



Physical and Chemical Characteristics of Soil in the Habitat of *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson in Tojo Una-Una Regency, Central Sulawesi

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Abstract: Sulawesi, particularly the Wallacea region, has a unique yet extreme ultramafic ecosystem for vegetation growth due to nutrient limitations and high heavy metal concentrations. This study aims to analyze the characteristics of the physical and chemical properties of the soil in the habitat of *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson in Tojo Una-Una Regency, Central Sulawesi. The study was conducted in Betaua and Podi Villages by dividing the locations based on distance from the river flow. Physical parameters analyzed included bulk density, soil texture, and permeability, while chemical parameters included N, P, K, pH, organic C, C/N ratio, and electrical conductivity (DHL). The results showed that the soil texture in Betaua Village was dominated by sand fractions, while Podi Village was dominated by silt fractions due to the influence of river sedimentation. Chemically, the soil is alkaline (pH 8.05–8.28) with low to very low nitrogen and phosphorus content, but has moderate potassium availability. The presence of *G. rumphianum*, an actinorhizal plant capable of fixing nitrogen, is a key factor in the adaptation and sustainability of vegetation in this marginal land. This study concludes that despite extreme edaphic constraints, soil-plant interactions and local environmental dynamics such as fluviality significantly determine the structure of the ultramafic habitat in the region.

Keywords: Edaphic properties; *Gymnostoma rumphianum*; Ultramafic Soil

Introduction

Sulawesi Island, particularly the Wallacea region, is known as one of the world's centers of biodiversity, boasting a high level of endemism and unique and complex environmental conditions. Variations in these environmental conditions, particularly edaphic factors such as soil physical and chemical properties, play a crucial role in determining the structure and composition of vegetation within an ecosystem (Pitopang et al., 2023; Vazquez-Marquez et al., 2024). One interesting ecosystem type to study in this region is that which thrives on ultramafic soils, which are widely distributed across several regions of Sulawesi, including

Tojo Una-Una Regency. Ultramafic soils are the result of the weathering of rocks rich in ferromagnesian minerals, such as peridotite and serpentinite, which possess distinctive and extreme chemical characteristics. These soils are generally characterized by low levels of essential nutrients (especially nitrogen, phosphorus, and potassium), an imbalanced calcium-to-magnesium ratio, and high concentrations of heavy metals such as nickel, cobalt, and chromium, which are toxic to most plants (Galey et al., 2017; Khan et al., 2025). Furthermore, ultramafic soils often have low water-holding capacity and physical properties that are less conducive to plant growth, creating strong ecological selection pressures for adaptable vegetation (Van Der Ent et al., 2015;

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Etesami, 2018). These extreme edaphic conditions lead to the formation of distinctive plant communities, with high levels of specialization and endemism.

Plants growing in ultramafic soils generally possess specific morphological, physiological, and biochemical adaptations to cope with nutrient limitations and heavy metal toxicity (Bourles et al., 2020; Aprima, 2023). The interaction between soil and plants (soil-plant interaction) is a key factor in determining the successful colonization and sustainability of vegetation in these habitats. One group of plants that plays a crucial role in ultramafic soil ecosystems is the Casuarinaceae family, including the genus *Gymnostoma* (Ray et al., 2025; Ripoll et al., 2025). These plants are known as actinorhizals, capable of forming a symbiotic relationship with *Frankia* bacteria to fix atmospheric nitrogen, enabling them to grow in soil conditions with low nitrogen availability (Buchbauerová et al., 2024; Shaárani et al., 2026). This ability makes *Gymnostoma* a pioneer species that plays a role in increasing soil fertility through the accumulation of organic matter and the cycling of nutrients, particularly nitrogen, phosphorus, and potassium (Temmink et al., 2023; Solangi et al., 2019). The presence of *Gymnostoma* in ultramafic habitats not only reflects their adaptability to extreme edaphic conditions but also demonstrates a reciprocal relationship between vegetation and soil properties. These plants can modify soil conditions through litter and biological activity, thereby contributing to the gradual improvement of soil chemical and biological properties (Z. Wang et al., 2025; Laghari et al., 2025).

However, soil physical characteristics such as texture, bulk density, and permeability remain important limiting factors that influence water availability and soil aeration, which ultimately impact plant growth and soil microbial activity (Xing et al., 2025; Lei et al., 2022). Although research on the ecology of ultramafic soils has been extensively conducted in various regions of the world, studies that comprehensively integrate soil physical and chemical properties in *Gymnostoma* habitats in Sulawesi, particularly in Tojo Una-Una Regency, are still very limited (Kierczak et al., 2021; Echevarria et al., 2018). A thorough understanding of soil physical and chemical properties is crucial for explaining plant adaptation mechanisms, nutrient dynamics, and soil-vegetation interactions in ultramafic ecosystems. This information not only contributes to the development of soil ecology and forestry science but also has practical implications for the management, conservation, and restoration of ecosystems that thrive on marginal lands.

Based on this, this research is crucial to examine the physical and chemical characteristics of soil in the habitat of *Gymnostoma rumphianum* (Miq.) L.A.S.

Johnson in Tojo Una-Una Regency, Central Sulawesi, as an effort to understand the relationship between edaphic conditions and vegetation presence in ultramafic ecosystems. This study aims to analyze the characteristics of physical properties (soil texture, bulk density, and permeability) and chemical properties of soil (nitrogen (N), phosphorus (P), potassium (K), soil pH, organic carbon (C-organic), C/N ratio, electrical conductivity (DHL), and soil water content) in the habitat of *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson in Tojo Una-Una Regency, Central Sulawesi, in order to understand the edaphic conditions that support the existence and growth of this species in the ultramafic soil ecosystem.

Method

This research was conducted in Tojo Una-Una Regency, Central Sulawesi, covering two villages, namely Betaua Village and Podi Village. In each village, sampling was conducted at two location conditions, namely an area relatively far from the river (A1) and an area close to the river (A2). The research was conducted during the period of December 2025 to March 2026.

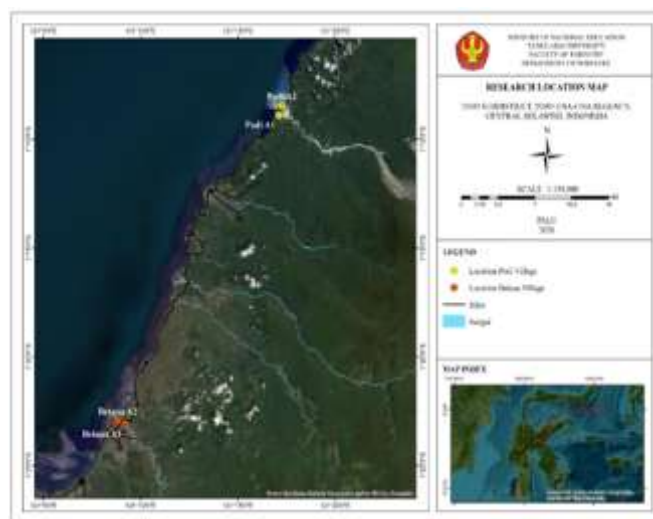


Figure 1. Sampling location map

Sampling Design

Soil sampling was conducted using a single plot method measuring 50 m × 50 m at each research location. Plots were established in areas where *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson was found, so sampling focused on zones representing the species' natural habitat. Sampling was conducted randomly around individual *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson within the plot. Soil samples were collected at a depth of approximately 20–30 cm from the soil surface. In Podi Village, sampling was carried out after first removing the surface sediment layer resulting

from flooding, ensuring that the soil analyzed was in-situ soil and not alluvial material resulting from recent deposition.

Soil Sample Types

At each location (Betaua A1, Betaua A2, Podi A1, and Podi A2), two types of soil sampling were conducted: undisturbed soil samples. Intact soil samples were taken at the center of the plot using a ring sampler at a depth of approximately 20–30 cm to maintain the soil's natural structure. These samples were used for analysis of soil physical properties, particularly bulk density. Disturbed soil samples were collected as composites from five points within the plot: four at the corners and one in the center. All samples were taken at the same depth and then mixed thoroughly to obtain representative samples for analysis of soil chemical properties.

Analyzed Parameters

The physical and chemical soil properties analyzed in this study were: The physical soil properties to be observed in this study were: Bulk density; Soil texture;

Permeability. The chemical soil properties to be observed in this study were: Nitrogen (N); Phosphorus (P); Potassium (K); Soil pH; Organic carbon (C-organic); C/N ratio; Electrical conductivity (E/C). Soil Water Content

Data Analysis

The data obtained were analyzed descriptively by comparing the values of each soil parameter between research locations (Betaua and Podi) and based on their location relative to the river (near and far from the river). This analysis aimed to identify patterns of variation in soil physical and chemical properties and their relationship to the habitat conditions of *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson.

Result and Discussion

Soil Physical Properties

Based on the analysis of the samples, the results of the soil physical properties analysis are presented in Table 1 as follows:

Table 1. Physical Properties of Soil in the Habitat of *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson

Paramater	Unit	Betaua A1	Betaua A2	Podi A1	Podi A2
Bulk Density	g/cm ³	1.19	0.98	1.48	1.52
Soil Texture					
Clayey	%	15.99	11.64	5.07	10.05
Dust	%	27.12	16.09	61.11	34.27
Sand	%	56.89	72.27	33.82	55.68
Permeability	cm/hour	30.15	25.63	16.61	20.66

Soil Bulk Density

The analysis results show that the soil bulk density values in the *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson habitat vary across study sites, ranging from 0.98 to 1.52 g/cm³. The highest bulk density value was found at the Podi Village A2 location (1.52 g/cm³), while the lowest value was found at the Betaua Village A2 location (0.98 g/cm³). In general, the locations in Podi Village showed higher bulk density values than those in Betaua Village. This difference in bulk density values indicates variations in soil physical conditions influenced by environmental factors, particularly the landscape's position relative to the river flow. The relatively high bulk density values at the Podi location, particularly in the area near the river (A2), are suspected to be related to sediment deposition due to flooding, which increases soil density. Furthermore, mechanical pressure from sediment and the possible low organic matter content may also contribute to the increased bulk density values. Conversely, lower bulk density values at the Betaua site, particularly at A2 (0.98 g/cm³), indicate looser soil conditions with higher porosity. These

conditions are generally associated with higher organic matter content and more intensive soil biological activity, thus increasing the formation of soil aggregates and pore space. Ecologically, this variation in bulk density has important implications for the growth of *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson. High bulk density values can limit root penetration, reduce soil aeration, and inhibit the movement of water and nutrients in the soil. Conversely, lower bulk density tends to support root system development and the activity of soil microorganisms, including symbiotic bacteria such as *Frankia*, which play a role in nitrogen fixation.

These results align with several previous studies showing that vegetation from the Casuarinaceae family can influence soil physical properties, particularly bulk density. Research by Miah et al. (2021) and Y. Wang et al. (2023) showed that the soil bulk density under Casuarina stands ranged from 1.24–1.38 g/cm³, which was lower than that of open land. This suggests that the presence of Casuarina vegetation plays a role in improving soil structure by adding organic matter from

litter. Furthermore, other studies have reported that planting *Casuarina equisetifolia* can significantly reduce soil bulk density due to increased organic matter content and soil porosity (Kugedera et al., 2025; Liu et al., 2014). This decrease in bulk density is related to the accumulation of leaf litter and root activity, which increases soil aggregation and pore space. Compared with the results of this study, the bulk density at the Betaua site (0.98–1.19 g/cm³) tends to be lower than the range reported in previous studies, indicating better physical soil conditions. Conversely, the bulk density at the Podi site (1.48–1.52 g/cm³) is relatively higher, even exceeding the typical range for soils under *Casuarina* stands. This shows that local environmental factors, such as the influence of sedimentation and fluvial dynamics, have a more dominant role than the effects of vegetation in determining soil density conditions.

Soil Texture

The analysis results show that soil texture in the habitat of *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson varies across study sites. The Betaua Village site is dominated by sand fractions (56.89–72.27%), while the Podi Village site is dominated by silt fractions, particularly in Podi A1 (61.11%). Clay content at all sites is relatively low to moderate (5.07–15.99%), indicating that the soils at the two sites have significantly different physical characteristics. The dominance of sand fractions in Betaua Village indicates that the soil has high macroporosity, supporting good aeration and rapid water movement. This condition is common in the habitats of plants from the *Casuarinaceae* family, which are able to adapt to coarse-textured soils with relatively low organic matter content, such as in coastal ecosystems (Istomo & Susanti, 2023). This study explained that the habitat of *Casuarina equisetifolia* in coastal areas is generally dominated by sandy soils, despite extreme environmental conditions, yet still able to support plant growth.

In contrast, the dominance of the dust fraction in Podi Village indicates a finer soil texture, which tends to have a higher water-holding capacity but lower permeability. This condition may be influenced by the deposition of fine material due to river flow dynamics, especially in locations close to water bodies. These results are also supported by other research showing that soil texture in *Casuarina equisetifolia* habitats does not always show significant differences between zones, despite varying environmental conditions (Sa'adah & Istomo, 2022). This indicates that species in the *Casuarinaceae* family have a high adaptability to variations in soil texture, both in sandy soils and soils with a higher fine particle content. Furthermore, in former tin mining areas revegetated with *Casuarina equisetifolia*, the soil was found to be dominated by a

very high sand fraction (up to ±94%), with a very low dust content. This condition indicates that species in the *Casuarinaceae* family are capable of growing in soils with extreme textures, including soils that are very poor in structure and nutrients.

Meanwhile, research on *Casuarina junghuhniana* stands showed that soil physical properties, including texture, were relatively stable and showed no significant changes with stand age (Paembonan et al., 2023). This indicates that soil texture is more influenced by soil formation factors than by the presence of vegetation, although vegetation still plays a role in improving soil structure. The dominance of sand texture in Betaua Village indicates more porous soil conditions and supports good aeration, thus contributing to lower bulk density values (Nugraha et al., 2024). Conversely, the dominance of silt fractions in Podi Village, particularly in locations near rivers, indicates the influence of sediment deposition, which can increase soil density and affect other physical properties such as permeability and water retention.

Soil Permeability

Analysis results show that soil permeability in the *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson habitat varies across study locations, influenced by differences in soil texture, organic matter content, and hydrophysical conditions. Soil permeability is fundamentally related to the soil's ability to transmit water through its pores, which is strongly influenced by particle size distribution and the hydrophobic nature of the soil surface. In soils dominated by sand fractions, such as those in Betaua Village, permeability tends to be higher because larger macropore sizes allow for faster water movement. However, in ecosystems dominated by vegetation from the *Casuarinaceae* family, this condition is not always linear. This is due to the phenomenon of soil water repellency (SWR), which can inhibit water infiltration into the soil. Research on *Casuarina equisetifolia* plantation soils shows that soil hydrophobicity can reduce infiltration rates and unsaturated hydraulic conductivity, especially under dry conditions (Leelamanie et al., 2021). It has been explained that organic layers such as litter and wax compounds from vegetation can form a hydrophobic layer on the surface of soil particles, thus inhibiting water penetration.

In fact, under certain conditions, water does not directly infiltrate the soil, but instead forms surface runoff. Furthermore, in former tin mining areas revegetated with *Casuarina equisetifolia*, the very sandy soil conditions (up to ±94%) indicate that water can move rapidly through the soil profile (Chen et al., 2024). However, the low organic matter content and damaged soil structure result in very low water retention capacity,

so that even with high permeability, the efficiency of water utilization by plants remains limited. The variation in permeability between Betaua Village and Podi Village is not only caused by differences in texture (sand vs. silt), but also by other factors such as organic matter content, soil pore distribution, and the possible presence of soil hydrophobicity. In Betaua Village, the high permeability due to the dominance of sand can be offset by the potential hydrophobicity that reduces

effective infiltration. Meanwhile, in Podi Village, with its finer texture, permeability tends to be lower, but its water-holding capacity is higher.

Soil Chemical Properties

Based on the analysis of the samples, the results of the soil chemical properties analysis are presented in Table 2 as follows:

Table 2. Chemical Properties of the Habitat of *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson

Parameter	Unit	Betaua A1	Betaua A2	Podi A1	Podi A2
Total N	%	0.12	0.08	0.08	0.03
Available P	ppm	3.07	5.27	2.03	3.26
Available K	ppm	185.51	165.69	185.77	192.50
pH	-	8.20	8.26	8.28	8.05
Organic C	%	1.71	1.67	1.37	1.36
C/N ratio	-	14.25	20.84	17.05	45.21
DHL	mS/cm	0.33	0.99	0.54	0.29
Moisture Content	%	9.77	6.83	17.21	16.46

Nitrogen (N)

Analysis results indicate that the total nitrogen content of the soil in the *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson habitat is low to very low, with values ranging from 0.03% to 0.12%. The highest value was found at the Betaua A1 site (0.12%), while the lowest value was found at Podi A2 (0.03%). In general, the locations in Betaua Village showed higher nitrogen content than those in Podi Village. The low nitrogen content at most of the study sites reflects the relatively nutrient-poor soil conditions common in ultramafic ecosystems. This type of soil is known to be limited in essential nutrients, including nitrogen, due to low organic matter content and soil chemistry that is less conducive to mineralization. However, the presence of *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson, a member of the Casuarinaceae family, provides an ecological advantage through its symbiotic relationship with Frankia bacteria, which fixes atmospheric nitrogen. This mechanism allows the plant to continue growing in soil conditions with low nitrogen content and contributes to a gradual increase in soil nitrogen.

Differences in nitrogen content between locations are thought to be influenced by several factors, including the availability of organic matter, the activity of soil microorganisms, and local environmental conditions. The higher nitrogen content at the Betaua location is likely related to the relatively higher organic matter content, which acts as a nitrogen source through decomposition. Conversely, the low nitrogen content at the Podi location, particularly in the area near the river (A2), may be influenced by leaching and sedimentation dynamics, which cause nutrient loss from the topsoil. Furthermore, finer soil textures and possible

environmental disturbances can also affect the activity of soil microorganisms in the nitrogen cycle. These results align with research on *Casuarina equisetifolia*, which showed that soil nitrogen content can decrease due to a decrease in organic matter and disruption of soil microbial activity, particularly in planting systems that do not support nutrient cycling. Furthermore, changes in the community structure of nitrogen-fixing microbes (diazotrophs) also affect nitrogen availability in the soil (Zhou et al., 2021). On the other hand, nitrogen content can be increased through the addition of organic matter, as demonstrated in research using biopore techniques, which increased soil nitrogen through increased decomposition activity (Nugraha et al., 2024).

Phosphorus (P)

Analysis results indicate that the available phosphorus (P) content in the *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson habitat is relatively low, with values ranging from 2.03 to 5.27 ppm. The highest value was found at the Betaua A2 site (5.27 ppm), while the lowest value was found at Podi A1 (2.03 ppm). In general, all study sites showed limited phosphorus availability. This low phosphorus content is a common characteristic of ultramafic soils, which are known to have low fertility due to limited essential nutrients, including phosphorus. Phosphorus in soil is generally in a form unavailable to plants because it is bound by soil minerals, especially at certain pH conditions, making its availability a major limiting factor for plant growth. Because the soil pH in this study was relatively alkaline (± 8), the low phosphorus availability can be explained by the mechanism of phosphate precipitation with cations such as calcium (Ca), which causes phosphorus

to become insoluble and difficult for plants to absorb. This indicates that in addition to total phosphorus, soil chemical factors such as pH also play a significant role in controlling phosphorus availability. These results align with research on the Casuarina ecosystem, which showed that soil phosphorus content is generally low and is a major limiting factor in the soil-plant system (Nong et al., 2025). Furthermore, other studies have shown that in soil ecological systems, phosphorus, along with nitrogen, is the element that most often limits plant productivity, especially in ecosystems with marginal soil conditions (Bao et al., 2023).

Furthermore, research on soils experiencing environmental stress, such as monoculture or degradation, shows that phosphorus content tends to decrease along with reduced organic matter and soil microbial activity (Moreira et al., 2025). This suggests that phosphorus cycling is highly dependent on biological processes, particularly the decomposition of organic matter. Comparing the study sites, the slightly higher phosphorus values in Betaua compared to Podi are likely related to more porous soil conditions and possibly higher organic matter content, which supports phosphorus mineralization. In contrast, at Podi sites, especially those near rivers, leaching and sediment deposition can cause uneven phosphorus distribution and tend to be lower.

Potassium (K)

Analysis results show that the available potassium (K) content in the *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson habitat ranges from 165.69–192.50 ppm. The highest value was found at Podi A2 (192.50 ppm), while the lowest value was found at Betaua A2 (165.69 ppm). In general, potassium content at all study sites was moderate to relatively high compared to other macronutrients such as nitrogen and phosphorus. Potassium is an essential nutrient that plays a role in various plant physiological processes, including stomatal regulation, water balance, and enzyme activation. Unlike nitrogen and phosphorus, which are strongly influenced by biological processes, potassium is more controlled by soil mineral factors and the weathering of parent material. In ultramafic soils, macronutrients such as nitrogen, phosphorus, and potassium are generally low due to extreme geochemical conditions. However, the results of this study indicate that potassium content is relatively higher than nitrogen and phosphorus, indicating a contribution from soil minerals or weathering processes that still provide some potassium. These results align with research on Casuarina ecosystems, which shows that soil potassium content can vary depending on environmental conditions and climatic factors, such as rainfall and soil moisture.

This variation suggests that potassium availability is determined not only by the parent material but also by environmental dynamics that influence the leaching and distribution of elements in the soil. Furthermore, research on Casuarina equisetifolia monoculture systems shows that soil potassium content can decrease with decreasing organic matter and soil microbial activity. This suggests that although potassium is not directly involved in the biological cycle like nitrogen, the presence of organic matter still plays a role in maintaining its availability in the soil. The relatively higher potassium levels at the Podi site, particularly near the river (A2), are thought to be related to the deposition of sedimentary material carrying nutrients, including potassium. Sediment carried by the water flow can provide an additional source of nutrients in the soil, increasing the potassium content at that location. Conversely, the relatively lower potassium values at the Betaua site may be due to the sandy soil conditions, which tend to have a low cation exchange capacity (CEC), making potassium more easily leached.

Soil pH

The analysis results showed that the soil pH values in the *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson habitat ranged from 8.05 to 8.28, indicating that all study sites have alkaline soil conditions. The highest pH value was found in Podi A1 (8.28), while the lowest value was found in Podi A2 (8.05). In general, there were no significant differences between the sites, but all were within the high pH range. This relatively alkaline pH value is a characteristic of ultramafic soils, influenced by the alkaline mineral content, particularly magnesium (Mg) and calcium (Ca), derived from the ultramafic parent rock. Furthermore, several types of ultramafic soils have also been reported to have high pH levels as a result of the weathering of peridotite and serpentinite rocks. Chemically, soil pH is a major factor controlling nutrient availability.

Under alkaline pH conditions, some essential nutrients, such as phosphorus, tend to precipitate and become unavailable to plants. This is consistent with the results of this study, which showed relatively low phosphorus levels across all locations, possibly influenced by high soil pH conditions. Furthermore, soil pH also affects the activity of soil microorganisms that play a role in nutrient cycling. Under certain pH conditions, microbial activity can be disrupted, impacting the decomposition of organic matter and nutrient mineralization. This suggests that pH not only directly influences nutrient availability but also indirectly through biological processes. These results are also supported by research showing that soil pH is a major factor determining soil quality and nutrient distribution in various land types, including disturbed

land such as mining activities (Paramasivam & Anbazhagan, 2020). In addition, other studies show that variations in soil pH can affect nutrient content and interactions between soil and plants in an ecosystem.

Organic Carbon

The analysis results show that the soil organic carbon content in the *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson habitat ranged from 1.36 to 1.71%. The highest value was found at the Betaua A1 site (1.71%), while the lowest value was found at Podi A2 (1.36%). In general, the organic carbon content at all sites was low to moderate, indicating that the soil at the study site has relatively limited fertility. This low organic carbon content is a common characteristic of ultramafic soils, which are known to have low organic matter content due to extreme environmental conditions and limited litter input and soil biological activity. Furthermore, nutrient-poor soil conditions can also slow the decomposition process, resulting in less than optimal organic matter cycling in the soil. Organic carbon is an important component of soil because it plays a role in increasing cation exchange capacity (CEC), improving soil structure, and providing an energy source for soil microorganisms. Therefore, organic carbon content is closely related to the availability of other nutrients, particularly nitrogen and phosphorus.

These results align with research in ultramafic ecosystems, which shows that soil organic carbon content is relatively low, yet still plays a crucial role in supporting ecosystem functions, including carbon storage and nutrient cycling (De Castro et al., 2025). Furthermore, research in *Casuarina equisetifolia* systems indicates that soil organic matter content can decrease due to soil degradation or repeated cropping systems, which impacts overall soil quality. Furthermore, other research indicates that organic carbon content is strongly influenced by environmental factors such as vegetation, soil moisture, and soil microbial activity. This suggests that variations in organic carbon content between locations may reflect differences in local ecosystem conditions.

C/N Ratio

The analysis results show that the soil C/N ratio in the *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson habitat varies significantly, with values ranging from 14.25 to 45.21. The lowest value was found at the Betaua A1 site (14.25), while the highest value was found at Podi A2 (45.21). This variation indicates differences in the rate of organic matter decomposition and nitrogen dynamics between the study sites. The C/N ratio is an important indicator in determining the rate of organic matter decomposition and the availability of nitrogen in the soil. A low C/N value ($\pm 10-15$) generally indicates that

the organic matter has decomposed well and that nitrogen is more available to plants. Conversely, a high C/N value (>25) indicates that the decomposition process is slow and that nitrogen tends to be bound in organic form, making it less available to plants. The C/N value at the Betaua site (14.25–20.84) indicates relatively better decomposition conditions, resulting in greater nitrogen availability. This is consistent with the relatively higher nitrogen content at that site. Conversely, the very high C/N value at the Podi A2 site (45.21) indicates an imbalance between carbon and nitrogen, indicating a slow decomposition process and the possibility of nitrogen immobilization by soil microorganisms.

This condition can be influenced by several factors, such as organic matter content, soil texture, and local environmental conditions. At Podi sites, particularly those near rivers, the dominance of dust fractions and the possible deposition of incompletely decomposed organic matter can lead to high C/N ratios. These results align with research showing that the C/N ratio is a key indicator in nutrient cycling, particularly in determining the balance between nitrogen mineralization and immobilization. Additionally, other research shows that changes in the C/N ratio can occur due to changes in soil conditions, such as land degradation or certain planting systems, which affect organic matter content and microbial activity. Furthermore, in forest ecosystems, the C/N ratio is also influenced by the quality of plant litter and the activity of soil microorganisms that play a role in the decomposition process. This suggests that the C/N ratio reflects not only the chemical conditions of the soil but also the biological dynamics occurring within it.

Electrical Conductivity (DHL)

The analysis results show that the soil electrical conductivity (DHL) values in the *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson habitat ranged from 0.29–0.99 mS/cm. The highest value was found at the Betaua A2 site (0.99 mS/cm), while the lowest value was found at Podi A2 (0.29 mS/cm). In general, the DHL values at all study sites were low to moderate, indicating relatively low dissolved salt content in the soil. DHL is an important parameter in assessing the concentration of dissolved ions in the soil, such as cations and anions (e.g., Ca^{2+} , Mg^{2+} , K^+ , Na^+ , Cl^-), which play a role in determining soil fertility and salinity conditions. Low DHL values generally indicate that the soil is not experiencing salinity problems and therefore still supports plant growth. Ultramafic soils generally contain low levels of essential nutrients, but they can contain various metal ions derived from the parent rock material. The relatively low DHL values in this study indicate that, although the soil is derived from ultramafic material, the concentration of dissolved ions

is not high enough to cause salinity conditions that inhibit plant growth (Gao et al., 2024).

These results align with research showing that DHL values are an important indicator in assessing soil quality, especially in areas experiencing disturbances such as mining activities or land-use changes (Riwanto & Ningrum, 2025). Furthermore, in ecosystems influenced by vegetation, such as Casuarina, DHL values can also be influenced by the accumulation of organic matter and interactions between soil and water (Ngom et al., 2020). Considering the study site conditions, the higher DHL values in Betaua A2 are thought to be related to higher accumulation of dissolved ions, which may originate from mineral weathering or groundwater movement. Conversely, the lower DHL value at Podi A2 may be due to leaching due to water flow, which reduces dissolved ions in the soil.

Soil Water Content

The analysis results show that the soil water content in the *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson habitat ranges from 6.83–17.21%. The highest value was found at Podi A1 (17.21%), while the lowest value was found at Betaua A2 (6.83%). In general, the soil water content at the Podi site is higher than that at Betaua. This difference in water content is closely related to soil texture characteristics and local environmental conditions. At the Podi site, which is dominated by silt fractions, the soil has a higher water-holding capacity due to smaller pore sizes, allowing water to be retained in the soil for longer. Conversely, at the Betaua site, which is dominated by sand fractions, water percolates more quickly, resulting in a relatively lower soil water content. Soil water content is a crucial factor influencing various physical, chemical, and biological processes in the soil.

Adequate water content increases nutrient solubility, making it easier for plants to absorb them. Furthermore, water content plays a role in controlling the activity of soil microorganisms involved in organic matter decomposition and nutrient cycling. These results align with research showing that soil water content significantly influences nutrient dynamics, particularly carbon, nitrogen, and phosphorus, in the soil-plant system (Muhanniah, 2024). Furthermore, changes in soil moisture conditions, such as those caused by variations in rainfall, can affect nutrient availability and interactions between soil and plants (Zlatić et al., 2023). Furthermore, soil water content is also related to environmental conditions such as proximity to water sources. At the Podi site, which is close to a river, soil water content tends to be higher due to the influence of environmental humidity and the possible availability of water from the local hydrological system. Conversely, at the drier, coarse-textured Betaua site, soil water content

is lower because water is lost more rapidly through infiltration and evaporation.

Conclusion

Soil characteristics in the habitat of *Gymnostoma rumphianum* (Miq.) L.A.S. Johnson in Tojo Una-Una Regency demonstrate a close relationship between physical and chemical properties in determining soil fertility. Soil texture is the primary controlling factor, with sandy soil in Betaua Village exhibiting lower bulk density, higher permeability, and lower water content, while finer-textured soil in Podi Village exhibits the opposite. Chemically, the soil at all locations has an alkaline pH (8.05–8.28), which reduces phosphorus availability, making this element the primary limiting factor. Nitrogen and organic carbon contents are low to moderate, with variations influenced by organic matter conditions and decomposition processes, as reflected in the C/N ratio. Meanwhile, potassium is relatively available and not a limiting factor, and the low DHL value indicates the absence of salinity stress in the soil. Future research is recommended to examine different locations and soil depths to obtain a more comprehensive picture of the soil characteristics in this habitat.

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Author Contributions

Conceptualization; R.; methodology.; Y.; validation; R. W.; formal analysis; R.; investigation; R. P.; resources; R.; data curation; Y.; writing – original draft preparation; Z.; writing – review and editing.; R. W.; visualization: R. and R. P. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The researchers funded this research independently.

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