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Influence on soil ecology, tea yield, and quality of tea plant organic cultivation: a mini-review

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Organic tea cultivation emerges as a pivotal strategy aligning with ecological sustainability and premium agricultural demands. This mini-review summarized the effects of organic cultivation on soil microecology, including raising the pH to the optimal range of 4.5–5.5, increasing soil nutrients, and optimizing enzyme activity and microbial community, thereby increasing the functional components of fresh tea leaves. However, persistent nitrogen limitation under long-term organic planting constrains amino acid synthesis and yield. Critical research frontiers need to focus on (1) organic mineral synergistic regulation technology based on the fertilizer demand pattern of tea plants; (2) ecological network modeling of soil animal insect climate interaction; and (3) analysis of the quality formation mechanism driven by the "Rhizobiont" theory. This review provides a theoretical framework for optimizing carbon and nitrogen cycling in tea gardens and intelligent cultivation of organic tea.

KEYWORDS

tea plant, organic cultivation, soil ecology, tea quality, tea yield

1 Introduction

Organic agriculture represents a sustainable farming system that strictly prohibits synthetic inputs including chemical fertilizers, pesticides, growth regulators, and genetically modified organisms. This approach effectively addresses critical environmental challenges associated with conventional agriculture, such as soil degradation from fertilizer overuse, erosion-induced land productivity loss, and biodiversity decline caused by agrochemical contamination (Reganold and Wachter, 2016; Seufert et al., 2017). As a pivotal strategy for ecological sustainability and premium agricultural production, organic practices have witnessed global expansion. Data reveal consistent growth in both certified organic farmland and consumer demand for organic products. Major organic crops encompass annual staples (rice, oilseeds, and legumes) and perennial cultivars, with coffee, olives, nuts, and grapes (Shennan et al., 2017; Willer et al., 2024).

The organic tea sector, a critical component of sustainable agriculture, has emerged as a strategic driver for both ecological and economic transformation within the tea industry.

China's Yunnan Province exemplifies this growth, hosting 176,466.67 hectares of certified organic tea plantations (32.96% of the province) as documented in the *2023 Yunnan Tea Industry Green Development Bulletin*, which was released by the Yunnan Provincial Department of Agriculture and Rural Affairs. The adoption of organic tea cultivation demonstrates dual environmental and socioeconomic benefits by systematically replacing synthetic agrochemicals with ecologically integrated practices. Environmentally, the development of organic tea can promote the use of pollution-free production technologies such as organic fertilizer and biological control of pests and diseases in tea gardens, improve the ecological status of tea gardens, comprehensively reduce pesticide residues in tea, and promote the green and sustainable development of the tea industry (Arhin et al., 2022; Zhen et al., 2023). Economically, organic tea is increasingly favored by domestic and foreign consumers (Bu et al., 2020; Hashem et al., 2021). Vigorously developing the production of organic tea can improve tea quality and its benefits, increase market competitiveness, and promote the revitalization of rural tea areas. Such synergistic outcomes position organic tea production as a viable model for reconciling agricultural productivity with ecological resilience in perennial cropping systems.

For instance, it demonstrated that organic tea adopters in Northern Vietnam earned approximately USD 8,400 ha/year more than the farmers still practicing conventional management despite lower tea yields, due to premium pricing and reduced input costs (Le et al., 2023). Additionally, in Wuyi County, China, even though the total cost and cost–profit ratio showed no significant differences, the organic farms showed significantly higher total revenue and profit than organic conversion and conventional tea farms (Zhen et al., 2023). Therefore, this economic advantage aligns with rural revitalization goals. However, for small-scale tea growers in the early stage of organic conversion, the net profit may not fully provide for the households' livelihood. They would attain more income only by ensuring a good and stable yield after organic conversion, which requires sufficient training, technical know-how, and adequate experience (Qiao et al., 2016; Deka and Goswami, 2020; Deka and Goswami, 2021).

Now, the scientific community has increasingly prioritized multidisciplinary investigations into organic tea production systems, particularly focusing on authentication protocols, biosafety assessments, quality characteristics, and planting and processing technology of organic tea (Hajiboland, 2017; Han et al., 2018; Collins et al., 2021; Shuang et al., 2024).

Soil–plant continuum dynamics emerge as critical determinants of cultivation optimization, where rhizospheric health parameters (pH, nutrient elements, enzyme activity, microorganism, etc.) and harvest indices (fresh leaf catechins, amino acids, and caffeine ratios, yield stability coefficients) serve as dual biomarkers for evaluating management efficacy. This review synthesizes current evidence on organic cultivation impacts across three key interfaces, including soil physical properties, soil organisms, tea yield and quality in tea plantations. By critically examining these interconnected systems, this work proposes mechanistic frameworks for precision organic management, ultimately advancing evidence-based strategies for sustainable tea agroecosystems.

2 Influence on soil ecology, tea yield, and quality of tea plant organic cultivation

The formation and development of organic agriculture has always revolved around the fundamental issue of how to improve soil fertility. According to the planting regulations of organic agriculture, strict control of soil management and pest control during the production process of organic tea are two crucial links. We know that soil matrix provides water and nutrients for the growth and development of tea trees. Under different cultivation and management modes, the nutrient contents of the soil itself vary, and the absorption efficiency of tea plant for nutrients will also vary (Yin et al., 2021). Research has shown that under organic cultivation mode, tea gardens can improve soil fertility and physical and chemical properties using organic fertilizers, including green manure, livestock manure, straw, cake fertilizer, biogas fertilizer, commercial organic fertilizer, and biochar (Yi, 2021).

2.1 Influence on soil physical property of tea plant organic cultivation

2.1.1 Influence on soil pH, nutrient, and metal elements

Soil pH is one of the main factors affecting the sustainable and healthy development of the tea industry. Organic tea cultivation elevates soil pH significantly above conventional practices (though still below natural forests), with long-term management driving phased increases—initial conversion years show marked pH rise followed by stabilization, alongside expanding optimal pH 4.5–5.5 soil proportions (Wang et al., 2023a; Wang et al., 2024). It indicates that organic planting could not only overcome soil acidification but also move a step closer towards the direction of the most suitable soil pH for the growth and development of tea plants (Shen et al., 2024).

Compared with tea fields under the conventional cultivation systems, organic cultivation increased soil organic carbon (SOC) and total nitrogen (TN) contents, but decreased inorganic N and available P (AP) and K (AK) concentrations (Han et al., 2013). A hallmark of long-term organic management is the progressive nitrogen limitation, evidenced by strong isotopic coupling between soil δ15N and tea δ15N indicative of constrained N cycling (Shuang et al., 2024). At depths of 10–20 cm, in organic tea gardens of Anxi (Fujian, China), superior soil structural parameters, such as bulk density, porosity, and relative water content, emerge when compared to conventional systems. These physical enhancements coincide with enriched nutrient reservoirs, including nutrient content like soil organic matter (SOM), TN, and total phosphorus (TP) concentrations (Ping et al., 2014).

Organic amendments further enhance soil functionality through two key mechanisms: (1) promoting organo-mineral complexation via clay–organic matter interactions and (2) elevating cation exchange capacity through increased exchangeable Ca^{2+} and Mg^{2+} concentrations (Wang et al., 2024). Notably, plant-available micronutrients (Fe, Mn, Cu, and Zn) and base cations (Ca, Mg, and Na) exhibit comparable concentrations between organic and conventional cultivation systems, suggesting that organic practices maintain essential nutrient accessibility despite reduced synthetic inputs (Li et al., 2022). Additionally, the heavy metal loads and residual toxicity in soil will be reduced under organic cultivation using biofertilizer (Maitra et al., 2024).

2.1.2 Influence on soil enzyme activity

Beyond achieving balanced soil nutrient stoichiometry, organic tea cultivation systems demonstrate enhanced enzymatic functionality critical for biogeochemical cycling. Soil urease activity in organic plantations increases compared to conventional systems, with multivariate analyses revealing that edaphic factors (pH, SOM, and N-P-K levels) collectively explain 77.03% of enzymatic activity variance, significantly outweighing seasonal effects (Wang et al., 2024). Organic fertilization elevates key enzyme activities of soil invertase, protease, phosphatase, and peroxidase activities, while mitigating urease activity decline rates. These biochemical enhancements are also influenced by fertilizer types and seasonal fluctuations (Yang, 2021). For example, organic amendments like soybean meal supply active organic matter and enzymatic substrates for microbial growth and reproduction, and green manure intercrops enhance rhizodeposition diversity, fostering microbial biodiversity and metabolic quotient (Liu et al., 2018; Wang et al., 2018; Zhang et al., 2022; Wang et al., 2023). Finally, it indirectly leads to an increase in soil enzyme activity.

2.1.3 Influence on soil structure and function

Land-use conversion from forest to conventional tea cultivation induces significant soil structural degradation, including soil aggregates mean weight diameter (MWD), and geometric mean diameter (GMD). Conversely, organic planting counteracts these effects through enhanced aggregate formation and stabilization via increased organic binding agents (Wang et al., 2023b). Comparative analysis of carbon pool dynamics reveals conventional tea systems reduce critical soil organic carbon (SOC) fractions relative to native forests, including liable carbon pools: easily oxidizable organic carbon (EOC), particulate organic carbon (POC); recalcitrant carbon pools: non-liable organic carbon (NLOC), mineral-associated organic carbon (MOC); carbon stability indices: POC/SOC, NLOC/SOC and soil carbon pool management index (CPMI). Such improvements derive from sustained organic planting, enhancing organo-mineral associations and microbial carbon processing efficiency (Zheng et al., 2024).

2.1.4 Existing problems and research directions of organic cultivation on soil physicochemical properties

In summary, organic cultivation of tea plantation significantly improves the acidic soil environment and enhances aggregate stability by increasing soil pH and optimizing carbon and nitrogen pool structure (Yi, 2021; Wang et al., 2023b). However, there are still contradictions in its impact mechanism such as the spatiotemporal heterogeneity of nutrient dynamics, imbalance in the effectiveness regulation of trace elements, and functional instability driven by enzyme activity. Regarding these issues, priority should be given to develop slow-release organic fertilizers based on the phenological requirements of tea plants; establish a pH-Eh-SOM regulation model through the chelation-release law of metal trace elements in humic acid nano mineral composites; stabilize enzyme activity via constructing synthetic microbial community (SynComs) enriched with functional enzyme genes; and forecast long-term ecological effects through quantifying the evolution law of carbon pool under organic cultivation for more than 20 years.

2.2 Influence on soil organism of tea plant organic cultivation

2.2.1 Influence on soil microbial diversity and community structure

Organic cultivation exerts profound impacts on soil microbial ecology through modified nutrient inputs and habitat conditions. Cross-study syntheses demonstrate that organic fertilization regimes enhance soil microbial biodiversity and restructure community composition (Gu et al., 2019; Zhang et al., 2020; Yang et al., 2022), particularly enriching plant-growth-promoting rhizobacteria (PGPR) while reducing rhizospheric heavy metal bioavailability through microbial immobilization mechanisms (Lin et al., 2019). Fungal community analyses reveal management-specific dynamics: although α-diversity remains unaffected by cultivation practices or topography, organic systems significantly increase beneficial fungal taxa (*Aspergillus* genus) and suppress phytopathogens (such as *Pestalotiopsis* and *Pseudopestalotiopsis*), concurrently enhancing fungal network robustness (Wang et al., 2022b).

Contrasting patterns emerge in bacterial communities; its α-diversity under organic planting patterns decreased remarkably and was influenced by slope positions. Organic planting mainly changes the soil bacterial community structure, promotes bacteria carbon and nitrogen metabolism, and enriches the beneficial bacteria (Wang et al., 2022a). As a forestland being converted for tea cultivation, the α-diversity of the soil *phoD*-harboring bacterial community significantly declined, while the dominant taxa driven by TN, TK, AN, and pH are different among the forestland, conventional, and organic planting gardens (Wang et al., 2023a). With the increase of organic planting and planting years, the abundance of soil bacteria increased, while the abundance of fungi decreased first and then increased (Yan et al., 2024).

Modern organic tea gardens surpass ancient counterparts in terms of rhizospheric biodiversity, showing strong nutrient–microbe correlations that underscore the synergy between organic inputs and microbial community assembly (Yu et al., 2024).

2.2.2 Influence on diseases and insect pests

The types and quantities of pests and natural enemies in tea gardens are important components of the tea garden ecosystem. Research results showed that the species richness and diversity index of organic tea plantation are significantly higher than those of non-polluted and common tea plantations. The quantity of pests in organic plantation was obviously lower, and the frequency of major natural enemies was significantly higher than that in two other tea plantations (Gu, 2019). Survey showed that after 45% of the tea gardens in China have passed organic certification, pest infestation decreased. Among all pests, whitefly (*Aleurocanthus spiniferus*) populations serve as a keystone bioindicator of integrated pest management success. The pest infestation degree shows negative correlation with organic tea plantation area and altitude, but significantly positively correlates with tea plant disease (r^2 = 0.71) (Dylan, 2020).

2.2.3 Existing problems and research directions of organic cultivation on soil organisms and pest control

Current research reveals critical bottlenecks in soil microbiome regulation, such as bacterial diversity–functional decoupling (declining bacterial α-diversity vs. enhanced metabolic gene abundance) (Wang et al., 2022b), the driving mechanism of C/N metabolism by microbe in long-term succession being unclear, and the risk of microbial functional gene discontinuity. In addition, blind spots in the co-evolution law of pests and disease needed to be clarified (Dylan, 2020). Therefore, the following aspects need to be explored: (1) analysis of microbial functional redundancy by quantifying the spatial heterogeneity of functional gene expression in rhizosphere microbe, which can be achieved via the combination of metagenomic binning and single-cell RNA-seq technology; (2) elucidation of a microbial carbon sink coupling mechanism by analyzing the temporal patterns of bacterial/fungal communities and activated C/N component transformation; and (3) establishment of an ecological network model of pests and diseases to reveal the key nodes of resistance signal transmission.

2.3 Influence on tea quality and yield of tea plant organic cultivation

For people, the ultimate concern is the tea quality and yield under organic planting patterns. Findings demonstrated that compared to conventional tea, the water extracts of organic tea had significantly higher concentrations of catechin (C), epigallocatechin gallate (EGCG), epigallocatechin (EGC), epicatechin gallate (ECG), and epicatechin (EC). Concentrations of proline and γ-aminobutyric acid were also statistically higher in some organic tea in eastern China. However, most of the free amino acids, particularly theanine, were lower in organic tea. It may be due to potential nitrogen deficiencies in soils with less nitrogen fertilizer application (Han et al., 2018; Piyasena and Hettiarachchi, 2023).

Compared with the tea plantation under long-term fertilization trials with 50% chemical fertilizer + 50% organic fertilizer, superior quality parameters (tea polyphenols, amino acids, and caffeine) and yield were presented under full organic regimes (100% organic fertilizer) (Ye et al., 2022b). Meanwhile, in the tea plantation under sheep manure fertilizers with continuous treatments with low dosage (6 to 15 t/hm^2), the content of tea quality indicators and tea yield showed increasing trends, mainly based on the strong transformation ability of ammonium nitrogen and the high ammonium nitrogen content in the soil (Ye et al., 2022a).

Now, the key challenge lies in maintaining tea quality/yield and soil nitrogen sustainability under long-term organic cultivation. Thus, in the future, studies need to develop *Azotobacter*-enhanced organic fertilizers, identify ammonium-N mobilization biomarkers, and track N allocation pathways and their relationships with quality compound biosynthesis. Finally, precision organic cultivation hinges on decoding the following tripartite interaction: rhizosphere microbiome composition → nitrogen speciation dynamics (NH_4^+/NO_3^- ratio) → secondary metabolite networks.

3 Conclusions and outlook

Organic cultivation pays attention to environmental protection, ecological balance, and maintaining the health and safety of producers and consumers, which will become the direction of agricultural development in the future. Compared with conventional cultivation, organic cultivation can improve the soil's physical environment and microbial community structure, benefiting from increasing tea quality and yield. However, existing research on tea plant organic cultivation mostly focused on the influence on soil ecology, tea yield, and quality. The mechanism of the impact is unclear and lacks in-depth and comprehensive research. In recent years, researchers have started to pay attention to some common planting modes in organic tea cultivation. For example, research on the molecular mechanism of intercropping green-manure crops, driving the improvement of soil and tea quality, is gradually developing (Lei et al., 2022; Wang et al., 2023; Duan et al., 2024). The following are some existing issues: the mechanism of nutrients like nitrogen dynamic imbalance is unclear, microbial functional redundancy and metabolic imbalance, and the fuzzy rhizosphere interaction mechanism.

Therefore, three critical research frontiers emerge in organic tea cultivation systems, demanding urgent scientific attention to optimize ecological and agronomic outcomes:

3.1 Precision nutrient management

Chronic nitrogen limitations in organic tea plantations induce suboptimal foliar amino acid synthesis and yield depression, necessitating the development of growth-stage-specific

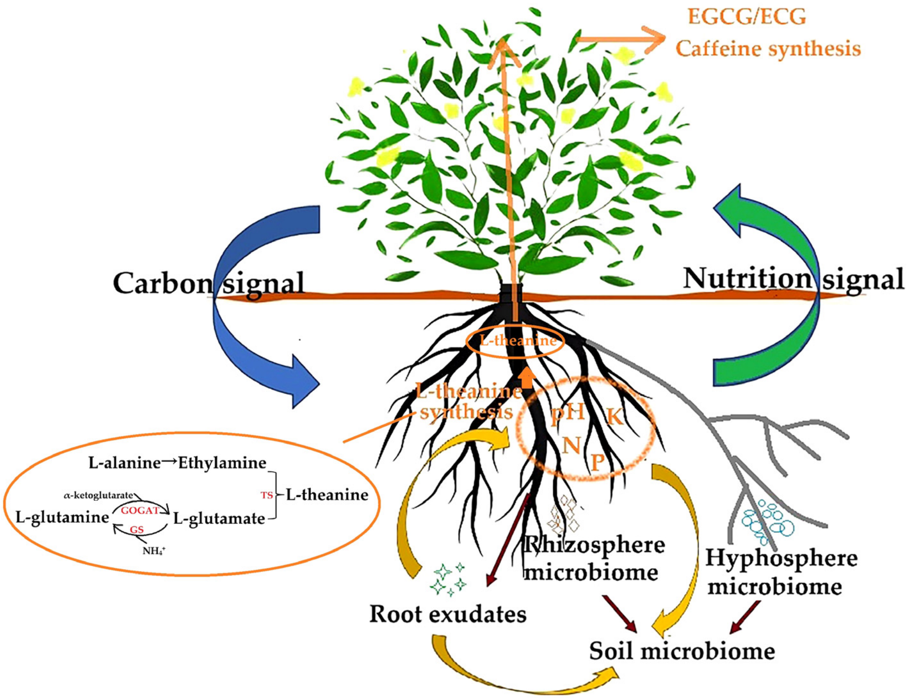

FIGURE 1
The model of the interaction among the rhizosphere ecological environment of tea plants driving the synthesis of theanine. GOGAT, glutamate synthetase; GS, glutamine synthetase; TS, theanine synthetase.

fertilization protocols. Current organic amendments fail to synchronize nutrient release with tea phenology, requiring intelligent delivery systems combining biochar-mediated slow-release and legume intercrop nitrogen fixation.

3.2 Soil fauna–environment nexus

Many studies about the influence on soil ecology, tea quality, and yield of interplanting green manure, and applying animal feces or commercial organic fertilizer have been reported (Huang et al., 2022; Lei et al., 2022; Wang et al., 2022; Duan et al., 2024). As ecological environment quality indicators for tea plantations, there are few reports on the qualitative and quantitative relationships between edaphic arthropod communities, aboveground insects, and soil environment or climate change, as well as their impact mechanisms on tea plant growth, which has application prospects.

3.3 Rhizobiont-driven quality formation

Based on the theory of "Rhizobiont," plant–root system–rhizosphere–hyphosphere–soil and its microorganisms are connected to form a "Rhizobiont" system with rhizosphere interaction as the core (Shen et al., 2021). It provides a practical and feasible solution for revealing the formation mechanism of quality components in fresh leaves of organic tea, which, as the raw material foundation of finished tea, directly affect tea processing, product quality, and economic benefits.

To operationalize the Rhizobiont theory, we may conduct research through the following aspects: (i) multi-omics profiling: integrate metagenomics (soil microbiome), metabolomics (root exudates), and transcriptomics (tea plant key metabolic genes) to map interactions within the rhizosphere–hyphosphere continuum (Figure 1); (ii) isotopic tracers: employ $^{15}N/^{13}C$ labeling to quantify nutrient flux between organic matter, microbial biomass, and tea plants; and (iii) modular field trials: compare Rhizobiont dynamics in organic vs. conventional plots using standardized metrics (e.g., microbial network complexity and enzyme stoichiometry). Then, we will identify (a) keystone microbial taxa driving nitrogen mineralization, (b) root exudate signatures that enhance stress resilience, and (c) molecular markers linking Rhizobiont functionality to theanine synthesis. Preliminary data from our team (unpublished) reveal that organic systems enrich eutrophic microorganisms in rhizosphere, which correlate with elevated L-theanine levels of tea plant.

Author contributions

ZL: Writing – original draft. QW: Formal Analysis, Writing – original draft. YM: Supervision, Writing – original draft. MZ: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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