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UTILIZATION OF TEA WASTE COMPOST ENRICHED MICROBES TO ENHANCE SOIL HEALTH AND TEA PLANT SUSTAINABILITY

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ABSTRACT

Tea plantations increasingly face challenges related to declining soil fertility, excessive reliance on inorganic fertilizers, and the accumulation of agro-industrial residues. This study evaluated the utilization of tea waste as a feedstock for bio-enriched compost and its effectiveness in improving soil quality and tea plant health in tea plantations of North Sumatra, Indonesia. Tea waste was composted for 45-60 days using microbial activators and subsequently enriched with beneficial microorganisms. A field efficacy trial was conducted using a factorial randomized block design with two factors: tea waste compost doses (0–4000 kg ha^{-1} $year^{-1}$) and inorganic fertilizer levels (0–100% of the recommended rate). Observed parameters included tea shoot productivity and shoot ratio (plant health). The best response was achieved with the application of 1000 kg ha^{-1} tea waste compost combined with 60% of the recommended inorganic fertilizer dose, resulting in an average 28% increase in shoot yield compared with the control. This treatment also improved peko shoot quality and enhanced production stability during dry periods. Increased soil organic matter, improved water retention, and greater microbial activity were identified as key mechanisms underlying these benefits. These findings demonstrate that tea waste compost represents a viable strategy for circular waste management and sustainable nutrient optimization in tea plantation systems, contributing to long-term soil health and resilient tea production.

Key words: Plant health; Soil fertility; Tea plantations; Tea production; Tea waste compost.

INTRODUCTION

Tea (*Camellia sinensis* L.) is one of the most important perennial plantation crops with significant economic value and contributes to the agricultural sector in many tea-producing countries. However, the sustainability of tea production is currently challenged by declining soil fertility and reduced soil quality due to intensive cultivation practices and continuous nutrient removal by tea plants. As a perennial crop cultivated for decades, tea plants continuously absorb essential nutrients from the soil through their extensive root systems. Without adequate nutrient replenishment, this process may result in nutrient depletion and degradation of soil functions, ultimately reducing tea productivity and quality.

Soil degradation in tea plantations is characterized by several indicators, including decreased soil organic matter content, reduced soil microbial diversity and activity, lower cation exchange capacity, soil compaction, nutrient leaching, soil acidification, and accumulation of polyphenolic compounds that may affect tea plant growth (Rachmiati and Salim, 2005). These problems are further aggravated by the intensive use of inorganic fertilizers, which are commonly applied to maintain productivity. Although chemical fertilizers provide rapid nutrient availability, their excessive and continuous application may negatively affect soil ecological functions by accelerating soil acidification, reducing microbial activity, disrupting nutrient balance, and decreasing soil organic carbon accumulation (Yang *et al*., 2018). Therefore, sustainable soil management practices are required to maintain soil fertility while supporting long-term tea production.

One of the approaches to overcome soil degradation is the application of organic amendments, particularly compost derived from agricultural and industrial residues. Compost application has been widely reported to improve soil physical, chemical, and biological properties by increasing organic carbon content, enhancing soil aggregation, improving water retention capacity, stimulating microbial activity, and increasing nutrient availability (Bernal *et al*., 2009). In tea cultivation systems, organic fertilization has also been demonstrated to improve soil fertility and contribute to carbon accumulation, which plays an important role in maintaining soil quality and crop productivity.

Tea waste, generated during the sorting and processing of black tea, represents an abundant organic residue with high potential for utilization as a soil amendment. Tea waste contains organic compounds and essential nutrients, including carbon (C), nitrogen (N), phosphorus (P), and potassium (K), which can contribute to soil nutrient improvement. Previous studies reported that fermented tea waste contains 26.9–41.9% organic carbon, 1.36–3.92% nitrogen, 0.20–0.68% phosphorus, and 0.43–1.89% potassium (Rahayu and Nurhayati, 2005). Considering the large amount of tea processing waste generated annually, converting tea waste into compost provides an environmentally friendly strategy for waste management while improving soil fertility.

Previous studies have demonstrated that compost derived from organic waste can enhance soil quality and crop productivity through nutrient supply and improvement of soil biological processes. However, the effectiveness of compost application is often limited by slow nutrient mineralization processes and variations in compost maturity and nutrient availability. The integration of beneficial microorganisms into compost has emerged as an innovative strategy to improve compost efficiency. Microbial enrichment can accelerate organic matter decomposition, enhance nutrient mineralization, increase nutrient availability, and stimulate plant growth through mechanisms such as biological nitrogen fixation, phosphate solubilization, production of plant growth-promoting substances, and improvement of rhizosphere microbial activity (Vessey, 2003; Bhattacharyya and Jha, 2012).

Despite these advantages, previous research has mainly focused on the application of compost or organic amendments as general soil conditioners, while studies specifically evaluating microbe-enriched tea waste compost for improving soil health and supporting tea plant sustainability remain limited. Furthermore, the combined effects of tea waste compost and beneficial microorganisms on nutrient efficiency, soil biological improvement, and tea plant productivity require further investigation. Therefore, developing a microbial-enriched tea waste compost technology represents an important research opportunity to bridge the gap between organic waste utilization, soil restoration, and sustainable tea plantation management.

The novelty of this research lies in the utilization of tea processing waste enriched with beneficial microorganisms as an integrated bio-organic fertilizer approach to improve soil health and enhance tea plant sustainability. This approach not only provides an alternative solution for managing tea industry waste but also contributes to reducing dependence on inorganic fertilizers, improving nutrient use efficiency, and maintaining long-term soil productivity in tea plantations. Therefore, this study aims to evaluate the effectiveness of microbe-enriched tea waste compost application in improving soil health, enhancing nutrient availability, and supporting sustainable tea plant growth and productivity. The findings are expected to provide scientific evidence for the development of sustainable nutrient management strategies in tea plantations.

MATERIALS AND METHODS

The study was conducted at a tea plantation located in North Sumatra, Indonesia, from January to September 2025. The experiment was carried out under field conditions to evaluate the effectiveness of tea waste compost application in improving tea plant growth, productivity, and soil sustainability.

The experiment was arranged using a Factorial Randomized Complete Block Design (RCBD) with two treatment factors. The first factor was the application rate of tea waste compost, consisting of five levels:

- T0: Tea waste compost 0 kg ha^{-1} $year^{-1}$
- T1: Tea waste compost 1,000 kg ha^{-1} $year^{-1}$
- T2: Tea waste compost 2,000 kg ha^{-1} $year^{-1}$
- T3: Tea waste compost 3,000 kg ha^{-1} $year^{-1}$
- T4: Tea waste compost 4,000 kg ha^{-1} $year^{-1}$

The second factor was the level of inorganic fertilizer application, consisting of four levels:

- K0: 0% recommended chemical fertilizer dose
- K1: 100% recommended chemical fertilizer dose
- K2: 80% recommended chemical fertilizer dose
- K3: 60% recommended chemical fertilizer dose

The combination of both factors resulted in 20 treatment combinations. Each treatment was replicated three times, resulting in a total of 60 experimental plots. Each plot had an area of 200 m^2, resulting in a total experimental area of 12,000 m^2 (1.2 ha) for the tea waste compost efficacy evaluation trial.

The experimental treatments were applied according to the designated treatment combinations, and observations were conducted throughout the experimental period to evaluate the effects of tea waste compost and inorganic fertilizer reduction on tea productivity and soil quality parameters.

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Figure 1. Research Plot

The parameters evaluated in this study included:

1. Tea Production

Tea shoot production was measured to evaluate the effect of tea waste compost and inorganic fertilizer treatments on tea productivity. The yield was recorded based on the weight of harvested fresh shoots from each experimental plot during the observation period.

2. Plant Health Based on Pekoe/Banji Shoot Ratio

Plant health and shoot quality were assessed using the pekoe/burung (banji) shoot ratio as an indicator of vegetative growth performance and plucking quality. A higher pekoe/burung ratio indicates better shoot development and a greater proportion of desirable young shoots for tea production.

3. Soil Nutrient Analysis

Soil samples were collected to evaluate the effects of tea waste compost application on soil fertility status. Soil analysis included key soil chemical properties and nutrient availability..


8

Figure 2. Tea Waste Compost Application and Obeservation

RESULTS AND DISCUSSION

Tea production

The application of tea waste compost showed a positive effect on tea shoot production compared with the control treatment. Based on the production trend throughout the observation period, all treatments showed similar seasonal fluctuations, with an increase in shoot production during periods of favorable environmental conditions and a decline during drier months. The highest shoot production was generally observed in May, followed by a reduction during July–August, which corresponded with the dry season period.

The application of tea waste compost, particularly in combination with reduced inorganic fertilizer doses, was able to maintain higher shoot production compared with treatments without tea waste compost. The treatment T1K6 (1,000 kg ha^{-1} tea waste compost + 60% inorganic fertilizer) showed a consistently high production response, especially during the peak production period in May, indicating that tea waste compost improved nutrient availability and supported active shoot growth. Similarly, the T2K6 treatment (2,000 kg ha^{-1} tea waste compost + 60% inorganic fertilizer) demonstrated good production stability during the observation period.

During the dry months (July–August 2025), shoot production decreased in almost all treatments due to limited water availability and environmental stress. However, plots receiving tea waste compost showed a smaller reduction in production compared with the control. This response indicates that tea waste compost contributed to maintaining plant performance under water-limiting conditions through improvements in soil organic matter content, soil structure, and water-holding capacity. Improved soil conditions allow tea plants to maintain root activity and nutrient uptake, supporting continuous young shoot formation.

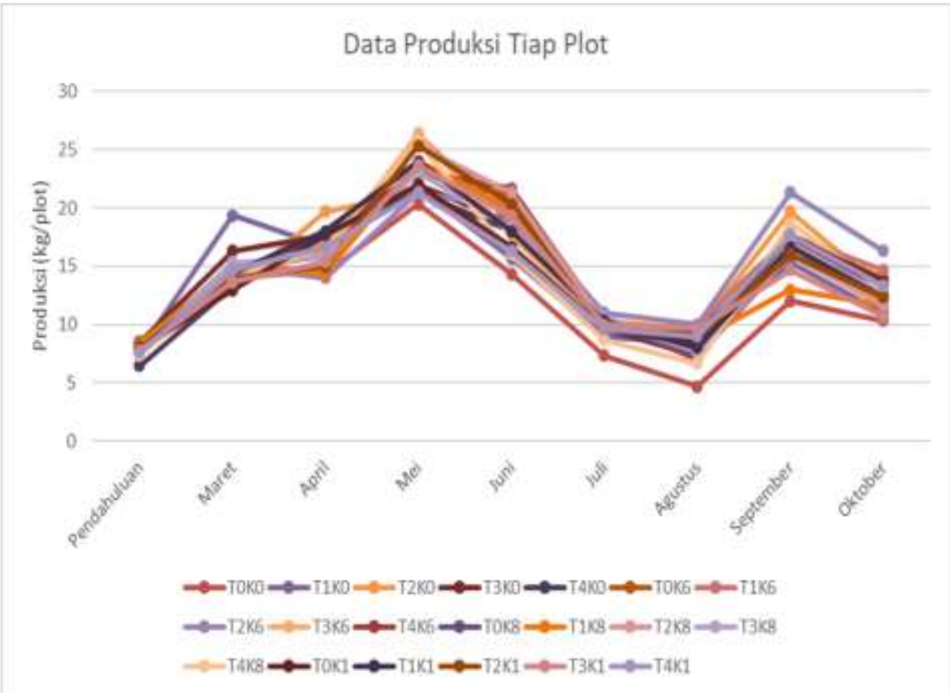

Figure 3. Shoot Production Data February until October 2025

The increase in shoot production following tea waste compost application can also be attributed to the gradual release of nutrients, particularly nitrogen (N) and potassium (K), which play important roles in vegetative growth, leaf development, and shoot formation. In addition, the presence of organic matter stimulates soil microbial activity, enhancing nutrient cycling and improving fertilizer use efficiency.

Overall, the results indicate that tea waste compost application can improve tea shoot productivity and reduce dependence on inorganic fertilizers. The combination of 1,000–2,000 kg ha^{-1} tea waste compost with 60% inorganic fertilizer provided the most favorable response, demonstrating its potential as a sustainable nutrient management strategy for maintaining tea production under variable environmental conditions.

Table 1. Statistical analysis of monthly shoot production data summary

Pendahuluan			Maret			April			Mei			Juni			Juli			Agustus			September			Oktober		
Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi
T3K0	9	a	T1K0	19	a	T2K0	20	a	T1K6	26	a	T4K6	22	a	T2K6	11	a	T1K6	10	a	T2K6	21	a	T2K6	16	a
T0K6	8	ab	T3K0	16	ab	T1K1	18	a	T3K6	26	a	T2K8	21	a	T3K8	11	a	T2K6	10	a	T2K0	20	ab	T1K6	15	ab
T0K8	8	ab	T0K0	15	b	T0K1	18	a	T4K8	26	a	T0K6	21	ab	T0K8	10	a	T2K0	10	ab	T4K8	19	abc	T0K6	14	ab
T1K6	8	ab	T3K8	15	b	T0K8	18	a	T2K1	25	a	T2K1	20	ab	T1K1	10	a	T3K1	10	ab	T0K1	18	abcd	T0K1	14	ab
T1K8	8	ab	T1K8	15	b	T3K0	18	a	T2K8	25	a	T1K8	20	ab	T2K0	10	a	T3K0	9	ab	T1K6	18	abcd	T3K0	13	ab
T2K6	8	ab	T2K6	15	b	T4K0	18	a	T0K8	24	a	T2K6	20	ab	T2K8	10	a	T0K6	9	ab	T4K1	18	abcd	T4K1	13	ab
T0K1	8	ab	T0K6	15	b	T4K6	18	a	T1K1	24	a	T0K8	20	ab	T4K6	10	a	T2K1	9	ab	T0K6	17	abcd	T2K0	13	ab
T1K1	8	ab	T4K1	15	b	T2K8	17	a	T1K8	24	a	T3K1	19	ab	T0K6	10	a	T4K1	9	ab	T4K0	17	abcd	T4K8	13	ab
T4K1	8	ab	T1K1	14	b	T1K0	17	a	T3K1	24	a	T1K6	19	ab	T3K1	10	a	T1K8	9	ab	T4K6	17	abcd	T3K8	13	ab
T4K6	8	ab	T2K8	14	b	T4K1	17	a	T0K6	23	a	T3K0	19	ab	T0K1	10	a	T0K1	8	ab	T3K0	17	abcd	T1K1	12	ab
T0K0	8	ab	T3K6	14	b	T4K8	17	a	T3K8	23	a	T3K8	18	ab	T1K8	10	a	T1K0	8	ab	T3K8	17	abcd	T2K1	12	ab
T1K0	8	ab	T0K8	14	b	T0K6	16	a	T4K6	23	a	T1K1	18	ab	T2K1	10	a	T3K6	8	ab	T1K1	17	abcd	T4K0	12	ab
T2K0	8	ab	T1K6	14	b	T3K6	16	a	T0K1	22	a	T4K0	18	ab	T3K6	10	a	T1K1	8	ab	T3K6	17	abcd	T4K6	12	ab
T2K1	8	ab	T2K1	14	b	T3K8	16	a	T3K0	22	a	T3K6	18	ab	T4K0	10	a	T2K8	8	ab	T0K8	16	abcd	T3K6	12	ab
T2K8	8	ab	T4K8	14	b	T3K1	15	a	T1K0	22	a	T0K1	17	ab	T4K1	10	a	T3K8	8	ab	T2K1	16	abcd	T0K8	12	b
T3K1	8	ab	T3K1	14	b	T2K1	15	a	T2K0	21	a	T2K0	16	ab	T1K6	9	a	T0K8	7	abc	T2K8	16	abcd	T1K8	12	b
T3K6	7	ab	T4K0	13	b	T1K6	15	a	T2K6	21	a	T4K1	16	ab	T3K0	9	a	T4K0	7	abc	T1K0	15	bcd	T2K8	12	b
T3K8	7	ab	T0K1	13	b	T0K0	14	a	T4K0	21	a	T4K8	16	ab	T1K0	9	a	T4K6	7	abc	T3K1	15	bcd	T1K0	11	b
T4K8	7	ab	T2K0	13	b	T1K8	14	a	T4K1	21	a	T1K0	16	ab	T4K8	9	a	T4K8	7	bc	T1K8	13	cd	T3K1	11	b
T4K0	6	b	T4K6	13	b	T2K6	14	a	T0K0	20	a	T0K0	14	b	T0K0	7	a	T0K0	5	c	T0K0	12	d	T0K0	10	b

Note: Numbers followed by the same letter in the same column indicate no significant difference based on Duncan's multiple range test at the 5% significance level.

The results show (Table 1) that shoot production varied significantly among treatments, indicating that nutrient management practices strongly influenced tea shoot growth dynamics. In the early growth period (preliminary to April), several treatments such as T3K0 and other improved fertilizer combinations showed relatively higher shoot production. This suggests that early shoot production is highly responsive to initial nutrient availability, particularly nitrogen, which plays a key role in stimulating vegetative growth in tea plants (Carr, 2010; Smith *et al*., 2019).

During the mid-season period (May to August), shoot production generally increased. Integrated nutrient management treatments combining organic inputs (tea waste compost) and reduced inorganic fertilizers maintained relatively stable and competitive shoot production. Organic amendments improve soil structure, microbial activity, and nutrient retention, which enhances long-term productivity (Wibowo *et al*., 2021; Sukartono & Utomo, 2012). This supports the concept that partial substitution of chemical fertilizers with organic materials can sustain crop yield while improving soil health.

In the late season (September to October), a decline in shoot production was observed across most treatments, likely due to seasonal climatic factors such as reduced rainfall or temperature fluctuations. Control treatment (T0K0) consistently showed the lowest performance and was significantly different from fertilized treatments, confirming the importance of nutrient input in maintaining shoot productivity.

Plant health based on pekoe/banji shoot ratio

The shoot ratio is an important indicator of tea plant health and plucking quality, as it reflects the proportion of desirable young shoots (pekoe) compared with dorman shoots (banji). A higher pekoe/banji ratio indicates better shoot development and more favorable conditions for producing high-quality tea shoots. Based on the observation data (Figure 4) from March to October 2025, the application of tea waste compost showed a positive effect on maintaining and improving the pekoe/banji shoot ratio compared with the control treatment. Although the ratio fluctuated throughout the observation period due to seasonal environmental variations, tea waste compost treatments generally maintained a higher proportion of pekoe shoots, particularly during critical periods of plant stress.

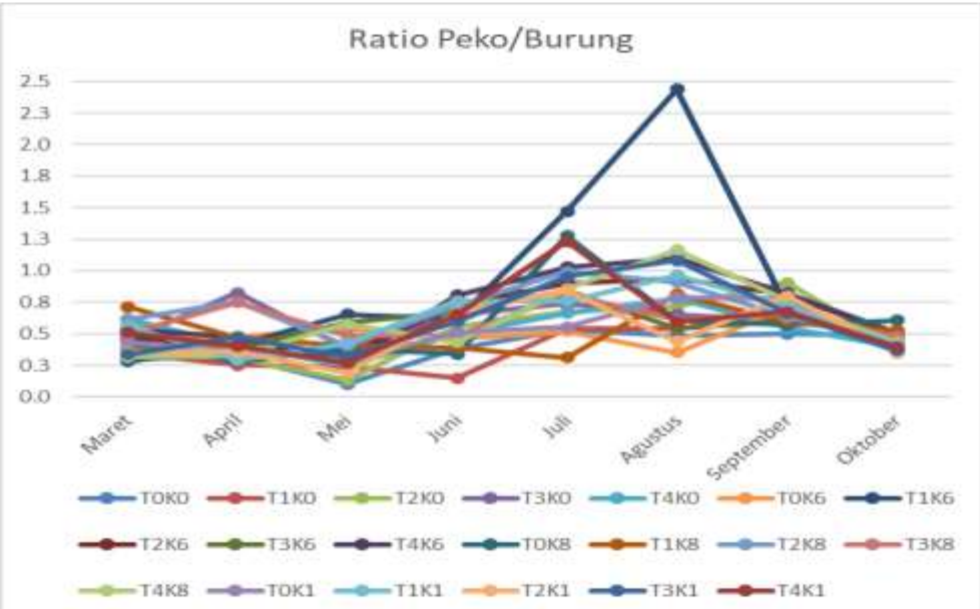

Figure 4. Shoot ratio Data March until October 2025

The highest pekoe/banji ratio was observed in the T1K6 treatment (1,000 kg ha^{-1} tea waste compost + 60% inorganic fertilizer), which reached approximately in August. This value was close to the ideal pekoe/banji ratio standard (2.33), indicating that this treatment provided favorable conditions for young shoot formation and improved shoot quality. Other tea waste compost treatments also showed better stability compared with treatments without compost application, particularly during July–August, when environmental stress conditions occurred.

During the dry period, most treatments without tea waste compost showed a decline in the pekoe/banji ratio, characterized by an increase in banji shoots. This response is commonly associated with limited water availability, reduced nutrient uptake, and reduced physiological activity of tea plants under stress conditions. In contrast, tea waste compost application helped maintain a higher proportion of pekoe shoots due to its ability to improve soil organic matter content, enhance soil water-holding capacity, and maintain nutrient availability.

The positive effect of tea waste compost on shoot quality is also related to increased microbial activity in the soil. Organic matter from tea waste compost provides a substrate for beneficial microorganisms, which contribute to nutrient mineralization, particularly nitrogen (N), which plays an important role in vegetative growth and young shoot development. Improved soil biological activity supports continuous nutrient supply and promotes healthier shoot formation.

However, the pekoe/banji ratio varied among treatments and months, indicating that shoot development was influenced not only by fertilizer management but also by environmental factors such as rainfall, temperature, and light intensity. During high rainfall periods, excessive moisture and reduced solar radiation may affect shoot quality, while during dry periods, water availability becomes a limiting factor.

Overall, the results demonstrate that tea waste compost application improved tea plant health by increasing the proportion of pekoe shoots and reducing the formation of banji shoots. The T1K6 treatment (1,000 kg ha^{-1} tea waste compost combined with 60% inorganic fertilizer) provided the most consistent improvement in shoot quality, suggesting that tea waste compost can enhance fertilizer efficiency and support sustainable tea production.

Table 2. Statistical analysis of monthly shoot ratio data summary

Maret			April			Mei			Juni			Juli			Agustus			September			Oktober		
Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi	Perlakuan	Hasil	Notasi
T1K8	0.71	a	T3K0	0.83	a	T1K6	0.66	a	T4K6	0.81	a	T1K6	1.47	a	T1K6	2.44	a	T2K0	0.91	a	T0K8	0.61	a
T4K0	0.62	a	T2K8	0.76	a	T3K6	0.59	ab	T1K1	0.77	a	T0K8	1.28	a	T4K8	1.17	b	T4K6	0.82	ab	T1K8	0.53	a
T2K8	0.62	a	T3K8	0.75	a	T4K8	0.58	ab	T2K6	0.73	a	T4K1	1.23	a	T4K6	1.10	b	T2K6	0.81	ab	T4K6	0.51	a
T2K0	0.61	a	T0K6	0.48	a	T0K6	0.54	ab	T2K8	0.73	a	T4K6	1.03	a	T3K1	1.08	b	T2K1	0.80	ab	T3K0	0.50	a
T1K1	0.56	a	T4K6	0.48	a	T3K8	0.49	abc	T3K6	0.68	a	T2K8	1.00	a	T1K1	0.96	b	T0K1	0.78	abc	T2K6	0.49	a
T4K6	0.53	a	T3K1	0.47	a	T1K1	0.43	abc	T2K1	0.67	a	T3K1	0.95	a	T2K6	0.94	b	T4K8	0.77	abc	T0K0	0.48	a
T4K1	0.51	a	T1K8	0.47	a	T1K8	0.41	abc	T4K1	0.66	a	T2K6	0.90	a	T2K8	0.91	b	T1K1	0.73	abc	T3K6	0.48	a
T3K8	0.50	a	T1K6	0.41	a	T2K8	0.41	abc	T3K0	0.65	a	T4K8	0.86	a	T1K8	0.81	b	T1K6	0.72	abc	T3K8	0.48	a
T2K6	0.49	a	T4K0	0.41	a	T3K0	0.39	abc	T1K6	0.62	ab	T2K1	0.85	a	T0K1	0.79	b	T0K6	0.71	abc	T1K0	0.47	a
T0K6	0.46	a	T4K1	0.40	a	T0K8	0.39	abc	T3K1	0.60	ab	T3K6	0.84	a	T4K0	0.78	b	T4K1	0.68	abc	T2K8	0.45	a
T0K8	0.46	a	T3K6	0.39	a	T2K6	0.33	abc	T2K0	0.56	ab	T3K8	0.81	a	T2K0	0.72	b	T3K1	0.67	abc	T1K6	0.44	a
T3K0	0.45	a	T0K1	0.36	a	T3K1	0.32	abc	T0K1	0.51	ab	T1K1	0.76	a	T3K0	0.65	b	T3K8	0.66	abc	T0K6	0.44	a
T0K1	0.43	a	T2K6	0.36	a	T0K1	0.29	abc	T4K0	0.50	ab	T3K0	0.74	a	T3K8	0.61	b	T1K0	0.64	abc	T4K8	0.43	a
T3K6	0.39	a	T2K1	0.35	a	T4K1	0.27	abc	T3K8	0.48	ab	T2K0	0.68	a	T0K8	0.60	b	T2K8	0.64	abc	T1K1	0.41	a
T2K1	0.36	a	T4K8	0.33	a	T4K6	0.27	abc	T0K6	0.46	ab	T4K0	0.66	a	T4K1	0.60	b	T3K6	0.61	bc	T4K1	0.40	a
T1K0	0.35	a	T0K0	0.32	a	T4K0	0.25	bc	T4K8	0.43	ab	T0K1	0.56	a	T3K6	0.54	b	T3K0	0.60	bc	T4K0	0.39	a
T3K1	0.33	a	T2K0	0.31	a	T1K0	0.24	bc	T1K8	0.39	ab	T1K0	0.54	a	T1K0	0.54	b	T1K8	0.60	bc	T2K0	0.39	a
T4K8	0.32	a	T1K1	0.29	a	T2K1	0.19	bc	T0K0	0.38	ab	T0K0	0.53	a	T0K0	0.49	b	T0K8	0.57	bc	T3K1	0.37	a
T0K0	0.30	a	T0K8	0.28	a	T2K0	0.13	c	T0K8	0.34	ab	T0K6	0.52	a	T2K1	0.44	b	T4K0	0.55	bc	T0K1	0.36	a
T1K6	0.28	a	T1K0	0.25	a	T0K0	0.10	c	T1K0	0.15	b	T1K8	0.31	a	T0K6	0.35	b	T0K0	0.50	c	T2K1	0.35	a

Note: Numbers followed by the same letter in the same column indicate no significant difference based on Duncan's multiple range test at the 5% significance level.

The data showed that tea waste compost application had a significant effect on shoot health, as indicated by a higher pekoe ratio and a lower number of banji shoots in several observation months compared with the control treatment, although the values were still below the ideal pekoe/banji ratio standard of 2.33. In general, plots receiving tea waste compost, either at 1,000 kg ha^{-1} or in combination with inorganic fertilizer, exhibited better shoot growth stability, particularly during dry periods such as May, July, and August. During these periods, most plots without tea waste application showed an increase in banji shoots, whereas plots treated with tea waste maintained a higher proportion of pekoe shoots.

This response occurred because tea waste compost improves soil organic matter availability, enhances soil structure, and increases soil water-holding capacity, thereby improving plant health and growth stability. During dry periods, improved soil physical conditions allow tea plants to maintain sufficient water availability and continue producing healthy young shoots. In contrast, plots without additional organic amendments are more susceptible to water stress, causing young shoots to develop into banji shoots. Furthermore, tea waste compost supports soil microbial activity, which contributes to gradual nutrient mineralization, particularly nitrogen (N) and potassium (K), which are essential nutrients for healthy shoot formation and development.

In addition, the data indicated that tea waste treatments provided better responses than control plots during wet months. Although high rainfall conditions may reduce shoot quality due to low solar radiation and excessive humidity, tea waste-treated plots were still able to maintain a higher pekoe ratio in most treatments. This indicates that tea waste compost not only supports plant performance under water deficit conditions but also helps reduce root stress caused by excessive water availability through improvements in soil porosity and aeration.

Overall, the results demonstrate that tea waste compost consistently improved shoot health, as reflected by the higher proportion of pekoe shoots compared with banji shoots during both dry and wet seasons. These findings confirm that tea waste application is an effective strategy for improving soil conditions, enhancing plant resilience, and supporting sustainable shoot productivity in tea plantations.

Soil nutrient analysis

The soil nutrient status analysis after the application of tea waste compost demonstrated improvements in several key soil fertility parameters, particularly organic carbon (C-organic), nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg). The distribution of nutrient status categories indicates that tea waste compost contributed to maintaining and improving soil nutrient availability in the experimental plots.

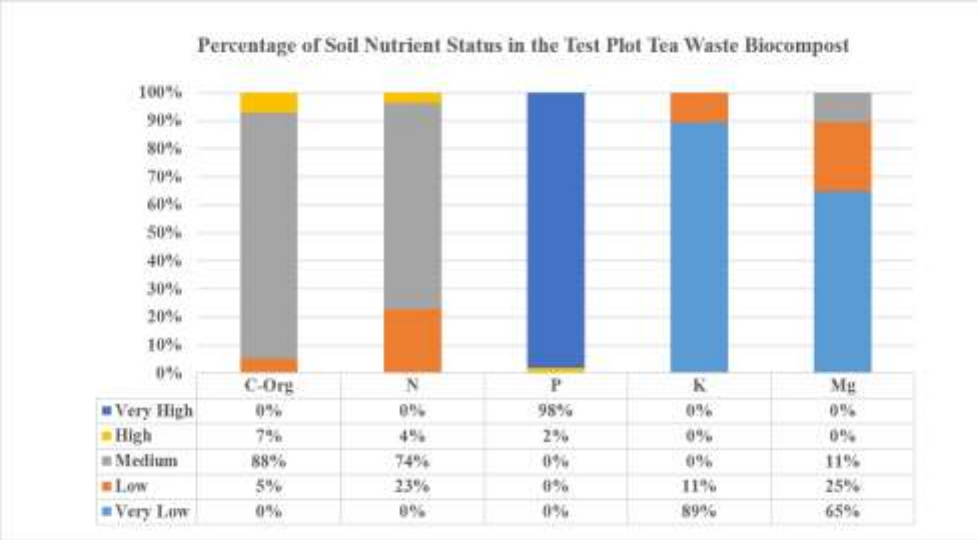

Figure 5. Percentage of Soil Nutrient in Plot

The C-organic content showed predominantly medium status (88%), with 7% categorized as high and only 5% classified as low. The improvement in soil organic carbon is closely related to the addition of tea waste compost, which contains a high proportion of organic materials. Organic amendments contribute to soil carbon accumulation, improve soil aggregation, increase water retention capacity, and provide a continuous energy source for soil microorganisms. Increased soil organic matter also plays an important role in enhancing nutrient retention and reducing nutrient losses through leaching (Bernal *et al*., 2009).

The soil nitrogen (N) status was mainly classified as medium (74%), with 4% categorized as high and 23% as low. The availability of nitrogen after tea waste compost application indicates a gradual nutrient release process through organic matter decomposition. Nitrogen in compost is released through microbial mineralization, converting organic nitrogen compounds into ammonium and nitrate forms that can be absorbed by tea plants. The gradual release mechanism from organic fertilizers can improve nitrogen use efficiency compared with rapid-release inorganic fertilizers (Agegnehu *et al*., 2017).

For phosphorus (P), the majority of soil samples (98%) were categorized as very high, indicating that tea waste compost application contributed to increased phosphorus availability. Organic matter in compost can improve phosphorus availability by forming organic acids during decomposition, which reduce phosphorus fixation and increase phosphorus solubility in soil. In addition, microbial activity stimulated by compost application can enhance phosphorus cycling through the activity of phosphate-solubilizing microorganisms (Bhattacharyya and Jha, 2012).

The potassium (K) status showed that most samples were categorized as very low (89%), with only 11% classified as low. Although tea waste compost contains potassium, the availability of K in soil may be influenced by soil mineral characteristics, leaching processes, and plant uptake, particularly in high rainfall tea plantation areas. Potassium is a highly mobile nutrient and can be easily lost through leaching, especially in acidic soils with high rainfall intensity. Therefore, additional potassium management may be required to optimize K availability for tea plants.

The magnesium (Mg) status showed that 65% of soil samples were categorized as very low, 25% as low, and 11% as medium. The relatively low Mg availability may be associated with acidic soil conditions commonly found in tea plantations, where Mg can be displaced from exchange sites and lost through leaching. Although organic amendments can improve cation exchange capacity (CEC) and nutrient retention, continuous nutrient removal by tea plants may reduce available Mg levels over time.

Overall, the results indicate that tea waste compost application positively influenced soil fertility, particularly by improving soil organic carbon, phosphorus availability, and maintaining nitrogen status. However, potassium and magnesium availability remained limiting factors, suggesting the need for balanced nutrient management combining organic amendments with targeted mineral fertilizer supplementation. The integration of tea waste compost with appropriate inorganic fertilizer management can improve nutrient use efficiency, enhance soil health, and support sustainable tea production.

CONCLUSION

1. The application of tea waste compost was able to increase tea shoot yield and plucking quality, with the best response obtained from the combination of tea waste compost at 1,000–2,000 kg/ha with 60% of the recommended chemical fertilizer dose.
2. The T1K6 treatment (1,000 kg/ha tea waste compost + 60% chemical fertilizer) showed the highest shoot production and a better peko/burung shoot ratio during the observation periods in May, July, and August 2025.
3. Under dry season stress conditions (July–August 2025), the application of tea waste compost was able to maintain higher shoot production compared to the control, particularly in the T1K6 and T2K6 treatments (2,000 kg/ha tea waste compost + 60% chemical fertilizer)
4. The results indicate that the utilization of tea waste compost has the potential to improve inorganic fertilizer use efficiency by up to 40%, while simultaneously supporting soil health improvement and sustainable tea

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