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Analysis of soil characteristics and microclimate based on smart sensor systems

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ABSTRACT
Background: Soil and microclimatic conditions play important roles in regulating ecosystem processes in tropical forest environments. However, information regarding these environmental characteristics in Tahura Ir. H. Djuanda based on smart sensor measurements remains limited. This study aimed to characterize soil and microclimatic conditions in the conservation area using a smart sensing approach. **Methods:** A quantitative descriptive field study was conducted in April 2026 at three observation points in Tahura Ir. H. Djuanda, West Java, Indonesia. Environmental parameters were measured using a 6-in-1 Intelligent Soil Tester (Model ST03). The observed variables included soil moisture, soil fertility, soil pH, soil temperature, light intensity, and air humidity. Data were analyzed descriptively through comparison and interpretation of measurements across observation points. **Findings:** Soil moisture remained consistently high (99%) at all observation points. Soil fertility ranged from 209 to 582 µS/cm, while soil pH varied between 6.5 and 7.0, indicating slightly acidic to neutral conditions. Soil temperature increased from 21.6 °C to 26.0 °C, light intensity ranged from 628 to 1,304 lux, and air humidity varied from 78% to 84%. These results indicate spatial variability in environmental parameters while maintaining conditions typical of tropical forest ecosystems. **Conclusion:** Tahura Ir. H. Djuanda exhibits favorable soil and microclimatic conditions characterized by high soil moisture, relatively fertile soils, near-neutral pH, warm soil temperatures, low understory light intensity, and high atmospheric humidity. These conditions support ecological processes and vegetation growth within the conservation area. **Novelty/Originality of this article:** This study provides baseline information on soil and microclimatic conditions in Tahura Ir. H. Djuanda using a smart sensor-based approach that supports future environmental monitoring and conservation management.

KEYWORDS: intelligent soil tester; microclimate; soil; Tahura Ir. H. Djuanda.

1. Introduction

Soil is one of the fundamental components of the Earth system, functioning as a medium of interaction among the atmosphere, hydrosphere, lithosphere, and biosphere (Zhu et al., 2014). As an integral part of ecosystems, soil plays essential roles in water storage, nutrient cycling, habitat provision for organisms, and the regulation of biogeochemical processes that sustain life (Teng et al., 2025). Soil characteristics are shaped by the interaction of several soil-forming factors, including parent material, climate, organisms, topography, and time, resulting in diverse physical and chemical properties across different locations (Brito Filho et al., 2025; Certini & Scalenghe, 2023). These variations influence environmental quality, ecosystem productivity, and the capacity of a landscape to perform its ecological functions. In volcanic forest ecosystems, soils are generally characterized by high water-holding capacity, abundant organic matter content, and efficient nutrient cycling processes

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that support ecosystem sustainability (Kurniawan et al., 2021; Suyana et al., 2025). Consequently, soil characteristics are widely recognized as important indicators of environmental quality and ecosystem health.

In addition to soil characteristics, microclimatic conditions play a crucial role in shaping ecosystem dynamics. Microclimate refers to climatic conditions at a local scale that are influenced by environmental factors such as vegetation cover, topography, humidity, temperature, and light intensity. Microclimatic parameters interact directly with soil properties and influence the physical, chemical, and biological processes occurring within soils (Karyati et al., 2026; Tiwari et al., 2025). Soil moisture, soil temperature, air humidity, and light intensity are among the most commonly used indicators for describing local environmental conditions (Yang et al., 2025). Variations in these parameters can affect soil organism activity, organic matter decomposition, nutrient cycling, and the capacity of soils to store water and carbon. The relationship between soil properties and microclimate is highly interconnected, as factors such as topography, vegetation, and climate simultaneously shape microclimatic conditions and influence soil physical and chemical properties. Conversely, soil conditions, including temperature, moisture, and nutrient availability, affect vegetation growth, which subsequently contributes to the formation of local microclimates (Hamid et al., 2023; Ugarković et al., 2023).

Forest conservation areas exhibit distinctive soil and microclimatic characteristics due to their relatively dense vegetation cover and lower levels of environmental disturbance compared with managed or cultivated landscapes. One of the most ecologically important conservation areas in West Java, Indonesia, is the Ir. H. Djuanda Forest Park. This protected area functions as a water catchment zone, provides habitat for diverse flora and fauna, and serves as an environmental buffer for the Greater Bandung region. Previous studies have demonstrated that microclimatic factors, including humidity, temperature, and light intensity, influence the distribution and abundance of various organisms within Tahura Ir. H. Djuanda (Ardyanty et al., 2023; Suryani et al., 2024). Therefore, continuous monitoring of soil and microclimatic conditions is essential because these parameters serve as important indicators of ecosystem health and the effectiveness of conservation management. Accurate environmental information is also necessary for evidence-based conservation planning and sustainable natural resource management (Smith et al., 2024).

Conventionally, soil and microclimate monitoring relies on field sampling and laboratory analyses. Although these approaches generally provide reliable data, they require substantial time, cost, and human resources, making them less suitable for rapid and continuous environmental monitoring (Nurwarsito et al., 2024; Qamar et al., 2024). Recent advances in smart sensing technologies have created new opportunities for environmental monitoring through direct in situ measurements of soil and microclimatic parameters. These technologies enable real-time data acquisition with greater efficiency and faster processing compared with conventional methods. One of the widely utilized devices is the 16-in-1 Intelligent Soil Tester, which can simultaneously measure multiple environmental parameters, including soil moisture, soil temperature, air humidity, light intensity, and soil fertility within a single instrument (Liu & Yi, 2025; Peng et al., 2024). Previous studies from Kumar et al. (2024) and Song (2025) have demonstrated the effectiveness of smart sensors in supporting environmental monitoring and data-driven natural resource management.

Despite these advances, the application of smart sensing technologies for integrated soil and microclimate characterization remains largely concentrated in agricultural and managed landscapes, while their use in tropical forest conservation areas remains limited. Furthermore, studies conducted in Tahura Ir. H. Djuanda have primarily focused on biodiversity and habitat-related aspects, whereas comprehensive information on soil characteristics and microclimatic conditions obtained through real-time sensor-based measurements remains scarce (Ardyanty et al., 2023). This lack of information highlights the need for studies capable of providing rapid, accurate, and field-based assessments of environmental conditions in conservation ecosystems. Therefore, this study aims to analyze soil characteristics and microclimatic conditions using smart sensor technology in Tahura

Ir. H. Djuanda through measurements of soil moisture, soil fertility, air humidity, soil temperature, and solar light intensity. The findings are expected to provide baseline environmental data for the conservation area and serve as a reference for technology-assisted monitoring and management of forest ecosystems.

2. Methods

2.1 Study area

This study was conducted in Ir. H. Djuanda Forest Park (Tahura Ir. H. Djuanda), West Java, Indonesia. The conservation area is located approximately 7 km north of Bandung City and is geographically situated at approximately 107°30′ E and 6°52′ S. Administratively, the park extends across several regions, including Ciburial Village in Cimenyan District, Bandung Regency; Mekarwangi, Cibodas, Langensari, and Wangunharja Villages in Lembang District, West Bandung Regency; as well as Dago Subdistrict in Coblong District, Bandung City. Tahura Ir. H. Djuanda serves as an important conservation area in the Greater Bandung region, functioning as a water catchment zone and habitat for diverse flora and fauna. The park covers an elevational range of approximately 770–1,350 m above sea level (a.s.l.) and is characterized by undulating to steep topography. The area supports rich biodiversity, with more than 100,000 individual trees representing 108 plant families and 524 species, including both native and introduced plant species. This dense vegetation cover contributes significantly to the regulation of local microclimatic conditions, including temperature, humidity, and light availability.

The park is dominated by forest vegetation and volcanic-derived soils, which play important roles in hydrological regulation, nutrient cycling, and ecosystem functioning. The combination of heterogeneous topography, divSerse vegetation cover, and varying environmental conditions creates substantial spatial variability in soil and microclimatic characteristics, making the area an appropriate site for investigating the interactions between soil properties and microclimatic conditions within a tropical forest ecosystem. The study area and sampling locations are presented in Fig 1.

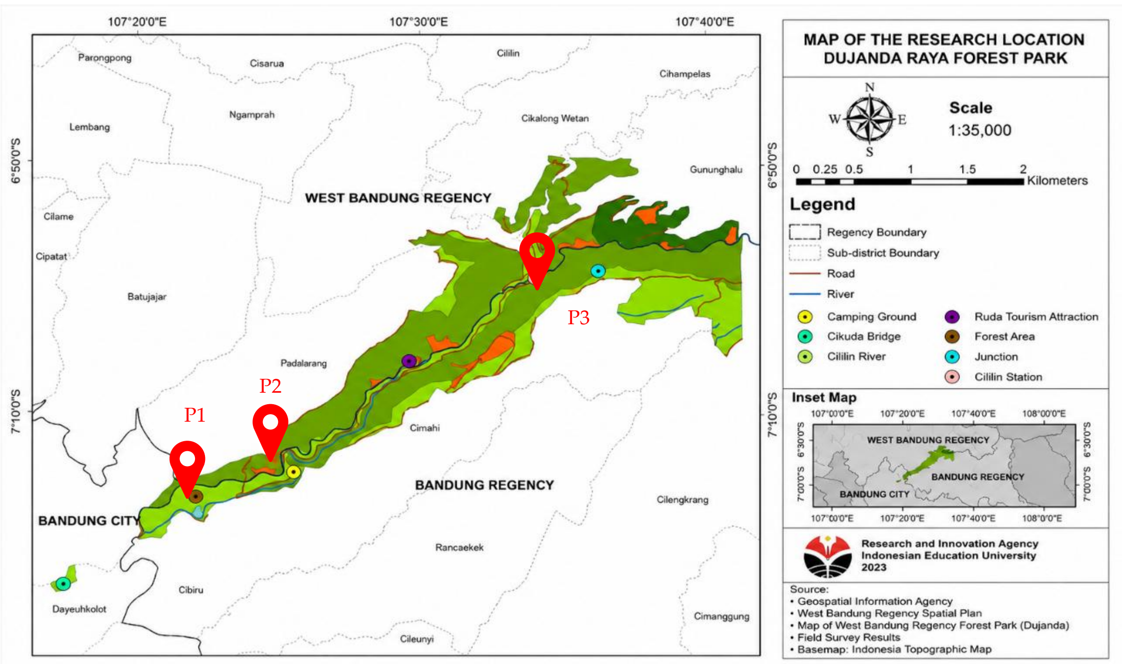

Fig. 1. Locations of the three observation points in Ir. H. Djuanda Forest Park, West Java, Indonesia (Dewi, 2023)

2.2 Research design

This study employed a quantitative descriptive design based on direct field observations. Data were collected in April 2026 using a 6-in-1 Intelligent Soil Tester at three observation points within the study area. To control temporal variability, all measurements were conducted within the same morning time window. Standardizing the measurement period was intended to reduce variations associated with diurnal changes in soil temperature and moisture, which may influence in situ soil sensor readings (Abdu et al., 2007; Chanzy et al., 2012). The research procedure consisted of a literature review, site survey, selection of observation points, field data collection, data processing, data analysis, and interpretation of the results.

The three observation points were selected purposively to provide spatial coverage across the accessible sections of the study area and to capture potential variations in local soil and microclimatic conditions. The selection also considered field accessibility, measurement safety, and the availability of undisturbed soil surfaces suitable for sensor insertion. As the study was designed as an exploratory field assessment, the three points were intended to provide preliminary baseline observations rather than a comprehensive spatial representation of the entire forest park. At each observation point, all six environmental parameters were measured three times after the sensor readings had stabilized. The three readings were averaged, and the resulting mean values were used for descriptive analysis.

2.3 Instrumentation and data collection procedures

Environmental parameters were measured using a 6-in-1 Intelligent Soil Tester (Model ST03), a multifunctional device designed for in situ soil and environmental assessment. The instrument is capable of measuring six parameters, namely soil fertility, soil moisture, soil pH, soil temperature, light intensity, and air humidity (Liu & Yi, 2025). The device is equipped with a rotatable digital display, facilitating data reading during field measurements. Prior to data collection, the sensor probe was cleaned to prevent contamination that could affect measurement accuracy (Peng et al., 2024). For each measurement, the metal probe was inserted vertically into the soil until the sensing section was fully embedded. The instrument was then allowed to stabilize before the displayed values were recorded. Measurements were conducted at each observation point, and three repetitions were performed for every parameter to improve data reliability. The recorded values were subsequently averaged and used for further analysis. After each measurement session, the probe was cleaned to maintain sensor performance and measurement consistency.

The data used in this study consisted of primary and secondary data. Primary data were obtained through direct field measurements, while secondary data were collected from literature sources, area maps, and other relevant references supporting the study. Primary data collection was conducted using a 6-in-1 Intelligent Soil Tester (Model ST03) to measure six environmental parameters, namely soil moisture, soil temperature, soil pH, soil fertility, light intensity, and air humidity. Measurements were performed at selected observation points within the study area. For soil-related parameters, the sensor probe was inserted into the soil until the sensing section was fully embedded and the displayed values became stable. Measurements of air humidity and light intensity were recorded directly using the instrument according to the manufacturer’s operating procedure. At each observation point, measurements were repeated three times to improve data reliability and minimize potential measurement errors. The recorded values were subsequently averaged and used for further analysis.

2.4 Data analysis

The collected data, including soil moisture, soil fertility, soil pH, soil temperature, light intensity, and air humidity, were analyzed using a descriptive approach. The measured values obtained from the three observation points were tabulated and compared to identify variations in soil and microclimatic conditions across the study area. Soil moisture data were interpreted based on the percentage values recorded at each observation point. Differences in soil moisture were used to describe variations in water availability within the soil environment. Soil fertility data, expressed as electrical conductivity (EC) values in µS/cm, were interpreted to provide information regarding relative nutrient availability and soil fertility conditions. Soil pH measurements were analyzed to determine the acidity, neutrality, or alkalinity of the soil environment at each observation point. Variations in pH values were used to characterize soil chemical conditions that may influence nutrient availability and biological activity. Microclimatic parameters, including soil temperature, light intensity, and air humidity, were analyzed descriptively based on the measured values obtained during field observations. Differences in these parameters among observation points were interpreted in relation to local environmental conditions, such as vegetation cover, topography, and exposure to solar radiation. The analyzed data were subsequently used to characterize the soil and microclimatic conditions of Tahura Ir. H. Djuanda and to provide an integrated description of environmental conditions across the observation sites.

3. Results and Discussion

3.1 Observation results

The soil and environmental conditions in Tahura Ir. H. Djuanda were assessed through direct field measurements using the Intelligent Soil Detector Model ST03 at three different observation points. The measured parameters included soil moisture, soil fertility, soil pH, soil temperature, light intensity, and air humidity. The observation results indicate variations in several environmental parameters among the three observation points. Soil moisture remained consistently high across all locations, suggesting favorable water availability within the study area. In contrast, soil fertility showed a decreasing trend from Observation Point 1 to Observation Point 3. Soil pH values ranged from slightly acidic to neutral conditions, while soil temperature generally increased across the observation sites. Similarly, light intensity and air humidity exhibited spatial variations, reflecting differences in local environmental conditions, vegetation cover, and microclimatic characteristics. These findings provide an initial overview of the soil and microclimatic conditions within Tahura Ir. H. Djuanda and form the basis for the subsequent discussion. The measurement results for each observation point are presented in (Table 1).

Table 1. The measurement results

Observation point	Sampling coordinates	Soil moisture (%)	Soil fertility (µS cm^{-1})	Soil pH	Soil temperature (°C)	Light intensity (lux)	Air Humidity (%)
Point 1	-6.858244, 107.630358	99	582	7.0	21.6	628	78
Point 2	-6.856607, 107.633001	99	308	7.0	23.5	1174	81
Point 3	-6.835256, 107.658534	99	209	7.0	26.0	1304	84

3.2 Soil moisture

The soil moisture measurements conducted in Tahura Ir. H. Djuanda showed identical values of 99% at all three observation points. These results indicate extremely high water availability within the soil environment and suggest that the soils were in a highly saturated condition during the measurement period. High soil moisture is a common characteristic of forest ecosystems, particularly in areas with dense vegetation cover, abundant litter accumulation, and reduced direct solar radiation reaching the soil surface (Neary et al., 2009). The consistently high soil moisture values observed across all observation points reflect the important hydrological function of the forest ecosystem. Dense vegetation and litter layers contribute to water retention by reducing surface runoff and minimizing water loss through evaporation (Shi et al., 2021). In addition, forest soils generally possess high organic matter content and well-developed pore systems, enabling them to retain substantial amounts of water and maintain favorable moisture conditions for biological activity.

The absence of variation in soil moisture among the three observation points deserves particular attention. Although the measurements were conducted at different locations, all observations produced the same value of 99%. This result may indicate that soil water content throughout the study area was extremely high during the measurement period. Alternatively, the recorded values may reflect the measurement characteristics of the sensor when soil conditions approach saturation, resulting in readings close to the upper detection limit of the instrument. Therefore, the obtained values should be interpreted as evidence of very wet soil conditions rather than proof that all observation points possessed exactly identical soil water content. High soil moisture conditions play a crucial role in supporting ecological processes within forest ecosystems. Adequate soil water availability facilitates nutrient transport, enhances microbial activity, promotes organic matter decomposition, and supports root development and vegetation growth (Nawaz et al., 2025). Furthermore, soil moisture contributes to maintaining ecosystem resilience by regulating water availability during periods of reduced precipitation and supporting the overall hydrological balance of the forest environment. The soil moisture measurements indicate that Tahura Ir. H. Djuanda possesses a highly favorable water regime characterized by abundant soil water availability. Such conditions are consistent with the ecological functions of tropical forest ecosystems, where soil moisture serves as a key factor supporting vegetation growth, nutrient cycling, and long-term ecosystem stability.

3.3 Soil fertility

The soil fertility measurements in Tahura Ir. H. Djuanda showed values of 582 µS/cm at Observation Point 1, 308 µS/cm at Observation Point 2, and 209 µS/cm at Observation Point 3. These results indicate spatial variations in soil fertility across the study area, reflecting differences in the concentration of dissolved ions and the relative availability of nutrients within the soil environment. The highest fertility value recorded at Observation Point 1 suggests a greater concentration of nutrients available for plant uptake compared with the other observation sites. Soil fertility is closely associated with the accumulation and decomposition of organic matter, nutrient cycling processes, and microbial activity occurring within the soil system (Khan et al., 2025). Forest ecosystems with continuous litter input generally maintain favorable nutrient availability through the decomposition of plant residues and the subsequent release of essential nutrients into the soil (Manzoni et al., 2008).

The observed differences in fertility values among the observation points may reflect variations in local environmental conditions, including vegetation characteristics, litter accumulation, soil biological activity, and nutrient redistribution processes (Keerthika et al., 2025; Kooch et al., 2025; Wang et al., 2021). Spatial heterogeneity in soil fertility is commonly reported in forest ecosystems because nutrient availability is influenced by multiple interacting physical, chemical, and biological factors operating at different spatial scales. Although Observation Points 2 and 3 exhibited lower fertility values than Observation Point 1, these results do not necessarily indicate degraded soil conditions. Variations in electrical conductivity measurements may occur naturally in forest environments due to differences in organic matter content, soil moisture conditions, root activity, and nutrient cycling dynamics (Fäth & Kneisel, 2024). Consequently, the observed fertility values should be interpreted as representing natural variability within the forest ecosystem rather than as evidence of declining environmental quality.

The fertility conditions observed in this study demonstrate the important role of forest ecosystems in maintaining nutrient availability through continuous ecological processes. Organic matter decomposition, microbial activity, and vegetation-soil interactions collectively contribute to sustaining soil fertility and supporting vegetation growth. These processes are essential for preserving ecosystem productivity and ecological stability within conservation forest areas. Overall, the soil fertility measurements indicate that nutrient availability varies across Tahura Ir. H. Djuanda, reflecting the complex interactions among soil properties, vegetation, and ecological processes. Such variability is a common characteristic of tropical forest ecosystems and highlights the dynamic nature of nutrient cycling within the study area.

3.4 Soil pH

The soil pH measurements conducted in Tahura Ir. H. Djuanda showed values of 7.0 at Observation Points 1 and 2, while Observation Point 3 recorded a slightly lower value of 6.5. These results indicate that the soils within the study area ranged from neutral to slightly acidic conditions, suggesting a relatively stable soil chemical environment. Soil pH is one of the most important indicators of soil quality because it regulates nutrient availability, microbial activity, and various biochemical processes occurring within the soil. Soils with pH values close to neutrality generally provide favorable conditions for plant growth because essential nutrients remain available and biological processes can proceed efficiently. The pH values observed in this study therefore indicate environmental conditions capable of supporting vegetation development and ecological functioning within the forest ecosystem (Ontman et al., 2023).

The slightly acidic condition observed at Observation Point 3 may be associated with natural ecological processes occurring in forest soils. The continuous decomposition of litter and organic matter produces organic acids that can gradually lower soil pH, particularly in areas with substantial organic material accumulation (Zhang et al., 2025). Similar soil pH conditions have frequently been reported in tropical forest ecosystems, where litter decomposition and nutrient cycling contribute to maintaining slightly acidic to neutral soil environments. The relatively small variation in pH among the observation points suggests that soil chemical conditions across the study area are generally homogeneous. This pattern may reflect the influence of similar parent materials, vegetation characteristics, and environmental conditions throughout the forest ecosystem. In addition, the consistently high soil moisture observed during the study may contribute to maintaining stable soil chemical conditions by facilitating nutrient transport and biogeochemical processes within the soil profile.

From an ecological perspective, the measured pH values indicate favorable conditions for nutrient cycling and biological activity. Soil microorganisms responsible for organic matter decomposition and nutrient transformation generally perform effectively under slightly acidic to neutral conditions, thereby supporting ecosystem productivity and long-term soil fertility (Wang & Kuzyakov, 2024). These conditions are particularly important in conservation forests, where ecological processes depend heavily on the interactions among soil properties, vegetation, and microbial communities. The soil pH measurements suggest that the soils of Tahura Ir. H. Djuanda possess relatively stable chemical characteristics, ranging from slightly acidic to neutral conditions. Such conditions are considered favorable for sustaining nutrient availability, biological activity, and the ecological functions of the tropical forest ecosystem (Cui et al., 2022).

3.5 Soil temperature

The soil temperature measurements conducted in Tahura Ir. H. Djuanda showed a gradual increase across the observation points. The lowest temperature was recorded at Observation Point 1 (21.6 °C), followed by Observation Point 2 (23.5 °C), while the highest temperature was observed at Observation Point 3 (26.0 °C). These results indicate the presence of spatial variation in soil thermal conditions within the study area. Soil temperature is an important environmental parameter because it influences a wide range of physical, chemical, and biological processes occurring within the soil. Variations in soil temperature affect microbial activity, organic matter decomposition, nutrient cycling, root development, and water movement within the soil profile (Bárcenas-Moreno et al., 2009). Consequently, differences in soil temperature can influence ecosystem functioning and vegetation performance in forest environments.

The increasing temperature trend observed from Observation Point 1 to Observation Point 3 may be associated with differences in local environmental conditions, particularly vegetation cover and solar radiation exposure. Areas receiving greater solar radiation generally exhibit higher soil temperatures because a larger proportion of incoming energy reaches the soil surface. Conversely, dense vegetation can moderate soil temperature by providing shade and reducing direct exposure to solar radiation. Such temperature regulation is a common characteristic of forest ecosystems and contributes to maintaining favorable conditions for ecological processes. The measured temperatures ranging from 21.6 °C to 26.0 °C indicate relatively warm soil conditions, which are typical of tropical environments. Similar temperature ranges have been reported in tropical forest ecosystems where soil thermal regimes are influenced by vegetation structure, climatic conditions, and topographic characteristics (Terschanski et al., 2024). These temperature conditions are generally suitable for sustaining biological activity and promoting the decomposition of organic matter that supports nutrient cycling within the ecosystem.

The relatively small temperature differences among the observation points also suggest that the forest ecosystem maintains a degree of thermal stability despite local environmental variations. Forest vegetation plays an important role in buffering extreme temperature fluctuations, thereby creating a more stable microenvironment for soil organisms and plant roots. This buffering effect is particularly important in conservation areas because it contributes to ecosystem resilience and the maintenance of ecological functions. Overall, the soil temperature measurements indicate that Tahura Ir. H. Djuanda exhibits warm and relatively stable thermal conditions characteristic of tropical forest ecosystems. These conditions are conducive to biological activity, nutrient cycling, and vegetation growth, supporting the ecological sustainability of the conservation area.

3.6 Light intensity

The light intensity measurements conducted in Tahura Ir. H. Djuanda showed values of 628 lux at Observation Point 1, 1,174 lux at Observation Point 2, and 1,304 lux at Observation Point 3. These results indicate spatial variation in the amount of solar radiation reaching the forest floor across the study area. Light intensity is an important microclimatic parameter because it influences photosynthetic activity, vegetation growth, soil temperature, and various ecological processes within forest ecosystems. The amount of light reaching the understory is largely regulated by canopy structure, vegetation density, and topographic conditions, which determine the degree of solar radiation penetration through the forest canopy.

The increasing trend in light intensity observed from Observation Point 1 to Observation Point 3 suggests differences in canopy openness and vegetation structure among the observation sites. Areas with more open canopy conditions generally allow greater amounts of solar radiation to reach the ground surface, resulting in higher light intensity values (Madhumali et al., 2025). In contrast, dense vegetation cover intercepts a substantial portion of incoming solar radiation, thereby reducing light availability within the understory environment. Despite the observed variation, all measurement points exhibited relatively low light intensity compared with open environments exposed to direct sunlight. This finding reflects the influence of forest canopy cover in regulating solar radiation and maintaining the characteristic microclimatic conditions of tropical forest ecosystems (Dai et al., 2021). Reduced light penetration is a common feature of forest environments and contributes to the development of cooler and more humid understory conditions that support diverse ecological communities.

Light availability also plays an important role in shaping local environmental conditions. Variations in solar radiation influence soil temperature, evaporation rates, and plant physiological processes, thereby contributing to spatial differences in microclimatic characteristics throughout the forest ecosystem. Consequently, the observed differences in light intensity provide valuable information regarding environmental heterogeneity within the study area. The measured light intensity values indicate that Tahura Ir. H. Djuanda maintains the low-light conditions typically associated with tropical forest understories. Such conditions contribute to the regulation of microclimatic stability and support the ecological functioning of the conservation area.

3.7 Air humidity

The air humidity measurements conducted in Tahura Ir. H. Djuanda showed values of 78% at Observation Point 1 and 81% at Observation Point 2, and 84% at Observation Point 3. These results indicate consistently high atmospheric moisture throughout the study area and reflect the humid environmental conditions characteristic of tropical forest ecosystems. Air humidity is an important microclimatic parameter because it influences evapotranspiration, plant physiological processes, soil moisture dynamics, and overall ecosystem functioning. High relative humidity is commonly associated with dense vegetation cover, continuous evapotranspiration, and reduced air circulation beneath forest canopies, all of which contribute to maintaining stable atmospheric moisture conditions.

The relatively high humidity values observed across all observation points suggest that the forest ecosystem effectively retains moisture within the local environment. Forest vegetation plays a crucial role in this process through transpiration, which continuously releases water vapor into the atmosphere and contributes to maintaining elevated humidity levels. In addition, canopy cover reduces direct solar radiation and wind exposure, thereby limiting moisture loss and promoting more stable microclimatic conditions. The gradual increase in humidity from Observation Point 1 to Observation Point 3 may reflect local variations in vegetation structure, canopy density, and environmental conditions within the study area (Britton et al., 2026). Similar patterns have been reported in tropical forest ecosystems, where differences in vegetation characteristics and microtopography contribute to spatial variability in atmospheric moisture conditions (O'Connor et al., 2021). Nevertheless, the relatively narrow range of values recorded in this study indicates that all observation sites experienced consistently humid conditions.

High atmospheric humidity is beneficial for many ecological processes occurring within forest ecosystems. Adequate humidity reduces water stress in vegetation, supports physiological processes such as transpiration and photosynthesis, and contributes to favorable conditions for soil organisms and microbial communities. Furthermore, humid conditions help maintain ecosystem resilience by supporting the continuous cycling of water between the soil, vegetation, and atmosphere (Baudena et al., 2008). Overall, the measured air humidity values indicate that Tahura Ir. H. Djuanda possesses a humid and relatively stable microclimate characteristic of tropical forest environments. Such conditions contribute to maintaining ecological processes, supporting vegetation growth, and sustaining the environmental functions of the conservation area.

3.8 Environmental conditions of Ir H. Djuanda Forest Park

The integrated analysis of soil and microclimatic parameters provides a comprehensive overview of the environmental conditions in Tahura Ir. H. Djuanda. The measured parameters indicate that the study area maintains environmental characteristics commonly associated with tropical forest ecosystems, including high soil moisture, relatively favorable soil fertility, near-neutral soil pH, warm soil temperatures, low understory light intensity, and high atmospheric humidity. The consistently high soil moisture values observed across all observation points suggest that the forest ecosystem possesses substantial water retention capacity. Such conditions support essential ecological processes, including nutrient transport, microbial activity, and vegetation growth. In addition, the relatively high air humidity recorded throughout the study area reflects the important role of forest vegetation in regulating local microclimatic conditions through canopy cover and evapotranspiration processes (Terschanski et al., 2024)

The soil fertility measurements revealed spatial variability among observation points, indicating that nutrient availability is not uniformly distributed throughout the study area. This variability is a common characteristic of forest ecosystems, where nutrient dynamics are influenced by litter accumulation, organic matter decomposition, vegetation composition, and soil biological activity. Nevertheless, the fertility values recorded in this study suggest that the ecosystem continues to support nutrient cycling processes necessary for vegetation development and ecosystem functioning. The measured soil pH values ranged from slightly acidic to neutral conditions, indicating a relatively stable soil chemical environment. Such pH conditions are generally favorable for nutrient availability and biological activity, thereby supporting plant growth and ecological processes within the forest ecosystem (Ontman et al., 2023). Combined with the observed warm soil temperatures, these conditions provide a suitable environment for microbial activity and organic matter decomposition, both of which contribute to sustaining soil productivity and ecosystem stability. The relatively low light intensity measured beneath the forest canopy further highlights the influence of vegetation structure on local environmental conditions. Reduced solar radiation reaching the forest floor contributes to maintaining cooler and more humid understory environments, which are important for supporting biodiversity and ecological resilience (Fotis & Curtis, 2017). Together with high soil moisture and atmospheric humidity, these conditions reflect the characteristic microclimate of a well-vegetated tropical forest ecosystem.

These environmental characteristics indicate that Tahura Ir. H. Djuanda maintains conditions that are conducive to ecosystem functioning and vegetation development. The findings of this study provide baseline information that can support future environmental monitoring and assist conservation managers in evaluating changes in soil and microclimatic conditions over time. In addition, the application of smart sensor technology demonstrates its potential as a practical and efficient approach for rapid environmental assessment in tropical forest ecosystems.

4. Conclusions

This study successfully characterized soil and microclimatic conditions in Tahura Ir. H. Djuanda using a 6-in-1 Intelligent Soil Tester (Model ST03). The results showed consistently high soil moisture across all observation points, indicating favorable water availability within the study area. Soil fertility varied among the observation sites, reflecting spatial differences in nutrient availability, while soil pH ranged from slightly acidic to neutral conditions, suggesting a relatively stable soil chemical environment. Soil temperatures were generally warm, light intensity remained relatively low due to forest canopy cover, and air humidity was consistently high, representing the characteristic microclimatic conditions of a tropical forest ecosystem.

The measured parameters indicate that Tahura Ir. H. Djuanda maintains environmental conditions that support ecological processes and vegetation growth. The combination of high soil moisture, favorable soil pH, variable but adequate soil fertility, warm soil temperatures, low understory light intensity, and high atmospheric humidity reflects the ecological functions of the conservation area in regulating water availability, nutrient cycling, and microclimatic stability. The findings provide baseline environmental information that can support future monitoring activities and contribute to the sustainable management of tropical forest ecosystems using smart sensing technologies. Nevertheless, the findings should be interpreted with caution because the measurements were conducted at only three purposively selected observation points during a single field campaign.

Therefore, the results represent preliminary, site-specific baseline observations and should not be considered a comprehensive characterization of the entire Ir. H. Djuanda Forest Park.

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Author Contribution

Author Contributions: Conceptualization, M.M. and W.L.; Methodology, R., Y.D.L., M.M., and W.L.; Investigation, R., Y.D.L., and M.M.; Resources, W.L.; Data Curation, M.M.; Writing - Original Draft Preparation, M.M.; Writing - Review & Editing, R., Y.D.L., and W.L.; Visualization, M.M.; Supervision, W.L.; and Project Administration, W.L. All authors have read and agreed to the published version of the manuscript.

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Declaration of Generative AI Use

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist in translating manuscript content from Indonesian into academic English and to improve grammar, clarity, and academic writing style. After using this tool, the authors reviewed, revised, and verified the content as needed and took full responsibility for the accuracy, originality, and final content of the publication.

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