Plant Gene and Trait 2026, Vol.17, No.5, 382-394
http://genbreedpublisher.com/index.php/pgt

Review and Progress Open Access

Effects of Different Harvesting and Canopy-Restoration Practices on Sustained Production in Tea Plantations

Xiaomin Wen [1,2]
1 Wenzhou Qinggeng Yudu Agricultural Development Co. Ltd., Pingyang, 325405, Zhejiang, China
2 Zhejiang Agronomist College, Hangzhou, 310021, Zhejiang, China
Corresponding email: angelwen531@163.com
Plant Gene and Trait, 2026, Vol.17, No.5 doi: 10.5376/pgt.2026.17.0027
Received: 05 Sep., 2026
Accepted: 06 Oct., 2026
Published: 14 Oct., 2026
Copyright © 2026 Wen, This is an open access article published under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
Preferred citation for this article:
Wen X.M., 2026, Effects of different harvesting and canopy-restoration practices on sustained production in tea plantations, Plant Gene and Trait, 17(5): 382-394 (doi: 10.5376/pgt.2026.17.0027)

Abstract This review examines the effects of harvesting frequency, plucking standards, leaf retention, pruning, and related resource management practices on sustained tea production. Thirty English-language research articles were selected for analysis, with direct experiments on tea plants distinguished from observational comparisons, molecular association studies, and mechanistic evidence from other species. The analysis identifies three interacting processes involved in sustained tea production: maintaining the continuous development of harvestable shoots, preserving functional leaves and stored resources, and rebuilding a canopy structure suited to the intended harvesting system. Through a comparative case analysis, this review finds that the effects of mechanical harvesting should be distinguished from differences in harvesting intervals. Earlier bud development or increased shoot weight also does not necessarily indicate higher annual yield. Based on these findings, the study proposes an integrated evaluation framework that considers cumulative marketable yield, recovery time, canopy function, product quality, labor requirements, and environmental costs. The central expectation is not that less intensive harvesting or stronger canopy restoration will always lead to better production performance. Rather, explicitly considering plant recovery processes is expected to improve the reliability of production decisions and reveal trade-offs among different production objectives that may be overlooked when evaluating a single successful harvest.
Keywords Tea (*Camellia sinensis*); Harvesting practices; Canopy restoration; Shoot regeneration; Yield stability; Sustainable tea production

1 Introduction

Tea production poses a distinctive management question: how much new growth can be removed while preserving the plant's capacity to support subsequent harvests ? Unlike crops harvested once at maturity, tea produces successive shoot cohorts within a perennial framework. Young shoots provide the commercial product, but their development depends on mature leaves, branches, and roots that remain after harvesting. Studies of pruned tea plants have identified metabolic responses in developing shoots and lateral roots, demonstrating that canopy interventions affect more than the visible cutting surface (Arkorful et al., 2020a; Arkorful et al., 2020b). Nitrogen measurements across twenty tea varieties also reveal differences among leaf ages, seasons, and genetic backgrounds (Zhang et al., 2020). Removing equivalent fresh weights may therefore remove different nutrient quantities and leave plants with different capacities for regrowth. Production should consequently be assessed through the relationships among harvested shoots, functional foliage, and the supporting framework. Here, sustained production means maintaining commercially useful output across successive harvests and recovery periods, rather than uninterrupted picking. Planned rest may support this objective when later benefits compensate for missed harvests. Sustainability has a broader meaning, encompassing resource use, soil condition, and economic feasibility; high annual yield alone cannot establish that these requirements have been met.

Harvesting practices influence this balance through several distinct but interacting operations. Fine plucking describes the developmental standard of harvested material, harvesting intensity describes the extent of tissue removal, and harvesting frequency concerns timing. These terms should not be used interchangeably. Selective removal of tender shoots and indiscriminate cutting through maintenance foliage can produce similar harvested quantities while leaving markedly different canopies. Pathiranage et al. (2019) identified immature shoot removal, harvesting severity, and maintenance foliage loss as distinct contributors to declining production under mechanical

harvesting. Separating these components is necessary because an adjustment directed at one may leave the others unchanged. Extending the interval between harvests, for example, does not necessarily protect developing shoots when the next operation remains indiscriminate. Conversely, frequent selective harvesting should not automatically be equated with excessive canopy disturbance. Evaluation must consider both the harvested material and the condition of the plant afterward. Relevant observations include the foliage retained, the developing shoots available for later collection, and the recovery time before another commercially useful harvest. This perspective shifts attention from the quantity collected on one occasion to the continuity of production and the biological costs associated with repeated removal.

Canopy restoration introduces comparable trade-offs. Vigorous regrowth after pruning does not necessarily indicate greater cumulative production, and higher concentrations of individual compounds do not automatically signify better tea. Li et al. (2022) associated non-pruning with amino acid accumulation and lower flavonoid and caffeine contents in their study material. Research on 'Dancong' tea likewise identified quality-related differences between plants maintained without pruning and those pruned annually (Chen et al., 2021b). Such findings caution against evaluating all tea systems through a single biochemical direction. The desired response depends on the intended product and its valued quality attributes. Recovery also occurs within an environmental context. Gu et al. (2020) documented extensive proteomic responses to drought, while Hazra et al. (2021) linked ecophysiological variation with secondary metabolite accumulation. Treatments applied under favorable conditions cannot therefore be assumed to perform identically when recovery is constrained. Management must consider plant condition, seasonal growth opportunities, and available resources together. The practical question is not simply whether harvesting or pruning promotes growth, but whether a particular intervention preserves acceptable production over a period long enough to include its recovery costs.

This review adopts a critical narrative review approach to examine the relationship between harvesting management and canopy restoration within a unified temporal framework. It distinguishes the different components of harvesting disturbance, explores how canopy restoration modifies the productive canopy of tea plants, and analyzes the physiological links between current shoot removal and subsequent regrowth. The study also examines the effects of cultivar differences while carefully considering the limitations of existing evidence in supporting breeding recommendations. In the case analysis, independently published studies are compared without treating them as a single integrated experiment. Particular attention is given to whether the reported results represent individual harvests, cumulative seasonal yields, or longer production cycles, as different observation periods support different conclusions about canopy recovery, yield stability, and management benefits. The central expectation of this review is that evaluating harvesting and recovery within a unified framework will help clarify the conditions under which protecting functional foliage and future shoots supports sustained production, and the circumstances in which short-term production benefits may be offset by subsequent costs.

2 Effects of Different Harvesting Practices on Tea Plant Growth and Production

2.1 Harvesting frequency and shoot regeneration

Harvesting frequency influences which developmental stages are present when workers or machines enter the field. A short interval is not intrinsically damaging: selective picking can remove suitable shoots while leaving younger cohorts intact. Conversely, a longer interval is not necessarily restorative when the subsequent operation removes a greater proportion of foliage and immature growth. Pathiranage et al. (2019) provide direct evidence that damage to future shoot cohorts must be considered alongside the immediate harvested crop. Their findings support separating the number of field visits from the biological severity of each visit.

A useful comparison therefore records both calendar time and plant development. The interval between cuts should be accompanied by the proportion of shoots meeting the intended standard, the immature shoots remaining afterward, and the time required for replacement growth. Otherwise, a treatment described as frequent harvesting may merely represent more selective access to the same developing population. Counting harvested shoots without identifying the cohorts that produced them can also obscure whether repeated returns reflect rapid renewal or depletion of shoots already present before treatment.

For experimental interpretation, frequency should be varied independently of cutting height and selectivity whenever possible. When commercial practice requires these factors to change together, the resulting treatment remains useful, but it represents a management package. Yield differences should then be attributed to that package rather than to interval alone. This distinction permits practical comparisons without overstating the physiological mechanism responsible for the result.

It is also important to separate delayed development from permanent loss of productive sites. The proposed measurements should follow shoots that were present before harvesting as well as shoots initiated afterward. A low count at one date could otherwise be interpreted as damage when a treatment has merely shifted development, or interpreted as harmless delay when the affected cohort never reaches the required standard. Repeated observations make these alternatives distinguishable.

2.2 Plucking standards and harvesting intensity

Plucking standards specify the material required by a processing system, commonly through combinations of a bud and a stated number of leaves. Harvesting intensity should instead describe how much potentially productive tissue is removed. These definitions prevent the assumption that a finer standard necessarily imposes greater physiological stress. Selectively collecting small tender units can leave substantial foliage, whereas a coarser cut may cross into the maintenance canopy. The remaining plant, not only the harvested sample, must be examined.

Luo et al. (2026) compared summer leaves collected at different standards and processed into green, yellow, white, and black teas. Material comprising one bud and one leaf produced favorable sensory attributes in their experiment, while processing substantially altered flavor expression. This establishes a relationship between raw-material selection and product quality, not a measured advantage in plantation regeneration or annual output. Extending the quality result into a production recommendation would require information on the quantity harvested, labor costs, and later shoot growth.

Selective mechanization offers one possible way to separate harvest quality from broad canopy removal. Chen and Chen (2020) demonstrated image-based localization of tea plucking points. Such work addresses recognition of suitable cutting locations; it does not by itself establish reliable field harvesting or improved long-term yield. For agronomic evaluation, the important outputs would include damage to retained shoots, unintended leaf removal, actual collection success, and performance under uneven canopy conditions, alongside the technical accuracy of the vision system.

2.3 Leaf retention and canopy photosynthetic capacity

Leaf retention matters because canopy recovery requires functioning tissues, not simply a minimum count of attached leaves. Leaf position, illumination, physiological condition, and age affect the interpretation of retained area. Chen et al. (2021a) showed that shading-induced chlorophyll accumulation in tea involves regulated changes in chlorophyll metabolism. Greener foliage should therefore not be assumed to indicate greater whole-canopy carbon gain. Chlorophyll concentration and productive canopy function are related measurements, but they answer different questions.

Evidence from repeated shade cultivation reinforces this distinction. Yamashita et al. (2020) identified physiological and phenotypic signs of overstress, including changes in photosynthetic performance, reserve status, and canopy temperature. Their experiments concerned shading rather than a harvesting treatment, so they provide diagnostic context rather than a direct estimate of the effects of leaf retention. Together with seasonal nitrogen variation among leaf classes (Zhang et al., 2020), the findings suggest that retained foliage should be assessed for function as well as quantity.

A practical evaluation would combine residual leaf area with representative gas-exchange measurements, leaf condition, and subsequent shoot production. More foliage may be useful when it supplies new growth, but preserving poorly positioned or declining leaves is not an objective in itself. No common numerical retention threshold can be inferred from the studies reviewed. The appropriate level should instead be calibrated for cultivar, canopy structure, harvest standard, and the environmental conditions expected during the recovery period.

3 Effects of Canopy-Restoration Practices on Tea Plant Recovery

3.1 Pruning intensity and canopy structural renewal

Pruning differs from harvesting because its immediate purpose is to alter the structural basis of future production. Light trimming removes a limited surface layer, whereas deeper operations replace more of the existing framework. Terminology is not fully transferable between studies. For example, Lu et al. (2022) defined heavy pruning by height above the ground but light and deep pruning by distance below the canopy top. A reported cutting height is therefore uninterpretable unless its reference plane is stated.

The expected benefit of structural renewal must be considered alongside the temporary removal of leaf area and harvestable shoots. Opening an old canopy may encourage new growth, but rebuilding that canopy takes time and resources. Kan et al. (2024) found substantial variation in pruning responses among twenty tea varieties. This supports cultivar-specific assessment and cautions against treating a single successful response as a general property of tea. Differences after pruning are also not sufficient, on their own, to establish the genetic stability of recovery traits across environments.

For management, the most informative measure is the trajectory from cutting through canopy reconstruction to resumed production. Recording only the final appearance can conceal a lengthy period without saleable output. Light, medium, and deep treatments should therefore be compared using actual tissue removal, recovery duration, and cumulative production. Where the objective is merely to maintain access or an even picking surface, a major structural intervention should not be assumed necessary. Where the framework itself is unsuitable, repeated superficial trimming may not address the underlying problem.

3.2 Canopy recovery through leaf retention and shoot management

Canopy rebuilding requires decisions about which developing shoots become future bearing structure and which enter the harvested crop. Removing every accessible shoot during recovery would make these two objectives compete directly. The review therefore proposes distinguishing a framework-building phase from a full production phase, while recognizing that the transition may be gradual rather than marked by a single date. Retained shoots should be evaluated through their distribution and contribution to canopy continuity, not merely through their number.

Summer-pruning research demonstrates why timing deserves attention. Zhang et al. (2021) observed different branch-growth and subsequent spring-production responses under alternative summer pruning dates and heights. The result indicates that the recovery period remaining after an intervention can matter as much as the fact that pruning occurred. It does not establish an identical seasonal calendar for every tea region. Local shoot development and the intended next harvest should define the relevant window.

Non-pruning studies provide a useful counterpoint. In ‘Dancong’ tea, Chen et al. (2021b) found higher levels of several quality-related constituents and characteristic aroma compounds in unpruned material. Retaining an established architecture may therefore serve a legitimate product objective. Restoration should not be equated automatically with removing more wood. Depending on the diagnosed limitation, it may involve moderated harvesting, selective shoot retention, limited structural correction, or a period without cutting. These alternatives require comparison against an explicit production objective rather than a visual preference for uniform, low bushes.

3.3 Post-harvest nutrient and water management

Resource management should support the timing of plant demand without assuming that stronger growth always requires larger fertilizer inputs. Using labeled nitrogen, Ma et al. (2021) showed that thermal conditions and application timing influenced uptake of autumn and winter fertilizer and its later contribution to spring tea. October application contributed more strongly to early spring tea than later applications at the two studied sites, linking resource acquisition with a subsequent crop. It also argues against applying one calendar-based fertilizer schedule across regions with different temperatures and growth patterns.

Nitrogen responses must be judged through both output and quality. Cai et al. (2024) compared fertilization levels in 'Jin Xuan' tea and documented treatment-dependent yield and compositional responses. Such results support evaluating several outcomes rather than selecting a rate solely because one biochemical indicator increases. After pruning, diagnosing supply should include soil conditions, leaf status, and the amount of new canopy being formed. Fertilizer should not be treated as a substitute for protecting functional foliage or allowing sufficient recovery time.

Water management presents the same need for context. Liu et al. (2025b) examined irrigation and mulching combinations in a northern Chinese tea plantation and identified differences in evapotranspiration-yield relationships and water productivity. Their study supports site-specific coordination of water supply and ground management; it was not a factorial test of irrigation after different pruning severities. The defensible implication is to assess water availability before imposing additional canopy disturbance and to evaluate the resulting crop with clearly defined fresh- or dry-mass measurements.

For future trials, irrigation and fertilization records should be expressed at plot scale and linked to canopy recovery observations. Equal fertilizer rates do not ensure equal nutrient availability, just as equal irrigation volumes do not establish comparable root-zone water conditions. Measuring the relevant plant and soil states would help determine whether an apparent pruning response reflects canopy treatment, a resource limitation, or an interaction between them. This is particularly important when treatments differ substantially in remaining foliage.

4 Physiological Mechanisms Linking Harvesting, Canopy Restoration, and Sustained Production

4.1 Photosynthetic performance and carbon allocation

A source-sink interpretation connects the retained canopy with developing shoots and roots. It is useful because harvesting changes both the tissues supplying assimilates and the organs demanding them. However, increased photosynthesis per remaining leaf cannot be assumed to compensate fully for a reduction in total functioning leaf area. Compensation must be evaluated at an appropriate scale, ideally over the period during which the canopy is being rebuilt. Leaf-level measurements describe a component of that process rather than the whole-plant balance.

Arkorful et al. (2020a) identified metabolic changes in lateral roots of pruned tea plants, while Arkorful et al. (2020b) associated pruning with changes in shoot growth and metabolism. These studies support considering belowground and aboveground responses together. They do not make every changed metabolite a demonstrated regulator of carbon allocation. Similarly, reserve concentration is not equivalent to reserve pool size: a concentration can change with tissue growth or sampling composition, even when the total amount stored follows a different trajectory.

Nutrient measurements require comparable care. Liu et al. (2022) associated pruning with lower leaf nitrogen, phosphorus, potassium, and magnesium concentrations, but higher calcium concentrations, across surveyed tea plantations. Such field-scale evidence identifies relationships worth testing, but differences among sites and management histories limit causal interpretation. A stronger carbon-allocation analysis would combine repeated measurements of organ biomass, nonstructural carbohydrates, leaf function, and new-shoot demand. Tracer experiments could then test whether recovery is supplied predominantly by current assimilation or previously stored resources, rather than inferring the answer from concentration differences alone.

4.2 Bud activation and vegetative growth regulation

Shoot removal changes the regulatory environment experienced by remaining buds. Hormonal signaling and carbohydrate availability are plausible interacting controls, rather than competing explanations. Bertheloot et al. (2020), working with non-tea systems, demonstrated that sugar availability can suppress an auxin-related strigolactone pathway and promote bud outgrowth. Fichtner et al. (2021) showed that trehalose 6-phosphate participates in branching regulation in *Arabidopsis*. These experiments provide mechanistic support for interactions between resource status and bud regulation, but they do not establish identical responses in mature tea bushes.

Tea-specific work supplies complementary evidence. Ye et al. (2024) combined transcriptome and hormone-metabolome analyses and associated pruning with altered growth and signaling profiles. The findings strengthen the case for coordinated regulation after canopy disturbance. Nevertheless, pathway enrichment, hormone abundance, and shoot growth measured after treatment do not by themselves determine the causal order. A signaling change might initiate growth, accompany it, or reflect differences in sampled developmental stages. These possibilities need to remain separate in interpretation.

Bud activation is also not synonymous with successful regeneration. A bud must develop into a shoot that survives, occupies a useful position, and reaches the intended harvest standard. Counting newly activated buds can therefore exaggerate recovery when many shoots remain weak, crowded, or unsuitable for collection. A complete assessment should follow marked buds through development and relate their fate to canopy conditions. The strongest mechanistic explanation would connect an experimentally tested regulator to this developmental sequence and ultimately to usable production, rather than stopping at a molecular response.

4.3 Yield formation and long-term production stability

Cumulative production can be understood by summing the number of acceptable shoots harvested in each round multiplied by their mean mass. This accounting identity clarifies why shoot density, shoot weight, and harvest number should not be interpreted independently. A heavier average shoot may be accompanied by fewer suitable shoots; more picking rounds may divide a similar total crop into smaller collections. The identity is not a predictive growth model, and it does not justify multiplying one measured shoot population by an assumed annual harvest frequency.

Quality adds another dimension. Hazra et al. (2021) documented relationships between physiological traits and secondary-metabolite accumulation, while Zhang et al. (2023) found that pruning-related growth benefits in Wuyi rock tea were accompanied by decreases in some measured quality constituents. Consequently, increased biomass cannot stand in for increased commercial value. Evaluation should identify the target tea type, comparable shoot maturity, processing conditions, and the proportion of output that meets an agreed standard. Fresh mass should also be distinguished from dry matter and processed-tea yield.

Production stability requires repeated observations over the relevant management horizon. The review proposes reporting annual totals alongside recovery gaps, within-year distribution, and variation among years. A low-yield system can be consistently poor, so small variation is not sufficient evidence of success. Conversely, an intentional renewal year may produce a temporary decline that is justified over a complete pruning cycle. Appropriate evaluation therefore asks whether cumulative acceptable output and plant condition remain satisfactory, not whether every individual harvest exceeds the preceding one.

5 Case Analysis: Integrated Harvesting and Canopy-Restoration Management in Tea Plantations

5.1 Case selection and analytical framework

The case analysis uses complementary published studies rather than presenting an undocumented integrated treatment as an established practice. The principal harvesting experiment was conducted at St. Joachim Estate, Ratnapura, Sri Lanka, using cultivar TRI 4042 in the second year of its pruning cycle. The site was approximately 30 m above sea level, with reported annual rainfall exceeding 3 200 mm. Four replicated blocks were followed for one year (Pathiranage et al., 2023). Pruning-cycle position is reported here without converting it into an assumed chronological plantation age.

A contrasting restoration study involved twenty-two-year-old ‘Jinfeng’ plants at Lanxi, Zhejiang, China. Pruning treatments were imposed in 2020, followed by spring-shoot observations in 2021 (Lu et al., 2022). A third study examined summer pruning of mature ‘Jin Guan Yin’ plants in a system harvesting spring tea and using two pruning operations annually (Zhang et al., 2021). These are different cultivars and production environments, not replicate observations of a common treatment.

The analytical framework separates intervention, immediate plant response, later harvest performance, and the duration actually observed. For harvesting, the questions concern removal selectivity and the condition of subsequent shoot populations. For restoration, they concern the timing and structure of regrowth. Quality evidence is considered only where a study measured relevant constituents or product attributes. This arrangement allows a shared management question to be examined without pooling incompatible yields. It also prevents an important interpretive error: using favorable outcomes from separate experiments to claim that their combined treatments have already been shown to interact positively.

5.2 Comparison of harvesting and canopy-restoration practices

In the Sri Lankan experiment, three motorized systems were compared with selective hand plucking. The machines included a picking-arm design and two reciprocating-blade designs. Crucially, machine harvesting occurred at fourteen-day intervals, whereas manual harvesting occurred at seven-day intervals (Pathiranage et al., 2023). The contrast therefore includes harvesting schedule as well as mechanism and selectivity. Randomized blocking strengthens the comparison between treatment packages, but it does not remove this built-in difference between their components.

This matters when interpreting restoration needs. A poorer subsequent crop could reflect damage to developing shoots, loss of maintenance foliage, altered shoot age at collection, or their combined effects. The trial can establish the performance of the tested packages; it cannot isolate a pure machinery effect at an identical interval. A factorial experiment with matched intervals would be needed for that narrower question. Treating this limitation explicitly preserves the practical importance of the study without giving its results a broader causal meaning than the design permits.

The Zhejiang study compared heavy pruning in mid-April, early May, and late May, included light and deep pruning in early May, and tested an additional autumn light cut after early-May heavy pruning (Lu et al., 2022). It was not a complete factorial crossing of every severity and date. In the summer-pruning study, one favorable treatment cut 30 cm above the preceding spring-pruning surface on July 25 (Zhang et al., 2021). This was not a cut 30 cm above ground. Together, these designs show why treatment names and numerical heights need operational definitions before studies are compared or recommendations are transferred.

5.3 Evaluation of yield, quality, and production stability

Pathiranage et al. (2023) reported annual made-tea yield estimates of 4296.2 kg/ha under manual harvesting and 1974.9-2297.2 kg/ha across the three motorized treatments, corresponding to reported reductions of approximately 46%-54%. These were calculated using a specified 21.5% processing outturn, rather than independently measured factory output. Changes in branch development and root starch accompanied the yield differences. The result is strong evidence against the tested continuous machine-harvesting packages under those conditions, not against every possible form of mechanization.

Lu et al. (2022) found that heavy pruning in mid-April or early May advanced subsequent spring-shoot development. Pruned treatments generally had higher median hundred-shoot weights at a comparable two-leaves-and-one-bud stage than the unpruned control. These observations establish changes in phenology and shoot characteristics. They do not establish greater cumulative annual harvest, recovery of all foregone production, or higher profit. Those outcomes would require additional measurements beyond a promising spring flush.

The summer-pruning study adds evidence that later cutting can restrict subsequent performance: the August 15 treatment reduced the following spring crop, while other treatment differences were not uniformly significant (Zhang et al., 2021). Quality must also remain a separate outcome. Zhang et al. (2023) observed growth and yield improvements after pruning in Wuyi rock tea alongside reductions in several measured quality constituents. A credible assessment would therefore retain distinct conclusions for yield, maturity, composition, and sensory performance. None of these case studies, considered alone, demonstrates that an integrated harvesting-restoration strategy maintains an advantage across multiple complete pruning cycles.

A further comparison should distinguish the quality of selected surviving shoots from the quality distribution of the whole harvest. Sampling only undamaged, uniform shoots after a severe treatment could miss an economically important increase in rejected material. The proposed evaluation would sample representative harvested batches, report the discarded fraction separately, and retain the same processing protocol across treatments. This would connect laboratory composition more directly with marketable plantation output.

5.4 Implications for tea plantation management

The central practical implication is to diagnose the source of production loss before choosing a restoration measure. When a harvesting operation repeatedly removes immature shoots, improving selectivity is a more direct response than assuming that heavier pruning will solve the problem. When the existing framework limits canopy renewal or access, changing harvesting interval alone may be insufficient. These are management deductions from the comparative evidence, not treatment combinations experimentally validated by the case studies.

Economic comparison also requires a realistic alternative (Figure 1). An experimental hand-plucked control represents the labor and timing actually provided in that trial. On a labor-constrained farm, the available alternative might involve delayed manual harvesting rather than the same timely selective service. An appropriate adoption trial would compare these feasible options and measure saleable output, working time, sorting requirements, and subsequent recovery. A machine can cover an area rapidly yet perform poorly per unit of acceptable product; a biologically favorable system can be impractical when labor is unavailable. Neither possibility should be resolved by assuming local prices or inventing a cost-benefit estimate.

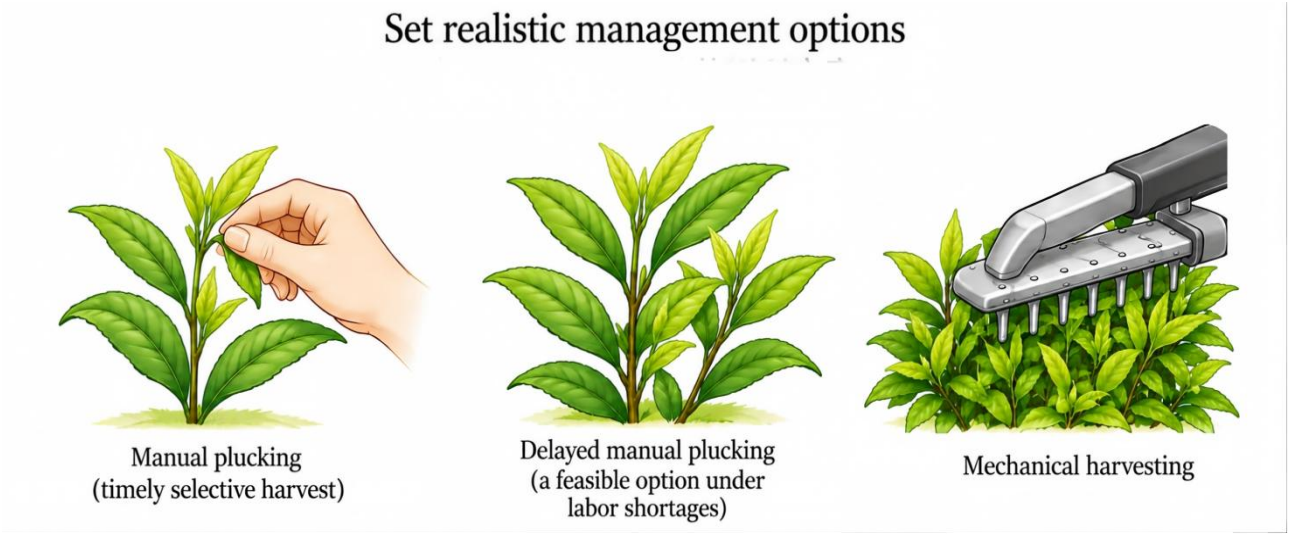


Figure 1 Schematic illustration of alternative harvesting management options under practical tea plantation conditions

Image caption: Three harvesting management options are illustrated according to labor availability and harvesting requirements: (1) Manual plucking, which involves timely and selective harvesting of shoots that meet the required standards to control harvesting positions and product quality; (2) Delayed manual plucking, which allows harvesting to be postponed under labor shortages but may affect shoot maturity and product quality; (3) Mechanical harvesting, which uses machinery to improve harvesting efficiency, although harvesting selectivity and subsequent sorting requirements still need evaluation. The suitability of these options should be assessed by considering marketable yield, working time, sorting requirements, and canopy recovery

Transfer between regions should therefore begin with small, monitored comparisons. The relevant checks include cultivar response, canopy geometry, shoot synchrony, soil moisture, the next harvest window, and the intended product. Earlier bud development may be valuable in an early-season market, but that value remains conditional on actual quality, collection capacity, and price. Likewise, protecting foliage during one round should be evaluated through the following rounds rather than credited automatically as a long-term benefit. The cases support adaptive coordination of harvesting and recovery. They do not identify one universally superior combination of harvesting frequency, cutting height, and restoration intensity.

6 Optimization Strategies for Sustained Tea Plantation Production

6.1 Coordination of harvesting intensity and canopy recovery

Coordination should begin with a shared record of canopy condition and recent operations. Before adjusting harvest intensity, managers need to know whether the limiting factor is a shortage of suitable shoots, damage to immature cohorts, inadequate functional foliage, or an unsuitable branch framework. The review proposes recording these conditions immediately before and after representative harvests. Observations should distinguish the upper harvesting surface from the maintenance layer beneath it. Without that distinction, a visually even canopy can conceal unwanted removal of the tissues expected to support the next crop.

The resulting decision rules should be tested locally. A decline in acceptable shoot density accompanied by repeated damage to younger shoots would justify examining selectivity and cutting position. Poor canopy rebuilding after structural pruning would justify reviewing the timing of renewed harvesting and the supply of water and nutrients. These responses should not be framed as fixed numerical thresholds derived from the present literature. The available studies differ too much in cultivar, environment, and treatment definition to support one universal trigger. Maintaining untreated or conventionally managed comparison strips would help distinguish an intervention response from seasonal change.

Monitoring technologies can improve the spatial coverage of these assessments. Liu et al. (2025a) integrated UAV and Sentinel-2 information to estimate seasonal tea yields at field scale. Such approaches can help identify uneven performance and prioritize field inspection. They do not reveal automatically whether a decline was caused by pruning, nutrition, drought, or harvest damage. Models developed under one canopy condition should be checked after substantial architectural change. For management, the strongest use of remote information is therefore a sequence of screening, field diagnosis, intervention, and follow-up measurement. Technology should strengthen that sequence rather than replace direct observation of the tissues removed and retained.

Recovery also needs a stopping rule for experimental evaluation. Rather than declaring restoration complete when the canopy looks closed, a trial should specify the functional and production conditions required for renewed harvesting. The rule should be established before outcomes are known and applied consistently across treatments. Otherwise, treatments may be compared after different degrees of recovery, making apparent advantages partly dependent on when investigators chose to resume picking.

6.2 Adaptive management across plantation development stages

Plantation stage changes the balance between building a productive framework and using an established one. For young stands, the proposed priority is to assess whether harvesting competes with formation of the intended canopy. For mature stands, attention shifts toward maintaining productive structure and matching harvesting operations to shoot development. For aging stands, chronological age should not be used as the sole justification for severe renewal. Uneven growth may reflect several constraints, and cutting harder without diagnosis could add recovery costs without addressing the original limitation.

Cultivar evaluation should be incorporated into these decisions. Wang et al. (2022) developed a comprehensive assessment of machine-harvested tea cultivars using multiple traits, illustrating the value of evaluating suitability beyond yield alone. Kan et al. (2024) identified ‘Zhongcha302’ and ‘EmeiWenchun’ as strongly contrasting varieties in their pruning-response evaluation. Together, these studies support screening architecture, regrowth, and harvest-related traits under the intended management system. However, cultivar rankings under one treatment are not equivalent to a demonstrated genotype-by-management interaction. Establishing that interaction requires cultivars to be compared across management treatments with an appropriate statistical design.

Stress responses add another dimension. Parmar et al. (2019) identified contrasting drought-responsive transcriptional patterns and candidate sequence variation among tea genotypes. These resources are relevant to future breeding, but they do not establish validated markers for sustained production after pruning. A cultivar with vigorous regrowth under favorable water supply may still perform differently during a dry recovery period. Breeding-oriented evaluation should therefore connect candidate traits with repeated field performance, retention

of product quality, and recovery under realistic resource constraints. The objective is not simply rapid shoot growth after cutting. It is reliable production from a canopy that remains manageable, physiologically functional, and suitable for the chosen harvesting method throughout its productive cycle.

6.3 Integrated evaluation of productivity and sustainability

An integrated assessment should keep biological, economic, and environmental outcomes visible rather than collapsing them immediately into a single score. Cumulative acceptable yield and quality describe what the plantation produces. Recovery duration and canopy condition describe its capacity to continue. Labor, machinery, and sorting requirements describe whether the system is feasible. A weighted index may help compare alternatives, but its weights represent priorities and should be reported transparently. Otherwise, an apparent improvement may simply result from assigning little importance to a deteriorating outcome.

Soil evidence shows why canopy management cannot be judged aboveground alone. Bora et al. (2022) reported lower microbial abundance and richness in their long-term pruned plot, although some potentially important bacterial groups had higher relative representation. Jiang et al. (2023) reported favorable soil and ecosystem responses to an umbrella-shaped canopy relative to the comparison architecture in their study. These findings should not be read as a universal ranking based on microbial diversity or canopy shape. Site conditions and treatment histories matter, while changes in microbial composition require links to measured soil functions and crop performance before they can guide firm recommendations.

Input costs also extend beyond expenditure. Jiang et al. (2025) examined nitrous oxide emissions and yield in a tea fertilization experiment with a twelve-year treatment history. Their study links production assessment with environmental consequences; the treatment history should not be mistaken for twelve years of continuous gas measurements. For integrated management, fertilizer demand, soil acidity, and emission intensity should be considered alongside the harvested crop. A practice that appears productive only because additional inputs compensate for repeated damage may be less attractive than its yield suggests. The preferred strategy should demonstrate acceptable output, manageable recovery costs, and efficient resource use over a clearly specified period, with uncertainties reported rather than hidden by a single favorable indicator.

7 Conclusions and Future Perspectives

Harvesting and canopy restoration should be treated as connected decisions within the recurring production cycle of tea plants. The value of a harvest depends not only on the shoots collected but also on the tissues retained for subsequent growth. Harvesting frequency, plucking standards, selectivity, and cutting severity represent distinct management factors whose effects should be evaluated separately. Functional leaf retention supports recovery, but more foliage does not necessarily mean greater photosynthetic capacity. Leaf condition, position, and contribution to new growth must also be considered. Canopy restoration may involve selective shoot retention, structural pruning, or temporarily reduced harvesting. Its effectiveness should be assessed through renewed marketable production and plant condition rather than canopy appearance or bud numbers alone.

Pruning can promote shoot development and modify harvest timing, but these benefits depend on cultivar, cutting position, season, and resource availability. The reviewed cases demonstrate that favorable short-term responses do not necessarily translate into higher annual yields. Comparisons between mechanical and manual harvesting must also account for differences in harvesting intervals and selectivity. Quality remains an independent production objective because increased shoot biomass or individual biochemical constituents cannot establish improved commercial value. The main conclusion is therefore conditional: coordinated harvesting and canopy recovery can support sustained production when management decisions consider cumulative yield, recovery costs, product quality, and realistic production constraints. No universal harvesting interval or pruning intensity can be recommended from the available evidence.

Future research should examine harvesting and restoration through coordinated field experiments covering complete pruning cycles. Harvesting intervals, selectivity, and restoration intensity should be compared across cultivars and environments using replicated designs and consistent measurement standards. Physiological

investigations should connect functional leaf area, photosynthesis, carbohydrate reserves, nutrient status, and subsequent shoot development. Carbon and nitrogen tracing could clarify the contributions of current assimilation and stored resources during recovery. Following marked buds through successive developmental stages would help distinguish successful regeneration from temporary growth responses. Molecular studies should test proposed regulatory mechanisms experimentally rather than relying solely on associations between gene expression and shoot development.

Breeding and management research should evaluate recovery as a combination of regrowth capacity, canopy architecture, quality retention, and performance under resource limitations. Multi-environment trials are needed to determine whether cultivar responses remain stable across harvesting systems. Remote sensing and yield prediction should be validated under different canopy conditions, with uncertainty clearly reported. Economic assessments should include labor requirements, missed harvests, sorting costs, and recovery duration, while environmental evaluations should consider resource use and associated impacts. Farmer-scale trials and shared research protocols would improve practical relevance and comparability. Future progress should focus on demonstrating how harvesting and recovery can be coordinated to maintain acceptable production throughout successive management cycles, rather than identifying isolated treatments that improve growth under favorable conditions.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Arkorful E., Hu S., Zou Z., Yu Y., Chen X., and Li X., 2020a, Metabolomic analyses provide new insights into signaling mechanisms for nutrient uptake by lateral roots of pruned tea plant (*Camellia sinensis*), Journal of Agricultural and Food Chemistry, 68(30): 7890-7903.
https://doi.org/10.1021/acs.jafc.0c02053

Arkorful E., Yu Y., Chen C., Lu L., Hu S., Yu H., Ma Q., Thangaraj K., Periakaruppan R., Jeyaraj A., Chen X., and Li X., 2020b, Untargeted metabolomic analysis using UPLC-MS/MS identifies metabolites involved in shoot growth and development in pruned tea plants (*Camellia sinensis* (L.) O. Kuntz), Scientia Horticulturae, 264: 109164.
https://doi.org/10.1016/j.scienta.2019.109164

Bertheloot J., Barbier F., Boudon F., Perez-Garcia M.D., Péron T., Citerne S., Dun E., Beveridge C., Godin C., and Sakr S., 2020, Sugar availability suppresses the auxin-induced strigolactone pathway to promote bud outgrowth, New Phytologist, 225(2): 866-879.
https://doi.org/10.1111/nph.16201

Bora S.S., Hazarika D.J., Gogoi R., Dullah S., Gogoi M., and Barooah M., 2022, Long-term pruning modulates microbial community structure and their functional potential in tea (*Camellia sinensis* L.) soils, Applied Soil Ecology, 176: 104483.
https://doi.org/10.1016/j.apsoil.2022.104483

Cai J., Qiu Z., Liao J., Li A., Chen J., Wu Z., Khan W., Sun B., Liu S., and Zheng P., 2024, Comprehensive analysis of the yield and leaf quality of fresh tea (*Camellia sinensis* cv. Jin Xuan) under different nitrogen fertilization levels, Foods, 13(13): 2091.
https://doi.org/10.3390/foods13132091

Chen J., Wu S., Dong F., Li J., Zeng L., Tang J., and Gu D., 2021a, Mechanism underlying the shading-induced chlorophyll accumulation in tea leaves, Frontiers in Plant Science, 12: 779819.
https://doi.org/10.3389/fpls.2021.779819

Chen Y., Zhou B., Li J., Tang H., Zeng L., Chen Q., Cui Y., Liu J., and Tang J., 2021b, Effects of long-term non-pruning on main quality constituents in 'Dancong' tea (*Camellia sinensis*) leaves based on proteomics and metabolomics analysis, Foods, 10(11): 2649.
https://doi.org/10.3390/foods10112649

Chen Y.T., and Chen S.F., 2020, Localizing plucking points of tea leaves using deep convolutional neural networks, Computers and Electronics in Agriculture, 171: 105298.
https://doi.org/10.1016/j.compag.2020.105298

Fichtner F., Barbier F.F., Annunziata M.G., Feil R., Olas J.J., Mueller-Roeber B., Stitt M., Beveridge C.A., and Lunn J.E., 2021, Regulation of shoot branching in *Arabidopsis* by trehalose 6-phosphate, New Phytologist, 229(4): 2135-2151.
https://doi.org/10.1111/nph.17006

Gu H., Wang Y., Xie H., Qiu C., Zhang S., Xiao J., Li H., Chen L., Li X., and Ding Z., 2020, Drought stress triggers proteomic changes involving lignin, flavonoids and fatty acids in tea plants, Scientific Reports, 10: 15504.
https://doi.org/10.1038/s41598-020-72596-1

Hazra A., Saha S., Dasgupta N., Kumar R., Sengupta C., and Das S., 2021, Ecophysiological traits differentially modulate secondary metabolite accumulation and antioxidant properties of tea plant [*Camellia sinensis* (L.) O. Kuntze], Scientific Reports, 11: 2795.
https://doi.org/10.1038/s41598-021-82454-3

Jiang F., Chang Y., Han J., Yang X., and Wu Z., 2025, Effects of long-term nitrogen fertilization on nitrous oxide emission and yield in acidic tea (*Camellia sinensis* L.) plantation soils, Agronomy, 15(1): 7.
https://doi.org/10.3390/agronomy15010007

Jiang Y., Lin X., Khan M.U., Jiang W., Xu Y., Li Z., and Lin W., 2023, Tea pruning for the umbrella-shaped canopy can alleviate rhizosphere soil degradation and improve the ecosystem functioning of tea orchards, CATENA, 222: 106885.
https://doi.org/10.1016/j.catena.2022.106885

Kan S., Tang D., Feng L., Tan X., Zhang Y., and Tang Q., 2024, Comparison of the effect of pruning on plant growth and transcriptome profiles in different tea varieties, Agronomy, 14(6): 1105.
https://doi.org/10.3390/agronomy14061105

Li R., Liu K., Liang Z., Luo H., Wang T., An J., Wang Q., Li X., Guan Y., Xiao Y., Lv C., and Zhao M., 2022, Unpruning improvement the quality of tea through increasing the levels of amino acids and reducing contents of flavonoids and caffeine, Frontiers in Nutrition, 9: 1017693.
https://doi.org/10.3389/fnut.2022.1017693

Liu H., Liu Y., Xu W., Wu M., Wang L., Lu N., and Ou G., 2025a, A seasonal fresh tea yield estimation method with machine learning algorithms at field scale integrating UAV RGB and Sentinel-2 imagery, Plants, 14(3): 373.
https://doi.org/10.3390/plants14030373

Liu Q., Wang Z., Cheng L., Wang K., Bai Y., Ding Q., Shao Z., and Zhang Y., 2025b, Assessment of evapotranspiration-yield relationships in northern China tea plantations: a basis for crop water productivity improvement, Agronomy, 15(8): 1955.
https://doi.org/10.3390/agronomy15081955

Liu Y., Tian J., Liu B., Zhuo Z., Shi C., Xu R., Xu M., Liu B., Ye J., Sun L., and Liao H., 2022, Effects of pruning on mineral nutrients and untargeted metabolites in fresh leaves of *Camellia sinensis* cv. Shuixian, Frontiers in Plant Science, 13: 1016511.
https://doi.org/10.3389/fpls.2022.1016511

Lu L., Luo W., Zheng Y., Jin J., Liu R., Lv Y., Ye Y., and Ye J., 2022, Effect of different pruning operations on the plant growth, phytohormones and transcriptome profiles of the following spring tea shoots, Beverage Plant Research, 2: 12.
https://doi.org/10.48130/BPR-2022-0012

Luo J., Liao S., Ding F., Dai Y., Liu Z., Zhang T., Yang T., Li Q., Fang S., Li Y., Fang W., and Shen Q., 2026, Effects of plucking standards and processing methods on the quality characteristics of summer tea leaves, Food Science & Nutrition, 14(10): e72445.
https://doi.org/10.1002/fsn3.72445

Ma L., Jiang S., Deng M., Lv L., Xu Z., and Ruan J., 2021, Thermo condition determines the uptake of autumn and winter applied nitrogen and subsequent utilization in spring tea (*Camellia sinensis* L.), Horticulturae, 7(12): 544.
https://doi.org/10.3390/horticulturae7120544

Parmar R., Seth R., Singh P., Singh G., Kumar S., and Sharma R.K., 2019, Transcriptional profiling of contrasting genotypes revealed key candidates and nucleotide variations for drought dissection in *Camellia sinensis* (L.) O. Kuntze, Scientific Reports, 9: 7487.
https://doi.org/10.1038/s41598-019-43925-w

Pathiranage S.R.W., Wijeratne M.A., and De Costa W.A.J.M., 2019, Evaluation of the impacts of mechanical harvesting on tea yield (cultivar TRI 2027) in the low country of Sri Lanka, Sri Lanka Journal of Tea Science, 84(1-2): 22-30.
https://doi.org/10.4038/sljts.v84i1-2.8

Pathiranage S.R.W., Wijeratne M.A., and De Costa W.A.J.M., 2023, Impact of motorized tea harvesters on tea yield and yield determining parameters, Tropical Agricultural Research, 34(4): 316-330.
https://doi.org/10.4038/tar.v34i4.8672

Wang Z., Peng H., Yue C., Li W., Tong Z., and Yang P., 2022, Selection of core evaluation indices and construction of a comprehensive evaluation method for machine-harvested tea plant cultivars, Euphytica, 218(11): 162.
https://doi.org/10.1007/s10681-022-03112-x

Yamashita H., Tanaka Y., Umetsu K., Morita S., Ono Y., Suzuki T., Takemoto T., Morita A., and Ikka T., 2020, Phenotypic markers reflecting the status of overstressed tea plants subjected to repeated shade cultivation, Frontiers in Plant Science, 11: 556476.
https://doi.org/10.3389/fpls.2020.556476

Ye J., Zhang Q., Shi L., Wang Y., Li M., Chen Y., Zhang M., Chen J., Chen M., Jia X., Xu C., Miao J., and Wang H., 2024, Joint analysis of transcriptome and hormone metabolome on the mechanism of pruning effect on tea tree (*Camellia sinensis*) growth, Industrial Crops and Products, 218: 118929.
https://doi.org/10.1016/j.indcrop.2024.118929

Zhang L., Li M., Li X., Yan P., Zhang L., and Han W., 2021, Summer pruning improves the branch growth and tea quality of tea trees (*Camellia sinensis*), Acta Physiologiae Plantarum, 43(4): 65.
https://doi.org/10.1007/s11738-021-03226-0

Zhang Q., Zhang Y., Wang Y., Zou J., Lin S., Chen M., Miao P., Jia X., Cheng P., Pang X., Ye J., and Wang H., 2023, Transcriptomic analysis of the effect of pruning on growth, quality, and yield of Wuyi rock tea, Plants, 12(20): 3625.
https://doi.org/10.3390/plants12203625

Zhang Y., Ye X., Zhang X., Huang W., and Zhao H., 2020, Natural variations and dynamic changes of nitrogen indices throughout growing seasons for twenty tea plant (*Camellia sinensis*) varieties, Plants, 9(10): 1333.
https://doi.org/10.3390/plants9101333

Disclaimer/Publisher's Note

The statements, opinions, and data contained in all publications are solely those of the individual authors and contributors and do not represent the views of the publishing house and/or its editors. The publisher and/or its editors disclaim all responsibility for any harm or damage to persons or property that may result from the application of ideas, methods, instructions, or products discussed in the content. Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.