Jurnal Kultivasi Vol. 24(3) December 2025
ISSN: 1412-4718, eISSN: 2581-138x

Rahmawati N · Maxiselly Y · Anjarsari IRD . Khomaeni HS · Renaldi G · Karuniawan A

Production analysis of seed-derived tea plants (*Camellia sinensis* (L.) O. Kuntze) across two different seasons

Abstract. Tea (*Camellia sinensis* (L.) O. Kuntze) is a major economic crop in Indonesia, yet its productivity is strongly influenced by environmental variability, particularly rainfall seasonality. Fluctuating yields under dry and wet conditions pose challenges for sustainable tea production. This study aimed to assess the effects of contrasting seasonal rainfall on seed-derived tea plants' yield and yield components. The research was conducted at a seed-derived tea plantation block in IRITC, West Java, across dry and wet seasons using field observations aon tea yield, shoot proliferation, plucking quality, and environmental parameters. Statistical analyses included independent t-tests to compare seasonal differences and Pearson correlation to evaluate the relationships between environmental variables and production outcomes. The findings revealed that tea yield and shoot growth were higher in the wet season than in the dry season, which was statistically significant. Correlation analysis showed that temperature negatively influenced yield and shoot development, while rainfall, soil moisture, and relative humidity were strongly and positively associated with production performance. Conversely, plucking quality (fine and coarse leaves) remained stable across both seasons, indicating resilience to climatic variability and the role of consistent management practices. In short, the wet season provides more favorable conditions for seed-derived tea cultivation, especially in enhancing shoot growth and yield components. At the same time, adaptive management is required to mitigate temperature stress during the dry season.

Keywords: Dry seasons · Seed-derived · Wet seasons · Tea yields · Yield components

Submitted: 9 September 2025, Accepted: 26 November 2025, Published: 31 December 2025
DOI: https://doi.org/10.24198/kultivasi.v24i3.66669

Rahmawati N[1] · Maxiselly Y[2] · Anjarsari IRD[2] . Khomaeni HS[3] · Renaldi G[4] · Karuniawan A[2]*
[1] Graduate Student in Master Program of Agronomy, Faculty of Agriculture, Universitas Padjadjaran, Jatinangor, 45363 Sumedang, Indonesia
[2] Department of Agronomy, Faculty of Agriculture, Universitas Padjadjaran. Jl. Raya Bandung-Sumedang Km. 21, Jatinangor, Sumedang 45363, West Java, Indonesia
[3] Research Institute for Tea and Cinchona (IRITC), Gambung, Ciwidey, Bandung 40972, West Java, Indonesia
[4] Division of Product Development Technology, Faculty of Agro-Industry, Chiang Mai University, Chiang Mai, Thailand
*Correspondence: agung.karuniawan@unpad.ac.id

Rahmawati N, Maxiselly Y, Anjarsari IRD, Khomaeni HS, Renaldi G, Karuniawan A. 2025. Production analysis of seed-derived tea plants (*Camellia sinensis* (L.) O. Kuntze) across two different seasons. Jurnal Kultivasi, 24(3): 321-329.

Introduction

Tea (*Camellia sinensis* L. (O.) Kuntze) is one of the most widely cultivated and economically important crops globally, primarily valued for its leaves used in producing various tea products. Tea production supports millions of livelihoods and represents a significant source of export income for several countries. Indonesia is the seventh-largest tea-producing country in the world with a total production of 129.259 tons in 2021 (Cahyaningsih et al., 2025). Tea production is one of the important contributors to Indonesia's foreign exchange earnings. However, despite the increasing global demand for tea, the productivity of tea in Indonesia has shown a fluctuating trend (Sita & Rohdiana, 2021). In 2022, the export volume decreased to 44.92 thousand tons, compared with 49.03 thousand tons in 2018. This unstable trend highlights the challenge of maintaining sustainable tea production in Indonesia, particularly under varying environmental conditions.

The productivity of tea is significantly influenced by both genetic and environmental factors, among which rainfall is a critical factor influencing plant performance. Rainfall regulates vegetative growth and modulates the secondary metabolite accumulation (Langát, et al., 2018; Boehm et al., 2016). Yield components such as pekoe shoots, dormant shoots, young, mature, and damaged leaves are crucial indicators of tea plant growth and productivity. These components exhibit considerable sensitivity to fluctuations in soil moisture availability, reflecting the plants' physiological adaptation to varying rainfall regimes (Ochieng et al., 2016; Langát, 2022). Therefore, understanding rainfall influence is important for agronomic performance and ensuring tea quality and market competitiveness.

Tea plants derived from seeds and those established through clonal cuttings differ primarily in their genetic diversity and uniformity. Seed-grown plants arise from sexual productivity, resulting in genetic variability among individuals, which enhances adaptability and resilience to environmental stresses genetically identical to the parent genotype, offering uniformity in growth, flavor, and quality, which is advantageous for commercial production but limits genetic adaptability (Xia et al., 2020). The genetic base of seed-derived plants may provide greater drought tolerance through enhanced water-use efficiency and survival under moisture-deficient conditions. Conversely, in high rainfall conditions, genetic variability may enable better adjustment to excessive soil moisture and associated risks such as root diseases, thereby supporting physiological resilience to waterlogging (Ding et al., 2021). Thus, seed-derived plants offer genetic diversity that supports adaptation to varying rainfall conditions, whereas cloned plants favor uniformity but may be more vulnerable to environmental extremes.

Low and high rainfall conditions differentially affect tea plants' tea yields and yield components. Limited water availability can cause a reduction in the number and growth of pekoe buds and young leaves. It also prolongs shoot dormancy, lowers the biomass and photosynthetic activity of mature leaves, and increases the occurrence of diminished overall productivity and quality, with the severity depending on the intensity and duration of drought as well as the tea plant's tolerance mechanisms (Hasan et al., 2023). Mature and damaged leaves tend to increase under high rainfall and humid conditions, where fungal infections and related stresses are more prevalent, negatively affecting leaf quality (Nyabundi et al., 2016). These contrasting responses highlight that rainfall impacts yield quantitatively and alters the balance of yield components, directly influencing the final harvested product.

Despite the recognized impact of seasonal factors on tea cultivation, limited research has specifically addressed the effect of different seasonal conditions on tea yields and yield components in seed-derived tea plants. Most existing studies have focused primarily on clonal varieties or have examined tea yields and yield components traits independently, without integrating their interactions within seed-derived populations that exhibit greater genetic and physiological diversity. Investigating yield traits such as pekoe shoots, dormant shoots, young leaves, mature leaves, and damaged leaves, alongside phenolic and flavonoid contents under contrasting rainfall regimes, could provide valuable insights into adaptive responses and help optimize cultivation practices across diverse agroclimatic conditions (Abdullah et al., 2024). This knowledge gap is critical in Indonesia, where seed-derived tea fields are still widely found, but little is known about their performance under different seasonal conditions.

Rainfall is well acknowledged for its influence on the trade-off between growth and quality in tea production. This complexity is particularly relevant in seed-derived tea populations, which contain a broader genetic base than clonal cultivars, making them potentially more resilient but also more variable in response to environmental factors (Abdullah et al., 2024). Understanding these dynamics is critical for sustaining yield stability and components under increasingly variable rainfall patterns caused by climate change. Therefore, this study aims to evaluate the effects of contrasting rainfall regimes on the yield components of seed-derived tea plants in order to identify seasonal advantages and provide practical recommendations for sustainable tea cultivation. By assessing growth performance, leaf quality, and production output, the research intends to provide empirical data on how seasonal dynamics influence seed-derived tea plants and to identify which season provides optimal conditions for tea production. Such insights will help determine the extent to which environmental factors affect agronomic traits and economic yield during each season, thereby supporting the development of more effective management and harvesting strategies.

Materials and Methods

The experiment was conducted at the Experimental Field in Indonesia Research Institute for Tea and Cinchona (IRITC), Gambung, Ciwidey, at an altitude of ±1.350 m asl. The research was conducted from October 2023 to August 2024. The plant material comprised seed-derived tea (A2 block) established since 1907, planted by R.E. Kerhoven, cultivated at a spacing of 120 × 110 cm. Samples were collected from a seed-derived tea field covering an area of 1 ha and consisting of approximately 8,000 plants. Harvesting was carried out three times each season, and each of these harvests was considered a replication. This study used existing field blocks with plants of similar age and management, so samples were taken using a blocking plot design, meaning the same plot areas were consistently observed each season. To obtain representative values for each replicate, all observations from each harvest were averaged. The primary parameters assessed included tea yields and yield components: shoot analysis and plucking analysis (fine plucking and coarse plucking). Supportive environmental and biotic parameters such as rainfall, temperature, relative humidity, soil moisture, and tea looper caterpillar incidence were also monitored. Seasonal differences in this research were evaluated based on the rainfall data recorded at the research site, which were classified according to the Oldeman climate classification, where a wet month is defined as having rainfall exceeding 200 mm, and a dry month as having less than 100 mm (Maru et al., 2016). Statistical analyses included the Shapiro–Wilk test to assess normality and Levene's test for homogeneity of variance. Differences between treatments (dry and wet seasons) were evaluated using independent samples t-tests at the 5% significance level. Additionally, Pearson correlation analysis was employed to determine relationships between tea plant production, yield components, and environmental factors.

Results and Discussion

Environmental factors. Environmental factors showed distinct seasonal patterns significantly affecting tea growth, productivity, and pest dynamics. The temperature was higher during the dry season (23.08 °C) than during the wet season (22.19 °C), which was significant at the 5% level. Elevated temperatures during the dry season can influence physiological processes in tea plants, including photosynthesis, evapotranspiration, and leaf development. Previous studies have reported that temperatures between 23 °C and 26 °C optimize metabolic activity and new shoot growth, whereas temperatures exceeding 28 °C may reduce yield and leaf quality (Benti et al., 2023). Li et al. (2025) stated that high temperatures can accelerate biochemical pathways, causing drought stress in plants, which lowers chlorophyll content and antioxidant capacity if soil moisture is insufficient. Moreover, drought stress driven by temperature can reduce catechin synthesis, a critical component of tea quality, particularly in subtropical regions (Omer et al., 2025). These findings highlight the need for adaptive management strategies to mitigate heat stress during hotter dry seasons to optimize tea yields (Yan et al., 2021).

Table 1. Environmental conditions between the two seasons in tea plantation

Seasons	Temperature (°C)	Relative humidity (%)	Soil moisture (%)	Pest (*Hyposidra talaca)* incidence (%)
Dry seasons	23.08 ± 0.11	83.08 ± 2.88	29.37 ± 7.59	9.27 ± 1.04
Wet seasons	22.19 ± 0.43	89.93 ± 1.01	37.46 ± 0.75	8.73 ± 1.54
T-test	*	*	ns	ns
C.V. (%)	3.32	2.26	7.67	16.36

Note: Values are expressed as mean ± standard deviation (SD. ns indicates non-significant differences (p > 0.05) according to the independent t-test. C.V. = coefficient of variation.

Relative humidity was significantly higher in the wet season (89.93%) compared to the dry season (83.08%), reflecting increased atmospheric moisture associated with rainfall. Elevated humidity improves stomatal conductance and reduces transpiration stress, supporting leaf turgor and promoting shoot growth. High atmospheric humidity creates a microclimate conducive to optimal physiological function, enhancing photosynthetic efficiency (Urban et al., 2017). However, increased humidity also influences pest and disease dynamics, as fungal pathogens and some insect pests often proliferate under wet conditions (Tapia et al., 2025). Thus, seasonal relative humidity fluctuations affect tea growth and require integrated pest and disease management strategies to maintain plant health and productivity.

In contrast, soil moisture showed higher average values in the wet season (37.46) compared to the dry season (29.37), but the difference was not statistically significant. This lack of significance may result from variability in soil properties such as texture, drainage, or agronomic practices like irrigation, mulching, or soil management, which moderate water availability (Hou et al., 2025). Stable soil moisture even during drier periods can sustain root water uptake, maintaining physiological functions and supporting consistent production (Li et al., 2023). Long-term organic and integrated soil management practices have improved water retention, promoting sustainable tea yields across fluctuating moisture conditions (Ţopa et al., 2025).

From a biotic perspective, the tea looper caterpillar (*Hyposidra talaca*) showed relatively stable population levels across seasons (9.27 in the dry season vs. 8.73 in the wet season), with no significant difference. Although the analysis did not show significant results in the percentage of *H. talaca* attack in two type difference seasons, this pest is an important threat to tea plants. Attacks caused by *H. talaca* can result in leaf perforation and the loss of young shoots on tea plants, which may lead to high yield losses (Kusumah et al., 2023). Larval development and population dynamics of this pest are influenced by temperature and humidity, where warmer temperatures accelerate larval development and increase the potential number of annual generations, and adequate moisture enhances growth while lowering mortality (Roy et al., 2017). Although seasonal differences in temperature and humidity were observed, the relatively stable population suggests that other factors, including microclimate variability and management practices, may moderate pest abundance. Nonetheless, the potential for outbreaks remains higher during warm, humid periods, emphasizing the importance of continuous environmental monitoring and timely pest management interventions.

Overall, the findings highlight that temperature and atmospheric humidity are the primary environmental factors strongly affected by seasonal shifts, whereas local conditions and management practices moderate soil moisture and pest population levels. Understanding these interactions is essential for optimizing tea production, as it identifies periods when plants are exposed to environmental stress and when pest pressures may intensify. The interplay between abiotic factors (temperature, humidity, soil moisture) and biotic factors (tea looper caterpillar) underscores the complexity of seasonal effects in tea agroecosystems and the need for integrated management strategies to sustain productivity and crop quality.

Tea yields and yield components. The comparative analysis of tea yields between the dry and wet seasons revealed a significant increase in production during the wet season. Tea yields rose from 281.23kg per ha in the dry season to 635.33kg per ha in the wet season, and the difference was statistically significant at the 5% level. This increase reflects the positive role of rainfall and moisture in supporting growth and development. The observed significant increase in tea production during the wet season aligns with agronomic principles, where optimal moisture conditions during the growth phase stimulate leaf expansion and bud development, which are critical for plucking quantity (Chen et al., 2025a). The enhanced water availability during the wet season likely improved leaf hydration, turgor, and photosynthetic efficiency, promoting shoot elongation and overall biomass accumulation (Ndagijimana et al., 2024).

Similar findings have been reported in Rwanda, where seasonal rainfall correlates strongly with tea production, and adequate soil moisture was critical in supporting leaf expansion and yield (Dushimimana & Nahayo, 2022). Moreover, climatic stability, including moderate temperature and consistent precipitation, amplifies seasonal yield differences by enhancing physiological processes essential for tea productivity (Ndagijimana et al., 2024). Therefore, the observed significant increase in tea yields during the wet season highlights the crucial role of seasonal rainfall and water availability in maximizing tea production, while also illustrating the importance of local microclimate and agronomic practices in modulating these effects.

Shoot analysis exhibited a significant seasonal effect, increasing from 38.66 in the dry season to 41.67 in the wet season, with the difference at 5%. Water availability, temperature, and relative humidity strongly influence shoot growth in tea plants. Higher moisture and moderate temperatures during the wet season promote bud break, leaf emergence, and shoot elongation, leading to greater biomass accumulation (Jayasinghe et al., 2018; Wulansari et al., 2022). Increased water availability enhances dry matter partitioning and new leaf production, while elevated CO_2 and stable climatic conditions further boost photosynthesis and shoot proliferation in tropical environments (Benti et al., 2023; Zhang et al., 2020). Recent studies confirm that rainfall and temperature interplay significantly regulate shoot growth and related metabolites, underscoring the importance of favorable seasonal conditions for tea development (Tukhvatshin et al., 2025).

Plucking analysis revealed that fine leaf proportion increased slightly from 75.66% in the dry season to 81.33% in the wet season. In contrast, coarse plucking decreased from 62.16% to 59.33%, but neither change was statistically significant. This indicates that seasonal variation affects shoot quantity rather than leaf class distribution. Leaf quality stability is supported by intrinsic plant regulation and agronomic practices such as consistent plucking frequency (Jayasinghe et al., 2018; Benti et al., 2023). Seasonal studies further show that chemical quality parameters, including catechins, methylxanthines, and flavor-related metabolites, remain relatively stable across harvests despite environmental fluctuations, ensuring consistent functional quality of fine plucking leaves used for high-grade tea (Tang et al., 2020; Ye et al., 2022; Chen et al., 2025b).

Overall, the findings demonstrate that tea yields and shoot growth respond strongly to seasonal climatic variation, with wet-season conditions significantly enhancing production through improved rainfall and moisture availability. In contrast, leaf plucking quality remains relatively stable across seasons, reflecting intrinsic plant regulation and the buffering role of consistent agronomic practices. These results highlight that rainfall-driven variability is the key determinant of yield performance, while leaf quality is maintained through physiological resilience and management strategies. Therefore, adaptive practices such as soil water conservation, irrigation management, and integrated pest control are essential to sustain productivity and ensure tea quality under changing climatic conditions.

Table 2. Yields and yield components of tea between two seasons at the tea plantation

Seasons	Tea yields (kg ha^{-1} per plucking round)	Shoot Analysis (%)	Plucking Analysis (%)	
			Fine Plucking	Coarse Plucking
Dry seasons	281.23 ± 170.13	38.66 ± 2.51	75.66 ± 8.73	62.16 ± 4.46
Wet seasons	635.33 ± 85.45	41.67 ± 0.57	81.33 ± 3.05	59.33 ± 1.52
T-test	*	*	ns	ns
C.V. (%)	3.29	3.78	3.27	2.11

Note: Values are expressed as mean ± standard deviation (SD. ns indicates non-significant differences ($p > 0.05$) according to the independent t-test. C.V. = coefficient of variation.

Jurnal Kultivasi Vol. 24(3) December 2025
ISSN: 1412-4718, eISSN: 2581-138x

Correlation between tea yields, yield components (kg ha^{-1} per plucking round), pest incidence (%), and environmental conditions such as rainfall, temperature, and humidity. Pearson correlation analysis evaluated the relationships between environmental factors (air temperature, relative humidity, soil moisture, rainfall, and tea looper infestation) and tea production parameters, including overall yield, shoot quality, and leaf plucking characteristics. Correlation coefficients (r) ranged from -1 to +1, with values close to +1 indicating strong positive relationships, values close to -1 indicating strong negative relationships, and values near 0 indicating weak or no association. Statistical significance was denoted by an asterisk (*).

Tea yields exhibited a strong negative correlation with air temperature (r = -0.84*), indicating that higher temperatures adversely affect production by disrupting physiological and biochemical processes essential for growth (Omer et al., 2025). Conversely, relative humidity (r = 0.97*) and rainfall (r = 0.95*) showed strong positive correlations with production, suggesting that higher moisture availability supports shoot growth, leaf hydration, and metabolic functions, thereby enhancing yield (Omer et al., 2025; Benti et al., 2023). Soil moisture (r = 0.52) and tea looper infestation (r = -0.58) showed moderate, non-significant correlations, indicating that their impact on yield is more variable and likely moderated by local management practices and microclimatic conditions (Dushimimana & Nahayo, 2022; Siahaan et al., 2024). Overall, these results confirm that tea production is highly sensitive to temperature extremes and moisture availability, consistent with previous studies highlighting the critical role of stable environmental conditions in maintaining physiological processes necessary for optimal yield.

Shoot proliferation and quality were similarly influenced by environmental factors. Air temperature was negatively correlated with shoot growth (r = -0.66*), reflecting the inhibitory effect of elevated temperatures on bud break and shoot elongation (Jayasinghe et al., 2018). In contrast, relative humidity (r = 0.78*), soil moisture (r = 0.94*), and rainfall (r = 0.71*) exhibited strong positive correlations with shoot development, supporting active cell division and elongation in tea shoots under favorable moisture conditions (Benti et al., 2023). Tea looper infestation showed a moderate negative correlation with shoot proliferation (r = -0.52), although this was not statistically significant, suggesting that while insect herbivory can reduce shoot vigor, environmental conditions primarily govern shoot growth (Jayasinghe et al., 2018; Benti et al., 2023). These findings emphasize that shoot development is particularly responsive to water availability and climatic stability, underscoring the importance of integrated environmental and pest management strategies to sustain high-quality shoot production.

The fine and coarse leaf plucking analysis revealed weak and non-significant correlations with all environmental factors, indicating that leaf quality remains relatively stable across seasonal and climatic variations. Fine leaf proportion increased slightly from the dry to wet season, while coarse leaf proportion decreased slightly, but neither change was statistically significant. This stability is attributed to intrinsic physiological regulation within the plant and consistent farm management practices, such as selective plucking and maintaining plucking frequency (Deka et al., 2021; Siahaan et al., 2024). Leaf quality parameters, including catechin and methylxanthine concentrations, are largely unaffected by moderate fluctuations in environmental conditions, suggesting that both biological and agronomic factors buffer plucking outcomes.

The correlation analysis demonstrates that tea yields and shoot quality are strongly influenced by environmental variables, with temperature exerting a negative effect and relative humidity, soil moisture, and rainfall exerting positive effects. Fine and coarse leaf plucking remain largely unaffected by these factors, reflecting intrinsic plant stability and the role of consistent management practices. These findings are consistent with the broader literature, highlighting the importance of moderate temperatures, sufficient moisture, and rainfall for optimal tea growth and production, while leaf quality remains resilient to seasonal variability (Omer et al., 2025; Jayasinghe et al., 2018; Benti et al., 2023; Deka et al., 2021; Siahaan et al., 2024). Understanding these correlations provides critical insights for designing adaptive agronomic strategies to optimize yield, shoot quality, and leaf characteristics in the face of climatic variability.

Table 3. Correlation between tea yields, yield components, and pest incidence with environmental conditions such as rainfall, temperature, and humidity.

	Rainfall	Temperature	Relative Humidity	Soil Moisture	Pest (*Hyposidra talaca)* incidence
Tea yields	0.95 *	-0.84 *	0.97 *	0.52	-0.58
Shoot analysis	0.71 *	-0.66*	0.78 *	0.94*	-0.52
Fine plucking	0.51	-0.4	0.52	0.88	0.45
Coarse plucking	-0.51	0.4	-0.52	-0.88	-0.45

Conclusion

This study demonstrates that seasonal variation plays a critical role in the productivity of seed-derived tea plants, with yields and shoot proliferation generally higher during the wet season than the dry season. The wet season provided more favorable conditions, particularly through increased rainfall and relative humidity, significantly enhancing shoot growth and contributing to better yield components. Shoot growth as a primarily yield component in tea plants increases significantly during the wet seasons, indicating the importance of water availability in supporting active vegetative growth. In contrast, the quality of leaf plucking (fine and coarse plucking) were not show significant differences between two type seasons, indicating that plucking quality is more influenced by plant physiology and the method of plucking. For practical applications, tea farmers are encouraged to optimize harvesting during the wet season to take advantage of improved shoot growth, while implementing adaptive measures such as soil moisture conservation and shading during the dry season to mitigate heat stress. Future research should extend to long-term seasonal monitoring and consider additional environmental factors, including solar radiation and soil nutrient dynamics, to develop more comprehensive strategies for sustaining tea production under increasingly variable climatic conditions.

Acknowledgments

The authors are thankful to the University of Padjadjaran for funding this through the research Academic Leadership Grant (ALG) and to the Head of Research Institute, Tea and Cinchona, who has permitted the authors to conduct this research.

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