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Global Tea Production: Current Status, Emerging Challenges, Technological Transformation, and Future Perspectives

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Abstract

Tea (*Camellia sinensis* (L.) Kuntze) is a globally important perennial beverage crop supporting agricultural economies, rural livelihoods, international trade and cultural systems. Global made-tea production reached approximately 7.074 million tonnes in 2024 and approximately 7.266 million tonnes in 2025. The sector is undergoing structural change as climate variability, water constraints, labour costs, soil degradation, market volatility and requirements for traceability and environmental performance increasingly interact with conventional production challenges. This review synthesizes recent evidence on global production, climate impacts, genetic resources, precision agriculture, artificial intelligence, intelligent processing, sustainability, circular economy and value-added development. Recent evidence shows a transition from productivity-centred production toward integrated systems combining genotype, environment, management and digital technologies. Climate change affects tea through temperature stress, altered

rainfall, drought and extreme events, with consequences for yield and biochemical quality. Advances in remote sensing, unmanned aerial vehicles, Internet of Things sensors, machine learning, computer vision, spectroscopy and robotics provide opportunities for real-time monitoring and precision management, although cost, data standardization, model transferability and smallholder access remain major constraints. Future tea production should integrate climate-resilient cultivars, precision resource management, intelligent processing, digital traceability and circular use of biomass. A Tea Production 2050 framework is proposed to connect genetic conservation, climate adaptation, smart production, artificial intelligence, processing, traceability and value creation. The review identifies priorities for research and technology deployment aimed at improving productivity, quality, resilience and sustainability across diverse tea-growing systems.

Keywords: *Camellia Sinensis*, Tea Production, Climate Change, Climate Resilience, Precision Agriculture, Artificial Intelligence, Remote Sensing, Tea Quality, Sustainability, Circular Economy, Genetic Resources

1. Introduction

Tea (*Camellia sinensis* (L.) Kuntze) is cultivated across a broad range of tropical and subtropical environments and is among the most widely consumed beverages globally. Its importance extends beyond beverage production because tea supports rural employment, smallholder livelihoods, export earnings and cultural systems. FAO reports that smallholder producers account for approximately 60% of world tea production, while the global tea economy generates roughly USD 19.5 billion annually in production value and about USD 9.4 billion in trade value. Global tea production was estimated at approximately 7.3 million tonnes in 2025 ^[1-3].

Production is geographically concentrated. The 2024 International Tea Committee statistics reported by the Tea Board of India indicate approximately 7.074 million tonnes of global production, with China accounting for 53%, India 18%, Kenya 8% and Sri Lanka 4%; together these four producers represented approximately 83% of global output. Global exports were approximately 1.952 million tonnes in 2024 ^[4]. In 2025, the International Tea Committee reported approximately 7.266 million tonnes of made tea and 2.009 million tonnes of exports, indicating continued expansion of both production and international trade ^[5].

Despite this growth, the production environment is becoming more uncertain. Tea is particularly sensitive to temperature, water availability, rainfall distribution and soil conditions. Climate change can therefore affect both yield and quality, while drought, heat, excessive rainfall and extreme weather may interact with pest and disease pressure. A systematic bibliometric

and content analysis of 328 peer-reviewed studies published between 2004 and 2023 demonstrated a substantial increase in research on climate impacts, adaptation, physiological responses, secondary metabolism and genomic mechanisms in tea [6].

At the same time, digital technologies are transforming the tea value chain. Computer vision, machine learning, spectroscopy, artificial sensors, big data, Internet of Things systems and blockchain are increasingly being investigated for crop monitoring, disease detection, quality assessment and traceability [7]. A recent review of AI across tea-garden management, harvesting and processing further emphasized the emergence of closed-loop systems connecting databases, decision algorithms and actuation devices [8].

The objective of this review is to synthesize the current evidence on global tea production and to identify the major technological, ecological and socioeconomic pathways that are likely to shape tea production toward 2050.

2. Materials and Methods

This study was structured as a scoping review with systematic evidence-synthesis principles. Scientific literature and authoritative statistical sources were searched for evidence concerning tea production, climate change, genetic resources, precision agriculture, artificial intelligence, processing, sustainability and value-added products. Priority was given to peer-reviewed studies, systematic reviews and institutional datasets. Searches covered Web of Science, Scopus-indexed literature accessible through major publishers, PubMed, ScienceDirect, Frontiers, MDPI and FAO and International Tea Committee publications. Search terms included combinations of “*Camellia sinensis*”, “tea production”, “tea climate change”, “tea drought”, “tea heat stress”, “tea quality”, “tea breeding”, “precision tea agriculture”, “artificial intelligence tea”, “remote sensing tea”, “tea processing”, “tea sustainability” and “tea circular economy”. Studies were included when they addressed production, environment, climate response, genetic adaptation, agronomic management, digital technologies, processing, sustainability or value creation in tea systems. Foundational studies were retained when necessary to establish established relationships, while greater emphasis was placed on evidence published from 2020 to 2026. The evidence was thematically synthesized into global production and trade, climate change, genetic resources, precision agriculture, artificial intelligence, processing and quality, sustainability and circular economy, and future value creation.

Because international statistical series may distinguish made tea from harvested green leaf, production figures are reported using the unit and definition of the cited source. The principal global comparison in this review uses made-tea production reported by the International Tea Committee and Tea Board of India. This distinction is important because green-leaf production cannot be directly compared with made-tea output without applying a processing conversion factor.

3. Results

3.1 Global production and trade

The global tea sector has maintained a long-term expansion trajectory. In 2024, global made-tea production was approximately 7.074 million tonnes, while the 2025 International Tea Committee bulletin reported

approximately 7.266 million tonnes, representing an increase of about 2.53% year on year. Global exports increased from approximately 1.968 million tonnes in 2024 to approximately 2.009 million tonnes in 2025, crossing two million tonnes for the first time [4, 5].

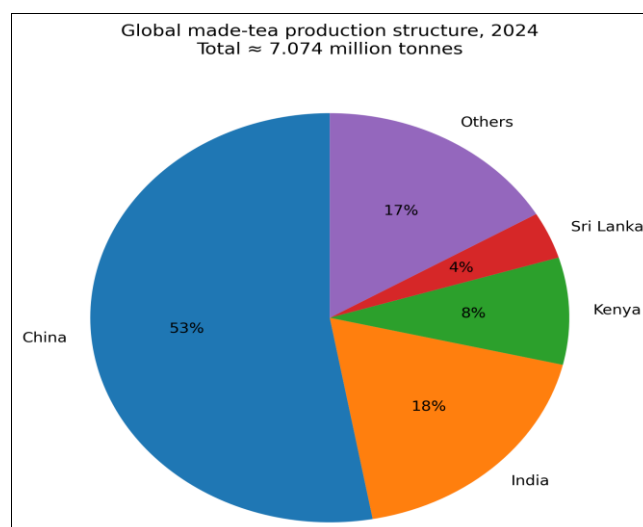


Fig 1: Global made-tea production structure in 2024. Data: International Tea Committee statistics as reported in the Tea Board of India Annual Report 2024–25 [4]

Table 1: Major global made-tea production shares in 2024. Source: Tea Board of India, using International Tea Committee statistics [4]

Country/group	Production 2024 (million kg)	Global share (%)
China	3,740	53
India	1,304	18
Kenya	598	8
Sri Lanka	262	4
Other producers	1,170	17
World total	7,074	100

The geographical structure has important implications for technology and policy. China combines very large production volume with substantial product diversification, while India has a mixed estate and smallholder structure. Kenya is especially important in export-oriented black tea, whereas Sri Lanka is strongly associated with internationally differentiated Ceylon tea. Vietnam occupies a smaller share of global made-tea output but possesses substantial agroecological and genetic diversity, creating opportunities for specialty products and climate-adapted production. The production system is therefore heterogeneous and requires context-specific technological pathways.

3.2 Smallholder production and socioeconomic resilience

Smallholders are central to the global tea economy. FAO estimates that approximately 60% of world tea production is generated by smallholder producers [1, 2]. This structure means that modernization strategies based exclusively on high-capital estates would address only part of the sector. Smallholders frequently face constraints in access to finance, extension, machinery, quality-control infrastructure and digital technology. These constraints become more significant under climate stress because drought, extreme rainfall and price volatility can simultaneously increase production risk and reduce investment capacity.

The future modernization of tea should therefore emphasize shared infrastructure, cooperative services, low-cost sensing,

digital advisory systems, collective processing and market differentiation. Technology adoption should be evaluated not only by technical accuracy but also by affordability, maintainability, data requirements and compatibility with local labour and knowledge systems.

3.3 Climate change as a structural constraint

Tea production is strongly dependent on temperature, rainfall, soil moisture, humidity and radiation. Climate change can therefore influence growth, yield, biochemical composition and the geographical suitability of tea-growing areas. A systematic review concluded that drought, uneven precipitation and extreme weather events are generally negative for tea production, while the effects of warming and elevated CO₂ are conditional and can become negative when temperatures exceed crop-specific optima [9].

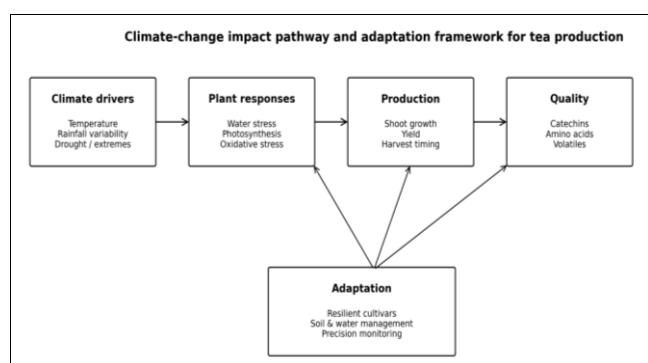


Fig 2: Conceptual pathway linking climate drivers to tea physiology, production, quality and adaptation. The figure is an original synthesis based on the reviewed literature [6, 9, 10]

Drought reduces leaf water status, photosynthesis, shoot initiation and shoot extension, although responses differ among cultivars and management systems [10]. Heat stress can alter photosynthetic activity, respiration and secondary metabolism. Excessive rainfall can increase erosion, nutrient loss and disease pressure. The combined occurrence of drought and heat is particularly important because multiple stressors may interact rather than produce independent effects. Current literature also identifies the need for field-scale studies because controlled experiments may not reproduce the complexity of soil, canopy, altitude, microclimate and management interactions [6].

3.4 Genetic resources and climate-resilient cultivars

Genetic improvement is a central pathway for long-term adaptation. Tea germplasm contains substantial variation in growth habit, stress response, biochemical composition, disease resistance, aroma and processing suitability. Future breeding should therefore move beyond yield as the principal selection target and incorporate drought tolerance, heat tolerance, water-use efficiency, nutrient-use efficiency, disease resistance and stable quality across environments.

Wild and locally adapted tea populations deserve particular attention because they may contain traits that have been maintained under environmental stress. Conservation should therefore be integrated with characterization and utilization. A modern germplasm platform should connect field conservation with genomic characterization, phenotyping, metabolomics and climate-response data. Such integration could accelerate the identification of donor material for climate-resilient breeding.

3.5 Precision agriculture and remote sensing

Precision agriculture offers a means of managing spatial and temporal variability within tea plantations. Satellite imagery, unmanned aerial vehicles, multispectral and thermal sensors, soil sensors and weather stations can provide information on canopy condition, soil moisture, nutrient status and disease risk. A 2026 multidisciplinary review reported growing evidence that combining UAV remote sensing with machine learning can improve precision tea management, while emphasizing persistent limitations related to data quality, weather interference, cost and the lack of standardized datasets across environments [11].

The most useful architecture is a closed feedback loop in which sensing is connected to diagnosis, decision support and field action. Such a system can potentially support variable-rate irrigation, targeted fertilization, disease scouting and harvest scheduling. The technical objective is not simply to collect more data but to convert data into management decisions with measurable economic and environmental benefits.

3.6 Artificial intelligence and intelligent harvesting

Artificial intelligence is increasingly being integrated into tea production and processing. Recent reviews identify computer vision, machine learning, spectroscopy, artificial sensors, big-data systems and Internet of Things technologies as major components of intelligent tea production [7, 8]. AI can support disease recognition, yield prediction, quality classification and process control. The performance of models, however, is highly dependent on dataset quality and representativeness.

Robotic harvesting remains technically challenging because tea shoots vary in position, size, maturity, density and illumination. Current research therefore emphasizes computer vision, lightweight models, autonomous navigation and robotic manipulation. The major unresolved issue is generalization across cultivars, seasons, canopy structures and production environments. Large standardized datasets and field validation are required before laboratory performance can be translated into reliable commercial systems [8, 11].

3.7 Intelligent processing and quality evaluation

Tea quality is generated through interactions among genotype, environment, harvesting stage and processing. Important chemical components include catechins, caffeine, L-theanine, amino acids and volatile compounds. Processing conditions influence oxidation, aroma, colour and taste. Traditional quality assessment relies substantially on sensory expertise, which is valuable but can be subjective and difficult to standardize at scale [7].

Spectroscopy, machine vision, electronic sensing and chemometric or machine-learning models offer opportunities for rapid, non-destructive assessment. Intelligent processing systems could eventually integrate raw-material information with temperature, humidity, oxidation and drying data to predict final quality in real time. The long-term transition is therefore from experience-based processing toward data-assisted and ultimately data-driven process control.

3.8 Sustainability and circular economy

Sustainable tea production requires simultaneous attention to environmental integrity, economic viability and social

resilience. Soil erosion, nutrient losses, pesticide use, water demand and biodiversity decline can reduce long-term productivity. Soil organic matter, mulching, ground cover, agroforestry and integrated pest management can contribute to resource conservation while improving resilience.

Tea residues and processing by-products also represent an opportunity for circular value creation. Biomass can potentially be converted into compost, biochar, organic amendments, bioactive extracts, biomaterials or energy, depending on composition and regulatory requirements. A circular tea system therefore seeks to reduce waste while creating additional economic outputs.

3.9 Specialty tea, terroir and value addition

Commodity tea competes strongly on volume and price, whereas specialty tea can compete through origin, cultivar, processing identity, sensory characteristics and cultural association. The concept of terroir is increasingly relevant because soil, altitude, climate, genotype and processing can jointly contribute to distinctive quality. Digital traceability can reinforce this differentiation by documenting production history and origin.

Value creation can also occur beyond conventional dried tea. Extracts, functional beverages, food ingredients, cosmetic ingredients and other products derived from tea biomass can diversify revenue streams. Such diversification should be supported by evidence-based quality and safety evaluation rather than relying solely on marketing claims.

4. Discussion

The evidence indicates that tea production is moving from a primarily productivity-oriented paradigm toward a resilience- and value-oriented paradigm. This transition is driven by the interaction of climate change, labour constraints, environmental requirements, consumer expectations and digital technology. The most important scientific implication is that production should no longer be analysed through isolated variables. Tea performance is

better represented as an interaction among genotype, environment, management, climate and time.

A central challenge is technology transfer. High-performing algorithms developed under controlled or single-site conditions may fail when exposed to different cultivars, illumination, canopy architecture, soil conditions or climates. This problem is not unique to tea but is particularly important for a perennial crop with geographically diverse production systems. Future research should therefore emphasize multi-location validation, domain adaptation, standardized data collection and transparent performance metrics.

Another challenge concerns equity. If digitalization is accessible only to large enterprises, the technological transition may increase rather than reduce structural inequality. Low-cost sensors, smartphone applications, cooperative UAV services, shared databases and cloud-based decision support are therefore important components of an inclusive modernization pathway.

5. Tea Production 2050: an integrated framework

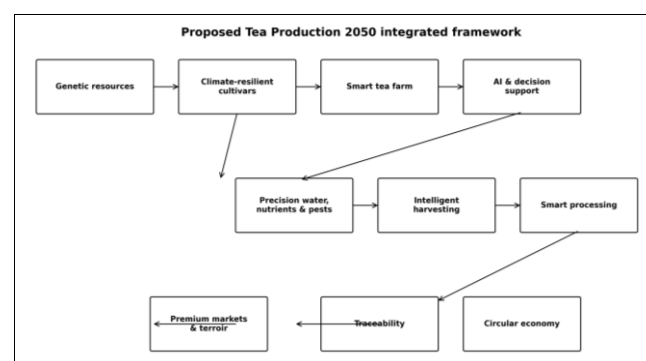


Fig 3: Proposed integrated Tea Production 2050 framework. The framework is an original synthesis linking genetic resources, climate resilience, precision production, AI, intelligent processing, traceability, circular economy and premium markets

Table 2: Priority research and technology pathways for tea production toward 2050

Research domain	Current direction	Priority toward 2050	Expected contribution
Genetic resources	Conventional germplasm evaluation	Genomics + phenomics + metabolomics + climate-response phenotyping	Climate-resilient and quality-oriented cultivars
Climate adaptation	Reactive management	Integrated genotype × environment × management strategies	Reduced yield and quality instability
Plantation management	Uniform field management	Sensors + UAV + satellite + AI	Efficient water, nutrients and crop protection
Harvesting	Manual/mechanical systems	Vision-guided automation and robotics	Lower labour burden and improved harvest precision
Processing	Experience-based control	Sensor-assisted and AI-supported process control	More consistent quality
Traceability	Batch-level records	Digital product identity and traceable supply chains	Origin verification and premium positioning
Circular economy	Limited residue utilization	Biorefinery and resource recovery	Lower waste and additional revenue
Markets	Commodity-oriented	Specialty, terroir and value-added products	Higher value per unit product
Smallholders	Limited technology access	Shared digital infrastructure and cooperative services	Inclusive modernization

6. Conclusions

Global tea production has entered a period of rapid technological and environmental transition. Production reached approximately 7.3 million tonnes in 2025, while smallholders remain responsible for approximately 60% of world output ^[1, 2, 5]. The future trajectory of the sector will be determined not only by production volume but by the capacity of tea systems to maintain productivity and quality under changing climatic and socioeconomic conditions.

Climate-resilient genetic resources, precision resource management, artificial intelligence, remote sensing, intelligent harvesting, sensor-assisted processing and digital traceability provide complementary pathways for transformation. Nevertheless, technology must be accompanied by field validation, standardized datasets, economic feasibility and mechanisms that allow smallholders to participate.

The proposed Tea Production 2050 framework integrates genetic conservation, breeding, climate adaptation, precision agriculture, AI, processing, traceability, circular economy and value-added markets. The principal research challenge is to connect these components into robust production systems that are scientifically validated, economically viable and environmentally sustainable. Such an integrated approach provides a basis for moving the global tea sector from conventional commodity production toward a resilient, intelligent and high-value agroecosystem.

7. Author Contributions

T.A.K.: Conceptualization, literature synthesis, methodology, writing—original draft preparation, and writing—review and editing.

8. Funding

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9. Data Availability Statement

No new experimental dataset was generated for this review. Statistical information and published evidence were obtained from publicly available scientific and institutional sources cited in the manuscript.

10. Conflict of Interest

The author declares no conflict of interest.

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