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A Review of Matcha (*Camellia sinensis*) Quality: Genetic, Agronomic, and Physiological Determinants

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Abstrak

Kualitas matcha superior sangat bergantung pada profil metabolit sekunder yang kompleks, sehingga diperlukan strategi terpadu antara genetik dan praktik agronomi. penelitian ini menggunakan metode studi literatur dan review artikel ilmiah untuk memperoleh informasi mengenai genetik dan praktik agronomi dalam produksi teh untuk diolah menjadi matcha premium. Pemilihan kultivar teh (genetik) merupakan faktor penentu yang mendasari rasa, warna, dan aroma spesifik matcha. Teknik penaungan merupakan praktik agronomi esensial yang memicu respons fisiologis optimal, terutama dalam meningkatkan Theanine dan Klorofil sekaligus menekan Katekin penyebab rasa pahit melalui intensitas penaungan sekitar 85%. Aroma segar, yang merupakan indikator kualitas, dikendalikan oleh senyawa volatil dan dapat ditingkatkan melalui strategi penaungan dan pemupukan yang tepat menggunakan NPK dikombinasikan dengan organik/biochar terbukti efektif dalam meningkatkan pertumbuhan, konsentrasi Klorofil, dan kualitas aroma. Penelitian mendatang harus memiliki fokus terhadap pemuliaan tanaman terintegrasi dengan marka molekuler untuk induksi gen yang berkaitan dengan Theanine, selain itu pengembangan praktik pertanian presisi yang mengintegrasikan genetik, penaungan dinamis, dan optimasi aroma sangat diperlukan untuk menjamin kualitas matcha yang konsisten dan berdaya saing global.

Kata kunci: Agronomi, Fisiologi, Genetik, Matcha, Theanin

Abstract

The quality of superior matcha is highly dependent on its complex secondary metabolite profile, requiring an integrated strategy between genetics and agronomic practices. This study used literature review and scientific article review methods to obtain information on genetics and agronomic practices in tea production for processing into premium matcha. The selection of tea cultivars (genetics) is a determining factor that underlies the specific taste, color, and aroma of matcha. Shading techniques are essential agronomic practices that trigger optimal physiological responses, particularly in increasing theanine and chlorophyll while suppressing catechins, which cause bitterness, through shading intensity of around 85%. Fresh aroma, which is an indicator of quality, is controlled by volatile compounds and can be enhanced through appropriate shading and fertilization strategies using NPK combined with organic/biochar, which has been proven effective in improving growth, chlorophyll concentration, and aroma quality. Future research should focus on integrated plant breeding with molecular markers for the induction of Theanine related genes.. Additionally, the development of precision farming practices that integrate genetics, dynamic shading, and aroma optimization is essential to ensure consistent matcha quality and global competitiveness.

Keywords: Agronomy, Genetic, Matcha, Physiology, Theanine

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INTRODUCTION

Tea plants (*Camellia sinensis*) are one of Indonesia's leading agricultural commodities. They are perennial plants classified as refreshment plants. Tea leaves are used to make beverages that have a refreshing effect and a pleasant taste (Aradea et al., 2025). Matcha is one of the most popular beverages in the world and contains high concentrations of phytochemicals that promote health (Kika et al., 2024). The antioxidant, antiviral, and anti-inflammatory effects of matcha can stimulate immune and detoxification processes, including flavonoids and phenolic acids, which comprise up to 30% of matcha's dry weight, thereby increasing interest in matcha's health benefits and involvement in the pharmacological effects of matcha flavonoids (Peluso & Serafini, 2017).

Tea cultivars (genetics) play a role in determining the sensory profile of matcha, due to differences in their primary secondary metabolite content, which affects L-theanine production, resulting in an intense umami flavor, and suppresses catechins that cause bitterness (Xiao et al., 2023). Theanine is produced in all parts of the tea plant except the fruit, with the highest concentration found in young leaves (Lin et al., 2023). Genetic differences between tea cultivars cause variations in the concentration of volatile components, thereby affecting the diversity of aromas in each type (Lan et al., 2023). Cultivar variation causes differences in the synthesis of chlorophyll produced, which is one of the determinants of whether matcha will have the desired bright green color or tend to be duller. The genetic potential of plants determines their adaptability limits, while ecological (environmental) factors such as temperature, humidity, light, and water, as well as different agronomic aspects, can trigger diverse physiological responses.

Shading is one of the main agronomic practices that can improve matcha quality, including increasing the chlorophyll content of tea buds, enhancing tea aroma formation, and reducing tea polyphenol content (Chen et al., 2022a). Shade produces darker green leaves, which is likely related to increased leaf chlorophyll content (Liu et al., 2020). A decrease in light intensity during tea plant growth will affect the composition of components related to quality in tea buds, thereby enhancing the flavor of matcha. Shading can increase amino acid content and decrease epigallocatechin content. This suggests that the increased freshness of tea from shaded plants may be related to increased theanine content and decreased polyphenol content. The decrease in catechin content may reduce the bitterness of the tea, while the increase in amino acid content may enhance the freshness of the tea's flavor and ultimately improve the quality of matcha (Xu et al., 2020).

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The superior quality of matcha in terms of color, the intense umami flavor from L-theanine, and the high content of beneficial phytochemicals are the result of a complex interaction between genetic factors and agronomic manipulation in triggering the desired physiological response, namely increasing chlorophyll and amino acid synthesis while suppressing the catechins that cause bitterness. Therefore, it is important to further investigate how the combination of superior tea cultivars with the application of appropriate shading intensity can be optimized to maximize the quality, functional, and sensory profile of matcha powder.

RESEARCH METHODS

The literature review based on case study research approach is a structured method for reviewing, combining, and summarizing important results from various scientific literature sources related to a subject. Through this method, we can find patterns, shortcomings, or differences of opinion in previous research, which ultimately results in a comprehensive understanding of the current state of knowledge on the topic (Aradea, 2025). This process begins with the formulation of clear research questions, followed by a comprehensive literature search using scientific databases such as MDPI, PubMed, Scopus, and Web of Science. Once the literature has been collected, the next step is to review and extract data from each selected article for analysis. Some keywords used in the article search include *Camellia sinensis*, genetic variation, agronomic practices, physiological traits, secondary metabolites, catechins, chlorophyll, and tea quality determinants.

To ensure the data reliability, this review article only use the original research articles from leading journals published from 2015 to 2025. The review article focus on tea plant genetics and their relationship with cultivation techniques in agronomy and the physiological response of tea, with a focus on efforts to improve the quality of matcha produced. This research method adopts a systematic literature review approach to ensure that the research understanding process is conducted objectively, transparently, and comprehensively. With these strict selection criteria, this literature review is expected to provide an in depth and accurate summary of strategies for producing superior, high quality matcha.

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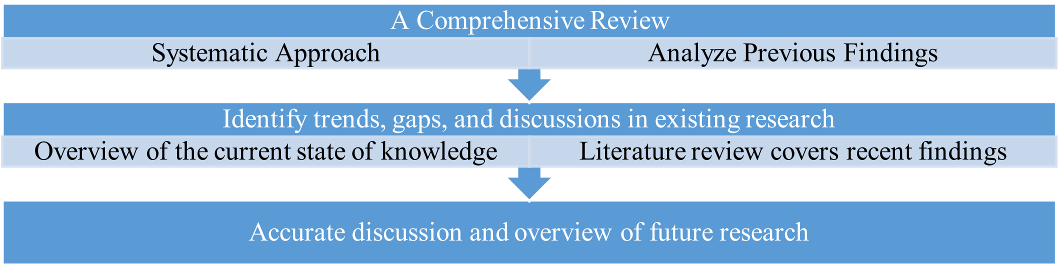

Figure 1. Review procedure flowchart

The skill of creating a solid literature review is very important for producing high quality scientific work, such as journal articles. A good literature review must critically evaluate previous studies to find gaps in knowledge and then formulate directions for further research. This review is a structured process that includes searching, discovering, reading, analyzing, and interpreting scientific works carefully, which plays an important role in advancing science (Chigbu et al., 2023). Meanwhile, scientific reviews (such as bibliometric analysis) are scientific approaches that analyze literature data quantitatively. This methodology is very useful for identifying trends, patterns, and conclusions from various research findings that have been published in a particular field or discipline (Merigó et al., 2017).

RESULTS AND DISCUSSION

This study aims to discuss the findings of research on optimizing the quality of matcha powder through an integrated approach between the genetic potential of *Camellia sinensis* cultivars and agronomic practices. The utilization of matcha, which has been proven to have high concentrations of beneficial phytochemicals such as flavonoids and phenolic acids involved in antioxidant and immunomodulatory effects, is highly dependent on its primary secondary metabolite profile.

Tea cultivars play a crucial role in determining sensory characteristics, particularly in the synthesis of L-theanine for umami taste and the suppression of catechins that cause bitterness. Furthermore, agronomic practices, particularly the application of shade, have been identified as effective physiological catalysts for increasing the accumulation of chlorophyll and amino acids while reducing polyphenols, which collectively contribute to improved matcha quality. Therefore, this discussion section will focus on analyzing in depth how the interaction between genetic differences and shading intensity affects the biochemical and physiological responses of tea plants, as well as identifying optimal

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strategies to maximize the quality, functional profile, and sensory value of the resulting matcha product.

Genetic

Research in plant genetics investigates various aspects, including how genes work and are regulated, how genetic variation and modification occur, how traits are inherited, and how genes interact with surrounding plant structures (Bailey-Serres et al., 2019). A deep understanding of plant genetics is key to influencing crop quality and quantity, because superior traits such as biochemical production, resistance to pests and diseases, and adaptability to extreme environmental conditions can be controlled by plant genetics with the aim of providing the desired benefits and superior characteristics.

The genetic role or type of tea (cultivar) is a crucial determining factor in plant cultivation for matcha production, as it directly affects the quality, taste, color, and aroma of the final product. Each cultivar has a unique potential of biochemical composition, particularly in the ratio of L-Theanine amino acids and catechins, which cause astringency. The cultivated variety determines whether the resulting matcha will have a strong umami flavor, natural sweetness, or a tendency toward bitterness. Yabukita, as the dominant cultivar, provides a stable, earthy flavor balance and is the industry standard. Cultivars like Okumidori are valued for their ability to produce a bright green color and a fresher taste, while Saemidori is often chosen for ceremonial grade matcha due to its mild, sweet, and umami rich flavor profile with minimal bitterness.

Table 1. Comparison of Several Tea Cultivars as Raw Materials for Matcha Production

Cultivar	Characteristic Taste & Aroma	Key Quality Notes	Potential Uses
Yabukita	The umami taste is stable and balanced, tends to be satisfying (early)	Industry Standard (Dominant). The result is a stable balance of flavors.	Good to premium quality matcha, stable for blending.
Okumidori	The taste is fresher (fresh) and a little lighter.	Produces a bright green color.	Used to enhance the color of blended matcha or matcha with a fresh taste.
Saemidori	Naturally sweet (sweet), rich in a mild umami flavor, with minimal potential bitterness.	Considered to have the mildest flavor profile.	Ideal for Ceremonial Grade Matcha (tea ceremony).

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Genetic relationships are part of molecular biology and are essential for various genetic and genomic research, as a basis for identifying the location of genes that control quantitative traits and comparative genomic analysis between species to understand and manipulate genetic information (Ott et al., 2015). Tea plants produce abundant and varied secondary metabolites. These compounds have two main functions: determining the quality characteristics of tea, including its distinctive color, aroma, and taste; and playing a vital role in helping plants respond to and survive biotic and abiotic environmental stressors.

Tea processing suitability refers to the inherent characteristics of a tea variety that make it ideal for processing into a specific type of tea in order to obtain the highest quality. Different tea plant cultivars naturally produce different flavor profiles and sensations (Xia et al., 2017), so the selection of tea cultivars for matcha production is certainly different from the tea plant varieties used for the production of green tea, oolong tea, white tea, and black tea.

Table 2. Representative Functional Genes in Tea Plants for Matcha Production

Gene symbol	NCBI Accession/identifier	Length (bp)	Function/Expression	Ref.
CsMYB5	KY827396	930	Regulate anthocyanin and proanthocyanidin biosynthesis	(Jiang et al., 2018)
CsTCS	AB031280	1438	Caffeine synthase gene Theanine biosynthesis	(Kato et al., 2000)
CsTSI	TEA015198[a]	2544	Theanine synthetase gene	(Wei et al., 2018)
CsAAPs	TEA031577[a]	2339	Encoding amino acid permease involved in theanine transportation	(Dong et al., 2020)
CsGT1	AB847092	1458	Converting volatile organic compounds into β-primeverosides for aroma biosynthesis	(Ohgami et al., 2015)

Theanine is an amino acid unique to tea plants and contributes significantly to the fresh taste of processed tea leaf products. Through a combination of genomic and transcriptomic analysis, scientists have successfully identified the gene responsible for producing the key enzyme in the theanine biosynthesis pathway, namely the gene named CsTSI. Theanine is a key component that provides flavor and acts as the main balancer by reducing bitterness, while catechins and caffeine are compounds that contribute to bitterness and astringency. To produce premium matcha, the ratio of theanine must be high

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relative to catechins and caffeine. Theanine is responsible for creating softness and richness of flavor, while catechins and caffeine provide bitter characteristics that must be controlled to achieve the perfect matcha flavor.

Precision agronomic strategies, such as dynamic shading and integrated fertilization, not only influence short term physiological responses but also activate regulatory networks at the transcriptomic level. For instance, the combination of NPK organic fertilization enhances nitrogen availability, a key precursor for theanine synthesis, while stimulating the expression of the CsAAPs gene (*amino acid permease*) for more efficient theanine transport. This synergy produces matcha with an intense umami taste and vibrant green color, where genetic excellence is maximally expressed through precise agronomic interventions. With this integrated approach, matcha quality no longer depends on a single factor but rather on the harmonious collaboration between *nature* (genetics) and *nurture* (agronomy)

Aroma plays a crucial role in determining the quality of tea and its appeal in the global market. Significant efforts have been made to identify the volatile components of various types of tea. The aim is to assess how these volatile compounds work and their specific contribution to the overall aroma of processed tea products (Zeng et al., 2019). A fresh aroma directly correlates with the umami flavor and smoothness of matcha, whereas a bland aroma indicates a degradation in matcha quality. Therefore, maintaining the integrity of volatile compounds will ensure a strong and pure aroma, resulting in premium matcha quality.

Agronomy and Physiology

This discussion focuses on an in-depth analysis of how agronomy, through specific and distinctive cultivation techniques, is one of the main determining factors for the final quality of the matcha powder produced. Premium matcha quality, characterized by its bright green color, deep umami aroma, and smooth texture, is not only the result of tea plant genetics, but is also influenced by unique practices such as shading before harvest to increase chlorophyll and L-theanine content, as well as the timing and method of harvesting.

Unique cultivation methods, especially shading techniques, determine the taste and nutritional content of matcha. The shading process effectively triggers a significant increase in the levels of bioactive compounds such as amino acids, particularly L-Theanine, which gives umami flavor, caffeine, and chlorophyll, which produces a deep green color, while at

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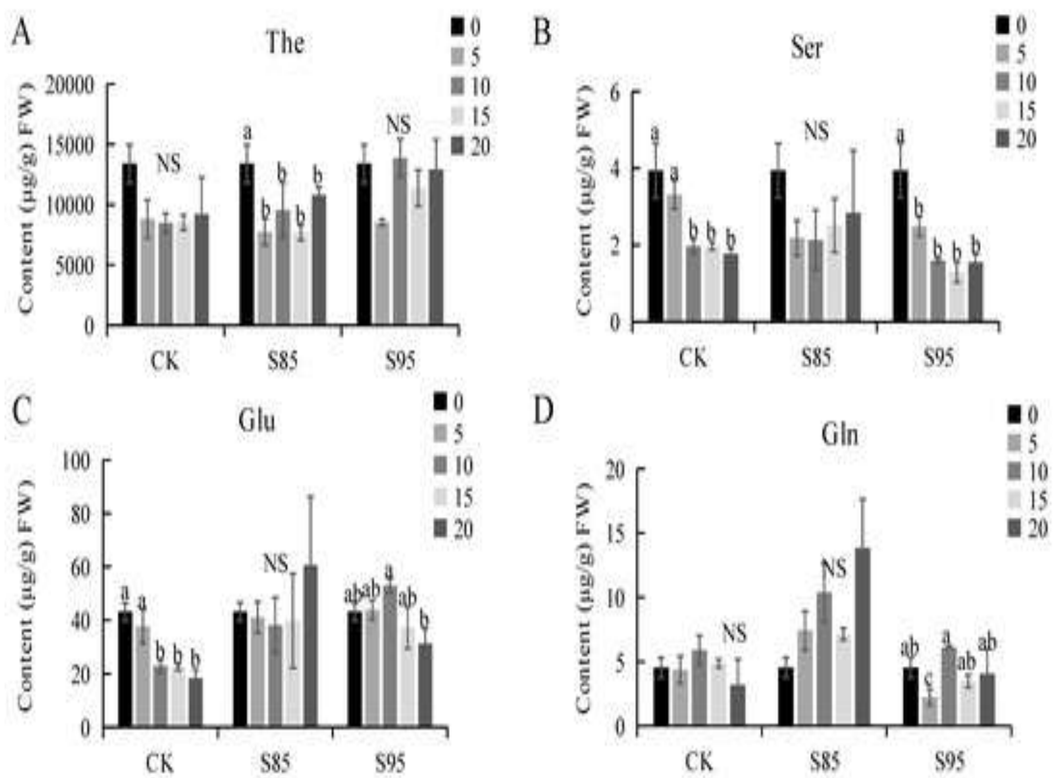
the same time reducing the levels of catechin compounds that cause bitterness and astringency (Yin et al., 2022). The unique balance of these compounds not only makes matcha rich in health benefits, but also critically shapes its organoleptic characteristics, including its distinctive taste, aroma, and color (Hu et al., 2024).

Research results show that shading practices on tea plants produce thinner, lighter, and less dense leaves compared to open field cultivation. Biochemically, shading increases SPAD values and leaf chlorophyll content, which can be estimated more accurately using an exponential equation that also considers leaf thickness. In addition, shading specifically affects bioactive compounds by increasing theanine and caffeine. Analysis shows that changes in leaf mass, chlorophyll, epicatechin, and epigallocatechin are the main properties most affected by the effects of shading (Sano et al., 2018).



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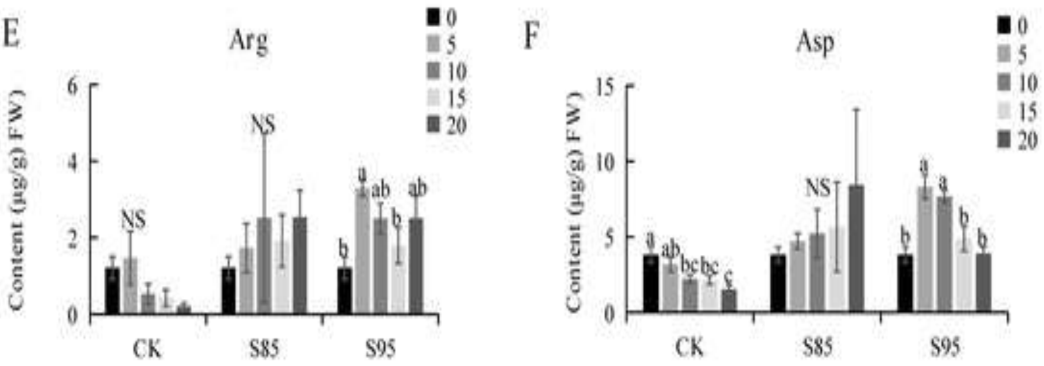

Figure 2. Effect of shading on the amino acid content of tea leaves. (**A**) Theanine content; (**B**) Serine content; (**C**) Glutamate content; (**D**) Glutamine content; (**E**) Arginine content; (**F**) Aspartic acid content. CK is the control. 'NS' and different letters above the bar indicate significant ($p < 0.01$; $n = 3$ biological replicates) differences between the control and shaded plants. (reproduced from *(Chen et al., 2022b)* under the term of CC-BY 4.0. License, copyright 2022 MDPI, Basel, Switzerland)

Fig 2. The amino acid content in tea plants increases when shaded. Specifically, the highest to lowest levels of theanine (the main amino acid) are S95, followed by S85, and finally the control (unshaded). However, for glutamine, which is the precursor to theanine, the order is different: S85, then S95, and the lowest is the control. This shows that light intensity greatly affects glutamine production, and excessive shading actually inhibits glutamine accumulation. Additionally, shading increases serine and glutamate levels. Meanwhile, arginine and aspartic acid levels increase under moderate shading (S85) but decrease over time under excessive shading (S95). Overall, moderate shading tends to increase amino acid levels, while excessive shading has the opposite effect.

Cultivating tea plants under shade can drastically change the phenotype of the plants. Tea plants grown in shaded conditions have darker green leaves than plants grown in open spaces. This color difference is caused by an increase in chlorophyll levels in shaded leaves (Yamashita et al., 2020). Changes in the catechin, caffeine, and amino acid content of tea due to shading are influenced by the intensity and duration of shading. The improvement in the quality and fresh taste of shaded matcha occurs because of higher theanine, which adds freshness, and lower catechins, which reduce bitterness (Matsunaga et al., 2016).

This study confirms that shading before harvest is a key factor in determining the quality of premium Matcha powder. The distinctive quality of Matcha is characterized by its bright green color, deep umami aroma, and smooth texture achieved through shading

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that triggers a significant increase in bioactive compounds. The shading process effectively increases the levels of chlorophyll and L-Theanine, which are key amino acids that give umami flavor, while reducing the levels of catechin compounds that cause bitterness and astringency. Research shows that shading profoundly alters leaf structure and biochemical composition; 85% shading yields optimal increases in amino acids such as theanine, serine, and glutamate compared to excessive or no shading. It is this unique balance of high theanine and low catechins that produces Matcha's distinctive flavor, aroma, and health benefits.

the strategic implementation of agronomic practices, particularly shading and integrated fertilization, serves as a physiological catalyst that unlocks the full genetic potential of *Camellia sinensis* for premium matcha production. The 85% shading intensity emerges as a critical intervention, not merely as an environmental modifier but as a physiological trigger that orchestrates complex biochemical pathways enhancing chlorophyll and theanine biosynthesis while suppressing bitter-tasting catechins. This physiological optimization, when synchronized with cultivar-specific genetic traits, creates a synergistic effect that transcends what genetics or agronomy could achieve independently.

Furthermore, the integration of precision fertilization combining NPK with organic amendments complements shading induced physiological changes by improving soil health and nutrient availability, thereby sustaining the metabolic processes essential for matcha quality. The future of matcha cultivation lies in developing dynamic, sensor-based agronomic protocols that can fine-tune these physiological responses in real-time, ensuring consistency and elevating global competitiveness. Ultimately, agronomy does not merely support plant growth, it actively directs physiological performance to achieve a harmony of color, flavor, and aroma that defines exceptional matcha.

The combination of special tea fertilizer (NPK: 18-8-12) and organic fertilizer is a recommended fertilization practice to increase the productivity and quality of tea plants, considering that organic fertilizer alone does not sufficiently meet nutritional needs. This combined fertilization has been proven to significantly increase the concentration of important aroma compounds in tea, such as D-limonene, cis-jasmon, nonanal, linalool, cis-3-hexenyl hexanoate, and cis-3-hexenyl benzoate (Huang et al., 2022). Studies have documented that organic fertilizers significantly increase the ratio of soil fungi to bacteria and soil enzyme activity, thereby increasing plant biomass (Ji et al., 2018).

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This study shows that integrated fertilization (NPK combined with organic fertilizer and biochar) significantly improves soil chemistry by increasing pH and the availability of macro and micro nutrients. These changes in soil chemistry are key factors in improving tea growth and quality compared to the application of mineral or organic fertilizers alone. Integrated fertilization also increases chlorophyll concentration (Chl a, b, and total). A significant positive correlation was found between tea growth/quality parameters and the content of macro nutrients (N, P, K, Ca, Mg), nitrate, ammonium, and micro nutrients (Cu, Mn, Fe, Zn) in the soil, confirming the potential of integrated fertilization as an effective strategy for improving the chemical properties of degraded tea gardens and increasing the productivity and quality of tea products (Manzoor et al., 2024).

This study consistently supports the use of integrated fertilization combining balanced tea-specific fertilizers (such as NPK 18-8-12) with organic fertilizers or combined with biochar as an optimal strategy to increase tea productivity and quality, because organic fertilizers alone cannot fully meet nutritional needs. This combined fertilization has proven to be superior to single fertilizer application because it significantly improves soil chemistry, increases pH, and enhances the availability of macro and micro nutrients, which are key factors in promoting growth and increasing chlorophyll concentration. Additionally, this practice can increase enzyme activity and the soil fungus-to-bacteria ratio, as well as specifically improve tea aroma quality through increased levels of important volatile compounds such as D-limonene and linalool, confirming the great potential of integrated fertilization for rehabilitating degraded tea gardens.

CONCLUSIONS AND SUGGESTIONS

The quality of premium matcha is fundamentally determined by the genetic potential of the tea cultivar. The genetic potential of tea is maximized through agronomic practices, especially pre-harvest shading, which acts as a key physiological catalyst to increase L-Theanine and Chlorophyll levels, while suppressing Catechins. Optimizing this quality is highly dependent on 85% shading intensity for the best Theanine yield, which is also supported by an integrated fertilization strategy (NPK combined with organic/biochar) that has been proven superior in enhancing growth, Chlorophyll concentration, and matcha quality. Research recommendations should prioritize genetic integration and precision agronomy. This includes plant breeding for high-theanine tea cultivars, development of dynamic shading protocols using smart farming, and studies linking aroma and flavor genes

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in matcha products with integrated fertilization for optimization of specific biochemical production in tea plants suitable as raw materials for premium matcha.

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