ISSN: 1412-4718, eISSN: 2581-138x

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Enhancing tea productivity through integrated fertilization and pruning management: A review

Abstract. Tea productivity is strongly influenced by agronomic management practices, particularly fertilization and pruning, which play critical roles in regulating plant growth, physiological performance, and shoot regeneration. This review aims to synthesize current scientific evidence on how integrated fertilization and pruning management can sustainably enhance tea productivity. A narrative review approach was employed by collecting and analyzing peer-reviewed articles published between 2015 and 2025 from reputable databases, including Google Scholar and major international journals. The review highlights that balanced fertilization strategies, combining inorganic, organic, and biofertilizers, significantly improve nutrient availability, photosynthetic efficiency, and shoot yield. Pruning, when properly timed and executed, stimulates vegetative growth, maintains canopy structure, and optimizes the distribution of assimilates. Several studies demonstrated that microbial-based biofertilizers enabled a 25% reduction in inorganic fertilizer inputs without compromising tea shoot yield, while optimum pruning cycles of four to five years-maintained productivity and canopy renewal. In addition, the proportion of pecco shoots was reported to decline from approximately 70% in the first year after pruning to 19% in the fourth year, emphasizing the importance of proper pruning management. Importantly, the integration of fertilization and pruning practices produces synergistic effects, resulting in enhanced shoot density, improved yield stability, and long-term sustainability of the plantation. This review emphasizes that integrated nutrient and canopy management is essential to address productivity decline and environmental challenges in tea plantations, providing a scientific basis for developing climate-resilient and resource-efficient tea cultivation systems.

Keywords: Tea productivity · Fertilization · Pruning · Integrated management · Sustainable agriculture

Submitted: 1 March 2026, Accepted: 2 July 2026, Published: 14 August 2026
DOI: https://doi.org/10.24198/kultivasi.v25i2.69997

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Anjarsari IRD, Murgayanti, Kadapi M, Mubarok S, Umiyati U, Salsabilah AN, Azmi A, Ramadhan AP, Husniah TH, Rosita, Azkiya A. 2026. Enhancing tea productivity through integrated fertilization and pruning management: A review. Jurnal Kultivasi, 25 (2): 175-189.

Jurnal Kultivasi Vol. 25 (2) August 2026
ISSN: 1412-4718, eISSN: 2581-138x

Introduction

Tea (*Camellia sinensis* L.) is one of the most important plantation commodities in Indonesia and worldwide, playing a major role in the economy, both as a source of foreign exchange and as a provider of employment. The productivity and quality of tea leaves are significantly influenced by the physiological condition of the plant and the soil fertility status, particularly the availability of macronutrients such as nitrogen (N), phosphorus (P), and potassium (K). These elements play an important role in biomass formation, the metabolism of secondary compounds such as catechins, and plant resistance to biotic and abiotic stresses (Tang et al., 2020; Huang et al., 2022). Therefore, proper fertilization practices, in terms of type, dosage, and timing of application, are key factors in enhancing tea productivity and quality.

However, the decline in tea productivity in recent years has become quite serious in various tea-producing countries, including Indonesia. Several studies indicate that one of the primary causes of this decline in productivity is the degradation of the soil's physical, chemical, and biological properties due to excessive and unbalanced use of inorganic fertilizers (Chen et al., 2021; Xi et al., 2023). High dependence on nitrogen fertilizers, for example, can cause soil acidification, base cation imbalance, and decreased soil microbial activity, which plays an important role in the nutrient cycle (Frontiers, 2022). Meanwhile, potassium deficiency has been shown to reduce tea quality and photosynthetic efficiency, which directly impacts crop yields (Xi et al., 2023; Huang, 2022).

The decline in soil quality due to unsustainable fertilization practices calls for a new approach to plant nutrient management. Several recent studies emphasize the importance of implementing integrated nutrient management (INM), which combines inorganic fertilizers with organic fertilizers and biostimulants to improve nutrient uptake efficiency and soil conditions (Rahman et al., 2021; Zhu et al., 2024). This strategy not only maintains crop yields but also improves soil fertility and reduces dependence on synthetic fertilizers (Manzoor et al., 2024). An aspect that is often overlooked but crucial in the context of tea productivity is the seedling stage. Good seedling quality determines the success of plant growth after transplanting to the field. At this stage, fertilization plays an important role in the formation of a strong root system, optimal vegetative growth, and increased resistance to environmental stress (Raguraj et al., 2022). The application of organic fertilizer, liquid biofertilizer, or a combination of NPK fertilizer has been proven to increase biomass, seedling height, and chlorophyll content in young tea plants (Tang et al., 2023; Rahman et al., 2021). Thus, optimizing fertilization during the seedling stage is a strategic step in overcoming tea productivity problems at the mature plantation level.

Integrated Nutrient Management (INM) not only plays a role in improving productivity and soil health but also has significant economic implications for the sustainability of tea plantations. The combined use of inorganic fertilizers, organic materials, and biofertilizers has been proven to increase nutrient use efficiency while reducing dependence on relatively expensive chemical fertilizers (Jianyun et al., 2020). Several studies have shown that the INM approach can reduce production costs by partially substituting inorganic fertilizers with organic and biological sources, without reducing yields and, in some cases, even increasing productivity. Furthermore, biofertilizers serve as a cheaper and more environmentally friendly alternative, thereby improving long-term cost efficiency. Within the context of sustainable agricultural systems, INM also contributes to reducing nutrient losses and improving soil quality, ultimately reducing future land rehabilitation and external input costs. This approach is increasingly relevant in the context of declining fertilizer subsidies and rising agricultural input prices (Gebrewold, 2018). Furthermore, recent studies confirm that INM is a climate-smart agricultural technology capable of increasing input efficiency while providing economic benefits through yield stability and reduced production risks, particularly in plantation systems in tropical and subtropical regions (Kugedera et al., 2025).

Pruning has been practiced as one of the standard management measures in tea plant cultivation and is not only a physical act of cutting but also an integral part of plantation management to maintain optimal productivity, especially when plants begin to age, grow too tall, or production begins to decline. regular pruning can rejuvenate tea plantations. Pruning can stimulate new shoot growth and lateral

branching, renew plant structure, and keep plants productive.

In addition to nutrient management, canopy management is one of the critical components in controlling tea production and quality. Pruning in tea plants is very important because regular pruning can rejuvenate tea plantations. Canopy architecture affects the microclimate within the tea plant through light interception, temperature, and humidity, thereby influencing photosynthesis and secondary metabolite production. In addition, correct canopy management techniques, like the umbrella-shaped system, have been observed to help restore the soil microbial population (Jiang et al., 2023). Tea tree pruning is an important management method in the process of tea tree planting. Tea tree pruning can stimulate the growth of lateral buds and the increase in lateral branches, which in turn can be beneficial for the increase in tea yield (Zhang et al., 2021).

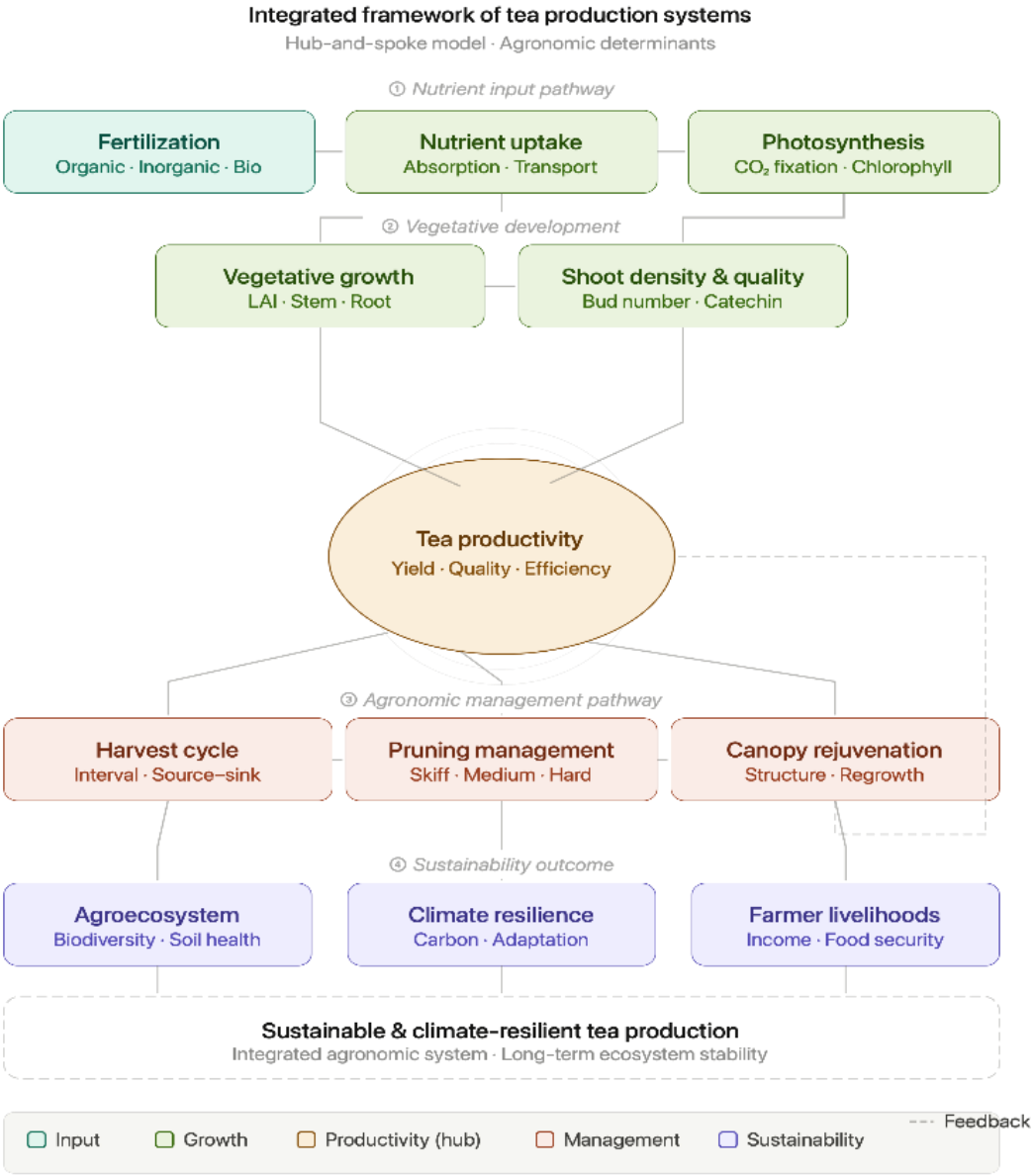

Figure 1. Integrated framework of tea production system

Jurnal Kultivasi Vol. 25 (2) August 2026
ISSN: 1412-4718, eISSN: 2581-138x

Pruning was beneficial for improving the yield of tea tree, but pruning was an abiotic stress that could lead to changes in the metabolic capacity of tea tree organisms (Das et al., 2022). In addition, pruning improves nutrient absorption and circulation in the soil by stimulating enzyme and microbial activity in the rhizosphere, ultimately supporting vegetative growth and increasing tea bud yield. Pruned tea plants are hypothesized to exhibit metabolic differences from unpruned ones (Mozumder et al., 2021), for instance, most enzymes involved in the biosynthesis of catechins were downregulated in leaves of unpruned tea plants (Chen et al., 2021). At the same time, tea tree pruning could reduce the labor force and improve the efficiency of tea harvesting. Based on the above, research and discussion on the effectiveness of fertilization and pruning in tea plants are highly relevant. The application of balanced, efficient, and environmentally friendly fertilization strategies is expected to provide a sustainable solution for enhancing tea plant productivity and quality while maintaining soil fertility in the long term.

Although numerous studies have investigated fertilization and pruning practices individually, comprehensive reviews addressing their interactive effects on tea productivity and sustainability remain limited. Existing studies are fragmented and mainly focus on specific management aspects without providing an integrated framework that links nutrient management, canopy architecture, and long-term productivity. Therefore, a comprehensive synthesis is required to elucidate the synergistic roles of fertilization and pruning in developing sustainable and climate-resilient tea production systems. Therefore, an integrated conceptual framework is presented in Figure 1 to summarize the major pathways linking fertilization and pruning management with tea productivity and long-term sustainability.

Based on this framework, the present review aims to synthesize recent findings on fertilization and pruning management and to provide a comprehensive understanding of their integrated roles in enhancing tea productivity and supporting sustainable tea production systems.

Materials and Methods

This study employed a systematic literature review (SLR) approach following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to synthesize scientific evidence related to improving tea productivity through fertilization and pruning management. The literature was collected from national and international journals published between 2015 and 2025 through the Google Scholar database using relevant keywords. Relevant literature published between 2015 and 2025 was retrieved from the Google Scholar database using combinations of keywords including "tea productivity", "*Camellia sinensis*", "fertilization", "nutrient management", and "pruning". A total of 70 articles were initially identified.

Based on the inclusion criteria, namely topic relevance, methodological quality, and completeness of data. Finally, 60 articles met the inclusion criteria and were included in the qualitative synthesis. The selected studies were analyzed to identify research approaches, major findings, and trends related to fertilization and pruning efficiency in tea cultivation. The extracted information was synthesized using qualitative thematic analysis to develop a conceptual framework of effective fertilization and pruning management strategies for enhancing tea productivity.

Results and Discussion

Basic Physiology of Tea Plants Related to Fertilization and Pruning. Tea plants are important plantation crops whose young shoots are harvested for tea. This plant has strong taproots with many lateral roots, densely branched woody stems, and young elliptical leaves as the main part that is harvested. Physiologically, shoot growth is greatly influenced by temperature, rainfall, and light, which play a role in photosynthesis and transpiration. Fertilization plays a major role in supporting vegetative growth and shoot production. The elements N, P, and K complement each other in supporting plant development. Pamungkas (2017) reported that the application of up to 180 kg/ha of nitrogen can increase plant height and the number of primary and secondary branches. Similar findings were reported by Haq et al. (2023), who found that mineral foliar fertilizer and liquid organic fertilizer can increase the number and weight of active shoots by enhancing photosynthetic activity and leaf quality. The combined application of organic and chemical

fertilizers significantly enhances the growth and quality of tea plants, as evidenced by increased leaf area, 100-bud weight, and chlorophyll content. This fertilization strategy improves the soil environment by increasing total nitrogen, total potassium, available nitrogen, organic matter, and soil pH, while also promoting soil enzyme activity and microbial functional diversity (Miaio et al., 2024).

In addition to fertilization, pruning is also an important factor because it aims to form productive shrubs by improving branching, rejuvenating tissue, and maintaining the harvest area. According to Anjarsari et al. (2021), clean pruning at a height of 50–60 cm combined with the application of 60 ppm BAP and 50 ppm GA is the best treatment for stimulating productive shoots. Research at the Kanaan State Tea Garden shows that shoots grow faster on small branches, while large branches produce more shoots. Productivity increases until the fourth year after pruning and begins to decline in the fifth year, so the ideal pruning cycle is in the range of 4–5 years (Haloho, 2022).

After the aspects of fertilization and pruning are fulfilled, the next important stage is shoots plucking. Harvesting not only serves as a means of obtaining yields but also plays a role in maintaining the shape of the plant, so that it can continue to produce new shoots. Therefore, harvesting techniques must consider the condition of the harvest area, the height of the shoots, and the number of leaves harvested to maintain a balance between production and shoot regeneration (Salimah et al., 2023). Adjusting the plucking cycle in line with pruning practices will produce more high-quality shoots and increase tea productivity and quality (Marostek, 2023; Prastiwi, 2019).

The physiological responses of tea plants to fertilization, pruning, and plucking management are closely associated with vegetative growth and shoot productivity. Each management practice plays a distinct role in regulating physiological processes, influencing plant development, and ultimately affecting yield. A summary of the physiological functions and their implications for tea productivity is presented in Table 1.

Table 1. Effects of fertilization and pruning practices on growth and productivity of tea plants

Management Factor	Physiological Effect	Growth Response	Impact on Yield	Source
nitrogen (N), phosphorus (P), and potassium (K) fertilization	Increased chlorophyll formation and photosynthesis	Increase plant height and the number of primary and secondary branches	Biomass formation, the metabolism of secondary compounds such as catechins, and plant resistance to biotic and abiotic stresses	Pamungkas (2017), Tang et al., 2020; Huang et al., 2022
Organic and chemical Fertilization	Increased leaf area, and chlorophyll content.	Enhances the growth and quality of tea plant	Increase bud weight	Miaio et al., 2024
Foliar liquid organic fertilizer	Increased chlorophyll content, enhancing photosynthetic activity and leaf quality.	Increase biomass (dry weight)	Increase the number and weight of active shoots, root starch content, and fresh shoot weight	(Tang et al., 2023; Rahman et al., 2021), Haq et al.(2023), Anjarsari et al., 2024
Biofertilizer and inorganic fertilizer	Enhancing photosynthetic activity	wet weight and shoot yield,	Increase the quantity of tea plant yield.	Anjarsari et al., 2025
Tea prunning	Stimulate the growth of lateral buds	and the increase in lateral branches	Stimulating productive shoots, high-quality shoots and increase tea productivity and quality	Zhang et al., 2021 Marostek, 2023; Prastiwi, 2019.
Proper pruning cycle	Maintained productive branches	Sustained vegetative growth	Stable productivity	Anjarsari et al., 2021,

Jurnal Kultivasi Vol. 25 (2) August 2026
ISSN: 1412-4718, eISSN: 2581-138x

Efficient Fertilization Strategies for Tea Plants. Primary nutrients such as nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), sulfur (S), and micronutrients play an important role in the vegetative and generative growth of tea plants (Camellia sinensis). Based on research by Syarifa et al. (2019), nitrogen is the element that most influences the height and number of branches in young tea plants. Increasing the nitrogen dose to the optimum level can accelerate the formation of the plucking area by increasing the number of productive branches and the canopy area of the plant. The N element plays an important role in the formation of chlorophyll and proteins, thereby supporting the process of photosynthesis and the growth of new shoots. However, excess N can inhibit root growth and reduce the efficiency of other nutrient use. In addition, phosphorus (P) is also important in root system formation and cell division, while potassium (K) plays a role in maintaining water balance and increasing plant resistance to environmental stress (Syarifa et al., 2019).

In addition to these three macroelements, secondary elements such as magnesium (Mg) and sulfur (S) also contribute to tea plant metabolism. Magnesium is an essential element in tea plants because it functions as the center of chlorophyll molecules. In addition, Mg also plays a role in nitrogen assimilation. Research by Zhang et al. (2023). Mg deficiency can cause chlorosis symptoms in older leaves, while S deficiency inhibits the growth of young shoots. Microelements such as Fe, Zn, Mn, and B are also necessary, albeit in small amounts, as they act as enzyme activators and improve the quality of tea shoots. Therefore, the balance between macro, secondary, and micronutrients are crucial to support optimal tea plant growth, increase the productivity of young leaves, and maintain crop quality.

Balanced fertilization is the key to maintaining productivity and sustainability in agroecosystems, especially for plantation crops such as tea.

According to Athallah et al. (2021), the use of inorganic fertilizers still dominates tea plantations in Indonesia because plants respond quickly to nutrients from chemical fertilizers (fast release). However, excessive and unbalanced application of inorganic fertilizers can reduce soil quality and disrupt the activity of microorganisms that play a role in mineralization and nitrogen fixation processes. As a result, soil health declines and the efficiency of nutrient uptake by plants decreases (Thakur et al., 2011; Shambhavi et al., 2017). Thus, maintaining a balance between the use of inorganic and organic fertilizers is crucial for ensuring soil fertility sustainability.

Fertilization is a crucial component in supporting the vegetative and generative growth of tea plants; therefore, the selection of fertilizer types must consider both short-term effectiveness and long-term sustainability. Inorganic fertilizers such as urea, TSP, and KCl are known to provide a quick response because their nutrients are readily available and immediately absorbed by plants. This makes inorganic fertilizers effective in stimulating plant height, number of young branches, and canopy area (Syarifa et al., 2019). However, excessive use of inorganic fertilizers can reduce soil health by disrupting microorganism activity and accelerating the decomposition of organic matter, thereby reducing soil productivity in the long term (Thakur et al., 2011; Shambhavi et al., 2017). Therefore, despite providing quick results, inorganic fertilizers carry the risk of reducing soil quality if not balanced with wise fertilization practices.

In contrast, organic fertilizers work more slowly because their nutrients are released gradually, but they have a positive impact on soil structure and biology. The phytohormone content, such as auxin, cytokinin, and gibberellin in liquid organic fertilizer (LOF), can stimulate cell division, improve plant metabolism, and increase resistance to environmental stress (Zhang et al., 2023). In addition, organic fertilizers increase soil microbial biomass, improve the physical and chemical properties of the soil, and support natural nitrogen fixation (Li et al., 2016; Diacono & Montemurro, 2015). The results of a study by Atthallah et al. (2021) show that applying 1% POC once every two weeks increases tea productivity by 6.88 kg plot^{-1}, proving that although the effect is not as fast as inorganic fertilizers, organic fertilizers

make a stable contribution to the vegetative growth of tea plants.

From a sustainability perspective, combining organic and inorganic fertilizers is the ideal strategy. Inorganic fertilizers can be used to meet the need for rapidly absorbed nutrients such as nitrogen, which is important for bud formation, while organic fertilizers maintain soil structure, reduce the risk of toxicity, and increase

long-term benefits for the agroecosystem (Hasani et al., 2016; Atthallah et al., 2021). Thus, a balanced fertilization approach between organic and inorganic inputs not only supports optimal plant growth but also ensures soil sustainability as a foundation for sustainable tea production. According to the results of Athallah et al. (2021) research, it is known that the application of 1% LOF every two weeks shows the potential to increase tea productivity by 6.88 kg plot^{-1} compared to other treatments. This shows that liquid organic fertilizer, even though it releases nutrients more slowly than inorganic fertilizer, is still able to support the stable vegetative growth of tea plants.

The phytohormone content, such as auxin, cytokinin, and gibberellin in LOF, can also stimulate cell division and elongation, which affects the increase in the number and weight of tea shoots (Gebrewold, 2018; Wong et al., 2015). In addition, organic fertilizers contribute to improving the physicochemical properties of the soil and increasing soil microbial biomass (Li et al., 2016; Diacono & Montemurro, 2015). Therefore, although the effects are not always significant in the short term, the sustainable use of organic fertilizers provides long-term benefits for soil productivity and health.

Meanwhile, inorganic fertilizers such as urea are highly effective because they are quickly absorbed by plants, especially N, which plays an important role in the formation of vegetative tissue. Proper nitrogen management ensures that both the yield and quality of tea are maximized, contributing to the long-term sustainability of tea production (Ali et al., 2024). The following is an overview of the effect of nitrogen on several tea quality parameters (Table 2).

However, the effectiveness of these inorganic fertilizers is highly dependent on the method and frequency of application. For example, applying urea to leaves only has a temporary effect and tends to be less efficient than applying it to the soil (Hasani et al., 2016). But excessive use of urea can even cause damage to plant tissues due to nitrogen toxicity (Davarpanah et al., 2017). Based on this, Athallah et al. (2021) emphasized the importance of a balanced fertilization approach between organic and inorganic inputs to achieve optimal results, where organic fertilizers play a role in maintaining soil structure and biological activity, while inorganic fertilizers provide a quick supply of nutrients for plant growth.

Table 2. The effects of Nitrogen application rates on various quality parameters of tea

Nitrogen Application Rate (kg/ha/year)	Total Polyphenol Content (%)	Catechin Content (mg/g)	Caffeine Content (%)	Amino Acid Content (mg/g)	Leaf Size (cm²)	Tea Yield (kg/ha)	Tea Quality Rating
0 (Control)	8.4	35	2.8	3.2	25	1200	Low
50	9.2	37	3.0	3.5	28	1350	Moderate
100	10.0	40	3.2	3.8	30	1500	Good
150	10.2	42	3.4	4.0	32	1600	Very Good
200	9.5	39	3.5	4.2	33	1650	Excellent
250	8.7	36	3.8	4.0	31	1700	Poor
150	10.2	42	3.4	4.0	32	1600	Very Good

Source : (Ali et al., 2024; Singh et al., 2023; Tesfaye ,2024)

- Tea Total Polyphenol Content (%, w/w): Polyphenols, especially catechins (−)-epigallocatechin gallate (EGCG), play an important role in the antioxidant properties of tea. Moderate nitrogen application typically increases their content.
- Catechin Content (mg/g): Catechins are an essential element in taste flavor and healthy benefits of tea. Optimal nitrogen rate increases catechin production.
- Caffeine Content%: The Responsible Agent of Tea Stimulation More nitrogen does lead to slightly higher caffeine levels, but too many causes unwanted bitter notes.
- Amino Acid Content (mg/g): Nitrogen underwrites amino acid production, crucial to umami flavor found in tea, particularly theanine. In general, higher nitrogen applications increased amino
- Leaf Growth (cm2): Adequate nitrogen application contributes to the proper growth of leaves and increases their area, which can enable better plucking.
- Tea Yield (kg/ha): The application of nitrogen has a very high effect on the yield. Moderate to high applications of nitrogen gave maximum tea yield.
- Tea quality rating: This is a subjective rating of the produced tea based on sensory evaluations (flavor, aroma and appearance) where moderate to high nitrogen applications produce better tea quality up until a specific threshold

Jurnal Kultivasi Vol. 25 (2) August 2026
ISSN: 1412-4718, eISSN: 2581-138x

Furthermore, to anticipate extreme conditions caused by climate anomalies, fertilization technology is also combined with the use of biofertilizers or biological fertilizers. The use of microbes such as Azotobacter sp. has been proven to increase nitrogen in the soil and maintain nutrient availability during the dry season (Van Dang, 2022). In addition, the application of organic matter and mulch also supports an increase in soil water holding capacity of 6.3% per 1% increase in organic matter, thereby increasing the effectiveness of inorganic fertilizers. The combination of inorganic, organic, and biological fertilizers is an integrated strategy to maintain soil nutrient balance and sustain tea plant productivity under unstable climatic conditions.

Modern fertilization technology for tea plants is increasingly moving towards an integrative strategy that combines soil fertilizer application with more efficient nutrient management. A study by Ruan et al. (2020) introduced the concept of Integrated Nutrient Management in tea gardens, where pruning and the use of chemical fertilizers are combined with organic fertilization and the application of special tea fertilizer formulas, which can increase nutrient efficiency without sacrificing crop yields. Furthermore, field research conducted by Hu et al. (2024) shows that rational reduction of chemical fertilizer application results in yield increases of 4.65–28.67% as well as improvements in agronomic efficiency (AE), nitrogen use efficiency (NUE), and fertilizer productivity (PFP). On the other hand, Zhao et al. (2024) successfully optimized nutrient management in albino tea cultivars by adjusting the N-P-K-Mg ratio and replacing some chemical fertilizers with organic rapeseed cake. This approach not only reduced the amount of chemical fertilizer by 25%, but also increased yield, quality (e.g., amino acid and polyphenol content), and agronomic efficiency. Additionally, research by Shiwakoti et al. (2023) confirmed that fertilizer application methods (both in terms of dosage and method) have a significant impact on crop productivity and the chemical composition of the black tea produced, indicating that regulating fertilizer application methods can improve fertilization efficiency and final product quality. Thus, smart fertilization technology through chemical reduction, organic substitution, and proper application has proven to be an effective strategy for improving nutrient efficiency, reducing excessive fertilizer use, and maintaining or improving tea yield and quality while ensuring environmental sustainability.

In addition to enhancing shoot yield, fertilization and pruning practices also influence tea quality by affecting the accumulation of secondary metabolites, particularly polyphenolic compounds. Variations in nutrient management and canopy regulation may alter the biosynthesis of phenolic constituents, thereby affecting the antioxidant properties and overall quality of tea leaves. A summary of previous studies reporting the effects of different management practices on total polyphenol content and related quality attributes is presented in Table 3.

Table 3. Effects of Different Management Practices on Polyphenol and Flavonoid

Management Practice	Total Polyphenol Content	Total Flavonoid Content	Source
Inorganic Fertilization	632.58 mg GAE/g dry extract	219.5 mg QE/g dry extract	Shiwakoti et al (2023)
Organic Fertilization	620.58 mg GAE/ g dry extract	358.74 mg QE/g dry extract	(Dwyer & Peterson, 2013). Vastrad et al., 2022 Shiwakoti et al (2023)
Organic Fertilization	443.7–506 µg GAE/g DW (white tea)		Yurteri et al., 2019
Biofertilizer	-	58.63 mg QE/sample	Anjarsari et al., 2024
Organic and inorganic fertilization	150.53 mg/g	67.13 mg/g	Zhang et al., 2025

The inorganic fertilizers provide readily available nitrogen sources which might favors development and growth of plant but does not favor the production of phytochemicals and other secondary metabolites. But due to the absence of readily accessible nutrients in organic treatment, which provide the nutrient more slowly than inorganic fertilizers, might leads to the exposure of plant in more stressful situations, thus initiating the production of secondary metabolites such as polyphenols in plants (Devkota et al., 2021; Mastura et al., 2017). Optimized fertilization requires comprehensive consideration of soil properties, microbial communities, and tea plant growth stages. Only through precise regulation of the N/P/K ratios and organic/inorganic combinations can the metabolic composition be directionally controlled, enabling sustainable tea plantation management (Wu et al., 2025).

Pruning Techniques for Optimal Productivity. Pruning is an important technique in tea cultivation that helps regulate shoot growth, bud quality, and the productive age of plants. On plantations, pruning is divided into several types, namely tipping, light pruning, medium pruning, and deep pruning. Tipping aims to stimulate fine branching and maintain the length of the harvested buds. Light pruning is done to keep the height of the plucking area low and produce high-quality shoots. Medium pruning is used to improve the shape of the plant canopy when yields begin to decline, while deep pruning or rehabilitative pruning is applied to older plants to stimulate new shoot growth (Haloho, Rahayu, & Wiendi, 2022; Wulansari, Athallah, & Pramudita, 2022). In line with Lu et al. (2022) classify pruning into four levels: light, moderate, deep, and heavy. Each has a cutting depth of 3–5 cm, 10–15 cm, 20–30 cm, and 40–45 cm from the soil surface, respectively.

Light pruning helps maintain the shape of the plant canopy and encourages lateral branching. Meanwhile, heavy pruning is used to rejuvenate plants that are old or diseased. These different types of pruning affect the quality of the shoots produced. Light pruning and tipping usually produce finer, more uniform shoots with a high pekoe ratio, making them suitable for premium tea production. On the other hand, moderate to heavy pruning encourages new branching and more vigorous shoots, but the shoots produced during early recovery are often coarse and larger in size, resulting in reduced quality until the plant stabilizes within 1–2 harvest seasons. This physiological effect is supported by research by Lu et al. (2022), which shows that heavy pruning carried out in April–May increases the weight of 100 shoots by up to 20.5 grams and accelerates bud formation through increased levels of the hormones IAA, GA_1, GA_3, and trans-zeatin. In addition, pruning also changes the mineral content in the leaves—reducing mobile elements such as N, P, K, and Mg, while increasing immobile elements such as Ca, Mn, and B, which affect the formation of metabolites that determine the aroma and taste of tea (Liu et al., 2022). This shows that the intensity of pruning not only affects the structure of the plant, but also the physiological quality of the shoots produced.

Various studies in Indonesia show a strong relationship between the type of pruning, shoot growth, and climatic and environmental conditions. Haloho and colleagues (2022) noted that pruning can promote faster shoot growth, especially in small branches compared to large branches. This is in line with the findings of Wulansari, Athallah, and Pramudita (2022), who stated that shoot productivity is greatly influenced by the timing of pruning and soil moisture content. Changes in soil moisture due to pruning type or land conditions affect the speed of shoot recovery, so the pruning schedule must be adjusted to local environmental conditions. In determining the timing of pruning, Indonesia generally follows the rainy season and the growth cycle of tropical plants. Lu et al (2022) recommend that heavy pruning be carried out around mid-April to early May to enhance the growth of the next season's shoots. Ramadhan et al (2023) add that the highest productivity levels in Indonesian tea plantations are achieved through light to moderate pruning, with heavy pruning cycles every 2 to 4 years.

In practice, large plantations in Indonesia, such as the Kanaan State Tea Plantation in Bandung, West Java, implements a heavy pruning cycle every 4 to 5 years, accompanied by routine pruning throughout the year to maintain the plucking area (Haloho et al., 2022). In addition, the effectiveness of pruning greatly depends on environmental conditions, especially soil moisture content, which determines the ability of plants to recover (Wulansari et al., 2022). When compared to other countries, there are significant differences in pruning strategies. In India and Sri Lanka, pruning generally follows a

Jurnal Kultivasi Vol. 25 (2) August 2026
ISSN: 1412-4718, eISSN: 2581-138x

fixed cycle of 3 to 4 years with strict formative pruning to maintain uniform plant height, as most harvesting is done manually. In China, the pruning system varies depending on the variety and production objectives. For example, premium green tea is pruned lightly and frequently to produce fine shoots, while certain oolong and black teas are pruned moderately to produce stronger shoots. In Japan, the pruning system is the most precise, with the use of high-tech trimming machines that require a very neat canopy, resulting in light pruning and precise plucking field formation being a priority. Indonesia falls between the Sri Lankan and Chinese models, where most pruning is done to maintain a flat plucking field with a moderate cycle (4–5 years), but there are still variations in methods depending on the altitude of the land and rainfall.

Advances in precision agriculture technology continue to improve modern pruning systems. Spatial analysis, as developed by Ramadhan et al. in 2023, uses image data from the Sentinel-2B satellite and the K-Means algorithm, enabling efficient classification of pruning intensity and monitoring of plant health over large areas. From a genetic perspective, Kan et al. (2024) found that plant species also influence their response to pruning; for example, the Zhongcha 302 variety has better shoot regeneration ability than Emei Wenchun due to higher CYP450 gene expression and lower NCED gene expression. On the mechanization side, there are innovations such as microcontroller-operated semi-automatic pruning machines (Hemalatha et al., 2020) and adaptive pruning systems that use PID algorithms (Zhang et al., 2025), allowing the pruning process to follow the canopy shape in real-time with an accuracy of approximately ±5 mm. This progress is reinforced by multi-sensor canopy detection algorithms, such as the "Onion Peeling Algorithm" by Han and Song (2025), which allows the machine to adjust the cutting height precisely according to the shape of the tea canopy surface.

Fertilization Integration – Pruning and Its Impact on Productivity. Pruning and fertilization are two practices that have a synergistic relationship and are key determinants of young shoot growth, shoot quality, and tea crop yield (Zhang et al., 2023). Pruning is done to rejuvenate branches, stimulate new shoot formation, and maintain plant height to facilitate harvesting (Zhang et al., 2023), and needs to be supported by fertilization that provides essential nutrients. The minerals like nitrogen, potassium, phosphorous and magnesium are essential nutrients and their deficiency leads to adverse effects on the yield and the quality of tea (Islam et al., 2017). These essential nutrients could be derived from fertilization. Fertilization, both organic and inorganic, is an important agricultural practice to increase crop yields, improve plant growth and development and maintain soil fertility by supplying nutrients to the plants (Qiu et al., 2014). Macro nutrients such as N are vital for promoting leaf growth and shoot formation, while P and K play a role in strengthening root systems and improving leaf quality. Micronutrients such as Mg, Ca, Zinc (Zn), and Boron (B) are also important in metabolism, which affects the compounds that determine the taste and aroma of tea (Liu et al., 2022). Although pruning can increase yields, this practice has the potential to reduce the levels of quality compounds such as caffeine, flavonoids, and free amino acids, as the plant shifts its focus to vegetative growth (Zhang et al., 2023). Therefore, pruning practices must be balanced with proper fertilization to increase productivity without reducing leaf quality.

Optimal tea plant management requires integration between fertilization, pruning, and climatic conditions to maintain growth and productivity. Nutrient requirements are dynamic based on the season and growth stage, so adjustments to the timing and dosage of fertilization are necessary to achieve optimal efficiency (Tang et al., 2020). Strategically, higher doses of nitrogen (N) are recommended immediately after pruning to encourage bud growth, followed by P and K in the middle of the rainy season or leaf formation phase to increase nutrient absorption efficiency (Tang et al., 2020; Tustiyani, 2023).

Pruning intensity should also take climate into account; deeper pruning is effective during warm seasons with sufficient light to stimulate new shoots, while heavy pruning should be avoided during cold or high rainfall periods to prevent growth retardation (Zhang et al., 2023). This integrated approach has been successfully implemented in several tea-producing countries. In Sri Lanka, a periodic pruning system accompanied by fertilizer application based on plant needs increased productivity by up to 18% on small tea plantations (Munasinghe et al., 2020). Research by Easwaran et al. (2023) in India shows

that treatment with 6 tons/ha of DCC + biofertilizer consistently after pruning produces more shoots and more uniform shoot size, which directly affects the quality of green and black tea. Meanwhile, in China, research by Chen et al. (2021) shows that plants that are not pruned in the long term do have higher polyphenol and theanine levels, but their production decreases. Although pruning has long been recognized as a key management practice in tea cultivation, recent research has revealed additional physiological, ecological, and productivity-related benefits that were previously less understood. To highlight these emerging developments, Table 4 summarizes recent advances in pruning management and their implications for tea productivity and sustainability.

Tabel 4. Recent study (2024–2025) in fertilization and pruning management of tea plants

Study	Research Focus	Main Findings
Hu et al. (2024)	Rational fertilizer reduction	Yield increased by 4.65–28.67%
Zhao et al. (2024)	Organic substitution strategy	Reduced chemical fertilizer by 25%
Kan et al. (2024)	Gene-based pruning response	Improved shoot regeneration
Zhang et al. (2025)	Adaptive pruning system	Precision pruning ±5 mm
Wu et al. (2025)	Nutrient optimization	Improved metabolite composition

Sustainability, Economic, and Policy Recommendations Perspectives. Fertilization and pruning are key components of tea cultivation that determine cost efficiency and productivity. Excessive use of chemical fertilizers is ineffective and can degrade soil quality, while reducing doses by 40–70% can increase yields by up to 28% and profits by up to 135% (Pei et al., 2025). The combination of organic fertilizers, biofertilizers, and the use of biochar and compost from pruning residues has been proven to increase nutrient efficiency and reduce dependence on chemical fertilizers (Athallah & Wulansari, 2022). Proper pruning methods and intervals are also important for maintaining long-term productivity (Athallah et al., 2021). Integrating both can save up to 30% on chemical fertilizers without reducing yields (Wulansari et al., 2021). From an environmental perspective, reducing chemical fertilizers and adding organic matter can reduce soil and water pollution and improve soil structure (Athallah & Wulansari, 2022; Wulansari et al., 2021). Efficient pruning maintains the plant canopy, thereby reducing erosion and nutrient runoff (Athallah et al., 2021).

Returning pruning biomass through compost or mulch enhances soil conservation and microbial activity that supports nutrient cycling (Wulansari & Pranoto, 2018). These efforts make tea gardens more environmentally friendly and sustainable. Training farmers is very influential in increasing the adoption of efficient technologies such as organic fertilizers, proper pruning, and nutrient management (Liu et al., 2022). The implementation of precision technology, soil sensors, and waste management requires policy support in the form of incentives, subsidies, and regulations so that small farmers can access them (Kumara et al., 2023). Going forward, research needs to focus on low-cost technologies suitable for tea gardens in Indonesia, economic-environmental analysis, and socio-institutional studies that influence technology adoption (Xie et al., 2022).

Conclusion

Fertilization and pruning are two key factors that determine tea plant productivity. Fertilization provides the nutrients needed for the formation of high-quality buds, while pruning helps rejuvenate plants and stimulate new shoots. Both practices must be applied appropriately, in a balanced manner, and in an integrated way. The wise use of fertilizers, pruning according to the growth phase, and technological support can increase yields while maintaining the sustainability of tea gardens. Our study recommends implementing balanced fertilization based on soil analysis to increase tea productivity in Indonesia, as many tea plantations have experienced declining soil fertility due to the excessive use of inorganic fertilizers. Regular pruning according to the age of the plant is important to rejuvenate shrubs, especially in tea. Integration between fertilization and pruning will accelerate the emergence of productive shoots and maintain the stability of the plucking area. The use of organic materials and

biofertilizers needs to be increased to improve soil quality and microbial activity. In addition, the use of simple to modern technology can help improve labor efficiency, costs, and sustainable tea plantation management.

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