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Driving sustainability in tea farming: insights on organo-mineral fertilizers

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Tea (*Camellia sinensis* L. O. Kuntze) is a globally important crop, yet its sustainability is threatened by nutrient depletion, acidic soils, and heavy reliance on synthetic fertilizers. Prolonged use of nitrogen-based inputs has intensified soil acidification, reduced microbial diversity, increased greenhouse gas emissions, and compromised tea quality. While organic fertilizers improve soil health, their low nutrient concentrations and slow-release limit effectiveness in intensive systems. Organo-mineral fertilizers (OMFs), which blend organic matter (compost, manure, biochar) with inorganic nutrients (N, P, K), offer a balanced solution. By combining fast- and slow-release nutrient pools, OMFs enhance soil structure, increase cation exchange capacity, improve water retention, and support beneficial microbial activity. Evidence indicates they can lower nitrogen leaching and phosphorus fixation, buffer soil acidity, and maintain consistent leaf flushing, essential for yield stability in rainfed tea systems. Field trials in Asia and Africa demonstrate superior yields, nutrient uptake, and tea quality compared to synthetic fertilizers alone. However, adoption in Africa remains limited due to knowledge gaps and policy constraints. This review highlights the potential of OMFs to transform tea cultivation into a more resilient, productive, and environmentally sustainable system.

KEYWORDS

integrated nutrient management, soil fertility, *Camellia sinensis*, organic fertilizers, tea farming, organo-mineral fertilizers, sustainability management, soil health

Introduction

Tea (*Camellia sinensis* L. O. Kuntze) is one of the world's most important commercial crops, cultivated across more than 48 countries and covering approximately 4.2 million hectares globally. Annual tea production is estimated at 6.34 million tons (1). As the second most consumed beverage worldwide after water, tea plays a vital role in the daily lives of nearly half the global population (2–5). Its economic significance extends well beyond consumption: tea contributes more than USD 17 billion annually in global production

value, and the international tea trade valued at USD 9.5 billion is a critical source of foreign exchange for low-income and emerging economies (5–7).

The leaves of the tea plant are harvested and processed into a non-alcoholic, caffeine-containing beverage known for its numerous health benefits. These benefits are largely attributed to secondary metabolites such as polyphenols, caffeine, theanine, and essential micronutrients (8–10). Based on processing techniques, teas are broadly classified into four categories: green tea (unfermented), white tea (lightly fermented), oolong tea (semi-fermented), and black tea (fully fermented). Among these, black tea dominates the global market, accounting for approximately 76–78% of total production, followed by green tea at 20–22% and oolong tea at around 2% (11). Although white tea represents a very small share, its popularity is growing due to its delicate flavor and high antioxidant content.

Global tea production is projected to expand steadily, with a compound annual growth rate (CAGR) of 5.7% from 2021 onward (7). A significant portion of this growth is driven by smallholder farmers, who produced approximately 60% of the world's tea in 2022, employing over 9 million individuals out of the 13 million people engaged in the global tea industry. The major tea-producing countries including China, India, Sri Lanka, Japan, and Kenya each report annual outputs exceeding 160,000 metric tons.

Within Africa, Kenya dominates production, yielding over 570,000 metric tons, which represents nearly 70% of the continent's total tea output, followed by Malawi, Tanzania, and Uganda (12).

In Tanzania, tea production is largely produced in plantations, although smallholder participation is gradually increasing. According to the Tea Board of Tanzania (TBT) Report (2024), tea production for the 2022/2023 season reached 26,754 metric tons (Figure 1). Of this, 16,074 metric tons (60.08%) came from estate growers, while 10,680 metric tons (39.92%) were produced by smallholder farmers. These figures indicate a notable increase in smallholder contribution, reflecting efforts to diversify production and enhance rural participation in the tea sector.

The cultivation of tea is highly nutrient-intensive due to the continuous harvesting of young leaves, which depletes vital soil nutrients. As a result, tea plants have substantial nutrient requirements, with nitrogen (N) being the most essential element, followed by potassium (K), calcium (Ca), phosphorus (P), sulfur (S), magnesium (Mg), and zinc (Zn). N is especially crucial, as it is a primary component of amino acids, proteins, and chlorophyll, making up 3.5–5% of the dry weight of tea leaves (14). To sustain growth and yield, recommended fertilizer rates typically range between 150–300 kg N ha⁻¹ yr⁻¹, 30–60 kg P₂O₅ ha⁻¹ yr⁻¹, and 120–240 kg K₂O ha⁻¹ yr⁻¹, with additional 20–40 kg S ha⁻¹ and 30–

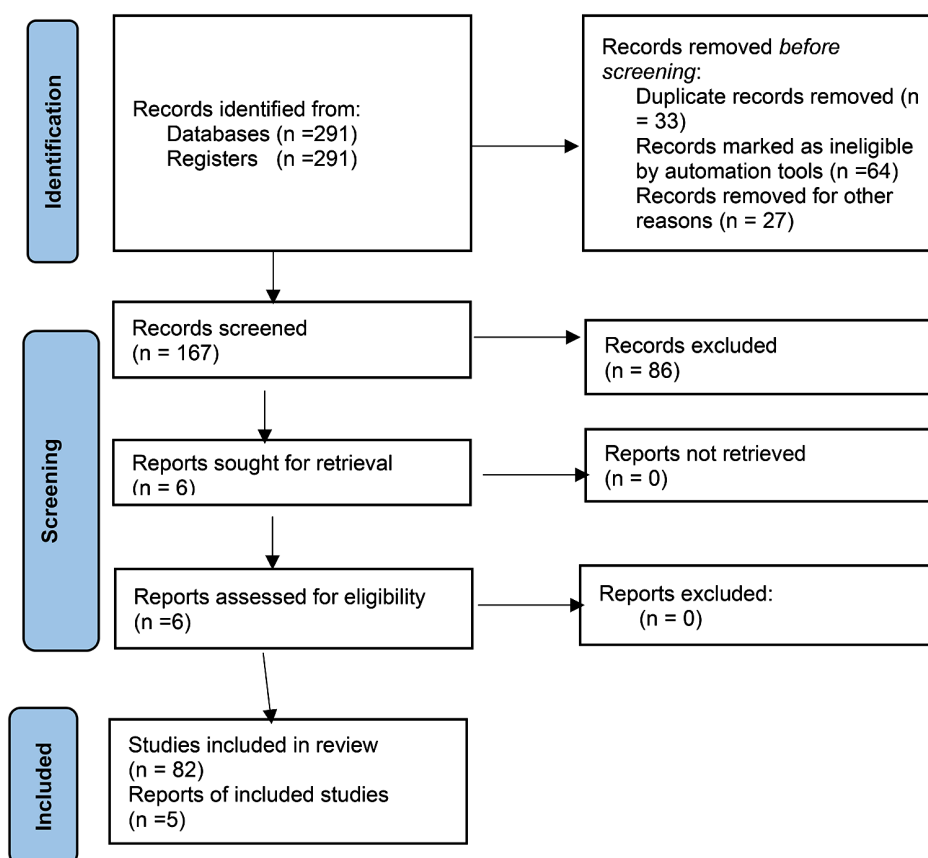


FIGURE 1
Flow chart system for assessing the eligibility of the review papers (13).

60 kg MgO ha⁻¹ to prevent deficiencies in sulfur and magnesium (15). Calcium inputs are often supplied indirectly through liming, which maintains soil pH in the optimal range (4.5–5.5) and enhances Ca availability, while micronutrient supplementation (e.g., 5–10 kg ZnSO₄ ha⁻¹ every 2–3 years) is recommended in deficient soils (14). Deficiencies in N, P, or K can lead to significant declines in chlorophyll content, photosynthetic efficiency, and resistance to abiotic stress, ultimately reducing both yield and leaf quality (16).

However, ensuring nutrient availability in tea-growing areas in Tanzania is challenging due to the acidic nature of most tea soils and high rainfall, which accelerates nutrient leaching. This acidic environment promotes P fixation, where up to 80% of applied phosphorus becomes unavailable due to reactions with Al, Mn, and Fe oxides and hydroxides (17–19). Beyond phosphorus, nitrogen (N) losses are substantial, with studies showing that in high-rainfall tea systems, only 30–50% of applied N is recovered by plants, while the rest is lost through leaching, denitrification, and volatilization (15). Similarly, potassium (K), a key nutrient for shoot growth and stress tolerance, is highly mobile in acidic, with losses often exceeding 40–60 kg K₂O ha⁻¹ yr⁻¹ due to leaching (1, 20). Calcium (Ca) and magnesium (Mg) are also vulnerable to depletion under such conditions; long-term fertilizer trials in East Africa reported that exchangeable Ca and Mg decline significantly after continuous cropping, particularly where acidic soils intensify leaching and Al³⁺ saturation (15). Sulfur (S), though supplied through rainfall deposition and fertilizers, is equally prone to leaching, with estimated losses of 15–30 kg S ha⁻¹ yr⁻¹ in tropical tea soils (21). Micronutrients such as zinc (Zn) also decline in availability under strong acidity, with tissue analysis often showing deficiencies below critical thresholds of 20–25 mg Zn kg⁻¹ leaf dry matter (22). These combined nutrient losses not only limit yield potential but also threaten long-term soil fertility, necessitating integrated management strategies such as site-specific fertilizer application, and use of organo-mineral inputs (1).

To address these challenges, organo-mineral fertilizers present a promising alternative, as they combine the benefits of both organic and inorganic fertilizers. These fertilizers supply essential macro and micronutrients while also enriching the soil with organic matter (O.M.), which helps in maintaining soil structure, microbial activity, and nutrient retention. Organic matter enhances soil water-holding capacity, improves aeration, and promotes the formation of stable soil aggregates, all of which contribute to improved plant health and productivity. Additionally, increased organic matter supports beneficial microbial communities that facilitate nutrient cycling and disease suppression, leading to healthier tea plants with improved resistance to environmental stressors.

Although the initial adoption of organo-mineral fertilizers may require higher investment costs, their long-term benefits often outweigh these expenses by enhancing soil fertility and supporting more consistent, higher yields (23). Sustainable tea cultivation practices that integrate organic matter not only reduce dependence on synthetic fertilizers but also lower production costs over time and strengthen resilience to climate variability. Consequently, incorporating organo-mineral fertilizers into tea farming systems

represents a viable pathway toward sustainable agriculture, delivering both environmental and economic advantages for growers. The purpose of this review is to critically examine the role and effectiveness of organo-mineral fertilizers in improving soil fertility, nutrient uptake, and sustainable yield in tea cultivation. Particular emphasis is placed on addressing nutrient limitations and soil degradation challenges prevalent in acidic, leaching-prone environments such as the Tanzanian highlands. By synthesizing current research findings, identifying existing knowledge gaps, and offering evidence-based recommendations, this review seeks to support the integration of organo-mineral fertilizers into sustainable tea farming practices.

Methodology adopted for the review

This review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, which, as outlined by Page et al. (13), offers a structured methodology to enhance scientific rigor, transparency, and reproducibility in systematic reviews. A modified PRISMA flow diagram was employed to guide and document the review process, ensuring methodological clarity and improved reporting standards, particularly for comprehensive literature reviews and meta-analyses.

The review process followed a structured three-stage approach: identification, screening, and inclusion, as illustrated in Figure 1. Comprehensive literature searches were conducted across seven major academic databases Science Direct, Google Scholar, Web of Science, Scopus, AGRIS, African Journals Online (AJOL), and SpringerLink to collect relevant peer-reviewed publications. In cases where published studies were limited, pertinent unpublished reports were also incorporated. To enhance the precision of the search and reduce irrelevant entries, carefully selected keywords were used, including: integrated nutrient management, soil fertility, *Camellia sinensis*, organic fertilizers, agroecological practices, tea farming, organo-mineral fertilizers, sustainability management, and soil health.

An initial pool of 291 journal articles and 3 technical reports was identified. After the removal of 124 duplicates, 167 records remained for screening based on their titles, abstracts, and full texts. A total of 86 articles were excluded for not aligning with the review's objectives, while an additional 13 were removed due to limited relevance. All three technical reports met the eligibility criteria. In the end, 82 journal articles and 5 technical reports were retained for detailed analysis and synthesis, focusing on the role of organo-mineral and synthetic fertilizers in tea plantations and their effects on soil health. The entire review process is summarized in Figure 1, following the PRISMA framework (13).

The review focused on publications from 2002 to 2025. A notable rise in the number of publications is observed from 2020 onwards, with peaks in 2022 and 2024, (Figure 2) indicated increased academic interest in topics related to tea cultivation, organo-mineral fertilizers, and sustainable soil management. Each bar represents the number of references published in a specific year, with values clearly labeled. The trend highlights a shift

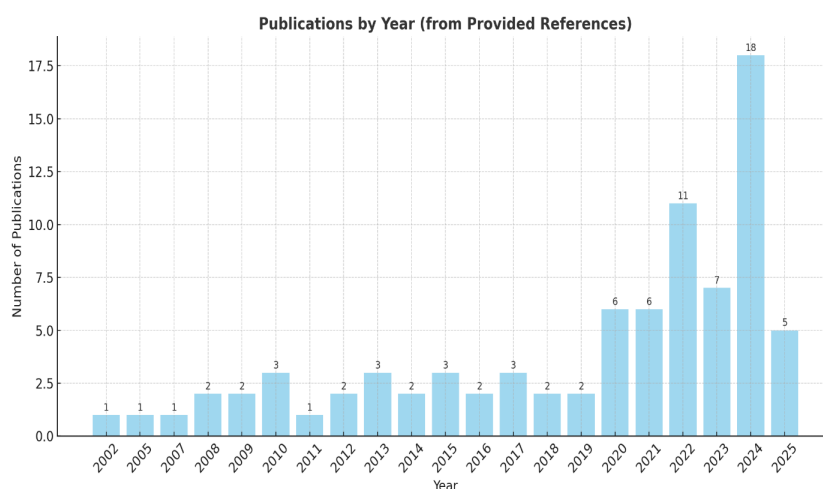


FIGURE 2

Temporal distribution of publications on organo-mineral fertilizers from 2000 to 2025.

toward more recent literature, reflecting the dynamic and evolving nature of research in sustainable agriculture and tea production systems.

Results and discussion

Nutrient demands and environmental impacts of synthetic fertilizer use in tea cultivation

Generally, the tea plant needs 16 nutrient elements for optimal growth and productivity; however, nitrogen (N), phosphorus (P), and potassium (K) are required in larger quantities to sustain production (24). The primary source of these nutrients is synthetic fertilizers, especially those high in nitrogen. According to the Institute of Himalayan Bioresource Technology in India, the cultivation of 1000 kg of dry weight tea leaves extracts between 40–50 kg of N, 4–8.5 kg of P, and 16–19 kg of K, while stems and old leaves contain approximately 50 kg of N, 12 kg of P, and 32 kg of K. However, the excessive use of synthetic fertilizers in conventional tea plantations leads to multiple forms of soil degradation that directly impact tea yield and quality. Firstly, it disrupts the natural nutrient balance, causing nutrient leaching and physical deterioration of soil structure resulting in compacted, less porous soil with poor water and air retention. Secondly, it reduces microbial diversity by favoring the overgrowth of certain species while suppressing beneficial ones like nitrogen-fixing bacteria and mycorrhizal fungi, thereby weakening nutrient cycling and plant resilience. Thirdly, it diminishes soil organic matter (SOM) as farmers reduce organic inputs, and nitrogen driven microbial activity accelerates SOM decomposition, reducing fertility, water retention, and root development. Lastly, it causes soil acidification through the oxidation of ammonium-based fertilizers, which release hydrogen ions and lower soil pH, leading to nutrient imbalances

and aluminum toxicity both harmful to root systems and overall plant health. Together, these changes degrade soil function, reduce nutrient availability, and ultimately diminish both the yield and quality of tea (23). Table 1 illustrates the environmental impacts associated with the frequent use of chemical fertilizers tea cultivation, particularly nitrogen-rich fertilizers, in tea plantations. However synthetic fertilizers are widely used for cultivating various crops and play a crucial role in plant growth. Their significance lies in providing a consistent supply of precise nutrients to the soil. Unlike organic fertilizers, which require decomposition before plants can absorb them, synthetic fertilizers act immediately (35). This rapid effectiveness is particularly advantageous for plants that are severely nutrient-deficient or struggling to survive.

In summary, Figure 3 illustrates the environmental impacts associated with the prolonged use of synthetic fertilizers in tea cultivation, capturing all key issues outlined in Table 1.

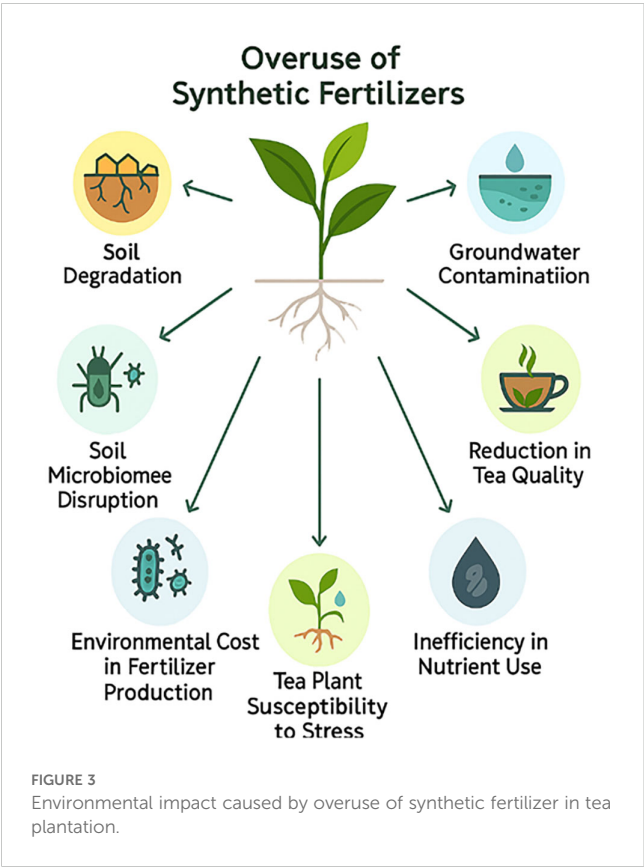
At the center is the tea plant, with arrows pointing to various adverse effects resulting from excessive fertilizer application.

These include soil degradation and disruption of the soil microbiome, both of which gradually undermine soil health. The diagram also highlights broader environmental concerns such as groundwater contamination and the significant carbon footprint linked to fertilize production. Additionally, overuse of fertilizers increases the tea plant's susceptibility to stress, leads to reduced tea quality, and causes inefficient nutrient utilization.

The excessive use of synthetic fertilizers in modern agriculture has led to significant environmental and health concerns, including soil degradation, water eutrophication, and increased greenhouse gas emissions. In response, global attention has increasingly shifted toward organic fertilizers as a more sustainable alternative (36). Organic fertilizers, derived from compost, manure, or plant residues, offer long-term soil fertility improvement and reduced ecological footprints. However, the exclusive use of organic fertilizers poses certain agronomic challenges. A key limitation is the delayed release of nutrients, which fails to meet the immediate

TABLE 1 The environmental impacts of synthetic fertilizer use in tea cultivation.

Authors	Findings	Location of study
Yang et al. (25); Qiao et al. (26); Siwik-Ziomek and Figas (27)	Prolonged use of nitrogen-based chemical fertilizers leads to soil acidification, depletion of exchangeable cations, nutrient inaccessibility, and reliance on additional applications, contributing to environmental degradation.	China (tea-growing regions); Kenya (Kericho tea estates); Sri Lanka
Mardekheh et al. (28)	Nitrate leaching from synthetic fertilizers used in tea fields threatens groundwater quality.	Iran (northern tea plantations)
Lui et al. (29)	Intensive synthetic fertilizer application reduced earthworm diversity and abundance in tea agroecosystems.	China (Zhejiang tea fields)
Deng et al. (30)	In tea cultivation, 4.8–6.4% of nitrogen applied as synthetic fertilizers is converted into nitrous oxide (N ₂ O), further increasing greenhouse gas emissions.	China (Hunan tea plantations)
Hazarika et al. (31)	Excess nitrogen from synthetic fertilizers caused poor secondary metabolite accumulation, reducing tea aroma and flavor.	India (Assam tea gardens)
Miao et al. (32)	High synthetic fertilizer disrupted microbial balance essential for sustainable soil health in tea plantations.	China (Anhui province plantations)
Dekamin et al. (33)	High-energy synthetic fertilizer production contributes indirectly to climate emissions from tea farms.	Bangladesh (Tea estates in Sylhet)
Mokaya (34)	Fertilizer nitrogen losses contributed to greenhouse gas emissions and water eutrophication risk.	Kenya (Nandi tea region)



nutrient demands of fast-growing crops. Moreover, organic materials typically have lower concentrations of essential macronutrients such as N, P, and K when compared to synthetic counterparts, thus requiring large volumes to satisfy crop nutrient

requirements. This volumetric inefficiency results in significant logistical constraints. According to Agyemang et al. (37), the high quantities required for effective application led to increased labor intensity and elevated transportation costs, especially in rural or peri-urban agricultural zones. Additionally, improper treatment of organic fertilizers, particularly animal manures and household composts, may introduce pathogenic microorganisms into agricultural fields, posing risks to both crop health and food safety (38). These limitations highlight the need for integrated nutrient management strategies, which combine the immediate availability of synthetic nutrients with the long-term soil health benefits of organics, to optimize productivity and sustainability.

Sustainable activities in tea cultivation

Selection of suitable clones or varieties

Tea productivity and resilience are strongly influenced by the choice of clones or cultivars. Breeding programs in East Africa and Asia have released several high-yielding and drought-tolerant clones. For example, TRFK 6/8, TRFK 31/8, and TRFK 201/6 (developed by the Tea Research Foundation of Kenya) are known for high yields and tolerance to drought stress (39, 40). Selecting site-specific varieties with tolerance to abiotic stress and resistance to pests and diseases ensures sustained productivity under changing climatic conditions.

Agronomic practices in tea cultivation

Good agronomic practices are central to sustainable tea production. Mulching with pruned tea leaves, grasses, or organic residues conserves soil moisture, reduces weed growth, and improves organic matter content (41). Contour planting and

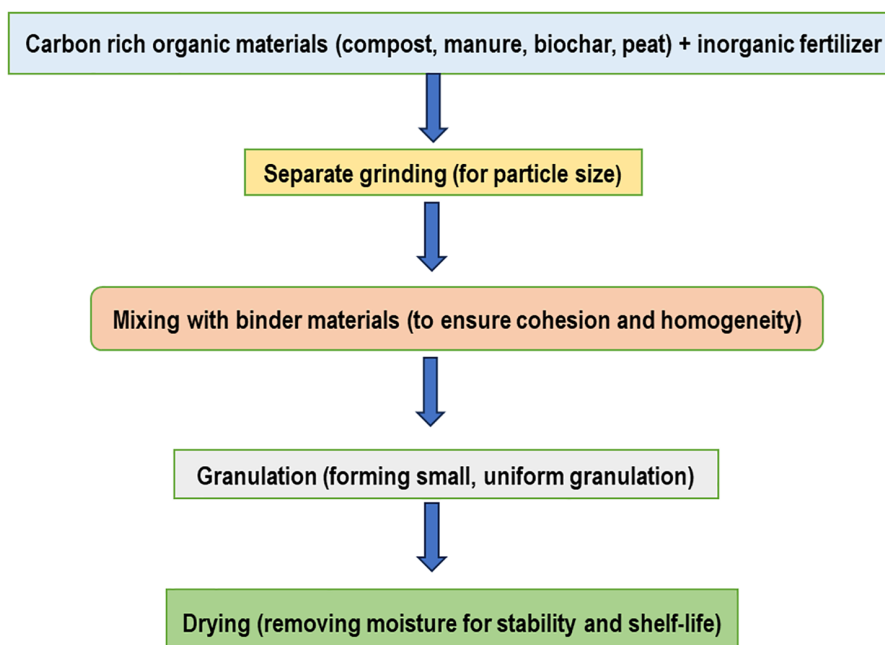


FIGURE 4
Flow chart of Organo-mineral fertilizer preparation.

terracing are used in hilly landscapes to prevent soil erosion, while shade trees and agroforestry systems improve microclimates, enhance biodiversity, and contribute to carbon sequestration (42). Regular pruning cycles improve leaf flush and facilitate harvesting. Climate-smart practices such as rainwater harvesting and drip irrigation enhance water-use efficiency, particularly in drought-prone areas (43).

Pest and disease management

Tea cultivation faces challenges from pests like the tea mosquito bug (*Helopeltis theivora*) and mites, as well as fungal diseases such as blister blight (*Exobasidium vexans*). Integrated Pest Management (IPM) strategies combine biological, cultural, and chemical controls to minimize yield losses. These include the use of biocontrol agents such as *Beauveria bassiana* and *Trichoderma* spp., maintaining shade diversity to reduce pest incidence, and adopting resistant clones (39). Minimizing pesticide use through monitoring and threshold-based applications helps protect beneficial insects and reduce chemical residues in tea products.

Water and climate-smart management

Tea is highly sensitive to rainfall variability. Sustainable water practices such as drip irrigation, rainwater harvesting ponds, and efficient drainage systems help buffer against both drought and flooding (43). Climate-smart measures include integrating shade trees (e.g., *Albizia* spp., *Grevillea robusta*) for microclimate regulation and soil fertility enhancement, while using localized climate data for adaptive agronomic planning (42).

Socio-economic and processing considerations

Sustainability in tea is not only biophysical but also socio-economic. Strengthening farmer cooperatives and fair-trade certification schemes improves income stability and market access (44). Empowering women and smallholders through training on good agricultural practices (GAPs) builds capacity for long-term sustainability (7). Environmentally friendly processing practices such as renewable energy adoption, waste recycling, and eco-friendly packaging further reduce the carbon footprint of tea production.

Organo-mineral fertilizers and their role in sustainable tea cultivation

Tea (*Camellia sinensis*) is predominantly cultivated on acidic, highly weathered soils (Ultisols, Acrisols, and Oxisols), which are naturally low in available phosphorus (P), nitrogen (N), and exchangeable bases (Ca, Mg, K) due to heavy leaching under high rainfall (15, 16). Traditional fertilization with synthetic inputs such as urea, ammonium sulfate, single superphosphate (SSP), and muriate of potash (MOP) has supported yield increases but often at the expense of soil acidification, nutrient imbalances, and reduced microbial activity (20). OMFs formulations combining organic amendments with mineral nutrients (Table 2) offer an integrated solution to these challenges in tea production.

Field trials in tea plantations have demonstrated that OMFs can provide comparable or superior yields compared to purely synthetic

TABLE 2 Types organic materials used for organo-mineral fertilizers formulations.

Organic material type	Examples	Key nutrients	Typical application doses	Application benefits	References
Animal-based	Cow manure, poultry litter, pig manure	N, P, organic C	Cow manure: 5–15 t/ha/yr Poultry manure: 2–5 t/ha/yr Pig manure: 5–10 t/ha/yr	Quick-release nitrogen; enhances microbial life; increases yield and soil fertility	Fachini et al. (45); Bhattacharyya et al. (46); Gichangi et al. (47)
Plant-based	Green manure (e.g., sunn hemp), crop residues, compost	Organic C, micronutrients	Green manure: 4–8 t/ha (fresh biomass) Compost: 5–10 t/ha/yr Mulched residues: 2–4 t/ha/season	Improves soil structure; enhances CEC and moisture retention; supports long-term fertility	Liu et al. (9); Li et al. (20); Murphy (48)
Urban/Industrial	Biosolids, food waste compost, paper sludge	N, P, micronutrients	Biosolids: 2–6 t/ha/yr (dry weight, treated) Food waste compost: 5–8 t/ha/yr Paper sludge: 3–6 t/ha/yr	Promotes waste recycling; supplies balanced nutrients when treated; improves soil organic matter.	Sakrabani et al. (49); Miao et al. (32); Srinivasrao et al. (50)
Mixed-source	Combinations of animal, plant, and urban wastes (e.g., manure + compost + biosolids)	Balanced NPK, organic C	Typically, 5–12 t/ha/yr, adjusted by formulation and soil tests	Customizable formulations; improves both short- and long-term nutrient availability; reduces dependency on synthetic fertilizers	Li et al. (20); Fachini et al. (45); Uddin et al. (51)

TABLE 3 Impact types posed by organo-mineral fertilizer.

Impact type	Specific effects of OMFs	Mechanism/Description	OMF volume & % improvement	References
Physical	Improved soil structure & aggregate stability	Organic matter in OMFs binds particles into stable aggregates, improving resistance to erosion	10–15 t ha ⁻¹ yr ⁻¹ manure – Aggregate stability increases 25–35%	Bhattacharyya et al. (46); Dexter et al. (67); David and Marghitas (68)
	Reduced soil bulk density	Organic colloids reduce compaction, improving porosity & root penetration	5–10 t ha ⁻¹ yr ⁻¹ compost – Bulk density decreases 10–18%	Atere (69)
	Increased water retention & infiltration	OMFs enhance porosity & field capacity (available water content)	8–12 t ha ⁻¹ yr ⁻¹ compost – Field capacity increase 20–30%; – Available water content increase 15–25%	Atere (69); Saha et al. (70); Ventura et al. (71)
	Enhanced aeration & hydraulic conductivity	Micro-/macro-pores improve oxygen diffusion & infiltration	10 t ha ⁻¹ yr ⁻¹ mixed OMF – Hydraulic conductivity increase 22%	Murphy (48); Naliukhin et al. (72)
Biological	Increased microbial biomass & activity	Organic substrates fuel microbial growth & enzyme activity	10 t ha ⁻¹ yr ⁻¹ manure – Microbial biomass increases 40–55%	Yang et al. (73); Miao et al. (32)
	Promotion of nutrient-cycling microbes	Stimulates N-fixers, P-solubilizers, decomposers	6–10 t ha ⁻¹ yr ⁻¹ OMF – Enzyme activity increase 30–45%	Yang et al. (25); Ipinmoroti et al. (74)
Chemical	Improved nutrient retention & reduced leaching	OMFs slow nutrient release; reduce nitrate leaching	8–12 t ha ⁻¹ yr ⁻¹ manure + compost NO ₃ ⁻ leaching decrease 59–65%	Saha et al. (70); Saha et al. (75); Pereira et al. (76); Shi et al. (77)
	Enhanced availability of N, P, K	Balanced fast- and slow-release nutrient pools	10 t ha ⁻¹ yr ⁻¹ poultry manure – N availability increase 20–28%; P increase 15–20%	Ipinmoroti et al. (74); Hakimi et al. (78)
	Buffering of soil acidity	OMFs (esp. with biochar) increase pH, reduce Al toxicity	8–10 t ha ⁻¹ yr ⁻¹ manure + biochar – Soil pH increase 0.5–1.2 units	Ipinmoroti et al. (74); Oshunsanya (79)
	Improved phosphorus efficiency in acidic soils	Biochar + phosphate fertilizers reduce fixation	5–8 t ha ⁻¹ yr ⁻¹ biochar mix – P-use efficiency increase 18–30%	Pogorzelski et al. (80); Wu et al. (81)

fertilizers while improving soil quality. For instance, in acidic tea soils of Kenya, the application of OMFs prepared with cattle manure and fortified with NPK at rates supplying 150 kg N, 30 kg P₂O₅, and 120 kg K₂O ha⁻¹ yr⁻¹ significantly improved leaf yields by 12–18% compared with synthetic NPK fertilizers alone (47). Similarly, studies in China showed that combining composted pig manure with SSP and MOP at 200 kg N ha⁻¹ yr⁻¹ not only enhanced green leaf yield but also increased leaf nitrogen and polyphenol contents, contributing to higher tea quality (9).

Importantly, OMFs help mitigate soil acidity one of the key constraints in tea-growing soils by supplying base cations (Ca²⁺ and Mg²⁺) from manure or compost. For example, replacing 25–50% of mineral NPK with organo-mineral formulations increased soil pH from 4.5 to 4.9 and raised exchangeable Ca and Mg levels by 10–15% within two years in Indian tea soils (46). These shifts reduce Al³⁺ toxicity and improve nutrient uptake efficiency, particularly for P and K.

Organo-mineral fertilizers and their influence on soil health and reaction

Chemical fertilizers are widely applied in tea plantations to enhance crop productivity; however, their extensive and long-term use poses significant threats to soil health, the soil environment, and associated ecological components (50, 52). In addition to these environmental concerns, the rising global cost of chemical fertilizers over the past decades has further challenged their sustained use (50).

One promising approach to maintaining sustainable tea production is the development and application of organo-mineral fertilizers (OMFs), which combine chemical fertilizers with organic inputs such as animal manures and crop residues (50, 53, 54). OMFs are manufactured by blending organic feedstocks (e.g., biosolids, livestock manure, crop residues, and food waste) with reduced quantities of mineral fertilizers (Figure 4). This integration not only supplies essential nutrients but also improves soil organic matter content and overall soil quality (50, 54).

The rationale behind OMF production lies in merging the slow-release characteristics of organic inputs with the immediate nutrient availability of mineral fertilizers, thereby reducing dependence on synthetic fertilizers. While the concept is relatively new, early applications have demonstrated promising results, particularly where biosolids have been used as a primary feedstock (55–58). Furthermore, innovative OMF formulations incorporating carbon capture technologies have produced fertilizers with crop yields comparable to conventional mineral fertilizers (59–62).

Beyond crop productivity, the recycling of organic wastes into OMFs contributes to a circular economy by offering a sustainable nutrient source while simultaneously enhancing soil organic matter. Thus, OMF technology represents a dual-benefit strategy: supporting crop nutrition and advancing soil restoration in tea-growing systems (50, 54).

Similarly, the production of organo-mineral fertilizers (OMFs) is influenced not only by chemical formulation but also by the

characteristics of the organic feedstock. Various processing techniques such as thermal conversion, anaerobic digestion, and solid-state fermentation can be employed depending on the nature of the input materials (53). The co-processing of mineral and organic components, rather than their separate application, is justified by the enhanced functional properties of the final product. These include improved nutrient bioavailability, increased chemical reactivity, and controlled-release characteristics, which collectively reduce the frequency and labor associated with multiple split applications of fast-release fertilizers (63). Moreover, OMFs have been shown to exert multiple agronomic benefits by improving soil physicochemical and biological properties, enhancing microbial activity, and positively influencing plant physiological responses, thereby contributing to more resilient and productive agroecosystems (55).

Literature (53, 64) shows that OMF requires trials (both long and short terms) to examine the persistence and evolution of OMF and its ingredients after successive crop cycles and cultural rotation, their effect on plants' agro-physiological traits and soil properties (aggregation, pH, enzymes, microbial diversity, population, and activities). Research works focusing on the bio-stimulant properties of OMF are obligatory. Research should also specifically examine the effect of OMF on root architecture and development and their effects on plant physiological features, as the effect of such products on plant tolerance to biotic and abiotic stresses, needs to be explained through targeted studies (53, 65, 66). Furthermore, OMFs have been indicated to positively affect soil biology, biochemistry, and nutrient cycling (Table 3); therefore, making plants resistant to drought and salinity (53). Therefore, new organo-mineral products in the market would be necessary to have research testimonies of their eloquent performance not only to increase crop yields but also for the improvement of different soil parameters.

Future focus on organo-mineral fertilizers

Future research should place greater emphasis on evaluating the long-term agronomic, environmental, and physiological impacts of organo-mineral fertilizers (OMFs) in tea cultivation, especially across a range of agroecological zones. Although current findings underscore the benefits of OMFs in improving soil structure, nutrient retention, and microbial health, there is a clear need for deeper, multi-seasonal investigations. These should assess the persistence and transformation of OMF components through successive cropping cycles, focusing on their effects on soil structure stability, organic carbon dynamics, pH regulation, and microbial diversity, particularly under varying climatic and edaphic conditions. Moreover, understanding the bio-stimulant effects of diverse organic feedstocks used in OMFs is essential. Research must delve into how these feedstocks influence plant physiological attributes such as root development, drought tolerance, nutrient uptake efficiency, and resilience to biotic and abiotic stresses, which are critical for sustainable tea production.

To ensure practical relevance, future studies should aim to develop standardized OMF formulations that are tailored to specific soil types, crop growth stages, and climatic conditions common in

tea-growing regions. These formulations must be evaluated for both agronomic performance and environmental safety, including their impact on soil and water systems. In addition, life-cycle assessments (LCAs) and carbon footprint analyses are necessary to quantify the climate mitigation potential of OMFs compared to conventional synthetic fertilizers, especially in relation to greenhouse gas emissions and energy use during production and application. Technological advancements should also be explored, such as the integration of biochar, nanomaterials, and carbon capture-enhanced inputs, which could significantly boost nutrient-use efficiency and reduce losses through leaching and volatilization.

Conclusion

Adopting the use of organo-mineral fertilizers (OMFs) in tea farming is an important step toward maintaining tea farming stability. Combining organic matter with essential minerals will improve soil health, crop yields, and environmental impacts. These fertilizers improve soil structure, and moisture retention, add nutrient availability, and simultaneously support the development of beneficial soil microbial communities. Their application tackles critical nutrient deficiencies especially in N, P, and K which are largely needed by tea plants and also contributes significantly to the mitigation of greenhouse gas emissions, making them an eco-friendly alternative to traditional chemical fertilizers.

Due to the global significance of tea as a cash crop and there is need for sustainable farming practices, integrating OMFs into tea cultivation gives an effective strategy for long-term productivity and environmental insurance. By optimizing nutrient use, enhancing soil properties, and reducing emissions, OMFs not only sustain tea production but also contribute to a healthier ecosystem.

However the use of OMFs in tea practices still very low especially in Africa where tea crop is grown including Tanzania, therefore strategies like encouraging the integration of OMFs into fertilization practices to improve soil fertility and crop productivity, training programs for tea farmers on the benefits and application methods of OMFs, research and development efforts to create OMF formulations optimized for tea cultivation, Promote the recycling of organic waste for OMF production to align agricultural practices with waste management strategies and Increase consumer awareness and farmers to adopt environmentally friendly practices.

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