

## Soil properties and climatic characteristics of lowland Tayu Tea (*Camellia sinensis* L) in West Bangka, Indonesia

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### ABSTRACT

Tayu tea (*Camellia sinensis* var. *sinensis*) is a local tea plant variety cultivated in the lowland areas of Bangka Barat Regency, a region that is uncommon for tea plantations. Tea plants are generally preferred to grow optimally in highland areas. This study aimed to evaluate soil fertility status and land suitability for Tayu tea cultivation based on soil chemical properties and agroclimatic conditions. In this regard, soil samples were taken from local Tayu tea plantations, and several key parameters, including soil pH, organic carbon, total nitrogen, available phosphorus, and exchangeable potassium, were analyzed. Additionally, agroclimatic data such as temperature and rainfall over the past year were used to describe the growing environment. Soil analysis showed that pH, nitrogen, organic carbon, and potassium levels are within acceptable ranges, but phosphorus was elevated and cation exchange capacity was reduced. Climate factors like precipitation, soil temperature, and solar radiation may limit growth of tea plants. PCA indicates that soil chemistry, especially phosphorus, influences flavonoid levels, and potassium differentiates locations, significantly affecting bioactive compound contents in Tea leaves. Organic carbon, nitrogen, and CEC impact phenolic compounds. These results suggest that Tayu tea can grow in lowland conditions, although environmental constraints may potentially affect its productivity. This research provides basic information for developing and managing tea cultivation in similar environmental conditions.

Keywords: *Camellia sinensis* var. *sinensis*, lowland tea, properties, soil chemical, Tayu tea

### INTRODUCTION

Soil fertility is essential for plant growth, productivity, and the quality of plant-derived products. In perennial crops such as tea (*Camellia sinensis* L.), soil physicochemical properties—including pH, organic matter, and nutrient availability—interact with climatic factors to regulate plant metabolism and adaptation (Oishy et al., 2025; Ren et al., 2025). These interactions become particularly important when crops are cultivated outside their typical ecological range.

The tea plant (*C. sinensis* L.) is typically associated with highland regions, where cooler temperatures and specific soil conditions are believed to be ideal for its growth and quality enhancement (Han et al., 2018; Liu et al., 2023).

In Bangka Barat, a local variant called Tayu tea has been seen growing in lowland areas. This unusual ecological setting for tea cultivation indicates specific soil and climate conditions that enable its cultivation.

Understanding soil and climate in atypical environments is key to explaining how tea plants grow and maintain quality under non-ideal conditions. Soil properties may compensate for environmental limitations, while local climatic conditions may interact with edaphic factors to create a suitable microenvironment (Bania et al., 2025; Karak et al., 2015; Zheng et al., 2012). Despite its potential significance, few studies have comprehensively reported soil fertility and climatic conditions in Tayu tea cultivation as a lowland *sinensis* tea variety.

Furthermore, interactions between soil fertility parameters and plant biochemical characteristics are often complex and involve numerous correlated variables. To clarify these relationships, multivariate statistical techniques such as Principal Component Analysis (PCA) has been used to identify the interaction between soil properties and bioactive variables. This approach enables the identification of dominant soil factors that may contribute to variations in the biochemical characteristics of Tayu tea grown under lowland conditions.

Therefore, this study aimed to characterize the soil properties and climatic conditions of a lowland Tayu tea plantation in Bangka Barat, and evaluate the associations between soil properties and bioactive characteristics using a multivariate approach. The findings are expected to provide a scientific basis for understanding the soil

characteristics and environmental conditions that support lowland Tayu tea cultivation and to serve as a reference for site-specific soil management and future tea development in similar environments.

## MATERIALS AND METHODS

This research was conducted by selecting three farmer plantations in Ketap Village, Jebus District, the largest Tayu tea-producing area in Bangka Belitung, Indonesia, as the sampling sites. The sampling sites were located in the primary tea cultivation areas, at elevations of approximately <50 meters above sea level. These locations were determined based on interviews with tea farmers who have long managed the plantations, as well as field observations. Figure 1 showed the locations.

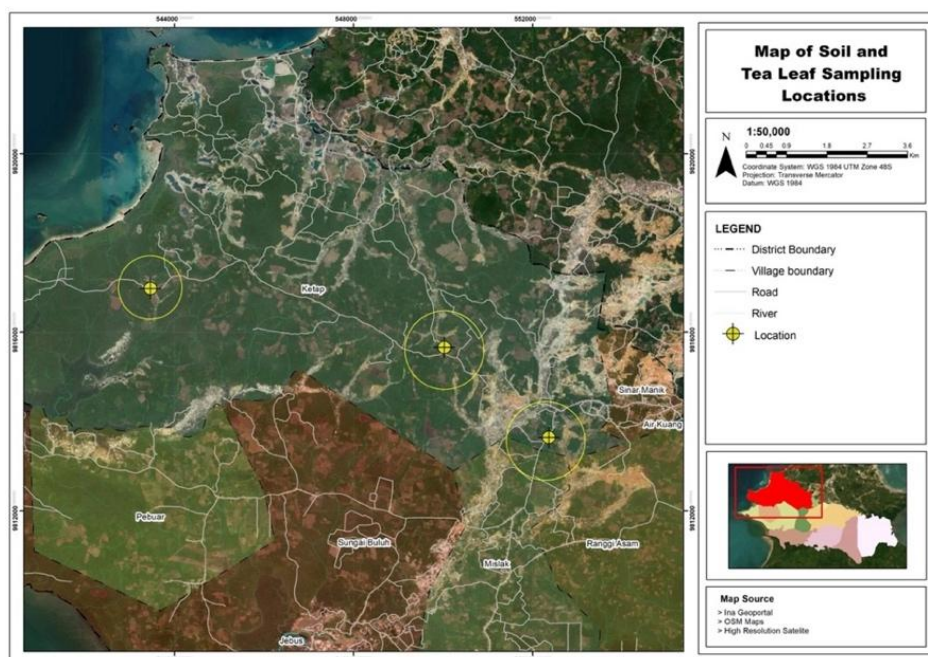


Figure 1. Map of soil sampling location

### Soil Sampling and Analysis

Soil samples were collected from three distinct points surrounding the tea plants at each specified site, at a depth of 0-20 cm. At each location, soil samples were collected in three replicates. Each replicate consisted of a composite sample prepared by combining soil from three sub-points surrounding the tea plants and then thoroughly homogenizing it. Analytical procedures included pH measurement using a water extract; organic carbon assessment via the Walkley-Black

spectrophotometric method; cation exchange capacity measured by ammonium saturation with 1N  $\text{NH}_4\text{OAc}$  at pH 7; total nitrogen quantification through the Kjeldahl titrimetric method; available phosphorus determined by Bray II spectrophotometry; and exchangeable potassium analyzed via flame photometry. Furthermore, mean climatic data were sourced from the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) to support environmental evaluation.

### Tea Leaves Sampling and Analysis

Leaf samples were collected from healthy plants near soil sampling points, with three samples per site. Bioactive compounds analyzed included total polyphenols via the Folin-Ciocalteu method (Musci & Yao, 2017), total flavonoids by spectrophotometry, tannins using the AOAC method (AOAC, 1990), and caffeine with the Shao and Zhang method. GABA levels were measured using the Acquity UPLC H-Class system with minor modifications.

### Data Analysis

Soil chemical parameters and bioactive compounds concentrations were assessed descriptively at each sampling location, with three sampling points considered as replicates. Additionally, Principal Component Analysis (PCA) was performed to investigate multivariate patterns and elucidate the intricate interaction between soil chemical characteristics and bioactive components in Tayu tea (*Camellia sinensis* var. *sinensis*) in the lowlands of West Bangka. The analysis was conducted using Python on the Google Colab platform. The main components were extracted based on eigenvalues  $>1$  to identify the variables that contribute most to data variation. The PCA results were visualized using a biplot to show the relationships between variables and the distribution of samples based on the principal components.

## RESULTS

The tea plantations analyzed in this research were collectively owned by the community and displayed a variety of characteristics, including different ages, locations, and agricultural practices (Figure 1). Plantation A is a 12-year-old community garden with a harvest frequency of 2-3 times a month. The plantation was fertilized twice a year with urea. Plantation B was 15 years old with a harvest frequency of 3 times a month and fertilization twice a year using NaCl. Plantation C, also known as the 150-year-old historical garden, was harvested twice a month and fertilized twice a year using a combination of NaCl and urea (Table 1). Observations from three locations show that the soil in which Tayu tea was cultivated has an average pH of 4.78 in the Tayu

tea plantation in Ketap Village, Bangka Belitung (Table 2).

The soil characteristics of the Tayu tea plantation showed that the average pH is 4.78, the average Total N was 160 g/kg, and the average organic C was 25.80 g/kg. Plantation 1 has the lowest organic C (21.90 g/kg), followed by Plantation 3 (27.00 g/kg), with Plantation 2 the highest (28.60 g/kg). The average exchangeable K is 78.20 mg/kg, with the lowest recorded at Plantation 1 (66.47 mg/kg) and the highest at Plantation 2 (93.84 mg/kg). For available P, Plantation 1 has the highest (52.27 ppm), and Plantation 2 the lowest (7.51 ppm). For CEC, Plantation 3 had the highest (4.20 cmol/kg), and Plantation 1 had the lowest (2.53 cmol/kg). For the physical characteristics, the average water-holding capacity of the Tayu plantation is 25.48%, and the soil texture was sandy loam. The characteristics shown in Figure 2. Agroclimatic data for September 2024 to September 2025 were sourced from the BMKG and calculated as annual averages (Table 3). The data show that at the Tayu tea plantation, total annual precipitation was 4440 mm, mean air temperature was 27.72 °C, average relative humidity was 82.62%, mean soil temperature was 28.65 °C, and average daily solar radiation was 4.82 kWh/m<sup>2</sup>.

Principal Component Analysis (PCA) was used to condense the 11 data variables into a more comprehensible and interpretable collection of dimensions. In accordance with Kaiser's Criterion (Eigenvalue  $\geq 1$ ), four Principal Components (PC1, PC2, PC3, and PC4) were effectively extracted. The extraction process is carried out based on the correlation matrix to identify the main dimensions that can represent the greatest variation in the dataset.

The four components combined accounted for 88.945% of the total variance in the data (Table 4), demonstrating PCA's efficacy in preserving most of the original information. The Biplot (Figure 2) visualizes only PC1 and PC2, which account for 62.210% of the variance; however, the Rotated Component Matrix (Table 5) provides a comprehensive interpretation of all four major components. The interpretation of soil properties in the Tayu tea plantation was supported by comparison with commonly reported land suitability criteria for tea cultivation, as outlined in FAO guidelines (Table 6).

Table 1. Characteristics of Tea Plantations in Ketap Village

| Parameter                 | Plantation A                  | Plantation B               | Plantation C                               |
|---------------------------|-------------------------------|----------------------------|--------------------------------------------|
| Age (years)               | 12                            | 15                         | 150                                        |
| Harvest frequency         | 2 – 3 times a month           | 3 times a month            | 2 times a month                            |
| Fertilization             | Twice a year using Urea       | Twice a year using NaCl    | Twice a year using NaCl and Urea           |
| Land Use Surrounding Area | Oil palm area; near coastline | Within oil palm plantation | Residential area; intercropped with durian |
| Coordinates               | 1.65584° S, 105.39080° E      | 1.66776° S, 105.44980° E   | 1.68602° S, 105.47078° E                   |
| Elevation                 | 34 masl                       | 35 masl                    | 33 masl                                    |

Table 2. Soil Physical and Chemical Properties of the Sampled Tea Plantations

| Parameter                  | Location 1    | Location 2   | Location 3    | Grand Mean    |
|----------------------------|---------------|--------------|---------------|---------------|
| pH                         | 4.79 ± 0.13   | 4.82 ± 0.07  | 4.75 ± 0.22   | 4.78 ± 0.14   |
| Total N (g/kg)             | 1.40 ± 0.01   | 1.80 ± 0.00  | 1.60 ± 0.03   | 1.60 ± 0.01   |
| Organic C (g/kg)           | 21.90 ± 0.49  | 28.60 ± 0.22 | 27.00 ± 0.80  | 25.80 ± 0.50  |
| Exchangeable K (mg/kg)     | 66.47 ± 0.02  | 93.84 ± 0.00 | 74.29 ± 0.00  | 78.20 ± 0.00  |
| Available P (ppm)          | 52.27 ± 24.40 | 7.51 ± 1.90  | 17.68 ± 10.37 | 25.82 ± 12.22 |
| CEC (cmol/kg)              | 2.53 ± 0.14   | 3.41 ± 0.47  | 4.20 ± 0.14   | 3.38 ± 0.25   |
| Water Holding Capacity (%) | 22.83 ± 0.12  | 29.46 ± 0.09 | 24.14 ± 0.11  | 25.48 ± 0.11  |
| Soil texture               | Sandy loam    | Sandy loam   | Sandy loam    | -             |

Note: Mean ± SD values from 3 sampling points per location

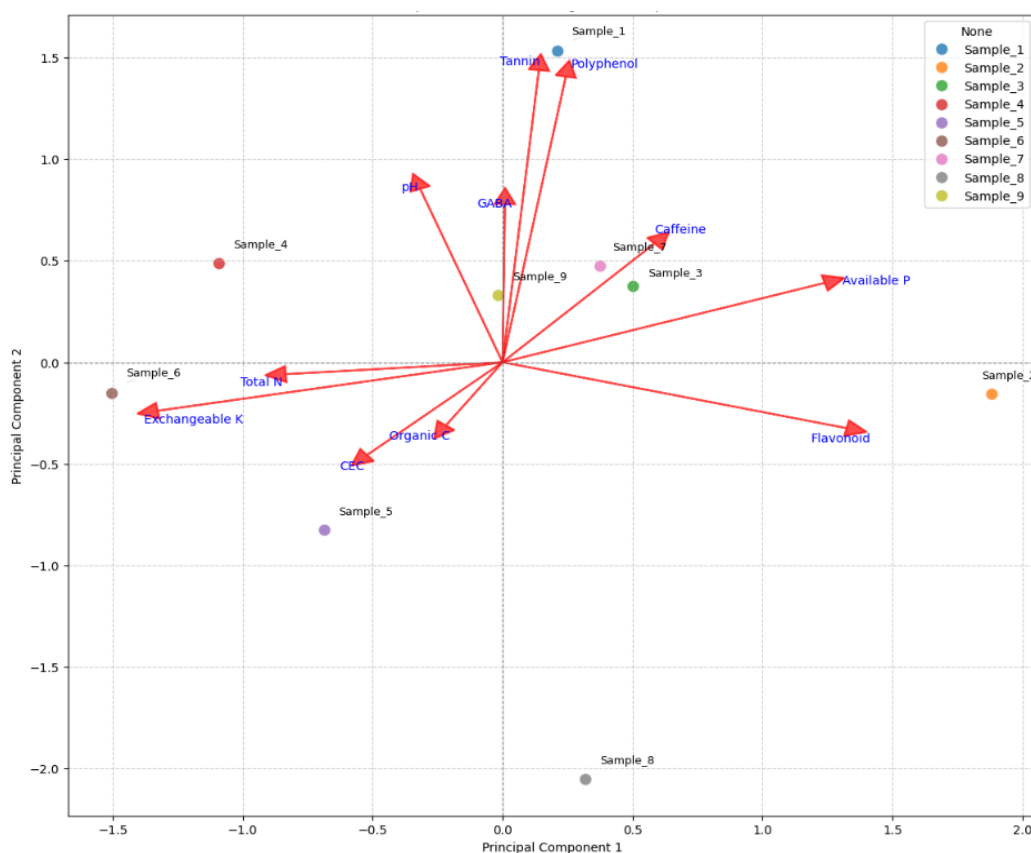


Figure 2. Biplot of Principal Component Analysis (PCA) Showing PC1 vs PC2

Table 3. Summary of meteorological parameters in the tea-growing sites (September 2024 – September 2025)

| Parameter                                               | Value |
|---------------------------------------------------------|-------|
| Annual Total Precipitation (mm/year)                    | 4440  |
| Main air temperature (°C)                               | 27.72 |
| Mean Relative Humidity (%)                              | 82.62 |
| Mean Soil Temperature (°C)                              | 28.65 |
| Average Daily Solar Radiation (kWh/m <sup>2</sup> /day) | 4.82  |

Table 4. Total variance explained

| Comp onent | Initial Eigenvalues |               |              | Extraction Sums of Squared Loadings |               |              |
|------------|---------------------|---------------|--------------|-------------------------------------|---------------|--------------|
|            | Total               | % of Variance | Cumulative % | Total                               | % of Variance | Cumulative % |
| 1          | 4.220               | 38.361        | 38.261       | 4.220                               | 38.361        | 38.261       |
| 2          | 2.623               | 23.849        | 62.210       | 2.623                               | 23.849        | 62.210       |
| 3          | 1.918               | 17.440        | 79.649       | 1.918                               | 17.440        | 79.649       |
| 4          | 1.023               | 9.296         | 88.945       | 1.023                               | 9.296         | 88.945       |

Table 5. Rotated component matrix (Varimax)

| Variable   | Component 1 | Component 2 | Component 3 | Component 4 |
|------------|-------------|-------------|-------------|-------------|
| pH         | -0.211      | 0.568       | 0.651       | -0.095      |
| TN         | -0.555      | -0.039      | 0.802       | 0.147       |
| Org-C      | -0.145      | -0.207      | 0.893       | 0.106       |
| Ex. K      | -0.883      | -0.159      | 0.230       | 0.044       |
| Av. P      | 0.825       | 0.260       | -0.145      | -0.225      |
| CEC        | -0.347      | -0.304      | 0.040       | 0.849       |
| Flavonoid  | 0.881       | -0.216      | -0.209      | 0.297       |
| Polyphenol | 0.162       | 0.936       | -0.162      | -0.110      |
| Caffeine   | 0.389       | 0.389       | 0.092       | 0.817       |
| Tannin     | 0.093       | 0.957       | 0.015       | 0.051       |
| GABA       | 0.006       | 0.518       | -0.437      | -0.513      |

Table 6. FAO-based land suitability classification for Tea (*Camellia sinensis*) cultivation

| Parameter    | S1 (Highly Suitable)                                            | S2 (Moderately Suitable)          | S3 (Marginally Suitable)                | N (Not Suitable) | Reference                                       |
|--------------|-----------------------------------------------------------------|-----------------------------------|-----------------------------------------|------------------|-------------------------------------------------|
| pH           | 4.5–5.5                                                         | 5.1–6.0/4.4–4.0                   | 6.1–6.5, <4.09                          | >6.5             | Rahaman & Aruchamy 2022; FAO 1976               |
| Soil Texture | Sand-Clay-Silt mixture, Loamy Sand, Clay, Sandy Loam, Silt Loam | Clay, Silty Clay Loam, Silty Clay | Clay (with some sand), Loamy Sand, Sand | Clay, sandy      | Rahaman & Aruchamy 2022; Jayasinghe et al. 2019 |
| Rainfall     | 2500-3500                                                       | 2000-2500                         | 1500-2000                               | 1000-1500        | Jayasinghe et al. 2019                          |
| Elevation    | 300-2000 m                                                      | 2000-2500 m                       | 100-300                                 | 0-100 m          | Jayasinghe et al. 2019                          |

## DISCUSSION

### Soil Properties of the Study Area

Tayu tea is a lowland tea species, the sole variety in the Bangka Belitung Islands, recognized as Indonesia's largest tin-producing area (Haryadi et al., 2025). This region has soil properties that are inadequate for several crop varieties. The interpretation of soil properties in the Tayu tea plantation was supported by comparison with commonly reported land suitability criteria for tea cultivation, as outlined in FAO guidelines (Table 6). However, this comparison was used solely as a literature reference and does not constitute a formal land suitability assessment.

Observations from three locations show that the soil in which Tayu tea is cultivated has an average pH of 4.78 in the Tayu tea plantation in

Ketap Village, Bangka Belitung (Table 2). Rahaman & Aruchamy (2022) assert that this pH value falls within the S1 (highly recommended) compatibility classification for tea plants. Tea prefers and tolerates acidic soils and the presence of aluminum (Al) in the soil; it requires Al for optimal growth (Ding et al., 2021). These parameters illustrate the viability of Tayu tea as a crop for marginal soils, with respect to pH and aluminum availability.

Nitrogen is an essential nutrient element that plays a vital role in vegetative growth, chlorophyll synthesis, and protein formation in tea plants (Zhang et al., 2023). Therefore, soil nitrogen levels are important to know because they can reflect soil fertility status and its potential to influence the formation of bioactive compounds in tea leaves. Tayu tea soil has total nitrogen (N)

levels of 1.4, 1.8, and 1.6 g/kg, as shown by its chemical properties (Table 3). These results align with prior research that examined nitrogen levels in diverse tea plantations. Karak et al. (2015) reported total nitrogen contents of 0.24–2.06 g/kg and 0.41–3.60 g/kg in tea plantations in India, particularly in the Dibrugarh and Tinsukia areas, respectively. At the research sites in Yangmei, Taoyuan County, Northern Taiwan, and Luku, Nantou County, Central Taiwan, the total nitrogen concentrations ranged from 0.6 to 1.9 g/kg (Chen et al., 2006). Tea plantations in Mengding Mountain, Sichuan Province, China, showed comparable total nitrogen content (Zheng et al., 2012).

Organic carbon is crucial for tea plants, serving as a primary indicator of soil fertility and root ecosystem health. Elevated organic carbon levels enhance the soil's ability to store water and nutrients, hence promoting sustainable nutrient availability for tea plants (Han et al., 2018). Wang et al. (2024) reported that soil organic carbon peaks in plantations aged 16–20 years; however, in plantations aged 35 years or older, organic carbon content generally declines. This study reveals that in a 150-year-old tea plantation, organic carbon content varied by only 1.6 g/kg compared with a 15-year-old plantation and was higher than in other plantations. This occurrence indicates that, despite plants' advancing age, environmental and management factors continue to sustain soil carbon stocks. The elements encompass the vegetation surrounding the plantation, an effective land-cover system, a favourable climate, and minimal disturbance from cultivation. In old plantations, the stability of organic carbon as humus and in mineral bonds has likely reached equilibrium, resulting in an insignificant decline in organic carbon levels. Moreover, the particular characteristics of Tayu tea plantations, characterized by relatively fine soil texture (sandy loam) and adequate drainage, might hinder the decomposition of organic matter.

The organic carbon levels in Tayu tea plantations are considered acceptable (21.90; 28.60; 27.00 g/kg) and comparable to various tea plantations in India; soils in Dibrugarh District exhibit organic carbon levels between 2.4 and 24.6 g/kg, whereas Tinsukia District shows a range of 3.1 to 47.3 g/kg (Karak et al., 2015). In addition, it has been reported that soil with organic carbon

levels exceeding 1 g/kg is adequate for intensive tea cultivation and an effective fertilization response. Consequently, the organic carbon levels in Tayu tea plantations are deemed elevated. This condition is probably attributable to farmers' practice of leaving prunings or fallen tea leaves on the land, which facilitates the decomposition of organic matter and enhances soil organic carbon content. The increased organic carbon content enhanced the soil's water retention capacity in gardens 1, 2, and 3, with values of 22.83%, 29.46%, and 24.14%, respectively.

Potassium (K) is vital for tea plants because it supports water regulation, enzyme activity, shoot development, flavor quality, and stress resilience. This study assessed exchangeable K, which is potassium associated with soil colloids and may be exchanged, thus serving as a reserve for plants. Measurements in Tayu tea fields indicated that the exchangeable potassium levels in gardens 1, 2, and 3 were 66.47, 93.84, and 74.29 mg/kg, respectively. Numerous studies in other tea-producing nations have also documented exchangeable potassium in their crops. During the 2009–2010 period, the mean exchangeable potassium across 54 districts across 16 principal tea-producing provinces in China was 81 mg/kg, with 73% of samples exhibiting exchangeable potassium levels below 100 mg/kg (Ruan et al., 2013). Compared with conditions in Tayu tea gardens, the observed exchangeable potassium values were typical and consistent with regions conducive to optimal tea cultivation. High potassium levels can correlate positively with accessible potassium, particularly when soil pH is moderately high, soil texture is not excessively fine or clayey, and organic carbon content is substantial, as shown in Tayu tea plantations. This relates to potassium fixation and the soil's nutrient-retention capacity. Karak et al. (2015) assert that potassium values between 60 and 100 mg/kg are deemed reasonable for tea plants. If the potassium availability in Tayu tea fields is calculated from the exchangeable potassium values, the land's potential for tea cultivation is typically regarded as moderate.

Available phosphorus (available P) refers to the fraction of total soil phosphorus that is accessible for plant absorption, often as  $\text{H}_2\text{PO}_4^-$  and  $\text{H}_4^{2-}$  ions in the soil solution. This form represents the "active" phosphorus that the tea plant's roots can

immediately absorb. The phosphorus concentration at the Tayu tea plantation varied across several observed locations. The values recorded in plantings 1, 2, and 3 were 52.27, 7.52, and 17.68 mg/kg, respectively. The difference may be due to microbial activity that converts insoluble phosphorus into soluble forms, or to the increased iron and aluminum content observed in plantation 2, which leads to increased phosphorus fixation and reduced availability. Wu et al. (2020) indicated that in traditional tea plantations in Baisha County, Hainan Province, the accessible phosphorus content at depths of 0–10 cm and 10–20 cm was 9.97 mg/kg and 4.48 mg/kg, respectively. In contrast, organic tea plantations had significantly higher levels, measuring 28.64% and 34.95% at the corresponding depths. Tayu tea is farmed using conventional methods; thus, compared with data from Baisha County, the phosphorus content in Tayu tea fields is elevated, despite farmers indicating in interviews that they did not apply phosphorus fertilizer. The results suggest that the Tayu tea fields in Ketap Village have an adequately accessible phosphorus concentration; however, further investigation of aluminum and iron content is necessary, as both may influence phosphorus availability in the soil.

This study also reveals cation exchange capacity (CEC) values of 2.53, 3.41, and 4.20 cmol(+)/kg at three Tayu tea farms in Ketap Village. The observed values are significantly lower than those documented in prior studies on *Camellia sinensis* var. *sinensis* plantations, including findings by Yong-dong et al. (2008) in Mengding Mountain, Ya'an, Sichuan, China (7.53–20.76 cmol(+)/kg), and Wang et al. (2020) in Hengxian, Guangxi, China (8.33–12.38 cmol(+)/kg), where cation exchange capacity tends to rise with plantation age. The low cation exchange capacity (CEC) in Tayu tea plantations can be related to various pedogenic factors, including a primarily sandy loam soil texture, an acidic pH (~4.7) that diminishes certain pH-dependent cation exchange sites, and a possible predominance of  $\text{Al}^{3+}$  and  $\text{H}^{+}$  ions that lowers the effective exchange capacity for plant nutrients. Despite the moderate organic carbon content, which should enhance cation exchange capacity by holding and attracting cations, these environmental factors still result in a lower cation exchange capacity than at comparable tea farms

under optimal conditions. The results reveal that the soil at the Tayu tea plantations have limited capacity to retain cations.

### Annual Climatic Conditions in the Study Area

Table 3 shows agroclimatic data for the period from September 2024 to September 2025. Data indicate an annual precipitation of 4,440 mm, a mean air temperature of 27.72 °C, an average relative humidity of 82.62%, a mean soil temperature of 28.65 °C, and an average daily solar radiation of 4.82 kWh/m<sup>2</sup>. Although the findings cover only one year, this information provides a synopsis of the agroclimatic conditions experienced by the Tayu tea plantation in Ketap Village, which is essential for explaining plant growth and the accumulation of bioactive chemicals.

The documented precipitation exceeded the ideal standard established by Jayasinghe et al. (2019), which defines class S1 as 2,500–3,500 mm/year (Table 6). Rainfall exceeding this ideal range affects soil dynamics and nutrient availability, especially in sandy-clay-textured soils at the research location. Excessive precipitation can enhance the leaching of base and phosphorus ions from the soil profile, consequently deteriorating nutrient availability in soils with low cation exchange capacity (CEC). Moreover, excessive moisture may increase the risk of waterlogging and root infections, while also altering abiotic stressors in plants and thereby affecting secondary metabolite production. The resilience of Tayu tea under extremely high rainfall makes it a viable crop for cultivation amid significant climatic changes.

The annual relative humidity at Ketap Village is 82.62%, falling within the ideal range (80–85%) for cultivating *Camellia sinensis* var. Tayu (Han et al., 2018). This humidity level facilitates consistent transpiration, preserves plant transpiration, and mitigates excessive water loss. Maintaining optimal humidity is crucial for preserving the quality of early shoots and mitigating the risk of physiological stress that may compromise their quality. Consequently, the study site is classified as S1 (extremely favorable) for tea var. *sinensis* growth in terms of relative humidity (Han et al., 2018), and this factor is not a major constraint on production. A slight difference in the humidity trend is observed. The

average yearly temperature of 27.72 °C marginally exceeds the optimum (18–23 °C) and normal (13–26 °C) limits for the tea *sinensis* variety. This indicates that temperature could be a minor limiting factor in lowland tea-producing systems. High temperatures can enhance respiration rates, accelerate leaf development, and diminish the formation of specific secondary metabolites. The Tayu tea population, generally suited to lowland conditions, can sustain stable development even when temperatures exceed those of its native subtropical habitat. Consequently, the annual temperature in Ketap Village is categorized as S2 (quite suitable)—suboptimal yet favorable for sustainable agriculture, particularly with increased humidity and precipitation (Han et al., 2018).

Measurements indicate that the mean soil temperature in the Tayu tea plantation reached 28.65 °C, while the average daily solar radiation of 4.8 kWh/m<sup>2</sup>/day is considered moderate for tropical regions (Pradana et al., 2023). The soil temperature is comparatively high relative to the ideal range for the cultivation of *Camellia sinensis* var. *sinensis* (18–25 °C) (Tantonf, 1982), although it remains supportive to the growth of Tayu tea populations that have acclimatized to tropical lowlands. Elevated soil temperatures can enhance root respiration rates and accelerate organic matter decomposition (Kotroczo et al., 2014), consistent with observations of soil chemical properties, in which organic carbon concentration remains relatively normal. Furthermore, soil temperature significantly influences nutrient availability, including nitrogen (N) and phosphorus (P) (Gavito et al., 2001). High temperatures enhance soil microbial activity, leading to accelerated breakdown of organic materials. Consequently, organic nitrogen in organic matter is transformed into mineral forms ( $\text{NH}_4^+ \rightarrow \text{NO}_3^-$ ) that are more easily assimilated by roots. Phosphorus, typically associated with  $\text{Al}^{3+}$ ,  $\text{Fe}^{3+}$ , or  $\text{Ca}^{2+}$  complexes, is influenced by soil temperature; higher temperatures may accelerate the breakdown of P into  $\text{H}_2\text{PO}_4^-$  or  $\text{HPO}_4^{2-}$  forms accessible to plants. This scenario helps explain why nitrogen levels in the Tayu tea plantation are somewhat normal, even though phosphorus is present in high quantities. Moreover, this adequate light intensity facilitates photosynthesis and carbohydrate accumulation, which are essential precursors for

the production of secondary metabolites. The combination of high soil temperatures and moderate radiation can induce mild abiotic stress, prompting adaptive responses in plants, including alterations in stomatal distribution and modifications in secondary metabolism to preserve shoot leaf quality (Qaderi et al., 2023). The daily soil temperature and radiation parameters in the Tayu tea plantation indicate a suboptimal lowland tropical environment for subtropical tea varieties. Tayu tea has altered its physiology and secondary metabolism to sustain high-quality leaf production, suggesting potential adaptation to climate change and rising temperatures. The distinctiveness of *Camellia sinensis* var. Tayu in Ketap Village is evident in its capacity to thrive in tropical lowlands characterized by high soil temperatures, ideal humidity, high precipitation, and moderate daily solar radiation. These climatic conditions suggest that the Tayu tea population has evolved physiologically to environmental stresses distinct from those of typical subtropical cultivars. Elevated soil temperatures, consistent humidity, and abundant precipitation facilitate plant growth and nutrient uptake, but they exceed the ideal range for subtropical species. Increasing global temperatures and altered precipitation patterns resulting from climate change suggest that Tayu tea can acclimatize to elevated heat and humidity in tropical environments. Consequently, agroclimatic analysis at the research location offers critical insights to advance sustainable tea farming in the face of climate change.

### Principal Component Analysis (PCA) of Soil and Bioactive Variables

Varimax rotation was used to enhance the contribution of variables to each component, thereby facilitating the designation of this new dimension (Table 4 and 5). PC1 (38.361% of variance) exhibited significant differentiation based on nutritional antagonism and metabolic responses. Agronomically, PC1 showed a nutritional disparity between positively associated Av. P ( $r=0.825$ ) and negatively correlated Ex. K ( $r=-0.883$ ). Physiologically, PC1 had a significant positive correlation with flavonoids ( $r=0.881$ ). This finding confirms the negative correlation identified between Ex. K and flavonoids in initial analyses, indicating that soil conditions conducive

to phosphorus availability, potentially in scenarios of restricted potassium availability, concurrently enhance the biosynthesis of secondary metabolites (flavonoids) as a defensive or adaptive strategy (Dixon & Paiva, 1995).

PC2 represents 23.849% of the variance and solely describes the biochemical quality of Tayu tea. This component is characterized by exceptionally high and positive loadings of Tannin ( $r=0.957$ ) and Polyphenol ( $r=0.936$ ). The proximity of these loading coefficients quantitatively confirms the strong positive correlation between them, suggesting that these two compounds are influenced by analogous biosynthetic pathways or environmental factors (e.g., oxidative stress, genotype, or altitude), with PC2 serving as a significant indicator of the astringent and antioxidant properties of Tayu tea. PC3, which accounts for 20.078% of the variance, captures agronomic soil quality. This component is mostly influenced by the variables Org-C ( $r=0.893$ ) and TN ( $r=0.802$ ). The elevated positive loadings indicate the strong interconnection between organic matter and nitrogen availability within the soil system (Lawrence & Upchurch, 1982; Vidya & Prasad, 2024). PC3 succinctly summarises the fertility level and fundamental nutritional potential of the cultivation site. PC4 (9.296% variance) signifies a correlation between soil physical characteristics and particular biochemical components. This component has substantial loadings on Cation Exchange Capacity (CEC) ( $r=0.849$ ) and Caffeine ( $r=0.817$ ), alongside a considerable negative association with GABA ( $r=-0.513$ ). This suggests that soil cation exchange capacity (CEC) in Tayu tea plantations in West Bangka may influence plant biochemical control, with caffeine (a stimulant) and GABA (a tranquilizer) acting in opposition.

The biplot representation (Figure 2) shows a distinct division of samples based on the contributions of PC1 and PC2. Sample 1 aligns strongly with the Polyphenols and Tannins vectors, indicating the highest concentration of phenolic compounds among all samples and potential influence from environmental conditions or specific post-harvest treatments. A strong contrast is observed on the PC1 dimension between Sample 2 and Sample 6; Sample 2 is positioned at the positive extreme of PC1 and is correlated with

elevated Av. P and Flavonoids, while Sample 6 is placed on the negative side of PC1, indicating high Ex. K and TN. This pattern indicates substantial agronomic diversity across growing sites. Moreover, Samples 8 and 9 appear to deviate significantly from the main cluster, suggesting outliers or unusual combinations of variables and necessitating further examination of the specific environmental conditions or genetic traits at these two locations. The PCA indicates that variations in bioactive compound content in Tayu Tea from the West Bangka lowlands are strongly influenced by soil chemical characteristics. Av. P appeared as the primary factor influencing flavonoid accumulation, but Ex. K exhibited a negative correlation that distinguished secondary metabolite profiles among locales. Organic carbon, total nitrogen, and CEC significantly influenced differences in phenolic and tannin content, affirming that the bioactive properties of tea arise from intricate interactions among soil variables. These findings offer a novel perspective on soil-plant interactions in the West Bangka lowland ecosystem and establish a scientific foundation

## CONCLUSION

Tayu tea, a landrace of *Camellia sinensis* var. *sinensis*, can thrive and yield in lowland areas below 50 meters above sea level. Soil and climatic conditions promote the accumulation of bioactive metabolites. The soil characteristics of the Tayu tea plantation, including pH, N, C, and K, are similar to those of some tea plantations in the highlands, but P is adequately available and CEC is low. Climate factors such as precipitation, soil temperature, and solar radiation limit growth. PCA indicates that soil chemistry significantly affects bioactive compounds, with phosphorus influencing flavonoid levels and potassium differentiating locations. Organic carbon, nitrogen, and CEC impact phenolic compounds.

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## REFERENCES

- Bania, J. K., Deka, J. R., Paul, A., Nath, A. J., Sileshi, G. W., & Das, A. K. (2025). Highly suitable areas for tea (*Camellia sinensis*) production will decline under future climate change scenarios. *Environmental and Sustainability Indicators*, 26. <https://doi.org/10.1016/j.indic.2025.100720>
- Chen, Y. M., Wang, M. K., Zhuang, S. Y., & Chiang, P. N. (2006). Chemical and physical properties of rhizosphere and bulk soils of three tea plants cultivated in Ultisols. *Geoderma*, 136 (1–2), 378–387. <https://doi.org/10.1016/j.geoderma.2006.04.003>
- Ding, Z. J., Shi, Y. Z., Li, G. X., Harberd, N. P., & Zheng, S. J. (2021). Tease out the future: How tea research might enable crop breeding for acid soil tolerance. In *Plant Communications* (Vol. 2, Number 3). Cell Press. <https://doi.org/10.1016/j.xplc.2021.100182>
- Dixon, R. A., & Paiva, N. L. (1995). Stress-Induced Phenylpropanoid Metabolism. In *The Plant Cell* (Vol. 7).
- Galvito, M. E., Curtis, P. S., Mikkelsen, T. N., & Jakobsen, I. (2001). Interactive effects of soil temperature, atmospheric carbon dioxide and soil N on root development, biomass and nutrient uptake of winter wheat during vegetative growth. 52, 1913–1923.
- Han, W., Li, X., Yan, P., Zhang, L., & Jalal Ahammed, G. (2018). Tea cultivation under changing climatic conditions (pp. 455–472). <https://doi.org/10.19103/as.2017.0036.19>
- Haryadi, D., Ibrahim, I., & Darwance, D. (2025). Migration dynamics and reclamation challenges: a case study on tin mining communities in Bangka Belitung. *Jurnal Ilmu Lingkungan*, 23(1), 218–227. <https://doi.org/10.14710/jil.23.1.218-227>
- Jayasinghe, S. L., Kumar, L., & Sandamali, J. (2019). Assessment of potential land suitability for tea (*Camellia sinensis* (L.) O. Kuntze) in Sri Lanka using a gis-based multi-criteria approach. *Agriculture (Switzerland)*, 9(7). <https://doi.org/10.3390/agriculture9070148>
- Karak, T., Paul, R. K., Boruah, R. K., Sonar, I., Bordoloi, B., Dutta, A. K., & Borkotoky, B. (2015). Major soil chemical properties of the major tea-growing areas in India. *Pedosphere*, 25(2), 316–328. [https://doi.org/10.1016/S1002-0160\(15\)60016-9](https://doi.org/10.1016/S1002-0160(15)60016-9)
- Kotroczó, Z., Veres, Z., Biró, B., Tóth, J. A., & Fekete, I. (2014). Influence of temperature and organic matter content on soil respiration in a deciduous oak forest. *Eurasian Journal of Soil Science (EJSS)*, 3(4), 303. <https://doi.org/10.18393/ejss.87903>
- Lawrence, F. W., & Upchurch, S. B. (1982). Identification of recharge areas using geochemical factor analysis. *Ground Water*, 20, 680–687.
- Liu, Z., Yang, D., Zhang, G., Zheng, L., Chen, C., Sun, X., & Yu, F. (2023). Effects of Soil Physical and Chemical Properties on the Quality of Nanjing ‘Yuhua’ Tea, a Type of Famous Green Tea. *Horticulturae*, 9 (2), 1–10. <https://doi.org/10.3390/horticulturae9020189>
- Oishy, M. N., Shemonty, N. A., Fatema, S. I., Mahbub, S., Mim, E. L., Hasan Raisa, M. B., & Anik, A. H. (2025). Unravelling the effects of climate change on the soil-plant-atmosphere interactions: A critical review. In *Soil and Environmental Health*, 3 (1). Elsevier B.V. <https://doi.org/10.1016/j.seh.2025.100130>
- Pradana, N. C. P., Rizki, M. A., Wahyuni, A., & Harsono, B. (2023). Solar panel implementation for household electricity in Indonesia: environmental and economic implications. *Academia Open*, 8 (2). <https://doi.org/10.21070/acopen.8.2023.7860>
- Qaderi, M. M., Martel, A. B., & Strugnell, C. A. (2023). Environmental factors regulate plant secondary metabolites. In *Plants*, 12 (3). MDPI. <https://doi.org/10.3390/plants12030447>
- Rahaman, S. A., & Aruchamy, S. (2022). Land Suitability Evaluation of Tea (*Camellia sinensis* L.) Plantation in Kallar Watershed of Nilgiri Bioserve, India. *Geographies*, 2(4), 701–723. <https://doi.org/10.3390/geographies2040043>
- Ren, X., Lin, M., Liu, J., Khan, W., Zhao, H., Sun, B., Liu, S., & Zheng, P. (2025). Effects of altitude on tea composition: dual regulation by soil physicochemical properties and microbial communities. *Plants*, 14 (11). <https://doi.org/10.3390/plants14111642>
- Ruan, J., Ma, L., & Shi, Y. (2013). Potassium management in tea plantations: Its uptake by field plants, status in soils, and efficacy on yields and quality of teas in China. *Journal of Plant Nutrition and Soil Science*, 176(3), 450–459. <https://doi.org/10.1002/jpln.201200175>
- Tantonf, T. W. (1982). Environmental factors affecting the yield of tea (*Camellia sinensis*). II. Effects of Soil Temperature, Day Length, and Dry Air. 18, 53–63.
- Vidya, V., & Prasad, G. (2024). Interpretation of Water Quality Using Principal Component Analysis – A Case Study from A Tropical Ramsar Wetland Site Adjacent to the Seafood Processing Facilities. *Ecology, Environment and Conservation*, 30(SUPPL), S305–S311. <https://doi.org/10.53550/eec.2024.v30i03s.053>
- Wang, M., Zhao, J., Chen, J., Zhang, X., & Zhu, S. (2024). Soil organic carbon content and its relationship with the stand age in tea plantations (*Camellia sinensis* L.) in Fujian Province, China. *Land*, 13(6). <https://doi.org/10.3390/land13060834>
- Wang, S., Yao, X., Zhang, Z., He, X., & Ye, S. (2020). Soil aggregation and aggregate-related exchangeable base cations under different aged tea (*Camellia sinensis* L.) plantations in the hilly regions of southern Guangxi, China. *Soil Science and Plant Nutrition*, 66 (4), 636–644. <https://doi.org/10.1080/00380768.2020.1780471>
- Wu, T., Liu, W., Wang, D., Zou, Y., Lin, R., Yang, Q., Gbokie, T., Bughio, M. A., Li, Q., & Wang, J. (2020). Organic management improves soil phosphorus availability and microbial properties in a tea plantation after land conversion from longan (*Dimocarpus longan*). *Applied Soil Ecology*, 154. <https://doi.org/10.1016/j.apsoil.2020.103642>
- Yong-dong, W., Na-na, F., Ting-xuan, L., Xi-zhou, Z., & Gui-tang, L. (2008). Available online at [www.sciencedirect.com](http://www.sciencedirect.com) Spatial Variability of Soil Cation Exchange Capacity in Hilly Tea Plantation Soils Under Different Sampling Scales. In *Agricultural Sciences in China*, 7 (1).
- Zheng, Z., He, X., & Li, T. (2012). Status and Evaluation of the Soil Nutrients in Tea Plantation. *Procedia Environmental Sciences*, 12, 45–51. <https://doi.org/10.1016/j.proenv.2012.01.245>