*Plant Archives* Vol. 25, Supplement 1, 2025 pp.770-781 e-ISSN:2581-6063 (online), ISSN:0972-5210

# Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.v25.supplement-1.102

# THE ROLE OF SOIL COMPOSITION IN SHAPING TERROIR BASED TEA QUALITY

**Bidisha Hazarika[1*], Binoy Kumar Medhi[2] and Aditi Smith Gogoi[1]**
[1]Department of Tea Husbandry & Technology, Assam Agricultural University, Jorhat, Assam, India
[2]Department of Soil Science, Assam Agricultural University, Jorhat, Assam, India
*Corresponding author E-mail: bidisha.hazarika.adj22@aau.ac.in
(Date of Receiving : 11-08-2024; Date of Acceptance : 09-10-2024)

**ABSTRACT**

Tea, a globally beloved beverage, owes much of its quality to its terroir, a concept encompassing the unique environmental factors such as soil composition, climate, altitude, and ecosystem that influence the growth and quality of tea plants. Among these, soil composition plays a pivotal role in shaping the physical and chemical properties of tea leaves, which in turn affect their overall quality. This paper delves into the intricate relationship between soil composition and tea quality, with a focus on how various soil nutrients and properties impact key quality indicators like polyphenols, amino acids, caffeine, and theanine. Essential soil nutrients, including nitrogen, phosphorus, potassium, magnesium, and calcium, have a profound effect on the biochemical makeup of tea leaves. For example, nitrogen boosts the levels of free amino acids and polyphenols, phosphorus enhances catechin content, and potassium increases both free amino acids and polyphenols. Soil pH, often referred to as the "master variable" of soil chemistry, significantly influences tea quality, with specific pH levels promoting the synthesis of compounds that shape tea's flavor and aroma. The concept of terroir further highlights the interaction between soil and other environmental factors in defining tea quality. For instance, Assam's distinctive clay soils contribute to the tea's briskness and malty notes, while Kenya's volcanic soils impart a rich mineral profile to the tea. This study also explores soil management strategies, such as the application of organic fertilizers and biochar, which can enhance soil health, mitigate acidity, and improve tea quality. Practices like inoculation with Arbuscular Mycorrhizal Fungi (AMF) and the long-term use of organic fertilizers have been found to improve soil conditions and elevate the concentration of beneficial compounds in tea leaves. In conclusion, optimizing soil health through well-designed management practices is crucial for producing high-quality tea that reflects the distinctive terroir of its region. Continued research into the interactions between soil composition, climate, and tea quality is vital for advancing tea cultivation methods and raising standards across the global tea industry.
***Keyword* :** Terroir, Tea, Soil, Quality, Management.

## Introduction

The tea plant *Camellia sinensis* (L.) O. Kuntze is a highly valued perennial crop, known for producing an infusion with a pleasant aroma, rich flavor, and health benefits. Globally, tea is the most widely consumed beverage, with production increasing from 9.55 million tons in 2019 to 10 million tons in 2020. The appearance, taste, and aroma of tea are essential indicators of its quality, directly influencing its market value. A key factor affecting these characteristics is the soil in which the tea is cultivated. Soil provides the essential physical structure and nutrients for optimal tea plant growth, while poor soil quality can result in unhealthy plants and less flavorsome tea. As the global demand for high-quality tea continues to rise, understanding the intricate relationship between soil properties and tea quality becomes increasingly important. Among the many factors that influence tea quality, soil is a primary determinant. Some of the critical soil parameters that impact tea quality both directly and indirectly include soil depth, texture, bulk density, pH, electrical conductivity, organic matter content, and the presence of essential nutrients. Good soil composition ensures robust tea plants with the ability to produce high-quality leaves. Conversely, nutrient-deficient soils can hamper plant health, resulting in lower yields and a decline in flavor and aroma. Soil quality plays a vital role in determining the quality of tea, and attention to soil management can significantly enhance tea production. By optimizing soil parameters, it is possible to produce superior tea that meets the growing demand for both flavor and health benefits.

## Objectives

1. Observe quality composition of tea leaves
2. Evaluate impact of various soil nutrients on tea quality
3. Soil management practices to enhance tea quality

## Methodology

The research employs exploratory and descriptive methodologies, focusing on qualitative analysis. As this study delves into the different quality composition of tea leaves, influence of soil properties on it and different management practices, the data utilized in this research is primarily sourced from secondary data.

## Tea quality composition

Tea quality is determined by a variety of chemical components, each contributing to its taste, aroma, color, and health benefits. Polyphenols, a group of compounds that includes catechins, theaflavins, thearubigins, tannins, and flavonoids, are essential for tea quality, influencing its antioxidant properties, bitterness, and overall taste. Amino acids, particularly theanine, are crucial for creating the sweet and savory umami flavor that distinguishes high-quality tea. Enzymes, such as polyphenol oxidase and peroxidase, play a key role in the oxidation process during tea production, particularly in the development of black and oolong teas, where they contribute to the flavor and color changes. Pigments like chlorophyll, carotenoids, and anthocyanins are responsible for the vibrant colors of different types of tea leaves, from the green of fresh leaves to the reddish-brown hue of processed tea. Carbohydrates, including starch and sugars, impact the energy content and subtle sweetness of the tea. Methylxanthines, which include caffeine, theobromine, and theophylline, provide tea's stimulating effects, offering a mild energy boost, and enhancing mental alertness. Minerals also play a significant role in tea quality, with over 28 types such as fluorine, manganese, arsenic, nickel, selenium, iodine, aluminum, and potassium present in tea leaves. These minerals contribute to both the nutritional value and the overall health benefits of tea. Volatile flavor compounds (VFCs) and aromatic compounds are particularly influential in shaping the tea's aroma and flavor profile. These compounds are responsible for the fresh, floral, fruity, or woody scents that give each tea its unique character, making them a key factor in the sensory experience of tea consumption. Overall, the balance and interaction of these components determine the final quality of the tea.

## Terroir

Terroir refers to the idea that the unique qualities of tea are shaped by the specific environment soil, climate, altitude, latitude, and ecosystem where the tea plants are cultivated, making these characteristics impossible to replicate elsewhere.

**Soil:** The soil in different regions has unique compositions, which influence the nutrients available to tea plants and, in turn, impact the flavour of the tea. Assam tea, known for its brisk and malty taste, thrives in the clay-rich soils of its tropical river valleys. In contrast, tea from the Fujian mountains of eastern China is influenced by the region's rocky soil, which imparts a mineral-rich, earthy "petrichor" flavour to the tea. Similarly, the volcanic soil in Kenya's tea-growing areas provides a wealth of minerals that enhance the tea's flavour profile.

**Climate*:*** Tea plants require specific temperatures and humidity levels, which vary significantly by region. Tea grown in cooler climates, such as Darjeeling in India or Uji in Japan, develops more delicate and subtle flavours. In warmer regions, like Yunnan in China or the Great Rift Valley in Kenya, the tea is often bolder and more robust due to the climate.

**Altitude:** Higher altitudes slow the growth of tea plants, allowing the leaves to develop more intricate and nuanced flavours. In contrast, tea grown at lower altitudes typically matures faster, producing leaves with a simpler, more straightforward taste.

**Latitude:** The amount of sunlight a tea plant receives is influenced by latitude. Tea plants grown at higher latitudes receive less direct sunlight (fewer than 11 hours 15 minutes), which slows their growth and leads to the production of more amino acids and other compounds. This results in tea leaves with a richer, more complex flavour profile.

**Ecosystem:** The surrounding flora and fauna also play a role in shaping tea flavour. Other plants and animals in the ecosystem can affect soil nutrients and the overall environment. For example, tea grown on flower-covered mountains may absorb floral notes from the air over time, while tea plants near bamboo can develop altered aromas and tastes due to changes in the soil composition from bamboo leaf litter.

Each of these environmental factors contributes to the distinctive characteristics of tea, highlighting the importance of terroir in tea cultivation.

**Impact of various soil nutrients on tea quality**

The presence of various soil nutrients plays a crucial role in influencing tea quality, as they contribute to the development of essential compounds responsible for its taste, aroma, and health benefits. Among these nutrients, nitrogen stands out for its ability to increase levels of free amino acids and polyphenols, two key compounds that affect the flavor and antioxidant properties of tea (Qiao *et al.,* 2018). Phosphorus is another vital nutrient, known to enhance the concentration of catechins, a group of polyphenolic compounds that are highly valued for their antioxidant potential and bitterness, directly impacting tea's overall taste and health benefits (Lin *et al.,* 2012). Potassium, like nitrogen, plays a role in boosting the levels of free amino acids and polyphenols, thus contributing to both the flavor and the quality of the final product (Liu *et al*., 2023). Sulfur, on the other hand, enhances the formation of theaflavins and thearubigins, two polyphenolic compounds that are particularly prominent in black tea. These compounds are responsible for the tea's bright color, brisk flavor, and strength (Bhuyan *et al.,* 2015). Magnesium also positively impacts tea quality by increasing the levels of free amino acids, which are key to the savory, umami notes often found in high-quality tea (Tseng *et al.,* 2022).

In addition to these macronutrients, certain micronutrients such as copper, calcium, and manganese also have significant effects on tea composition. Copper is involved in the production of polyphenol oxidase (PPO), an enzyme that plays a key role in the oxidation of tea leaves, particularly in the production of black tea, where it influences flavor and color (Steffens *et al.,* 1994). Calcium has been found to raise the caffeine content of tea, which can enhance the tea's stimulating effect and slightly bitter taste (Penn *et al.,* 2019). Manganese, like nitrogen and magnesium, increases the concentration of free amino acids, further contributing to the richness of tea flavor (Tseng *et al.,* 2022). In summary, the right balance of soil nutrients is essential for producing high-quality tea. These nutrients directly influence the chemical composition of tea leaves, affecting both its sensory characteristics and health-promoting properties.

**Physical Properties of tea growing soil and its correlation with tea quality**

The physical properties of tea-growing soil, particularly bulk density, have a significant impact on tea quality. Research has shown a negative correlation between soil bulk density and the content of free amino acids and polyphenols in tea leaves, while the polyphenol/amino acid ratio and caffeine content are positively correlated with bulk density. Lower bulk density indicates higher soil porosity, which promotes better root growth and development. However, such soils often have poor nutrient retention, emphasizing the need to improve soil fertility in these areas. A reduction in bulk density has been linked to higher levels of free amino acids and polyphenols in tea leaves, both of which are important for enhancing tea quality. Conversely, higher bulk density is associated with a higher phenol-ammonia ratio, indicating that decreasing bulk density could improve tea quality. One approach to lowering soil bulk density is the addition of biochar, which has been found to not only reduce bulk density but also improve soil properties and promote environmental sustainability by reducing greenhouse gas emissions from acidic soils in tea plantations. However, caution is needed when adding biochar, as it is typically alkaline, and excessive amounts may harm tea plants. While biochar can improve soil structure, it's important to apply the correct amount to avoid negative effects on tea growth. Additionally, caffeine content has been positively correlated with soil bulk density, suggesting that increased bulk density can be detrimental to tea plant development. Studies also indicate that higher caffeine levels may result from nutrient deficiencies in the soil, which can negatively impact the overall quality of tea leaves.

**Table 1 :** Soil physical properties in the three sites of China (Liu *et al.,* 2023)

| Sites | Depth (cm) | Clay % | Silt % | Sand % | Soil Classification | Bulk Density (g/cc) |
|---|---|---|---|---|---|---|
| Huanglongxian (A) | 0-20 | 2.70 ± 0.44 a | 90.04 ± 0.86 ab | 7.27 ± 1.16 ab | Silt Silt | 1.44 ± 0.12 a 1.53 ± 0.03 a |
| | 20-40 | 2.41 ± 0.18 a | 88.11 ± 1.77 b | 9.49 ± 1.86 a | | |
| Zhongshanling (B) | 0-20 | 2.33 ± 0.66 a | 87.86 ± 2.07 b | 9.82 ± 2.35 a | Silt Silt | 1.52 ± 0.14 a 1.56 ± 0.07 a |
| | 20-40 | 3.24 ± 0.1 a | 89.14 ± 0.88 b | 7.62 ± 1.63 ab | | |
| Pingshan (C) | 0-20 | 2.33 ± 0.51 a | 91.47 ± 1.21 a | 6.21 ± 1.5 b | Silt Silt | 1.06 ± 0.07 b |
| | 20-40 | 2.08 ± 0.87 a | 92.58 ± 1.27 a | 5.34 ± 0.76 b | | 1 ± 0.14 b |

All the sites show high percentage of silt content and average BD

Site (C) shows lower BD as compared to other two sites

**Table 2 :** Soil physical properties in the tea plantation sites of Taiwan (Huh *et al.,* 2008)

| Sites | Depth(cm) | Clay % | Silt % | Sand % | Soil Classification | Bulk Density (g/cc) |
|---|---|---|---|---|---|---|
| Tea plantation (1) | 0-20 | 37 | 50 | 13 | Silt Clay | 1.36 |
| Tea plantation (2) | 0-20 | 35 | 46 | 19 | Silt Clay | 1.41 |
| Tea plantation (3) | 0-20 | 34 | 49 | 17 | Silt Clay | 1.43 |

**Table 3 :** Correlations of soil physical property & tea quality compositions (Liu *et al.,* 2023)

| Tea Chemical Components | Soil Physical Properties | |
|---|---|---|
| | Depth (0–20 cm) | Depth (20–40 cm) |
| | BD | BD |
| Free Amino Acid | –0.838 ** | –0.899 ** |
| Tea polyphenols | –0.788 * | –0.814 ** |
| Polyphenols/Amino acid ratio | 0.675 * | 0.689 * |
| Caffeine | 0.826 ** | 0.901 ** |

**Free amino acid** and **polyphenol content:** Negatively correlated with BD
**Polyphenol/Amino acid ratio** & **Caffeine**: Positively correlated with BD

**Chemical properties of tea growing soil and its correlation with tea quality**

The correlation between soil properties and the chemical components of tea leaves was consistent at both 0–20 cm and 20–40 cm soil depths across different locations. A negative correlation was observed between soil pH and the levels of free amino acids and tea polyphenols in tea leaves, while effective nitrogen, phosphorus, and potassium content in the soil showed a positive correlation with these components. Conversely, the ratio of phenol to amino acids and the caffeine content in tea leaves had a significant positive correlation with soil pH, while available nitrogen, potassium, and phosphorus were negatively correlated with these factors.

Soil pH, often regarded as the "master variable" of soil chemistry, influences the solubility, mobility, and bioavailability of various soil elements, either directly or indirectly. Specifically, a negative correlation was found between soil pH and the levels of amino acids, tea polyphenols, and theanine in tea. As the pH decreased, the free amino acid and polyphenol content in tea leaves increased, while the phenol-amino acid ratio rose with higher pH levels. This suggests that slightly lowering the pH could improve tea quality. However, reducing soil pH below four is not advisable, as this falls outside the optimal range for tea plants. Studies indicate that when soil pH drops below four, tea shoot growth is hindered more than nitrogen absorption, leading to an accumulation of free amino acids in the leaves, which may enhance amino acid content but reduce overall tea yield.

Further studies revealed that free amino acid levels could be increased by raising soil pH, exchangeable calcium (Ca), magnesium (Mg), total manganese (Mn), and copper (Cu) within suitable ranges, while reducing soil electrical conductivity (EC). These findings align with previous research. Consequently, soil pH is a crucial factor in managing tea plantations. Free amino acid content increases with higher pH values, within a range of 3.50–5.21. Exchangeable magnesium is identified as an essential factor for increasing theanine content and maintaining the activity of key enzymes in tea roots, such as nitrate reductase, glutamine synthetase, and theanine synthetase. Additionally, the correlation between soil exchangeable Ca, Mg, total Mn, and Cu with leaf nutrients like phosphorus (P), calcium, manganese, copper, and zinc highlights the importance of soil factors in tea garden management. These results suggest that proper fertilization plays a key role in enhancing the flavour quality of tea by influencing free amino acid levels.

**Table 4 :** Soil chemical properties in the three sites in China (Liu *et al.,* 2023)

| Sites | Depth(cm) | pH | AN | AP | AK | WSC |
|---|---|---|---|---|---|---|
| | | | mg kg$^{-1}$ | | | |
| Huanglongxian (A) | 0-20 | 4.95 ± 0.56 ab | 11.17 ± 2.41 b | 11.67 ± 6.9 b | 34.67 ± 11.27 b | 120 ± 26.46 b |
| | 20-40 | 5.17 ± 0.37 ab | 17.27 ± 5.23 b | 22.11 ± 2.22 b | 39.07 ± 5.2 b | 336.67 ± 176.16 b |
| Zhongshanling (B) | 0-20 | 5.54 ± 0.19 a | 10.47 ± 2.57 b | 20.37 ± 7.58 b | 24.33 ± 11.75 b | 916.67 ± 125.03 a |
| | 20-40 | 5.65 ± 0.18 a | 9.67 ± 1.55 b | 24.58 ± 4.29 b | 32.4 ± 7.14 b | 916.67 ± 128.97 a |
| Pingshan (C) | 0-20 | 4.54 ± 0.09 b | 72.63 ± 3.76 a | 96.86 ± 25.42 a | 123.47 ± 24.91 a | 190 ± 20 b |
| | 20-40 | 4.67 ± 0.27 b | 79.67 ± 18.99 a | 67.24 ± 4.72 a | 179.63 ± 25.85 a | 130 ± 34.64 b |

AN: Available nitrogen; AP: Available phosphorus; AK: Available potassium; WSC: Water-soluble calcium

**Table 5 :** Correlations of soil chemical properties & tea quality compositions in the three of China

| Tea Chemical Components | Soil Chemical Properties | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Depth (0–20 cm) | | | | | Depth (20–40 cm) | | | | |
| | pH | AN | AP | AK | WSC | pH | AN | AP | AK | WSC |
| Free Amino Acid | –0.792* | 0.878** | 0.747* | 0.882** | –0.76* | –0.874** | 0.844** | 0.84** | 0.874** | –0.853** |
| Tea polyphenols | –0.736* | 0.839** | 0.738* | 0.84** | –0.84** | –0.785* | 0.832** | 0.797* | 0.839** | –0.933** |
| Polyphenols/ Amino acid ratio | 0.799* | –0.667* | –0.562 | –0.669* | 0.871** | 0.81** | –0.685* | –0.606 | –0.649 | 0.862** |
| Caffeine | 0.519 | –0.941** | –0.921** | –0.878** | 0.131 | 0.606 | –0.874** | –0.953** | –0.92** | 0.446 |

BD: Bulk density; AN: Available nitrogen; AP: Available phosphorus; AK: Available potassium; WSC: Water-soluble calcium (Significance correlation levels: * $p < 0.05$; ** $p < 0.01$)

- **Free amino acid** and **polyphenol content:** Negatively correlated with pH & WSC, positively correlated with AN, AP, AK for both the layers.
- **Polyphenol/Amino acid ratio** & **Caffeine**: Positively correlated with pH & WSC, negatively correlated with AN, AP, AK for both the layers.
- Caffeine levels in tea increase when the quality of the tea leaves is reduced due to nutrient deficiencies in the soil (Jahan *et al.,* 2022)

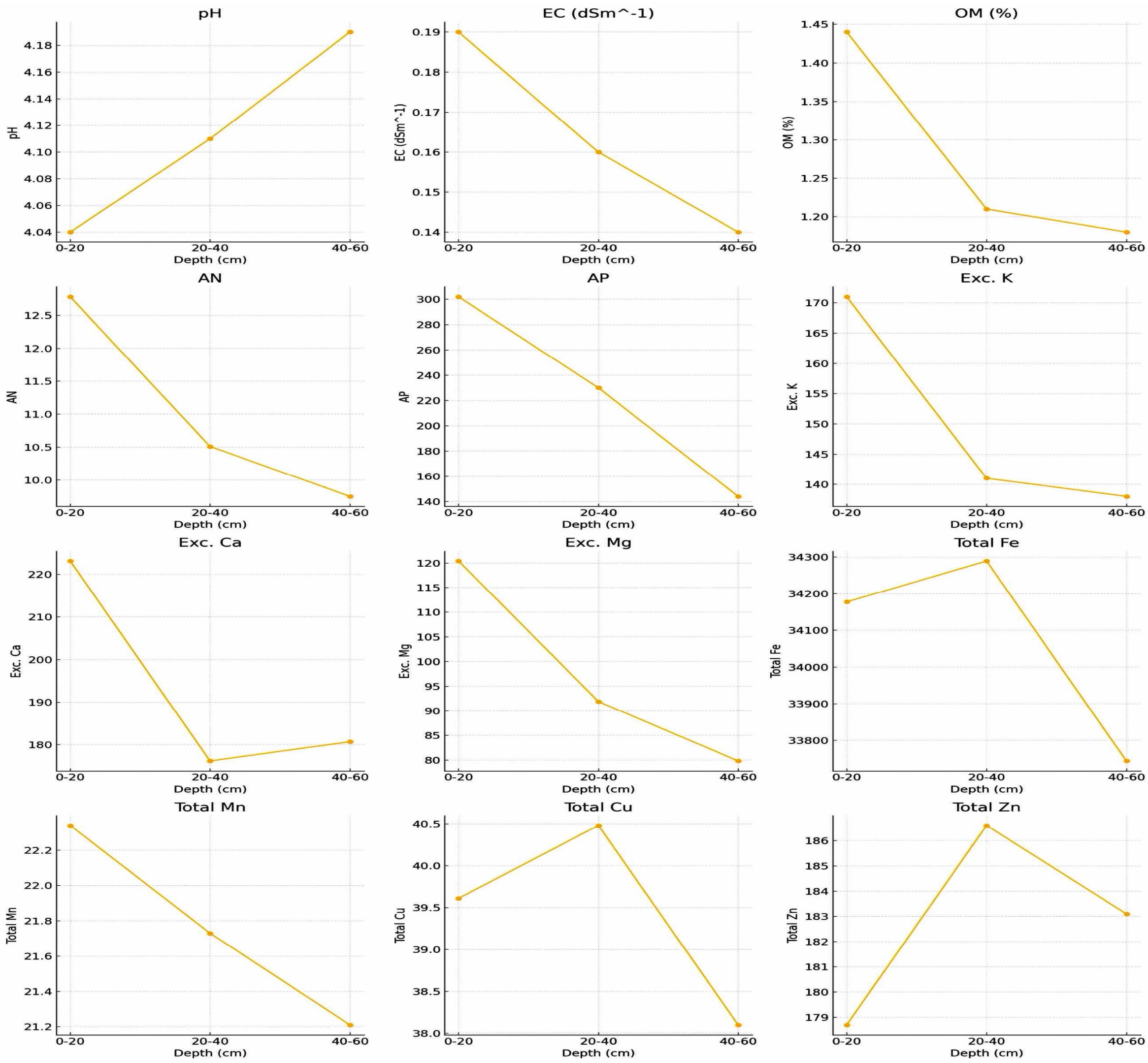
* These results are also supported by Ma *et al.*, 2017; Venkatesan *et al*., 2017; Mudau *et al*., 200; Lin *et al*., 2012; Ruan *et al*., 2013; Liu *et al*., 2017

**Table 6 :** Soil chemical properties in the tea plantation sites in Taiwan (20 Gardens) (Tseng *et al.,* 2022)

| Depth (cm) | pH | EC dSm$^{-1}$ | OM % | AN | AP | Exc. K | Exc. Ca | Exc. Mg | Total Fe | Total Mn | Total Cu | Total Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | mg kg$^{-1}$ | | | | | | | | |
| 0-20 | 4.04±0.41 | 0.19±0.09 | 1.44±0.50 | 12.78±8.20 | 302±195 | 171±93 | 223.1±216 | 120.4±86.2 | 34177±6142 | 22.34±9.77 | 39.61±15.6 | 178.7±62 |
| 20-40 | 4.11±0.41 | 0.16±0.08 | 1.21±0.48 | 10.51±7.63 | 230±180 | 141±62 | 176.2±160.3 | 91.9±65.3 | 34289±5975 | 21.73±9.43 | 40.48±15.4 | 186.6±62.7 |
| 40-60 | 4.19±0.49 | 0.14±0.09 | 1.18±0.48 | 9.75±6.78 | 144±122 | 138±63 | 180.7±218.7 | 79.82±52.35 | 33744±5707 | 21.21±7.06 | 38.1±13.2 | 183.1±65.1 |

EC, electrical conductivity; OM, organic matter; Avail., Available; Exch., Exchangeable

- Acidic pH becomes marginally less acidic with depth
- EC and OM content decrease slightly as depth increases
- AN and AP decrease with depth (nutrient availability is higher near the surface)
- Exc. K, Ca, and Mg are also decreasing with depth
- Total Mn, Cu, and Zn remain relatively stable across different depths except Fe, which shows high accumulation in different depths

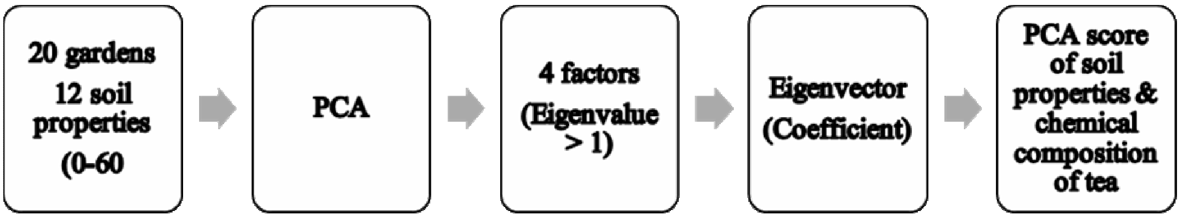



(Tseng *et al.*, 2022)

**Fig. 1 :** Graphical representation of Soil chemical properties in the tea plantation sites in Taiwan

**Correlations of soil chemical properties & tea quality compositions in tea plantation sites of Taiwan**

Principal Component Analysis (PCA)




(Tseng *et al.*, 2022)

**Table 7 :** The selected eigenvalues greater than one of PCA by database in 0–60 cm soil properties

| Factor | Eigenvalue |
|---|---|
| 1 | 4.766357 |
| 2 | 2.648132 |
| 3 | 1.807001 |
| 4 | 1.344880 |

(Tseng *et al.*, 2022)

**Table 8 :** The eigenvectors for variations of PCA by dataset in 0–60 cm soil properties

| Soil Properties | Eigenvectors | | | |
|---|---|---|---|---|
| | Factor 1 | Factor 2 | Factor 3 | Factor 4 |
| pH | **0.96997** [1] | –0.08209 | –0.10654 | 0.02801 |
| EC | **–0.82808** | 0.38307 | 0.05349 | 0.02407 |
| OM | –0.30358 | 0.18986 | **0.80489** | 0.01164 |
| Available N | 0.13583 | –0.01854 | **–0.71906** | –0.13002 |
| Available P | –0.10006 | **0.75000** | 0.11796 | –0.45127 |
| Exch. K | –0.18370 | **0.82988** | –0.39554 | 0.13329 |
| Exch. Ca | **0.87540** | 0.31566 | –0.03509 | 0.08174 |
| Exc. Mg | **0.79310** | 0.38077 | 0.02259 | 0.06946 |
| Total Fe | –0.13880 | 0.44980 | –0.40353 | **0.63010** |
| Total Mn | **0.72756** | 0.38698 | 0.28273 | –0.22302 |
| Total Cu | **0.85063** | 0.33240 | 0.26894 | 0.12923 |
| Total Zn | 0.39439 | –0.55213 | 0.20015 | 0.57520 |

(Tseng *et al.,* 2022)

**Table 9 :** PCA correlations between PCA score of average soil properties at 0–60 cm depth and leaf quality composition

| Leaf quality Composition | PC1 | | PC2 | | PC3 | | PC4 | |
|---|---|---|---|---|---|---|---|---|
| | ***r*** [1] | ***p*** **value** | ***r*** | ***p*** **value** | ***r*** | ***p*** **value** | ***r*** | ***p*** **value** |
| Polyphenols | 0.332 | 0.1521 | 0.005 | 0.9837 | 0.413 | 0.0702 | **–0.656** | **0.0017** |
| Catechins | –0.077 | 0.7482 | 0.236 | 0.3162 | –0.349 | 0.1313 | –0.129 | 0.5867 |
| Flavones | –0.343 | 0.1392 | 0.369 | 0.1091 | **–0.470** | **0.0364** | 0.216 | 0.3604 |
| Free Amino Acid | **0.715** | **0.0004** | –0.170 | 0.4737 | 0.338 | 0.1449 | **–0.471** | **0.0359** |
| Caffeine | 0.059 | 0.8048 | 0.214 | 0.3644 | –0.034 | 0.8881 | **–0.526** | **0.0172** |

[1] $-0.7 \leq r \geq 0.7$ indicate strong correlation; the bold values assigned to show the statistically significant result when *p* value is less than 0.05

(Tseng *et al.,* 2022)

- **PC1:** Positive correlation with FAA **(Soil pH, exch. Ca, exch. Mg, total Mn and total Cu)** Negatively correlated with FAA **(Soil EC value)** (Tongsiri *et al.,* 2020)
- **PC2:** There is no signification correlation
- **PC3:** Negatively correlated with Flavone **(Soil OM);** Positive correlation with Flavone **(Soil Available N)**
- **PC4:** Negatively correlated with Polyphenol, FAA & Caffeine **(Total Fe)**

**Soil management practices to enhance tea quality**

- **Improvement of tea quality parameters through inoculation with Arbuscular Mycorrhizal Fungi (AMF) in acidic soil under net house conditions**

Indigenous arbuscular mycorrhizal fungi (AMF) consortia from natural (NTR) and cultivated tea rhizospheres (CTR) were used as inocula, each containing nine common morphospecies, including *Acaulospora spinosa* and various *Glomus* species. The NTR consortia also included *Acaulospora foveta* and *Glomus intraradices*, while the CTR consortia featured species like *Glomus multicaule* and *Scutellospora* sp. 1. Full details of the identified AMF morphospecies can be found in Singh *et al.* (2008a).

After cracking, germinated tea seeds were transplanted into polybags filled with non-sterilized soil. Stem cuttings were treated with Bavistin before being transferred into polybags. AMF inoculation involved adding 10 g of crude soil-based consortia (30–40 spores) to each bag under the seedlings or cuttings. Control groups remained uninoculated, and 100 replicates were used for each treatment, including controls. The plants were grown in net-house conditions (50% shade), watered with tap water every other day, and no fertilizers were applied during the experiments. Weeds and pests were manually removed. Growth data were collected one year post-inoculation, and tea quality parameters were evaluated across three flushes. Results showed that the NTR treatment led to the most significant improvements in quality parameters for both seed- and cutting-raised plants. While the CTR treatment also enhanced quality compared to the control, its effects were generally less pronounced than NTR. Both treatments significantly improved quality parameters, such as soluble sugars, proteins, amino acids, polyphenols, and caffeine levels, compared to the control. Differences in quality-related parameters between control, seed-raised, and cutting-raised plants were attributed to clonal variations, as different tea clones show wide variation in biochemical composition. These results emphasize the importance of selecting the right AMF inoculation and treatment strategies to optimize tea quality. The significant improvements seen with NTR treatment suggest it may be especially beneficial for tea growers aiming to enhance the biochemical profile of their tea. Furthermore, understanding clonal differences and their influence on tea quality can guide breeding and selection of tea cultivars that respond well to specific treatments, maximizing the benefits of AMF inoculation. Future research could explore the long-term effects of these treatments and their interactions with various tea cultivars to further optimize tea cultivation practices.

**Table 10 :** Effect of inoculation with AMF from NTR and CTR on quality parameters of seed-raised tea plants under net-house conditions

| Flush | Treatment | Soluble sugars (mgg−1) | Proteins (mgg−1) | Amino Acids (mgg−1) | Polyphenols (mgg−1) | Caffeine (mgg−1) |
|---|---|---|---|---|---|---|
| 1st | Control | 244.0±4.6 | 1.4±0.14 | 2.7±0.1 | 19.3±0.6 | 20.2±0.8 |
| | NTR | 266.3±3.2* | 2.8±0.1* | 3.6 ± 0.1* | 22.3±0.9 | 24.3 ± 0.3* |
| | CTR | 284.6±2.3* | 1.9±0.0* | 3.2 ± 0.1* | 12.0±1.1 | 22.9 ± 0.5* |
| 2nd | Control | 255.0 ± 3.2 | 2.0 ± 0.0 | 3.4 ± 0.1 | 30.6 ± 1.2 | 1.4 ± 0.0 |
| | NTR | 295.3±1.8* | 3.1±0.1* | 4.2 ± 0.1* | 36.0±1.7 | 1.9±0.0* |
| | CTR | 296.3±2.4* | 2.4±0.1 | 3.9 ± 0.0* | 26.2±0.6 | 1.8±0.1* |
| 3rd | Control | 274.3 ± 0.8 | 2.0 ± 0.1 | 4.0 ± 0.1 | 84.3 ± 1.2 | 19.5 ± 0.2 |
| | NTR | 314.0±6.6* | 3.2±0.1* | 4.7 ± 0.1* | 96.0±1.1* | 22.1 ± 1.0* |
| | CTR | 329.0±5.5* | 2.4±0.0* | 4.1±0.1 | 90.3±0.8* | 21.9 ± 0.9* |

Tea leaves and buds were collected after 1 year of inoculation in the months of March (first flush), November (second flush), and again in following March (third flush) *p=0.05, shows significant difference

(Sing *et al.,* 2010)

- NTR treatment generally resulted in the highest improvements across all measured quality parameters
- CTR treatment also enhanced quality parameters compared to the control but was generally lower than the NTR treatment
- Both treatments showed significant benefits in improving the quality parameters of tea plants under net-house conditions

**Table 11 :** Effect of inoculation with AMF from NTR and CTR on quality-related parameters of cutting-raised plants of tea under net-house conditions

| Flush | Treatment | Soluble sugars (mgg−1) | Proteins (mgg−1) | Amino Acids (mgg−1) | Polyphenols (mgg−1) | Caffeine (mgg−1) |
|---|---|---|---|---|---|---|
| 1st | Control | 302.0 ± 2.6 | 2.2 ± 0.1 | 3.4 ± 0.1 | 11.0 ± 0.5 | 16.0 ± 0.5 |
| | NTR | 329.6 ± 1.7* | 2.4 ± 0.0 | 3.9 ± 0.1* | 31.6 ± 0.8* | 18.9 ± 0.5* |
| | CTR | 311.3 ± 1.8* | 2.5 ± 0.1 | 4.0 ± 0.1* | 21.5 ± 0.2* | 21.5 ± 1.3* |
| 2nd | Control | 312.6 ± 3.2 | 2.8 ± 0.1 | 3.8 ± 0.1 | 12.3 ± 0.8 | 1.3 ± 0.1 |
| | NTR | 323.6 ± 2.1* | 3.2 ± 0.1 | 4.3 ± 0.2 | 33.2 ± 0.3* | 1.8±0.9* |
| | CTR | 315.6 ± 4.7 | 3.5 ± 0.1* | 4.1 ± 0.0 | 28.0 ± 0.5* | 1.7±0.1 |
| 3rd | Control | 326.0 ± 1.1 | 2.5 ± 0.1 | 4.4 ± 0.1 | 69.3 ± 2.0 | 19.4 ± 0.2 |
| | NTR | 345.3 ± 2.3* | 2.9 ± 0.0* | 5.1 ± 0.1* | 82.6 ± 1.7* | 21.5 ± 0.6* |
| | CTR | 338.0 ± 1.1* | 2.9 ± 0.1* | 4.6 ± 0.1 | 73.8 ± 1.6* | 22.7 ± 0.1* |

(Sing *et al.,* 2010)

Tea leaves and buds were collected after 1 year of inoculation in the months of March (first flush), November (second flush), and again in following March (third flush) *p=0.05, shows significant difference

Overall, inoculation with AMF, particularly from NTR, enhances the quality-related parameters of tea plants, improving soluble sugars, proteins, amino acids, polyphenols, and caffeine content compared to the control

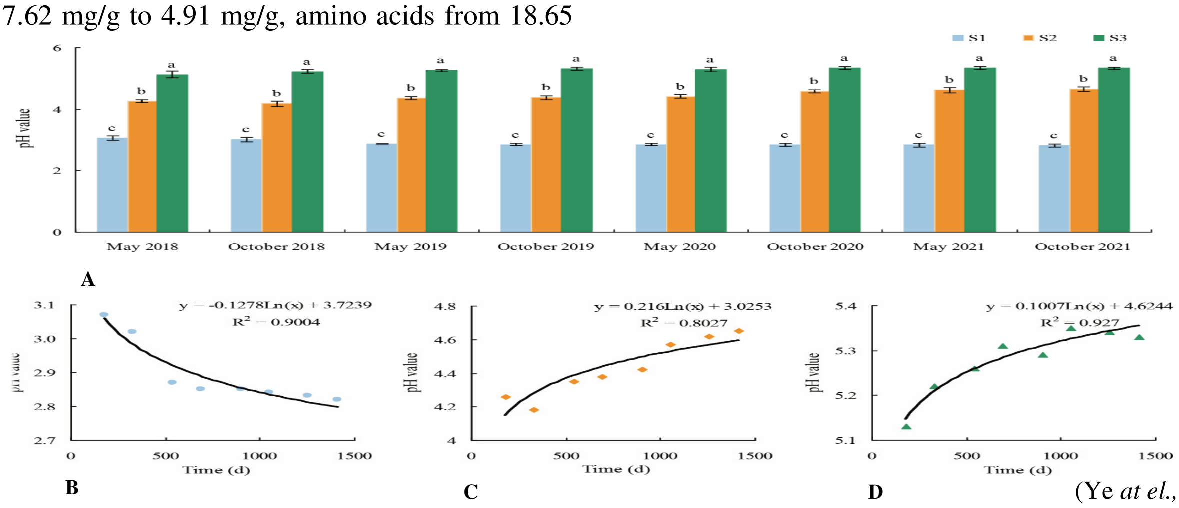
***Variation in different quality-related parameters in control, seed- and cutting-raised tea plants can be related to clonal variation of both types of plants as different tea clones show a wide variation in different biochemical constituents

- **Mitigating soil acidification in tea plantations through long-term application of organic fertilizers and its impact on tea quality**

Enhancing tea quality is essential for boosting the economic returns of tea production (Hazrarika *et al.,* 2018; Bhargava *et al.,* 2022). Key secondary metabolites in tea, including theanine, caffeine, and polyphenols, are crucial for determining the tea's taste and aroma. Moreover, amino acids, as primary metabolites, contribute significantly to the umami and sweet flavours of tea (Miyauchi *et al.,* 2014; Ye *et al.,* 2016; Jia *et al.,* 2018; Chen *et al.,* 2021). Indicators like tea polyphenols, theanine, amino acids, and catechins are commonly used to assess the impact of biotic or abiotic stress on tea quality, with higher levels of these compounds reflecting superior quality (Yan *et al.,* 2020; Wen *et al.,* 2021; Le *et al.,* 2022; Tang *et al.,* 2022). This study investigated the effects of various fertilization treatments and soil acidification on tea leaf quality, focusing on these indicators. The findings revealed that fertilization had a significant impact on the tea quality markers, including tea polyphenols, theanine, amino acids, caffeine, and catechins. The differences in quality among the different fertilization treatments were statistically significant, with the highest quality observed in tea plantations using organic fertilizers and the lowest in those relying on chemical fertilizers.

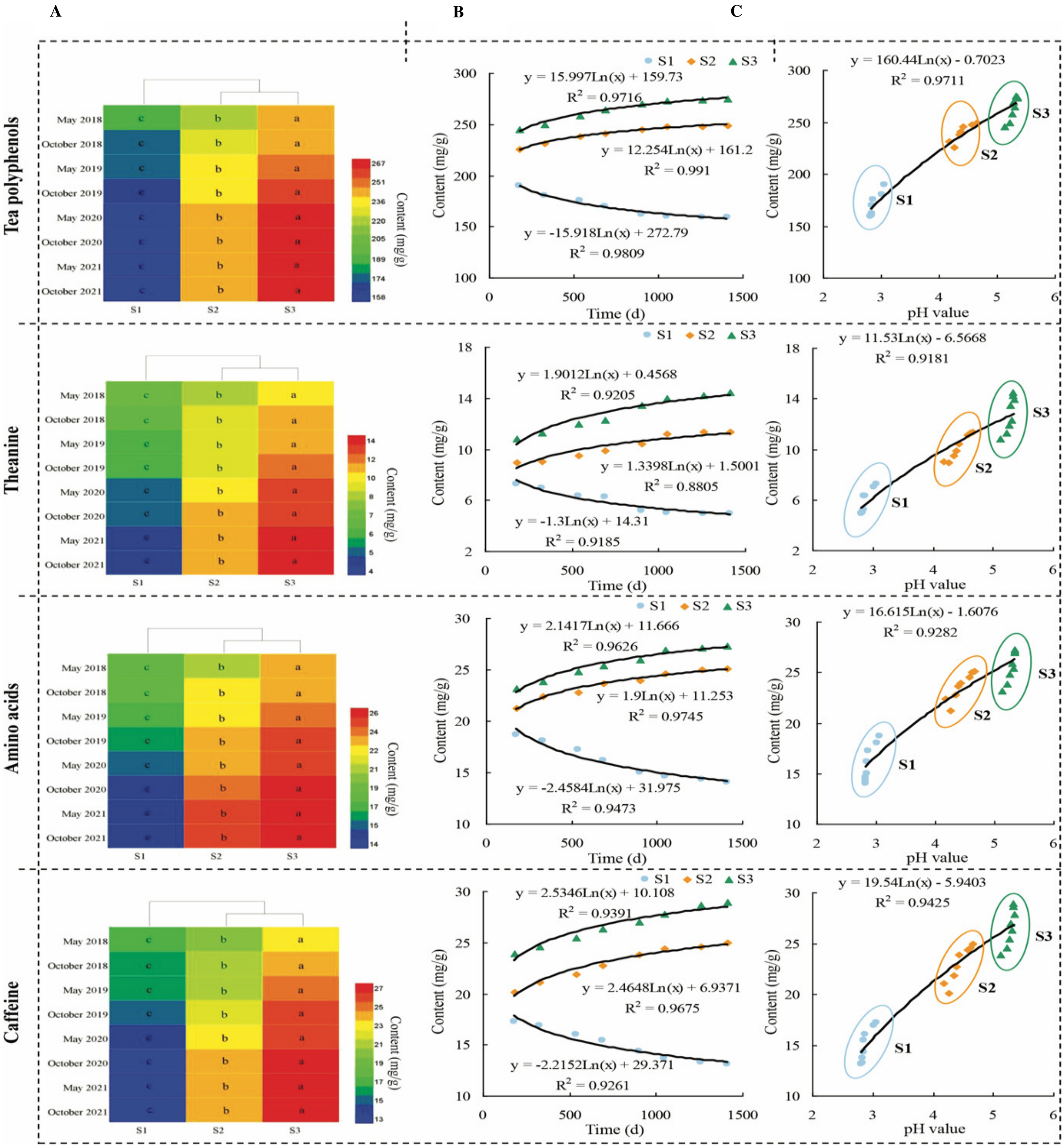
An analysis of the long-term effects of different fertilization regimes on tea quality indicators showed that continuous use of chemical fertilizers in the S1 tea plantation (2017–2021) resulted in a noticeable decline in tea quality. Specifically, tea polyphenol content dropped from 189.67 mg/g to 158.84 mg/g, theanine from 7.62 mg/g to 4.91 mg/g, amino acids from 18.65 mg/g to 14.03 mg/g, caffeine from 17.23 mg/g to 13.07 mg/g, and total catechins from 45.54 mg/g to 38.96 mg/g. In contrast, the S2 plantation, which used a combination of organic and chemical fertilizers, showed significant improvements in tea quality during the same period. Tea polyphenol content increased from 225.36 mg/g to 249.25 mg/g, theanine from 8.93 mg/g to 11.38 mg/g, amino acids from 21.25 mg/g to 25.12 mg/g, caffeine from 20.14 mg/g to 24.97 mg/g, and total catechins from 64.96 mg/g to 77.64 mg/g. The S3 plantation, which used only organic fertilizers, saw the most substantial improvements, with tea polyphenols rising from 245.37 mg/g to 274.95 mg/g, theanine from 10.85 mg/g to 14.74 mg/g, amino acids from 23.16 mg/g to 27.31 mg/g, caffeine from 23.98 mg/g to 28.93 mg/g, and total catechins from 91.89 mg/g to 102.51 mg/g.

Further analysis of the relationship between soil pH and tea leaf quality revealed a significant positive correlation, showing that as soil pH increased, tea quality improved. In the S1 plantation, the prolonged use of chemical fertilizers led to continuous soil acidification, inhibiting tea plant growth and lowering tea quality. The S2 plantation, which used a blend of organic and chemical fertilizers, saw gradual improvements in soil pH, reduced soil acidification, and steady improvements in tea quality. The S3 plantation, where only organic fertilizers were used, experienced significant improvements in soil acidification, supporting healthy tea plant growth and resulting in the highest tea quality. Therefore, the long-term use of organic fertilizers in tea plantations not only mitigates soil acidification but also enhances tea quality.



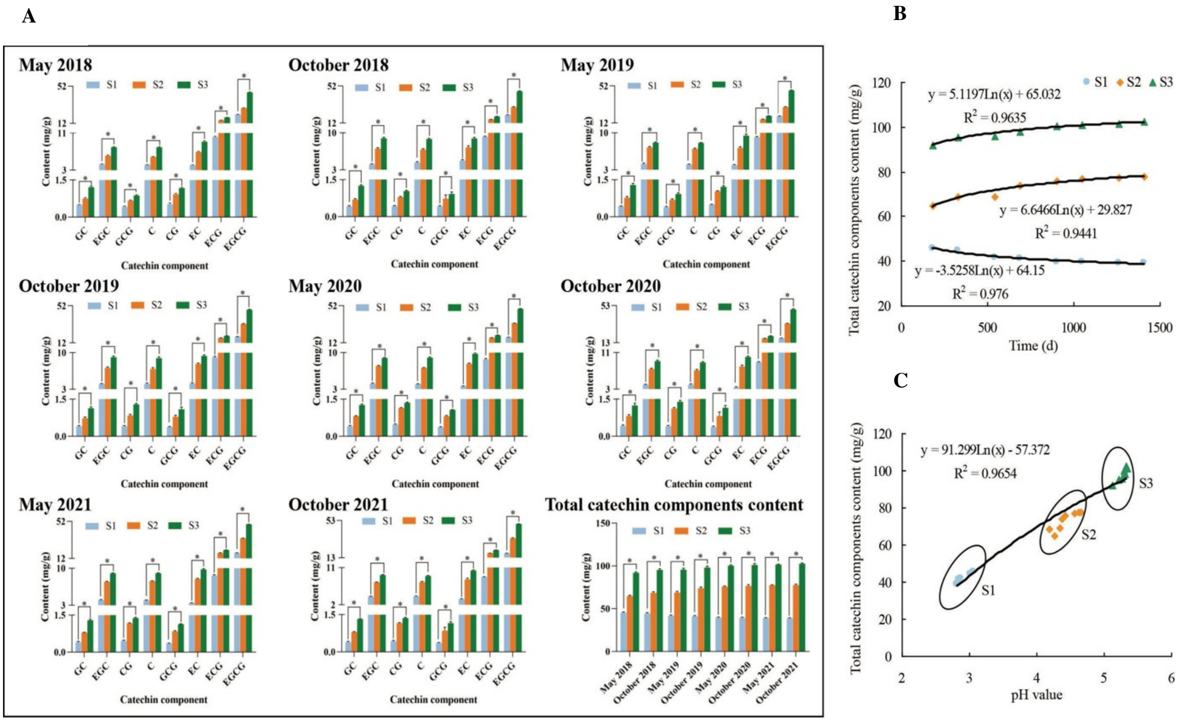

(Ye *at el.,* 2022)

**Fig 2. (A) :** Effect of 4 consecutive years of fertilization on soil pH in tea plantation; **(B)** Trend analysis of soil pH after 4 years of continuous treatment in S1 tea plantation; **(C)** Trend analysis of soil pH after 4 years of continuous treatment in S2 tea plantation; **(D)** Trend analysis of soil acidity after 4 years of continuous treatment in S3 tea plantation; Different lowercase letters indicate the significant difference at $P < 0.05$ levels among different treatments




(Ye *at el.,* 2022)

**Fig 3. (A) :** Effect of 4 consecutive years of fertilization treatment on the quality tea leaves; (B) Trend analysis of influence of fertilization treatment on the quality tea leaves after 4 consecutive years; (C) Trend analysis of influence of soil pH on the quality tea leaves. Different lowercase letters indicate the significant difference at $P < 0.05$ levels among different treatments.




(Ye *at el.,* 2022)

**Fig 4. (A) :** Changes of catechin content in tea leaves after continuous fertilization; **(B)** Trend analysis of the effect of 4 consecutive years of fertilization on the content of catechin components in tea leaves; **(C)** Trend analysis of the influence of soil pH on the content of catechin components in tea leaves; * indicate the significant difference at $P < 0.05$ levels among different treatments

- Long-term use of chemical fertilizers (S1) would aggravate soil acidification in tea plantations, which lead to a continuous decrease in tea quality
- The combination of organic fertilizer and chemical fertilizer (S2) could alleviate soil acidification and improve tea quality to a certain extent, but the effect was poor
- Long-term use of organic fertilizer (S3) could significantly improve soil acidification and tea quality

## Conclusion

Tea quality is intricately connected to soil composition and environmental factors. By emphasizing soil management practices, nutrient availability, and the broader influence of climate and terroir, tea producers can cultivate exceptional teas that embody the distinctive characteristics of their region. Localized research to explore the interactions between soil composition, climate, and terroir is crucial for refining cultivation methods and raising tea quality standards in specific geographical areas. By enhancing soil health, optimizing nutrient availability, and managing environmental conditions, tea growers can produce premium teas that highlight the unique terroir of their region.

**Acknowledgement**

I would like to express my sincere gratitude to all those who have supported and contributed to the completion of this article. I am deeply thankful to all the authors for their invaluable guidance, constructive feedback, and continuous encouragement throughout the research process. Special thanks to my colleagues and peers for their insightful discussions and collaboration. Finally, I am grateful to the researchers whose work provided the foundation for this article.

## References

Ahmed, S., Unachukwu, U., Stepp, J.R., Peters, C.M., Long, C.L., Kennelly, E. (2010). Pu-erh tea tasting in Yunnan, China: Correlation of drinkers' perceptions to phytochemistry. *J. Ethnopharmacol*., **132**, 176–185.

Alasalvar, C., Topal, B., Serpen, A., Bahar, B., Pelvan, E., Gokmen, V. (2012). Flavor Characteristics of Seven Grades of Black Tea Produced in Turkey. *J. Agric. Food Chem*., **60**, 6323–6332.

Dai, W.D., Qi, D.D., Yang, T., Lv, H.P., Guo, L., Zhang, Y., Zhu, Y., Peng, Q.H., Xie, D.C., Tan, J.F., *et al.* (2015). Nontargeted analysis using ultraperformance liquid chromatography-quadrupole time-of-flight mass spectrometry uncovers the effects of harvest season on the metabolites and taste quality of tea (*Camellia sinensis* L.). *J. Agric. Food Chem*. **63**, 9869–9878.

FAOSTAT. 2020 Food and Agriculture Data. Available online: https://www.fao.org/faostat/en/#data/QCL (accessed on 22 January 2022).

Henss, L., Auste, A., Schürmann, C., Schmidt, C., von Rhein, C., Mühlebach, M.D., Schnierle, B.S. (2021). The green tea catechin epigallocatechin gallate inhibits SARS-CoV-2 infection. *J. Gen. Virol*. **102,** 001574

Khan, N., Mukhtar, H. (2018). Tea Polyphenols in Promotion of Human Health. *Nutrients,* **11**, 39

Liang, Y.R., Lu, J.L., Zhang, L.Y., Wu, S., Wu, Y. (2003). Estimation of black tea quality by analysis of chemical composition and colour difference of tea infusions. *Food Chem*., **80,** 283–290.

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), 189.

Mhatre, S., Srivastava, T., Naik, S., Patravale, V. (2021). Antiviral activity of green tea and black tea polyphenols in prophylaxis and treatment of COVID-19: A review. *Phytomedicine*, **85**, 153286.

Singh, S., Pandey, A., Kumar, B., & Palni, L. M. S. (2010). Enhancement in growth and quality parameters of tea [*Camellia sinensis* (L.) O. Kuntze] through inoculation with arbuscular mycorrhizal fungi in an acid soil. *Biology and fertility of soils*, **46**, 427-433.

Thesis: Implications of Aluminium and fluoride in plucked tea leaves and soils of Doomdooma area in Assam (Namrata Rajbonshi)

Tseng, W. Y., & Lai, H. Y. (2022). Comprehensive analysis revealed the specific soil properties and foliar elements respond to the quality composition levels of tea (*Camellia sinensis* L.). *Agronomy*, **12**(3), 670.

Wang, S., Moustaid-Moussa, N., Chen, L., Mo, H., Shastri, A., Su, R., Bapat, P., Kwun, I., Shen, C.-L. (2014). Novel insights of dietary polyphenols and obesity. *J. Nutr. Biochem*. **25**, 1–18.

Wei, C., Yang, H., Wang, S., Zhao, J., Liu, C., Gao, L., Xia, E., Lu, Y., Tai, Y., She, G., *et al*. (2018). Draft genome sequence of Camellia sinensis var. sinensis provides insights into the evolution of the tea genome and tea quality. *Proc. Natl. Acad. Sci. USA*, **115,** 4151–4158.

Wen, B., Ren, S., Zhang, Y., Duan, Y., Shen, J., Zhu, X., Wang, Y., Ma, Y., Zou, Z., Fang, W. (2020). Effects of geographic locations and topographical factors on secondary metabolites distribution in green tea at a regional scale. *Food Control*, **110**, 106979.

Xianchen, Z., Huiguang, J., Xiaochun, W., Yeyun, L. (2020). The effects of different types of mulch on soil properties and tea production and quality. *J. Sci. Food Agric*., **100**, 5292–5300.

Xing, L., Zhang, H., Qi, R., Tsao, R., Mine, Y. (2019). Recent Advances in the Understanding of the Health Benefits and Molecular Mechanisms Associated with Green Tea Polyphenols. *J. Agric. Food Chem*. **67**, 1029–1043.

Yan, Z., Zhong, Y., Duan, Y., Chen, Q., Li, F. (2020). Antioxidant mechanism of tea polyphenols and its impact on health benefits. *Anim. Nutr.*, **6**, 115–123.

Yang, C.S., Zhang, J., Zhang, L., Huang, J., Wang, Y. (2016). Mechanisms of body weight reduction and metabolic syndrome alleviation by tea. *Mol. Nutr. Food Res*., **60**, 160–174.

Ye, J., Wang, Y., Wang, Y., Hong, L., Jia, X., Kang, J., ... & Wang, H. (2022). Improvement of soil acidification in tea plantations by long-term use of organic fertilizers and its effect on tea yield and quality. *Frontiers in Plant Science*, **13**, 1055900.

Zhang, L., Cao, Q.-Q., Granato, D., Xu, Y.-Q., Ho, C.-T. (2020). Association between chemistry and taste of tea: A review. *Trends Food Sci. Technol*. **101**, 139–149.