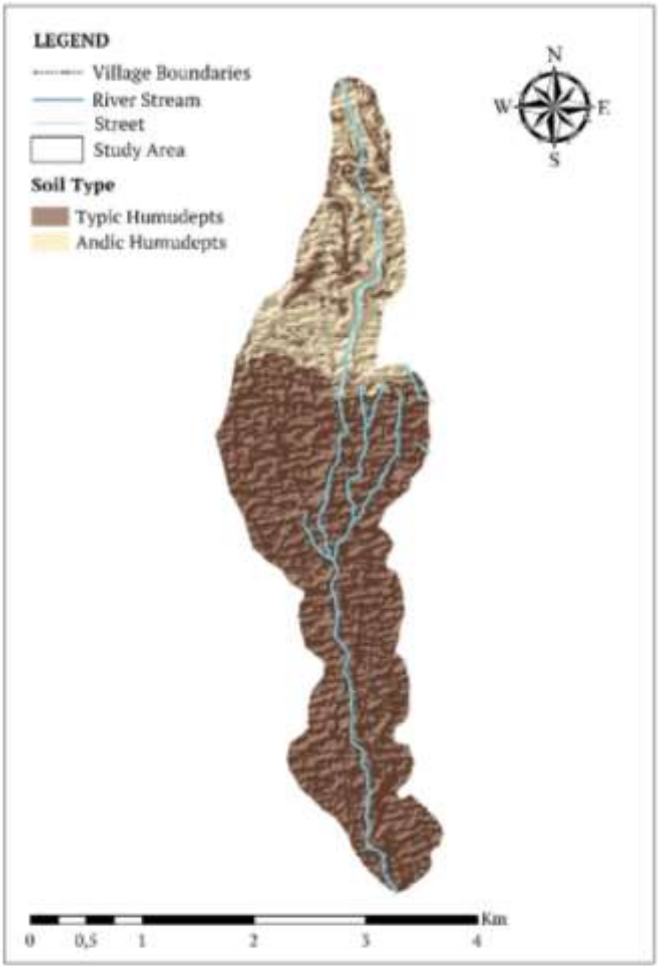


Figure 6. Spatial distribution of soil classification in of the Curahkemadu Micro Watershed

The validation values obtained from the RF method were based on the internal validation based on observation points (Table 4). Map prediction values were extracted at 14 observation points and compared with field data. The comparison was made using a confusion matrix to determine the classification error rate. The validation results showed an overall accuracy of 85.7%, with 12 correctly classified samples out of 14 validation points. These results meet the United States Geological Survey (USGS) standard, which stipulates that test results must be at least 85% accurate. (Sampurno & Thoriq, 2016). The Cohen's Kappa coefficient was 0.69, indicating a good level of agreement between the predicted soil map and field observations (Kusuma et al., 2019; Sari et al., 2023). These results indicate that the model generated can be used for the classification of soil subgroups at the research site.

Table 4. Confusion Matrix

	Andic Humudepts	Typic Humudepts	Total
Andic Humudepts	4	1	5
Typic Humudepts	1	8	9
Total	5	9	14

The resulting model certainly has limitations that restrict its results when applied to other locations. These limitations include the use of very few variables without using other variables that can support the distribution of soil subgroups, such as rainfall, temperature, and land use. This is because the study area is not very large, so the supporting variables that were not used have the same value. The number of points used was limited, so the model only has a small amount of data, which can cause bias. Therefore, even though this model produces a very good level of accuracy, other factors that can improve data accuracy must still be considered.

Conclusion

Based on the analysis of soil sub-groups in the Bocek spring catchment area, it can be concluded that this region has Inceptisol soils with two main soil sub-groups, namely Andic Humudepts and Typic Humudepts. The distribution pattern of these two soil types is influenced by topographical conditions, particularly slope inclination, sub-landforms, and elevation. The Random Forest method has proven to be effective in mapping the spatial distribution of soil subgroups with good classification accuracy, as indicated by the overall accuracy (85.7%) and Cohen's Kappa (0.69). This model is able to describe the distribution of soil that is consistent with the variation of these topographical factors. The dominant factors depicted by variable importance analysis in the model shows that slope has the greatest influence on soil subgroup classification, at 40%, followed by sub-landform at 35.7% and elevation at 24.3%. These findings confirm that topographic dynamics, including erosion and deposition processes, play an important role in shaping soil properties in catchment areas. Although the model relies on only three variables, there is potential for improved accuracy if additional variables such as land use, vegetation density, curvature, and aspect are included in the modelling, especially in areas with more complex characteristics.

Acknowledgments

The authors would like to express their sincere gratitude to all individuals who contributed to the preparation of this research article. We also extend our appreciation to the landowners who permitted the use of their land during the research process. This study was completed and published with the generous support and cooperation of all parties involved.

Author Contributions

"Conceptualization, R.M.I. and S.S.; methodology, R.M.I; software, R.M.I.; validation, K.S.W.; formal analysis, R.M.I.; investigation, R.M.I.; resources, S.S.; data curation, R.M.I.; writing—original draft preparation, R.M.I. and R.U.; writing—review and editing, R.M.I. and R.U.; visualization, R.M.I.; supervision, K.S.W., S.S., and R.U.; project administration, S.S.; funding acquisition, S.S. All authors have read and agreed to the published version of the manuscript."

Funding

This research was funded by Hibah Penguatan Ekosistem Riset GB DRPM Year 2024 No. 00144.6/UN10.A0501/B/PT.01.03.2/2024.

Conflicts of Interest

The authors declare no conflict of interest.

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