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Effects of integrated biological and chemical fertilization on pecco and banji shoot development in tea plants

Abstract. Tea productivity and quality are largely determined by shoot structure, particularly the balance between pecco shoots (tender buds and young leaves) and banji shoots (older, less productive shoots). Conventional reliance on inorganic fertilizers often enhances overall growth but does not necessarily improve shoot structure, while biofertilizers alone provide limited nutrient availability. This study aimed to evaluate the effects of combining microbial-based liquid biofertilizers with inorganic fertilizers on the structure of tea shoots. The experiment was carried out on seed-derived tea plants using a randomized block design with several fertilization treatments, including sole biofertilizer, sole inorganic fertilizer, and their combinations. The parameters observed were the number and weight of pecco and banji shoots. The results revealed that the combined application of microbial-based biofertilizers and inorganic fertilizers significantly increased both the number and weight of pecco shoots compared with single applications. Conversely, the proportion of banji shoots decreased under integrated fertilization treatments, indicating an improvement in shoot structure toward more productive harvests. The synergistic effects of microbial activity and balanced nutrient supply enhanced nutrient uptake, regulated shoot differentiation, and promoted a higher ratio of productive shoots. In conclusion, the application of biological and chemical fertilizers affected the growth of pecco shoots and banji shoots of tea plants. Treatment 40 L/ha biological + 100% chemical fertilizer) produced the highest weight and number of pecco, while treatment 30 L/ha biological + 75% chemical fertilizer produced equivalent results, allowing for a reduction in chemical fertilizer dosage by up to 25%.

Keywords : Banji shoots · Biofertilizer · Integrated fertilization · Pecco shoots · Tea plant

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Introduction

The quality of tea is determined by the composition of primary and secondary metabolites, including amino acids, flavonoids, theanine, and alkaloids such as caffeine, which collectively influence flavor, aroma, and functional properties (Wu et al, 2025). In tea production systems, harvestable young shoots consisting of the apical bud (pecco) and adjacent leaves play a central role in determining both yield and quality. Beyond total shoot biomass, the structural composition of tea shoots—particularly the proportion and weight of pecco and banji shoots—has a direct influence on harvesting efficiency and the consistency of raw material quality. Therefore, optimizing tea shoot structure represents a key objective in sustainable tea plantation management.

Nutrient management is one of the most critical agronomic practices for regulating tea shoot growth and development. In many tea plantations, nitrogen, phosphorus, and potassium required for continuous shoot flushing are primarily supplied through chemical fertilizers (Manzoor et al., 2024). Although chemical fertilizers can rapidly enhance shoot growth, excessive or prolonged use often leads to nutrient imbalance, soil degradation, and reduced nutrient use efficiency. Moreover, inappropriate fertilization practices may negatively affect metabolite composition, thereby compromising tea quality (Zhang et al., 2025).

Previous studies have demonstrated the positive effects of chemical fertilizers and biofertilizers on tea growth and yield. However, most existing research focuses on general growth performance or total yield, while limited attention has been given to how fertilization strategies influence tea shoot structural characteristics. In particular, the combined application of chemical fertilizers and microbial-based biofertilizers remains underexplored with respect to their role in shaping shoot structure, despite their importance for both productivity and quality. Based on available literature, there is a lack of integrated studies that explicitly evaluate how such combined fertilization strategies affect tea shoot structural composition, especially pecco development.

Microbial-based biofertilizers containing plant growth-promoting rhizobacteria (PGPR) offer a promising approach to improving fertilizer efficiency and sustainability in tea plantations. PGPR enhances nutrient availability through mechanisms such as nitrogen fixation, nutrient solubilization, and phytohormone production, which may regulate shoot initiation and development (Yorlady et al., 2024). The novelty of this study lies in evaluating how the combination of biofertilizers with reduced chemical fertilizer doses affects tea shoot structure, rather than focusing solely on yield or nutrient uptake. The findings are expected to provide scientific evidence for optimizing fertilization strategies that support sustainable tea production while maintaining high-quality shoot characteristics.

Materials And Methods

The experiment was conducted from July to November 2024 at the Tea and Cinchona Research Center experimental Plantation in Gambung, Bandung Regency. The elevation ranged from ± 1,000 m to 1,800 m above sea level, rainfall ranged from 2,000 to 3,000 mm/year, and the average air temperature was 14 to 25°C. The soil order was mostly Andisol.

The materials used in this experiment included seed-derived tea plants aged 75–85 years and Fertomax PPKS liquid biofertilizer. Based on laboratory analysis, the biofertilizer contained a consortium of functional microorganisms with populations ≥10^7 cfu mL^{-1}, including nitrogen-fixing bacteria (*Azospirillum* sp. and *Azotobacter* sp.), phosphate-solubilizing bacteria (*Bacillus* sp. and *Pseudomonas* sp.), and indole-3-acetic acid (IAA)-producing bacteria. In addition, the biofertilizer contained plant growth hormones, namely auxin (≥65 ppm), gibberellin (≥82 ppm), and cytokinin (≥34 ppm). Chemically, it contained organic carbon (≥0.17%), total nitrogen (≥0.12%), P_2O_5 (≥0.006%), K_2O (≥0.022%), and micronutrients including Fe, Cu, Zn, and B.

Inorganic fertilization was conducted using single-nutrient fertilizers rather than compound NPK, consisting of urea (46% N), SP-36 (36% P_2O_5), KCl (60% K_2O), and kieserite (27% MgO). Application rates were calculated based on the standard fertilizer recommendation for mature tea plants grown on Andisol soils issued by the Indonesian Tea and Quinine Research Institute Gambung with annual rates of 558 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1}, 214 kg K_2O ha^{-1}, and 119 kg MgO ha^{-1}. During the experimental period, 30%

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of the annual recommendation was applied at three fertilization levels (50%, 75%, and 100%). For a 100 m² plot, the 100% rate corresponded to 1.67 kg urea, 0.23 kg SP-36, 0.64 kg KCl, and 0.36 kg kieserite, with proportional adjustments for the lower levels.

The equipment used in this experiment included a knapsack sprayer for applying liquid organic and inorganic fertilizers; measuring cups for preparing treatment solutions; pruning shears for harvesting shoots; plastic bags for sample collection and storage; an analytical balance for weighing shoot samples; and an oven for drying the samples.

The experiment employed a Randomized Block Design (RBD) comprising ten treatments with three replications, yielding a total of 30 experimental plots. Each plot measured 10 × 10 m, giving a total experimental area of 3,000 m². The treatment combinations of liquid biofertilizer and chemical fertilizer, ranging from the sole application of 100% recommended chemical fertilizer to reduced levels of chemical fertilizer supplemented with 20–40 L/ha biofertilizer. The treatments included: (A) 100% recommended chemical fertilizer (control), (B) 20 L/ha biofertilizer + 50% recommended chemical fertilizer, (C) 30 L/ha biofertilizer + 50% recommended chemical fertilizer, (D) 40 L/ha biofertilizer + 50% recommended chemical fertilizer, (E) 20 L/ha liquid biofertilizer + 75% recommended chemical fertilizer, (F) 30 L/ha biofertilizer + 75% recommended chemical fertilizer, (G) 40 L/ha biofertilizer + 75% recommended chemical fertilizer, (H) 20 L/ha biofertilizer + 100% recommended chemical fertilizer, (I) 30 L/ha biofertilizer + 100% recommended chemical fertilizer, and (J) 40 L/ha biofertilizer + 100% recommended chemical fertilizer. The research method used was a completely randomized design with 10 treatment combinations. Each treatment was repeated three times.

All data collected were subjected to variance analysis and followed by Duncan's multiple range test in SASMAgri software to test the differences between treatments. Chemical fertilizer is applied once after the initial harvest by scattering it on the tea rows, while liquid biofertilizer is applied twice at two-month intervals, namely after the initial harvest and after the second harvest. Plucking is carried out every 30 days using plucking shears with a medium plucking (p+2m, p+3m, b+2, b+3) (Santoso et al., 2020). A total of 100 g of shoot samples from each plot were collected for the analysis of pecco and dormant shoot numbers, with sampling conducted routinely after each production plucking at a one-month plucking cycle. Plant maintenance is carried out by mechanical weed control and routine pest control.

Results and Discussions

Weight of pecco shoots. Measuring the fresh weight of pecco shoots is important because this parameter reflects the production capacity of tea buds, the physiological condition of the plant, nutrient absorption efficiency, and the plant's response to the cultivation practices applied. Pecco shoots play a crucial role because they are the youngest part of the plant and are rich in secondary metabolites, such as polyphenols, caffeine, and amino acids, which significantly impact the quality of the tea brew. The fresh weight of tea buds can be used as an indicator of the vegetative growth of tea shoots and is closely related to the potential yield and quality of the tea produced (Turkmen et al., 2009).

The analysis results show that the combination of chemical fertilizer and biofertilizer has a significant effect on the fresh weight of pecco shoots. Fresh weight of pecco shoots differed significantly among treatments (Table 1), indicating that shoot productivity responded to the interaction between biofertilizer rate and chemical fertilizer level. The highest fresh weight was observed in treatment J (40 L ha^{-1} biofertilizer + 100% chemical fertilizer), confirming that sufficient nutrient supply combined with microbial activity can maximize shoot biomass. This condition suggests that adequate nutrient availability from chemical fertilizers, combined with the role of microbes in biofertilizers, can promote optimal shoot growth. Microbes effective in biological fertilizers are known to increase nutrient availability through nitrogen fixation, phosphate solubilization, and the production of growth regulators that stimulate shoot growth (Miao et al., 2024).

Table 1. Combined application of biofertilizers and chemical fertilizers on the weight of fresh pecco shoots

Treatment	Weight of fresh shoot (g)
A 100% recommended chemical fertilizer (control)	62 bc
B 20 L/ha biofertilizer + 50% recommended chemical fertilizer	93 ab
C 30 L/ha biofertilizer + 50% recommended chemical fertilizer	77 abc
D 40 L/ha biofertilizer + 50% recommended chemical fertilizer	51 c
E 20 L/ha biofertilizer + 75% recommended chemical fertilizer	84 ab
F 30 L/ha biofertilizer + 75% recommended chemical fertilizer	95 ab
G 40 L/ha biofertilizer + 75% recommended chemical fertilizer	48 c
H 20 L/ha biofertilizer + 100% recommended chemical fertilizer	90 ab
I 30 L/ha biofertilizer + 100% recommended chemical fertilizer	71 bc
J 40 L/ha biofertilizer + 100% recommended chemical fertilizer	112 a
CV	11.89%

Note: Means followed by different letters in the same column indicate significant differences based on Duncan's Multiple Range Test. CV – coefficient of variance.

Interestingly, treatments with lower doses of chemical fertilizer, namely B (20 L/ha biofertilizer + 50% chemical fertilizer), C (30 L/ha biofertilizer + 50% chemical fertilizer), E (20 L/ha biofertilizer + 75% chemical fertilizer), F (30 L/ha biofertilizer + 75% chemical fertilizer), and H (20 L/ha biofertilizer + 100% chemical fertilizer) treatments were not significantly different from treatment J. This shows that the combination of biofertilizer with a 25–50% reduction in chemical fertilizer is still capable of producing equivalent fresh shoot weight. The use of biofertilizers allows for a reduction in chemical fertilizer inputs without reducing productivity. Thus, the integration of biofertilizers is a potential strategy for improving fertilizer efficiency and reducing the negative environmental impacts of excessive chemical fertilizer use (Kumar et al., 2022).

Physiologically, the increase in fresh weight of pecco shoots is closely related to the supply of essential nutrients, especially nitrogen, phosphorus, and potassium. Nitrogen is needed for the formation of chlorophyll and proteins, phosphorus plays a role in energy metabolism and meristematic tissue growth, while potassium regulates osmotic balance and the translocation of photosynthates to shoot tissues (Shambhavi et al., 2016). Optimal nutrient availability will increase cell division and enlargement in young shoots, resulting in higher fresh weight of pecco (Ruan et al., 2010). The role of biofertilizer in increasing nutrient availability and stimulating physiological activity supports more vigorous shoot growth (Nepolean et al., 2012).

Thus, the use of biofertilizers in tea fertilization systems can be a sustainable approach. In addition to increasing the fresh weight of pecco shoots, the integration of biofertilizers enables the efficient use of chemical fertilizers without compromising productivity. These implications are very important in the management of modern tea plantations, which are required to maintain a balance between productivity, cost efficiency, and environmental sustainability. According to Miao et al. (2024) The rational application of fertilizers in tea plantation improves the soil environment of tea plantations, enhances the quality of tea leaves, and achieves sustainable tea production.

Weight of banji shoots. In addition to pecco shoots, which are the main target in tea harvesting, tea plants also produce banji shoots, which are shoots that do not have young leaves because their apical shoots are dead or undeveloped. Banji shoots are unproductive because they cannot be harvested to produce young leaves, so their contribution to tea yield is very limited. The presence of banji shoots can even reduce the quality of the harvested buds, because buds that contain too many banji shoots will reduce the yield and quality of the tea brew. Measuring the weight of tea shoots is important for evaluating the effectiveness of cultivation practices. This parameter describes the extent to which a practice can reduce the formation of unproductive shoots and increase the proportion of economically valuable shoots. Thus, analyzing the weight of tea shoots can provide a more comprehensive picture of tea shoot growth, not only in terms of productivity but also in terms of yield quality.

The results of statistical analysis in Table 2 show that the application of various combinations of chemical and organic fertilizers

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did not have a significant effect on the weight of banji shoots. This indicates that the formation of banji shoots is more influenced by plant physiological factors and environmental conditions, while fertilization factors also indirectly affect the growth of banji shoots.

Banji shoots formation is caused by the cessation of apical meristem activity, preventing the terminal bud from developing into a productive shoot. This phenomenon can be caused by internal factors such as apical dominance and growth hormone balance, especially cytokinin and auxin, as well as external factors such as light availability, temperature, and environmental stress (Chen et al., 2014). Thus, although fertilization can increase nutrient supply, it does not necessarily reduce the formation of banji shoots.

The presence of banji shoots in the composition of harvested shoots is undesirable because banji shoots are classified as unproductive shoots that cannot be harvested further. The dominance of banji shoots will reduce the quality of the shoots produced and have implications for a decline in the quality of the tea brew, because this part tends to produce coarse biomass with lower secondary metabolite content (Wang et al., 2022). Supporting this interpretation, Wulansari and Rezamela (2017) reported that a high proportion of dormant or bird shoots (40–30%) reflects plant stress arising from nutritional imbalance and unfavorable environmental conditions, which ultimately induce shoot dormancy and banji shoot formation.

From a management perspective, the absence of significant differences in banji shoot weight among fertilization treatments suggests that improving tea shoot quality cannot rely on fertilization manipulation alone. Instead, effective suppression of dormant shoots requires integrated crop management practices, including appropriate pruning regimes, shade management, and proper plucking techniques that regulate shoot turnover and hormonal balance. The integration of these practices is therefore expected to play a more decisive role in reducing banji shoot dominance and increasing the proportion of productive pecco shoots.

Number of pecco shoots. The number of pecco shoots is an important parameter in determining the potential production of high-quality tea. Not only the fresh weight, but also the number of pecco that appear will directly affect the productivity of the plant because pecco are the main ingredient in plucking (Anjarsari et al., 2024). The higher the number of pecco formed, the greater the chance of increasing the yield and quality of tea buds that can be harvested. Variations in the number of pecco between treatments reflect the physiological response of plants to environmental conditions and cultivation treatments. Therefore, analyzing the number of pecco is an important step in understanding the dynamics of tea shoots' growth more comprehensively.

Table 2. Combined application of biofertilizers and chemical fertilizers on the weight of banji shoots

Treatment	Weight of banji shoot (g)
A 100% recommended chemical fertilizer (control)	249 a
B 20 L/ha biofertilizer + 50% recommended chemical fertilizer	250 a
C 30 L/ha biofertilizer + 50% recommended chemical fertilizer	242 a
D 40 L/ha biofertilizer + 50% recommended chemical fertilizer	247 a
E 20 L/ha biofertilizer + 75% recommended chemical fertilizer	245 a
F 30 L/ha biofertilizer + 75% recommended chemical fertilizer	248 a
G 40 L/ha biofertilizer + 75% recommended chemical fertilizer	265 a
H 20 L/ha biofertilizer + 100% recommended chemical fertilizer	268 a
I 30 L/ha biofertilizer + 100% recommended chemical fertilizer	270 a
J 40 L/ha biofertilizer + 100% recommended chemical fertilizer	238 a
CV	10.68%

Note: Means followed by different letters in the same column indicate significant differences based on Duncan's Multiple Range Test. CV – coefficient of variance.

Table 3. Combined application of biofertilizers and chemical fertilizers on the number of pecco shoots

Treatment	Number of Pecco Shoots
A 100% recommended chemical fertilizer (control)	80 b
B 20 L/ha biofertilizer + 50% recommended chemical fertilizer	108 ab
C 30 L/ha biofertilizer + 50% recommended chemical fertilizer	100 ab
D 40 L/ha biofertilizer + 50% recommended chemical fertilizer	95 b
E 20 L/ha biofertilizer + 75% recommended chemical fertilizer	105 ab
F 30 L/ha biofertilizer + 75% recommended chemical fertilizer	125 a
G 40 L/ha biofertilizer + 75% recommended chemical fertilizer	102 ab
H 20 L/ha biofertilizer + 100% recommended chemical fertilizer	100 ab
I 30 L/ha biofertilizer + 100% recommended chemical fertilizer	94 b
J 40 L/ha biofertilizer + 100% recommended chemical fertilizer	129 a
CV	14.91%

Note: Means followed by different letters in the same column indicate significant differences based on Duncan's Multiple Range Test. CV – coefficient of variance.

Statistical analysis shows that the combination of biofertilizer and chemical fertilizer affects the number of pecco shoots (Table 3). The number of pecco shoots was the most responsive parameter to fertilization treatments. Treatment J produced the highest number of pecco shoots, followed closely by Treatment F (30 L ha^{-1} biofertilizer + 75% chemical fertilizer). Notably, Treatment F achieved pecco numbers statistically equivalent to the full chemical fertilizer treatment, demonstrating that a 25% reduction in chemical fertilizer input did not reduce productivity.

This result clearly indicates that Treatment F represents the best compromise between productivity and input efficiency. The enhanced pecco formation is likely associated with improved nutrient availability and phytohormone production by biofertilizer-associated microbes, which stimulate bud initiation and meristem activity. These findings strongly support the role of biofertilizers in improving fertilizer efficiency and sustaining high-quality tea production. This is in line with the concept of sustainable agriculture, which emphasizes input efficiency and reducing environmental impact (Le et al., 2021). A high number of pecco is an important indicator in tea production, as pecco are the main raw material for high-quality tea (Owuor & Obanda, 2007). Younger tea plant leaves contain higher concentrations of phenolic compounds than the stems and roots, contributing both significantly to flavor and pharmacological health benefits (Techane et al., 2025). Thus, these results show that the integration of biological and chemical fertilizers not only maintains productivity but also has the potential to increase fertilization efficiency.

The increase in the number of shoots in the combination of biological fertilizer and chemical fertilizer treatments is thought to be related to the role of microbes in biological fertilizers, which can increase nutrient availability and stimulate shoot growth through the production of phytohormones such as auxin and cytokinin (Vejan et al., 2016). The presence of chemical fertilizers as a source of macro nutrients directly supports the formation of new tissue, so that the synergy between the two can accelerate the growth of productive shoots.

Number of banji shoots. In tea cultivation, in addition to pecco shoots which have high economic value, there are also banji shoots or inactive buds. Dormant buds generally do not develop into productive buds and are therefore considered to be less profitable vegetative parts. A high proportion of dormant buds in a bud population can reduce plucking efficiency and result in a decline in the quality of the harvested buds (Cheruiyot et al., 2007). Therefore, agronomic management that can suppress the formation of banji shoots is an important factor in efforts to improve tea quality and productivity.

Statistical analysis shows that the number of banji shoots significantly varies between treatments (Table 4). Treatment A produced more banji shoots than the other treatments, but was not significantly different from treatments C, D, G, H, and I. A high number of banji shoots is undesirable in tea production because these buds are inactive and do not develop into productive buds.

Table 4. Combined application of biofertilizers and chemical fertilizers on the number of banji shoots

Treatment	Number of Banji Shoots
A 100% recommended chemical fertilizer (control)	371 a
B 20 L/ha biofertilizer + 50% recommended chemical fertilizer	296 c
C 30 L/ha biofertilizer + 50% recommended chemical fertilizer	311 abc
D 40 L/ha biofertilizer + 50% recommended chemical fertilizer	333 abc
E 20 L/ha biofertilizer + 75% recommended chemical fertilizer	288 c
F 30 L/ha biofertilizer + 75% recommended chemical fertilizer	298 bc
G 40 L/ha biofertilizer + 75% recommended chemical fertilizer	361 ab
H 20 L/ha biofertilizer + 100% recommended chemical fertilizer	318 abc
I 30 L/ha biofertilizer + 100% recommended chemical fertilizer	317 abc
J 40 L/ha biofertilizer + 100% recommended chemical fertilizer	288 c
CV	10.54%

Note: Means followed by different letters in the same column indicate significant differences based on Duncan's Multiple Range Test. CV – coefficient of variance.

An increase in the number of banji shoots can reduce harvesting efficiency and affect the quality of the harvested shoots (Cheruiyot et al., 2009) . The results show that the combination of certain biological and inorganic fertilizers, particularly in treatments B (20 L/ha biological fertilizer + 50% recommended inorganic fertilizer), E (20 L/ha biological fertilizer + 75% recommended inorganic fertilizer), and J (40 L/ha of organic fertilizer + 100% of the recommended inorganic fertilizer), were able to suppress the formation of bird beaks compared to treatment A without the optimal combination.

This phenomenon indicates that the application of organic fertilizer can play a role in improving the physiological balance of plants, so that photosynthetic energy is directed more towards the formation of productive shoots (pecco) rather than inactive shoots. Microbes in biofertilizers can increase nutrient availability and produce bioactive compounds that support cell division and differentiation (Yorlady et al., 2024). Thus, the right combination of fertilizers not only increases the number and weight of pecco buds but also reduces the proportion of banji shoots, resulting in optimal productivity and quality of tea buds. The sustainability implication (chemical fertilizer reduction) is well supported and could be emphasized more clearly as a key contribution.

Conclusion

The application of biological and chemical fertilizers significantly affected the growth of pecco shoots and banji shoots of tea plants. Treatment J (40 L/ha biological + 100% chemical fertilizer) produced the highest weight and number of pecco shoots, while treatment F (30 L/ha biological + 75% chemical fertilizer) produced equivalent results, allowing for a reduction in chemical fertilizer dosage by up to 25%.

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