SOIL PROPERTIES AND RAINFALL REGIMES IN CINNAMON (*Cinnamomum burmannii*) PLANTATIONS IN MANDAILING NATAL, NORTH SUMATRA

Sifat Tanah dan Pola Curah Hujan pada Perkebunan Kayu Manis (Cinnamomum burmannii) di Mandailing Natal, Sumatera Utara

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ABSTRACT

The sustainable cultivation of *Cinnamomum burmannii* in tropical regions requires a thorough understanding of soil properties and rainfall patterns, as these factors critically influence nutrient availability, plant growth, and long-term productivity. This study evaluates the soil properties and climatic conditions of Sawahan Village, Mandailing Natal Regency, to assess their suitability for the cultivation of *C. burmannii*. Soil samples were analyzed for physical and chemical characteristics, including organic carbon, total nitrogen, phosphorus, potassium, pH, exchangeable aluminum, macro- and micronutrients, and soil texture. Rainfall data over 25 years were also examined to understand the water availability and potential influence on soil fertility. The results indicate that the soils possess moderate organic matter and nutrient content, slightly acidic to near-neutral pH, absence of exchangeable aluminum toxicity, and a sandy loam texture conducive to drainage and root growth. The region experiences high and well-distributed rainfall, which supports perennial crop development but may increase nutrient leaching in sandy soils. These findings suggest that Sawahan Village provides favorable conditions for *C. burmannii* cultivation, provided that sustainable soil management practices, such as organic amendments, balanced fertilization, and erosion control, are implemented. The study highlights the importance of integrating climatic and soil assessments to optimize cinnamon productivity and provides baseline data for future land management and agroforestry planning in tropical regions.

Keywords: *Cinnamomum burmannii*; Cinnamon Cultivation; Rainfall; Soil Fertility; Soil Management

ABSTRAK

Budidaya berkelanjutan *Cinnamomum burmannii* di wilayah tropis memerlukan pemahaman mendalam mengenai sifat tanah dan pola curah hujan, karena faktor-faktor ini sangat mempengaruhi ketersediaan nutrien, pertumbuhan tanaman, dan produktivitas jangka panjang. Penelitian ini mengevaluasi karakteristik tanah dan kondisi iklim di Desa Sawahan, Kabupaten Mandailing Natal, untuk menilai kesesuaiannya dalam budidaya *C. burmannii*. Sampel tanah dianalisis untuk sifat fisik dan kimia, termasuk karbon organik, nitrogen total, fosfor, kalium, pH, aluminium dapat ditukar, makro dan mikronutrien, serta tekstur tanah. Data curah hujan selama 25 tahun juga dianalisis untuk memahami ketersediaan air dan pengaruhnya terhadap kesuburan tanah. Hasil penelitian menunjukkan bahwa tanah memiliki kandungan bahan organik dan nutrien yang moderat, pH sedikit asam hingga netral, tidak terdapat toksisitas aluminium dapat ditukar, serta tekstur berpasir-lom yang mendukung drainase dan pertumbuhan akar. Wilayah ini menerima curah hujan tinggi dan merata, yang mendukung perkembangan tanaman tahunan namun dapat meningkatkan pencucian nutrien pada tanah berpasir. Temuan ini menunjukkan bahwa Desa Sawahan memiliki kondisi yang kondusif untuk budidaya *C. burmannii*, dengan catatan penerapan praktik pengelolaan tanah yang berkelanjutan, seperti penambahan bahan organik, pemupukan seimbang, dan pengendalian erosi. Penelitian ini menekankan pentingnya integrasi analisis tanah dan iklim untuk meningkatkan produktivitas kayu manis dan menyediakan data dasar untuk perencanaan pengelolaan lahan dan sistem agroforestri di daerah tropis.

Kata kunci: Budidaya Kayu Manis; *Cinnamomum burmannii*; Curah Hujan; Kesuburan Tanah; Pengelolaan Tanah

A. INTRODUCTION

Cinnamomum burmannii, commonly known as Indonesian cinnamon, is a high-value spice plant widely cultivated in Indonesia for its aromatic bark, which is used in food, beverages, and traditional medicine (Yuwanda *et al.* 2023). Beyond its culinary and medicinal applications, *C. burmannii* has considerable economic potential, providing additional income for smallholder farmers and contributing to local agroforestry systems (Dandi *et al.* 2022). Cultivation of this species requires appropriate soil and environmental conditions, as the growth, yield, and quality of cinnamon bark are highly influenced by soil chemical and physical properties.

Mandailing Natal, located in North Sumatra Province, Indonesia, is characterized by a tropical climate with high annual rainfall, averaging over 2,500 mm, and mean temperatures ranging from 23 °C to 32 °C (CSAI 2014). The region's hilly terrain and diverse soil types create both opportunities and challenges for agricultural production. While the climate is favorable for the growth of cinnamon, variations in soil fertility, pH, and texture can affect nutrient availability and the overall productivity of *C. burmannii* plantations. Understanding these soil characteristics is essential for developing effective land management strategies and ensuring sustainable cultivation.

Soil chemical properties, such as organic carbon content, total nitrogen, available phosphorus, exchangeable potassium, base cations (Ca, Mg, Na), and micronutrient concentrations (Cu, Mn, Zn, Fe), are critical factors that determine soil fertility and nutrient supply for cinnamon growth (Antony *et al.* 2024). Meanwhile, soil acidity and exchangeable aluminum can limit nutrient availability and affect root development. Physical properties, including texture (proportions of sand, silt, and clay), bulk density, and water retention capacity, play a crucial role in root penetration, aeration, and moisture availability, which directly influence plant growth and yield (Ge *et al.* 2011). A comprehensive assessment of both chemical and physical soil properties is therefore necessary to support successful agroforestry management and sustainable cultivation practices in Mandailing Natal.

In addition to agricultural productivity, the cultivation of *C. burmannii* also has environmental implications. Agroforestry systems incorporating cinnamon can improve soil health, reduce erosion, and enhance biodiversity compared to monoculture cropping systems (Fahad *et al.* 2022). By maintaining tree cover and integrating perennial species, these systems contribute to carbon sequestration and promote more resilient landscapes under changing climatic conditions .

Despite its economic and ecological importance, there is limited site-specific information on the chemical and physical characteristics of soils under *C. burmannii* cultivation in Mandailing Natal (Nguyen *et al.* 2022). The absence of detailed baseline soil data may lead to inappropriate fertilizer application, inefficient land management practices, declining productivity, and potential long-term soil degradation. Without accurate information on soil fertility status and physical constraints, farmers may rely on generalized recommendations that do not reflect local soil variability, ultimately affecting yield stability, bark quality, and farm profitability.

Therefore, the main objective of this study was to characterize the chemical and physical properties of soils in *C. burmannii* cultivation areas in Mandailing Natal, North Sumatra. Specifically, this study aims to (1) assess key soil fertility indicators, including macro- and micronutrients, soil acidity, and exchangeable aluminum; (2) evaluate soil physical characteristics related to root growth and water availability; and (3) provide baseline data to support site-specific land management recommendations. The generated data are expected to contribute to sustainable agroforestry management, improved cinnamon productivity, environmental conservation, and evidence-based agricultural planning in the region.

B. METHODS

Research Location

This study was conducted in Sawahan Village, Mandailing Natal Regency, North Sumatra, Indonesia (0°36'17"N–99°41'33"E), at an elevation of approximately 2,145 meters above sea level, with a humid tropical climate and distinct wet and dry seasons. The area is dominated by smallholder agroforestry systems, where *C. burmannii* is cultivated alongside other tree crops. Soil sampling was carried out at a cinnamon-growing site and a nearby reference site without cinnamon vegetation. Sampling points in the cinnamon-growing area were selected purposively at three different corners of the plot to capture spatial variability. At each point, a composite soil sample was collected from the 0–20 cm topsoil layer using a soil auger, resulting in three replicates for statistical analysis. For the reference site, one composite sample was collected using the same method. Although limited by resources, the three sampling points provide basic spatial replication. The collected samples were air-dried, sieved through a 2 mm mesh, and prepared for physical and chemical analyses in the laboratory.

Laboratory Analysis

Physical and chemical analyses of the soil samples were carried out at the Soil, Plant, Fertilizer, and Water Laboratory of the Agricultural Instrument Standardization Testing Center, North Sumatra (Balai Penerapan Standar Instrumen Pertanian Sumatera Utara). All analyses followed standard procedures established by the Indonesian Agency for Agricultural Instrument Standardization. Soil pH was measured in a 1:2.5 soil-to-water suspension using a calibrated pH meter. Organic carbon (C-organic) was determined using the Walkley–Black wet oxidation method, while total nitrogen (N-total) was analyzed with the Kjeldahl digestion method. Available phosphorus (P) was extracted using the Bray I method, and exchangeable potassium (K-dd), calcium (Ca), magnesium (Mg), sodium (Na), and aluminum (Al) were determined through ammonium acetate extraction (pH 7.0), followed by atomic absorption spectrophotometry (AAS). Micronutrients including copper (Cu), manganese (Mn), zinc (Zn), and iron (Fe) were extracted using the DTPA method and quantified with AAS. Soil texture was determined using the hydrometer method to estimate sand, silt, and clay fractions.

Soil Data Processing and Interpretation

All laboratory results were expressed on an oven-dry weight basis and analyzed using descriptive statistical methods. The mean and standard deviation were calculated for each parameter to evaluate soil variability within and between sites. Comparative interpretation between the cinnamon-growing soils and the reference soil was conducted descriptively due to the limited replication at the reference site. Therefore, statistical inference was not performed, and the comparison should be interpreted cautiously as preliminary evidence rather than definitive proof of soil improvement. Soil fertility status was classified based on criteria established by the Indonesian Soil Research Institute (Eviati & Sulaeman 2009) and cross-referenced with FAO guidelines (Fao 2018). The relationships among key soil chemical parameters were interpreted in relation to *C. burmannii* growth requirements and potential site suitability. The findings provide baseline information for soil fertility management, sustainable land use, and future development of cinnamon-based agroforestry systems in North Sumatra.

Rainfall Data

Rainfall data for the study area were obtained from two official sources: the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) and the Badan Pusat Statistik (BPS) Mandailing Natal Regency. Monthly rainfall records from 1997 to 2021 were collected from the nearest BMKG meteorological station and supplemented with local data from BPS. The datasets were combined to provide a comprehensive record of the study area's rainfall patterns. Data after 2021 were not included because official records for 2022 and later have not yet been updated or published. The compiled data were analyzed to calculate mean monthly and annual rainfall, which were used to characterize climatic conditions and support the assessment of land suitability for *C. burmannii* cultivation.

C. RESULTS AND DISCUSSION

Actual Suitability Land for Cinnamomum Plants

The soil physicochemical characteristics of the study area provide essential baseline information for evaluating land suitability for *C. burmannii* cultivation in Sawahan Village, Mandailing Natal Regency. Comprehensive soil analysis was conducted to assess key fertility indicators, including macronutrients, micronutrients, soil reaction, and texture, which strongly influence plant growth and productivity. These parameters reflect the capacity of the soil to supply nutrients, support root development, and maintain favorable chemical conditions under tropical environments. The summarized results of soil properties analyzed using standard laboratory methods are presented in Table 1.

1. Organic Carbon and Total Nitrogen

The soil from Sawahan Village shows an organic carbon (C-organic) content of 2.09% and total nitrogen (N-total) of 0.19%, indicating moderate soil fertility status. These values suggest that the soil contains a sufficient amount of organic matter to support biological activity and nutrient cycling, which are essential for the sustainable growth of *C. burmannii*. Organic carbon plays a crucial role in improving soil structure, enhancing water-holding capacity, and serving as an energy source for soil microorganisms, while nitrogen is a key macronutrient required for vegetative growth and chlorophyll formation. Based on these values, the calculated C/N ratio (2.09/0.19) is approximately 11, which falls within the optimal range for balanced mineralization (generally 10–15). This ratio indicates that organic matter decomposition is likely proceeding at a moderate rate, allowing efficient nitrogen release without substantial immobilization (Khan *et al.* 2025). A

C/N ratio within this range reflects a relatively stable equilibrium between carbon and nitrogen dynamics, supporting continuous nutrient availability for plant uptake (Paulsen *et al.* 2018).

Table 1. Physicochemical properties of soil in Sawahan Village, Mandailing Natal Regency

No	Soil Parameter (Unit)	Value[a]	Analysis Method	Value[b]
1	C-organik (%)	2.09	IK 0.1.5.0 (Spectrophotometry)	-
2	N-total (%)	0.19	IK 0.1.6.0 (Kjeldahl)	moderate
3	P-Bray I (ppm P)	13.87	IK 0.1.7.0 (Spectrophotometry)	-
4	K-dd (me/100g)	0.5	IK 0.1.8.0 (AAS)	-
5	pH-H_2O	6.42	IK 0.1.3.0 (Electrometry)	5-7
6	pH-KCl	5.92	IK 0.1.3.0 (Electrometry)	-
7	Al-dd (me/100g)	0	IK 0.1.4.0 (Titrimetry)	-
8	Ca (me/100g)	13.89	IK 0.1.8.0 (AAS)	-
9	Mg (me/100g)	9.7	IK 0.1.8.0 (AAS)	-
10	Cu (ppm)	9	IK 0.1.8.0 (AAS)	-
11	Mn (ppm)	43	IK 0.1.8.0 (AAS)	-
12	Zn (ppm)	16	IK 0.1.8.0 (AAS)	-
13	Fe (ppm)	87	IK 0.1.8.0 (AAS)	-
14	Na (me/100g)	0.27	IK 0.1.8.0 (AAS)	-
15	Texture			
	Sand (%)	58,44	IK 0.1.9.0 (Hydrometer)	Silty Loam, loam, silty clay loam, sandy clay loam, clay loam, and sandy clay
	Silt (%)	19,69	IK 0.1.9.0 (Hydrometer)	
	Clay (%)	21,87	IK 0.1.9.0 (Hydrometer)	

Notes: [a]this study, [b]Ritung *et al.* (2011)

The observed C-organic and N-total levels are comparable to soils reported under cinnamon plantations in other parts of Indonesia, where C-organic values commonly range from 2.0–3.0% and N-total from 0.15–0.35% (Antony *et al.* 2024). Moderate nitrogen availability indicates that mineralization of organic matter is occurring, although supplemental nitrogen inputs may still be required to meet crop demand during peak growth stages (Pérez-Llorca *et al.* 2025). Maintaining organic matter through organic amendments or mulching is therefore recommended to prevent long-term nutrient depletion, especially under continuous cultivation systems (Valenzuela 2023).

2. Available Phosphorus (P-Bray I) and Potassium (K-dd)

The available phosphorus (P-Bray I) content in the soil is 13.87 ppm, which falls within the moderate availability range, while exchangeable potassium (K-dd) is 0.50 me/100 g, indicating moderate to high potassium status. Phosphorus is essential for root development, energy transfer (ATP), and early plant establishment, whereas potassium plays a vital role in enzyme activation, osmotic regulation, and resistance to biotic and abiotic stress (Khan *et al.* 2023; Song *et al.* 2022). The moderate P availability suggests that phosphorus fixation may occur, which is common in tropical soils due to interactions with iron and aluminum oxides. Although potassium levels are relatively sufficient, the sandy nature of the soil increases the risk of K leaching, particularly under high rainfall conditions typical of Mandailing Natal. Previous studies have reported that *C. burmannii* responds positively to balanced P and K fertilization, especially in soils with moderate nutrient reserves (Antony *et al.* 2024). Therefore, site-specific fertilizer management is necessary to ensure optimal nutrient availability throughout the growing season.

3. pH and Aluminum Saturation

The soil pH measured in water (pH-H_2O) is 6.42, while pH-KCl is 5.92, indicating slightly acidic soil conditions. Exchangeable aluminum (Al-dd) is 0 me/100 g, suggesting the absence of aluminum toxicity. This pH range is considered optimal for *C. burmannii*, as it maximizes nutrient availability while minimizing the solubility of toxic aluminum ions. Soils with pH between 5.5 and 7.0 are widely recognized as suitable for cinnamon cultivation, allowing efficient uptake of macronutrients such as nitrogen, phosphorus, calcium, and magnesium (Xia *et al.* 2024). The absence of exchangeable aluminum further indicates adequate base saturation and good buffering capacity, which are critical for maintaining soil chemical stability under tropical weathering conditions. Similar findings have been reported in cinnamon-growing areas

across Sumatra, where slightly acidic soils without aluminum constraints supported healthy root development and biomass accumulation (Rahayu 2020).

4. Exchangeable Calcium and Magnesium

The soil contains 13.89 me/100 g of Ca and 9.70 me/100 g of Mg, reflecting high levels of exchangeable base cations, while exchangeable sodium (Na) is relatively low at 0.27 me/100 g. Calcium and magnesium are essential for cell wall formation, photosynthesis, and enzyme activation, and their adequate presence indicates good soil fertility and structural stability. High Ca and Mg concentrations contribute to improved soil aggregation and root penetration, which are particularly beneficial in sandy-textured soils (Bronick & Lal 2005).

From a cation balance perspective, the Ca/Mg ratio is approximately 1.43, slightly below the commonly suggested optimal range (2–6) (Yang *et al.* 2024). This indicates a relatively high proportion of Mg compared to Ca, although both nutrients remain at sufficient levels (Nguyen *et al.* 2017). In contrast, the Ca/K and Mg/K ratios (27.8 and 19.4, respectively) show a clear dominance of divalent cations over potassium. Such disproportion may influence competitive cation uptake dynamics, as excessive Ca and Mg can potentially limit K availability through ionic competition at root exchange sites. Therefore, while overall base saturation is favorable, potassium management may require attention to maintain balanced nutrient uptake.The low sodium content suggests no risk of sodicity or soil dispersion, ensuring favorable physical conditions for cinnamon root growth (Peker *et al.* 2024). Overall, the balance of base cations in the Sawahan soil supports the physiological requirements of *C. burmannii* and reduces the need for liming or soil amelioration.

Although the study area is characterized by relatively high rainfall, which generally promotes base cation leaching and increases the risk of aluminum (Al) mobilization under acidic conditions, no indication of Al toxicity was observed. This condition may be explained by several pedological factors. The relatively high concentrations of exchangeable Ca and Mg likely provide buffering capacity against excessive acidification, thereby limiting the activity of soluble Al^{3+} in the soil solution (Rahman *et al.* 2018). In addition, the moderate organic carbon content (2.09%) may contribute to the formation of stable organo-Al complexes, reducing Al bioavailability and phytotoxic effects (Yang *et al.* 2024). The influence of parent material and soil mineralogy may also play a role in moderating Al dynamics under high rainfall conditions.

5. Micronutrients Availability

Micronutrient analysis shows concentrations of Cu (9 ppm), Mn (43 ppm), Zn (16 ppm), and Fe (87 ppm), indicating adequate to high availability of essential micronutrients. Iron and manganese levels are relatively high, which is typical for slightly acidic tropical soils, as lower pH increases their solubility (Baker *et al.* 2006). Copper and zinc concentrations are within sufficient ranges for woody perennial crops, supporting enzymatic reactions, lignin synthesis, and reproductive development. Adequate Zn availability is particularly important for cinnamon, as zinc deficiency has been associated with reduced growth and lower essential oil yield (Abd El-Hack *et al.* 2020). The overall micronutrient status of the soil suggests no immediate deficiency constraints, although continuous monitoring is recommended to prevent potential imbalances under long-term cultivation.

6. Soil texture

The soil texture consists of 58.44% sand, 19.69% silt, and 21.87% clay, classifying the soil as sandy loam. This texture provides good drainage and aeration, which are highly favorable for *C. burmannii*, a species that is sensitive to waterlogging and poorly drained conditions. However, sandy loam soils generally have lower water and nutrient retention capacity, increasing susceptibility to nutrient leaching (Matichenkov *et al.* 2020). The incorporation of organic matter, cover crops, or mulch is therefore essential to enhance soil moisture retention and improve cation exchange capacity. Previous studies have recommended sandy loam soils with adequate organic inputs as the most suitable medium for cinnamon cultivation in Indonesia (Rahayu 2020; Yuwanda *et al.* 2023).

Climatic Condition In The Study Area

Rainfall is a critical climatic factor influencing soil formation, nutrient dynamics, and crop suitability in tropical regions. Based on long-term rainfall data from Mandailing Natal Regency covering the period 1997–2021 (Figure 1), the area exhibits a humid tropical climate with high annual and monthly rainfall variability. The mean monthly rainfall ranges from 76.07 mm in July to 286.58 mm in November, with consistently high precipitation occurring from October to December, indicating a pronounced wet season (Luo *et al.* 2024). Annual rainfall distribution suggests favorable moisture availability for perennial crops such as *C. burmannii*, which requires adequate and well-distributed rainfall for optimal growth.

The high rainfall regime has a direct influence on the observed soil chemical characteristics. Moderate levels of soil organic carbon (2.09%) and total nitrogen (0.19%) indicate active organic matter decomposition under humid conditions, where warm temperatures and sufficient moisture accelerate microbial activity. However, prolonged and intense rainfall

can also enhance nutrient leaching, particularly of nitrogen and potassium, which is consistent with the moderate N-total and exchangeable K (0.50 me/100 g) observed in the soil. This highlights the importance of organic matter management to improve nutrient retention under high-rainfall conditions (Liu *et al.* 2025).
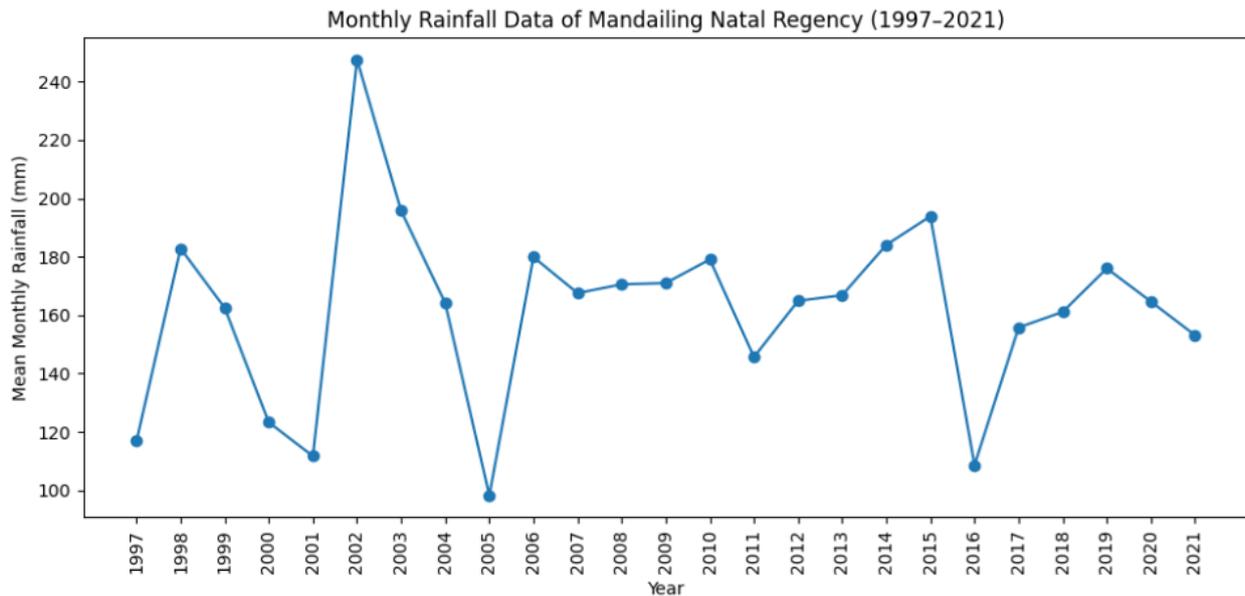

Figure 1. Monthly rainfall data of Mandailing Natal Regency (1997–2021)

Rainfall patterns also play a significant role in shaping soil acidity and base cation status (Huang *et al.* 2025). Despite high precipitation, the soil pH (pH-H_2O 6.42) remains slightly acidic and no exchangeable aluminum was detected, indicating that base cations such as calcium (13.89 me/100 g) and magnesium (9.70 me/100 g) are still sufficiently retained in the soil. This condition suggests that the parent material and relatively high base saturation help buffer soil acidity, even under intense leaching environments commonly associated with tropical rainfall (Fujii *et al.* 2017). Such soil reaction is highly favorable for *C. burmannii*, as excessive acidity and aluminum toxicity can restrict root development and nutrient uptake.

The interaction between rainfall and soil texture further explains the soil's physical and chemical behavior. The sandy loam texture (58.44% sand, 19.69% silt, and 21.87% clay) promotes good drainage, which is advantageous under high rainfall by preventing waterlogging and root suffocation. However, sandy-dominated soils combined with high rainfall increase the risk of nutrient losses through leaching, particularly during peak rainfall months (Huang & Hartemink 2020). This condition underscores the need for adaptive soil management practices, such as mulching, organic amendments, and split fertilizer applications, to maintain soil fertility and ensure sustainable cinnamon production.

Overall, the rainfall characteristics of Mandailing Natal Regency are well aligned with the ecological requirements of *C. burmannii*, provided that appropriate soil and nutrient management strategies are implemented. The combination of high rainfall, favorable soil pH, adequate base cations, and well-drained soil texture creates a suitable environment for cinnamon cultivation, while emphasizing the importance of sustainable land management to mitigate nutrient depletion under humid tropical conditions.

Implications for Cinnamon Cultivation

Overall, the soil characteristics of Sawahan Village, Mandailing Natal Regency, exhibit several attributes consistent with reported optimal conditions for *C. burmannii* cultivation. The moderate levels of organic carbon and total nitrogen, slightly acidic to near-neutral pH, absence of apparent aluminum toxicity, sufficient macro- and micronutrients, and sandy loam texture collectively provide conditions generally regarded as favorable for cinnamon growth in tropical agroecosystems. These properties fall within ranges commonly described for productive cinnamon-growing soils in Indonesia and other Southeast Asian regions. In addition, the local rainfall regime, with mean monthly precipitation ranging from approximately 76 to 287 mm and higher rainfall during October–December, supports adequate water availability for perennial crop development.

However, sustained high rainfall combined with sandy loam texture may enhance nutrient leaching, particularly of nitrogen and potassium, highlighting the importance of appropriate soil fertility management. Therefore, rather than categorizing the site as unconditionally "highly suitable," the findings suggest that the area is generally suitable for *C. burmannii* cultivation when supported by proper nutrient management strategies. Sustainable practices such as the addition of organic amendments, balanced fertilization, and erosion control measures are recommended to mitigate

nutrient losses and maintain long-term soil productivity (Liu *et al.* 2025). Furthermore, integrating agroforestry or mixed cropping systems may enhance soil health, biodiversity, and economic resilience for cinnamon farmers in the region.

D. CONCLUSION

This study demonstrates that the soil and climatic conditions of Sawahan Village, Mandailing Natal Regency, are generally well suited for the cultivation of *C. burmannii*. The soils exhibit moderate organic carbon and nitrogen levels, favorable pH, absence of exchangeable aluminum toxicity, adequate macro- and micronutrient availability, and a sandy loam texture that supports good drainage and root development. These soil characteristics are complemented by a humid tropical rainfall regime with well-distributed annual precipitation, ensuring sufficient water availability for perennial cinnamon growth. Despite these favorable conditions, the combination of high rainfall and sandy loam texture increases the risk of nutrient leaching, particularly for nitrogen and potassium, which may affect long-term soil fertility. Therefore, sustainable soil management practices, including organic matter addition, balanced fertilization, and erosion control, are essential to maintain productivity and soil health. The findings of this study provide important baseline information for land suitability assessment and sustainable management of cinnamon plantations in Mandailing Natal Regency. Future research should focus on long-term monitoring of soil nutrient dynamics, evaluation of fertilizer efficiency under high-rainfall conditions, and the integration of agroforestry systems to enhance soil resilience and cinnamon productivity.

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AUTHOR'S DECLARATION

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are ours.
- No animal studies are present in the manuscript.
- No human studies are present in the manuscript.
- No potentially identified images or data are present in the manuscript.

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