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Research Article

Comparative effect of different systems of farming on soil properties and productivity of tea in South India

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Abstract

Tea, one of the world's most widely consumed beverages, has undergone significant cultural and economic transformation over the past century, driven by increasing consumer demand for sustainable and high-quality production systems. Contemporary tea cultivation is primarily practiced under three farming systems: conventional, organic, and biodynamic. Unlike conventional and organic farming, biodynamic agriculture (BDA) adopts a holistic approach that integrates ecological processes and biological inputs to enhance soil fertility and crop productivity. This study compared conventional, organic, and biodynamic tea farming systems with respect to crop yield, soil physicochemical properties, and soil fertility, with particular emphasis on beneficial soil microflora. A long-term field experiment was conducted in the High Range region of Kerala, India, where each experimental block consisted of approximately 500 tea bushes. Yield was recorded during each plucking round, and soil samples were collected periodically for nutrient and microbial analyses. Results from the 20-year agronomic study showed that conventional farming produced the highest yield, recording a 33.8% increase over organic cultivation, while biodynamic farming achieved an 18.8% higher yield than the organic system. In contrast, organic and biodynamic systems supported significantly greater populations of beneficial soil microorganisms, largely due to the absence of synthetic chemical inputs. Enhanced microbial activity was associated with improved soil fertility and long-term soil health. Overall, the findings indicate that although conventional farming maximizes yield, biodynamic and organic systems promote a healthier soil ecosystem, with biodynamic farming providing a favorable balance between productivity and ecological sustainability.

Keywords: Tea Farming, Conventional, Organic, Biodynamic farming, Soil fertility

Introduction

India is one of the world's largest producers and consumers of tea, with major production regions located in Assam, West Bengal, and the southern hill tracts, including the Nilgiris and the High Ranges of Kerala and Tamil Nadu. Behind every cup of tea lies a complex production process that begins in the tea plantations. Tea is cultivated under different farming systems, each influencing productivity, quality, and environmental sustainability. Over the past few decades, organic tea production has gained considerable attention due to its perceived environmental and human health benefits, despite generally lower yields than conventional systems. Recent research has shown that organic farming systems produce tea with higher concentrations of catechins and improve soil organic carbon and microbial biomass (Han *et al.,* 2013). In contrast, conventional systems often produce higher levels of quality-related compounds such as theaflavins and thearubigins while achieving greater yields through intensive fertilizer application (Ranasinghe *et al.,* 2005). Understanding these differences is essential for developing sustainable tea production strategies that balance yield, quality, environmental stewardship, and economic viability in an increasingly quality-conscious global market.

Organic tea cultivation emphasizes the conservation of natural ecosystems and habitats by minimizing soil and water pollution while maintaining sustainable production. Biodynamic agriculture, an advanced form of organic farming, has been reported to improve soil quality compared with conventional farming systems (Reganold, 1995). However, a study conducted in tea estates of Assam found that biodynamic practices exhibited lower nutrient-use efficiency than other organic management approaches (Chatterjee *et al.,* 2014). Despite the ecological advantages associated with biodynamic farming, conventional and organic systems continue to be the predominant cultivation practices adopted by tea growers. Therefore, the present study was undertaken to evaluate the long-term effects of conventional, organic, and biodynamic farming systems on soil fertility, microbial diversity, and tea yield. A field experiment initiated in the High Range region of Kerala, India, was monitored over a period of two decades to assess changes in soil health and crop productivity under the different farming systems. The findings of this study provide valuable insights into the long-term sustainability and productivity of alternative tea farming practices in South India.

Materials and methods

Experimental site

The field study was conducted at a tea estate in the High Range region of Idukki District, Kerala, India, located at an altitude of 1,452 m above mean sea level (MSL) (10.0699° N, 77.0878° E). The region receives an average annual rainfall of approximately 450 cm and experiences both the southwest and northeast monsoons.

Field experiment

A long-term, non-replicated field trial was established in 2002 in a seedling tea plantation with a spacing of 1.2 × 1.2 m. Each treatment block consisted of approximately 500 tea bushes, separated by adequate guard rows to minimize treatment interference. The experimental treatments were as follows:

i) Conventional farming: The conventional farming system followed the recommendations of the United Planters' Association of Southern India (UPASI) for the application of fertilizers, foliar micronutrients, pesticides, fungicides, and herbicides. Fertilizers were applied to the experimental plots in four equal splits annually.

ii) Biodynamic farming: The biodynamic system followed the recommendations of the Bio Dynamic Association of India (BDAI), including the use of biodynamic preparations and the biodynamic calendar. The plots received compost at 10 t ha^{-1}. Biodynamic preparations BD 500, BD 501, and Cow Pat Pit (CPP) manure were applied monthly during April, May, and September to November at a rate of 5 kg ha^{-1} in 100 L of water per hectare.

iii) Organic farming: The organic system involved the use of organic inputs approved by the International Federation of Organic Agriculture Movements (IFOAM), including compost (10 t ha^{-1}), organic fungicides, and micronutrients. During severe infestations of red spider mite, paraffinic oil (1.5 mL ha^{-1}), lime sulphur (1:40 dilution), wettable sulphur (1 kg ha^{-1}), and Neem Kernel Aqueous Extract (NKAE) at 5% were applied. Common fungal diseases were managed using copper oxychloride at 420 g ha^{-1}.

All treatments were applied according to the recommended schedules. Weed management in the organic and biodynamic plots was carried out manually through hand weeding.

Soil analysis

Soil samples were collected from both the pre-treatment (2002) and post-treatment (2022) periods, 90 days after fertilizer application and following a minimum cumulative rainfall of 15 cm. All analyses were performed using air-dried soil samples. For pH determination, 30 g of soil sieved through a 2 mm mesh was mixed with distilled water, and pH was measured using a pH meter (Schofield & Taylor, 1955). Electrical conductivity (EC) was determined using a 1:2 soil-to-water suspension (Mason & Obenshain, 1939). Organic matter (OM) was estimated using the Walkley and Black method (Walkley & Black, 1934). Exchangeable potassium was determined according to Hanway and Heidal (1952), available phosphorus by the Bray and Kurtz method (Bray & Kurtz, 1945), and exchangeable calcium and magnesium following the procedure described by Heald (1965).

Enumeration of beneficial soil microflora

Soil samples were collected annually from 2002 to 2022 for the enumeration of beneficial microorganisms. The microbial groups quantified included total bacteria, total fungi, actinomycetes, *Azospirillum*, phosphate-solubilizing bacteria (PSB), potassium-solubilizing bacteria (KSB), *Trichoderma*, and *Pseudomonas*. Nutrient agar was used for total bacteria (Gordon *et al.,* 1973), Rose Bengal agar for fungi (Martin, 1950), starch casein agar for actinomycetes (Küster & Williams, 1964), N-free malic acid medium for *Azospirillum* (Day & Dobereiner, 1976), Pikovskaya's medium for PSB (Pikovskaya, 1948), Aleksandrov medium for KSB, Trichoderma Selective Medium (TSM) for *Trichoderma*, and King's B medium for *Pseudomonas* (King *et al.,* 1954).

For microbial enumeration, 10 g of soil was suspended in 100 mL of sterile distilled water to obtain a 10^{-1} dilution. The suspension was vortexed for 5 min to ensure uniform dispersion of microorganisms and serially diluted up to 10^{-7}. Aliquots (1 mL) from dilutions ranging from 10^{-4} to 10^{-7} were transferred to sterile Petri dishes, followed by the addition of approximately 15 mL of the appropriate culture medium cooled to 45 °C. The inoculum was mixed gently, and the plates were incubated in an inverted position at 30 °C for 2-7 days. Phosphate-solubilizing bacterial colonies were identified by the formation of clear halos around the colonies. Colony counts were expressed as colony-forming units (CFU) per gram of dry rhizosphere soil.

Yield analysis

Tea yield was estimated as made tea (kg ha^{-1}) from harvested green leaf using the following equation:

$$Made\,tea\ yield\left(kg\ ha^{-1}\right) = \frac{Green\,leaf\ yield\left(kg\right)\times 6{,}800\times 0.225}{Number\ of\ bushes\ in\ the\ plot}$$

where 6,800 represents the standard bush population per hectare, and 0.225 is the conversion coefficient corresponding to a 22.5% recovery from green leaf to processed tea (Ponmurugan & Baby, 2007).

Statistical analysis

Yield data were analysed using two-way analysis of variance (ANOVA) without interaction. Mean comparisons were performed using Tukey's Honest Significant Difference (HSD) test at a significance level of $p \leq 0.05$. Statistical analyses were conducted in R using the agricolae package (Gomez & Gomez, 1984; Schumacker & Tomek, 2013). Graphs were prepared using Microsoft Excel 2021, and error bars represent the corresponding standard errors.

Results and discussion

Physicochemical features of tea-growing soil

Soil analysis conducted before and after the imposition of different farming systems revealed marked improvements in nutrient status across all treatments. Post-treatment soil pH showed a slight increase under organic and biodynamic management compared with the conventional system, while electrical conductivity remained low and relatively stable. Organic matter content increased under all treatments, with the greatest improvement recorded under organic management (8.5%). Phosphorus levels increased substantially, particularly in the conventional (42 mg kg^{-1}) and biodynamic (32 mg kg^{-1}) plots, compared with the organic treatment (12 mg kg^{-1}). Potassium concentration was highest under organic management (190 mg kg^{-1}), whereas calcium accumulation was also greatest in the organic plots (505 mg kg^{-1}) compared with the conventional and biodynamic treatments. Magnesium levels increased across all treatments, with biodynamic management recording the highest post-treatment concentration (118 mg kg^{-1}). Overall, the results indicate that organic and biodynamic amendments significantly improved soil fertility parameters compared with the conventional system, although the magnitude of improvement varied among individual nutrients (Table 1).

The findings demonstrate that organic and biodynamic farming systems exert differential effects on soil physicochemical properties, with the most pronounced improvements observed in soil physical and biological characteristics rather than chemical properties. Organic farming consistently enhanced soil organic matter content in tea cultivation systems, and this improvement became more evident with prolonged adoption, suggesting cumulative benefits from continuous organic inputs (Han *et al.,* 2013). Organic matter concentrations reached 44 g kg^{-1} in organically managed soils compared with 24 g kg^{-1} in conventionally managed fields. These findings are consistent with those of (Erhart & Hartl, 2009), who reported 6-34% higher soil organic carbon and up to 21% greater total nitrogen under organic management. Similarly, (Choudhary *et al.,* 2020) observed significantly higher organic carbon and available phosphorus levels in organically managed farming systems.

Biodynamic farming has also been reported to enhance soil fertility while reducing dependence on external inputs compared with conventional agriculture (Maeder *et al.,* 2002). However, the specific relationship between biodynamic tea cultivation and magnesium availability remains largely unexplored. In the present study, biodynamic management recorded the highest magnesium concentration among the three farming systems. Magnesium plays a critical role in tea quality by enhancing caffeine and polyphenol synthesis while reducing the phenol-to-amino acid ratio, thereby producing less astringent and more flavourful tea (Ma *et al.,* 2025). Furthermore, magnesium supplementation has been shown to promote the biosynthesis of important catechins, including epigallocatechin gallate (EGCG), and to improve the profile of volatile aromatic compounds (Feng *et al.,* 2025). Previous comparative studies have also demonstrated that biodynamic farms possess superior soil quality compared with neighbouring conventional farms, exhibiting improved physical, biological, and chemical soil properties. A comprehensive review of biodynamic agriculture further emphasizes the importance of compost application as a key component of biodynamic management, contributing substantially to improved soil fertility, enhanced microbial activity, and long-term soil health.

Microflora diversity in soil

Across the twenty-year assessment (2002–2022), microbial populations exhibited distinct temporal trends under biodynamic, conventional, and organic farming systems, with notable differences in their ability to sustain beneficial microbial communities. Total bacterial populations were consistently higher in the organic plots during the initial years (17.8×10^{6} cfu g^{-1} in 2002); however, microbial populations in all three farming systems converged to comparable levels by 2022. At the end of the study period, biodynamic farming recorded the highest bacterial population (3.1×10^{6} cfu g^{-1}), followed by organic (2.4×10^{6} cfu g^{-1}) and conventional farming (2.2×10^{6} cfu g^{-1}).

Fungal populations exhibited greater temporal variation, with conventional plots recording the highest initial population (23.5×10^{5} cfu g^{-1} in 2002), followed by a gradual decline to levels comparable with those of the biodynamic and organic systems (approximately 2.2–2.5×10^{5} cfu g^{-1}) during the later years. Phosphobacteria were consistently maintained at relatively higher populations under biodynamic management, reaching 12.3×10^{6} cfu g^{-1} in 2014, whereas conventional plots remained consistently lower. By 2022, the organic system recorded the highest phosphobacteria population (3.6×10^{6} cfu g^{-1}) compared with the other two farming systems.

Similarly, the population of *Azospirillum* was highest under organic management (1.2×10^{6} cfu g^{-1}), followed by biodynamic (0.9×10^{6} cfu g^{-1}) and conventional farming (0.5×10^{6} cfu g^{-1}). In contrast, *Pseudomonas* populations

Table 1: Effect of different farming systems on physicochemical property of tea soil

Nutrients	Pre Treatment (2002)			Post Treatment (2022)		
	Conventional	Organic	Biodynamic	Conventional	Organic	Biodynamic
pH	4.8	5.2	4.5	4.5	4.9	5.0
EC (dS m^{-1})	0.05	0.06	0.10	0.17	0.06	0.06
OM (%)	7.8	6.0	6.9	9.2	8.5	7.8
Phosphorus (mg/Kg)	2.0	2.0	2.0	42	12.0	32
Potassium (mg/Kg)	165	80	70	145	190	145
Calcium (mg/Kg)	75	351	50	350	505	86
Magnesium (mg/Kg)	68	68	46	47	83	118

showed intermittent peaks in the organic system, reaching 10.5×10^6 cfu g^{-1} in 2006. By the end of the experiment, however, biodynamic farming supported the highest *Pseudomonas* population (2.2×10^6 cfu g^{-1}), followed closely by conventional farming (2.0×10^6 cfu g^{-1}). *Trichoderma* populations were initially highest under organic management (18.1×10^6 cfu g^{-1} in 2002) but gradually declined to negligible levels across all farming systems over time. Actinomycetes exhibited greater persistence, with biodynamic plots recording peak populations of 11.1×10^6 cfu g^{-1} in 2010, while organic plots maintained relatively stable populations ranging from 1.3 to 2.2×10^6 cfu g^{-1} throughout the study period.

Collectively, these findings indicate that although organic farming initially promoted greater microbial abundance and diversity, biodynamic farming demonstrated superior long-term resilience in sustaining functionally important microbial groups, particularly phosphobacteria and actinomycetes. This suggests a comparative advantage of biodynamic management in maintaining soil microbial health under long-term tea cultivation. Overall, both biodynamic and organic farming systems supported significantly higher populations of beneficial soil microorganisms than the conventional system (Figures 1-6).

The influence of biodynamic farming on beneficial soil microflora remains variable across published studies, indicating complex interactions between biodynamic preparations and soil microbial communities. Milke *et al.* (2024) reported significantly higher abundances of putative plant growth-promoting amplicon sequence variants in biodynamically managed soils than in organically managed soils across 24 European locations. These contrasting observations may reflect methodological and environmental differences, as Olimi *et al*. (2022) identified site-specific microbial communities associated with biodynamic preparations and reported differential colonization patterns, including the enrichment of beneficial *Pseudomonas* species in apple rhizospheres. In contrast, Aher *et al.* (2018) observed that conventional organic management outperformed biodynamic systems with respect to soil microbial populations and enzymatic activities under semi-arid conditions, whereas Pintaric *et al*. (2024) reported the highest microbial abundance and enzyme activities in biodynamic soils. Collectively, these contrasting findings suggest that the effectiveness of biodynamic preparations depends on several factors, including soil type, climatic conditions, cropping system, and the duration of management practices. Further research is therefore required to elucidate the mechanisms governing interactions between biodynamic preparations and soil microbial communities.

Yield analysis

Conventional farming consistently outperformed biodynamic and organic farming systems in terms of crop productivity throughout the study period. Results from the long-term field experiment conducted between 2002 and 2022 showed that the organic farming system recorded the lowest yield (37,922 kg ha^{-1}) among the three cultivation

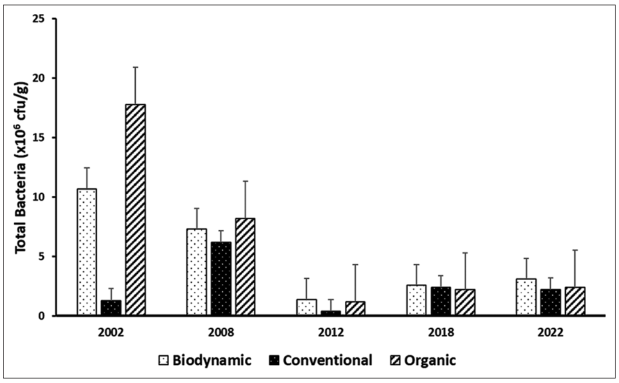

Figure 1: Establishment of total bacteria under different farming systems

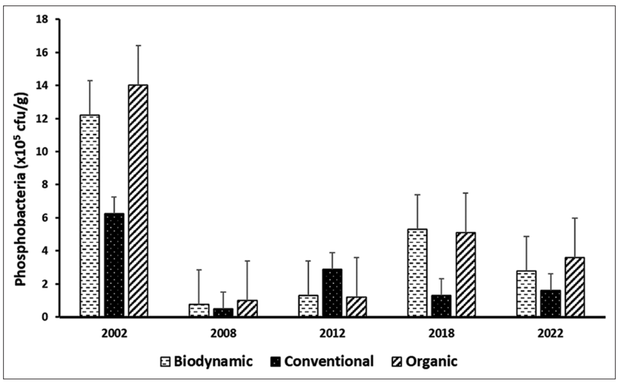

Figure 2: Establishment of total fungi populations in the experimental plot

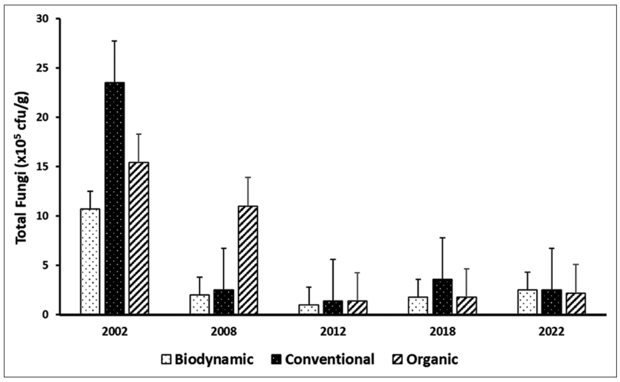

Figure 3: Establishment of Phosphobacteria (PSB) in the different farming systems

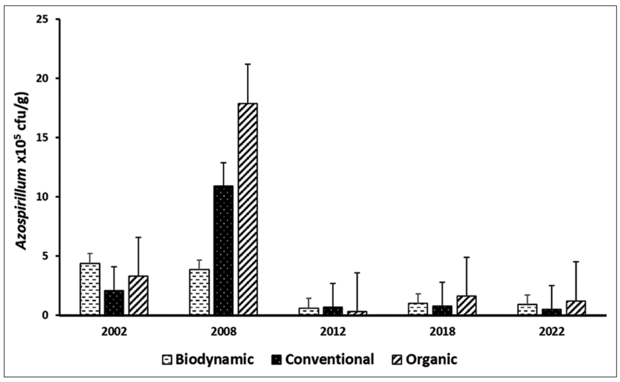

Figure 4: Effect of different farming treatments on N_2-fixer (*Azospirillum)*

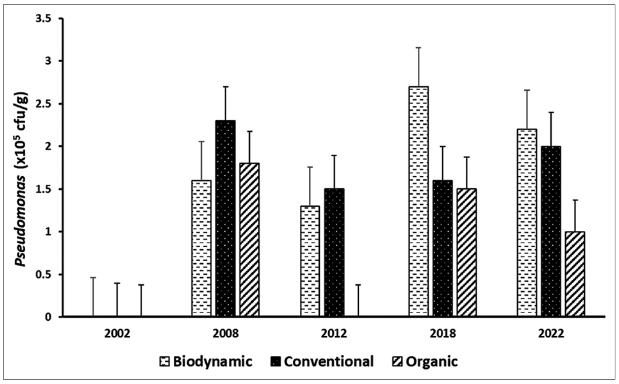

Figure 5: Establishment of bacterial bio control agent (*Pseudomonas* spp.) in the experimental plot

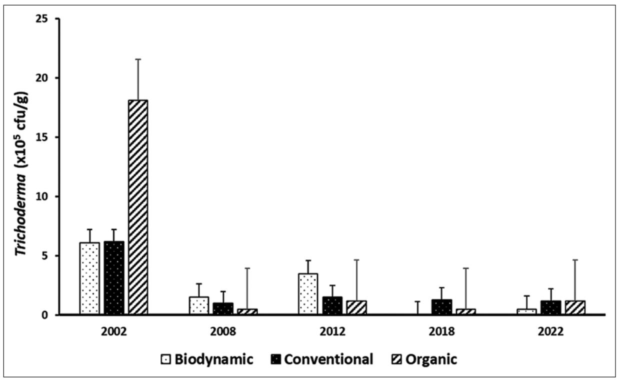

Figure 6: Establishment of fungal bio control agent (*Trichoderma* spp.)

practices. Biodynamic farming produced an average yield that was 18.83% higher than the organic system, whereas conventional farming recorded the highest yield (50,746 kg ha^{-1}), representing a 33.82% increase over organic cultivation (Table 2).

Greater weed infestation was observed in both biodynamic and organic tea plantations, resulting in increased competition with tea bushes for water and essential nutrients, which contributed to reduced productivity. Furthermore, the foliar application of bioproducts and biodynamic preparations resulted in comparatively slower nutrient release and assimilation, limiting immediate bud break and shoot elongation. In contrast, synthetic fertilizers used in the conventional system supplied readily available nutrients, promoting rapid nutrient uptake, vigorous vegetative growth, and higher yields. A greater incidence of pests and diseases was also recorded under organic and biodynamic management, further contributing to the lower yields observed in these systems.

Despite their comparatively lower productivity, organic and biodynamic tea cultivation offer important economic advantages through premium market prices and increasing consumer demand for sustainably produced tea. Since its commercial introduction in the late 1980s, the global market for organic tea has expanded considerably. Organic tea generally commands prices three to four times higher than conventionally produced tea, making it an attractive

Table 2: Effect of different farming systems on made tea yield across four pruning cycles in high elevation tea plantation of south India

Pruning Cycle	Age of the field	Yield (Made tea Kg/ha^{-1})*		
		Conventional	Biodynamic	Organic
First Pruning cycle (2002-2006)	1st year	807	896	742
	2nd year	2526	2262	2032
	3rd year	3667	3420	3148
	4th year	2474	2296	1943
	5th year	2554	2636	2316
Second Pruning cycle (2007-2011)	1st year	1722	1184	998
	2nd year	3170	2718	2008
	3rd year	3977	3318	3003
	4th year	3504	3313	2319
	5th year	3455	3254	2539
Third Pruning cycle (2012-2017)	1st year	1829	1828	1244
	2nd year	3269	2575	2112
	3rd year	3356	2417	2155
	4th year	2065	1907	1412
	5th year	2203	1596	1409
Forth Pruning cycle (2018-2022)	1st year	1044	901	784
	2nd year	1828	1534	1171
	3rd year	2733	2709	2593
	4th year	2214	2644	2564
	5th year	2349	1654	1430
Total yield		50746^{a}	45062^{b}	37922^{c}
± Over organic in %		33.82	18.83	0
p-value adjusted		0.0016712	0.0000954	0.0
SE (m)		192.9	176.9	159.4

*Total yield followed by different letters are significantly different from each other ($p<0.05$) according to Tukey's HSD post-hoc test. **Yield data collected from 2002 to 2022 across four pruning cycles during the study period under different farming system

option for growers despite higher production costs and lower productivity (Muraleedhran, 2001).

The improved soil quality associated with biodynamic farming is accompanied by certain productivity trade-offs. Biodynamic systems generally produce lower crop yields than conventional systems but often achieve comparable or higher net returns per hectare owing to premium market prices and reduced dependence on external inputs (Reganold, 1995). Improvements in soil quality are largely attributed to the integrated use of biodynamic preparations and organic amendments, which enhance biological soil properties and promote root development compared with organic systems that do not employ biodynamic preparations. These findings suggest that although biodynamic farming may compromise short-term yield, it offers measurable improvements in soil health that can support long-term agricultural sustainability.

Globally, the adoption of biodynamic farming remains limited but continues to expand, with more than 5,500 farmers practicing biodynamic agriculture and Demeter-International-certified production increasing from 42 to 55 countries. Germany currently has the largest number of biodynamic farms (1,552). Biodynamic agriculture is predominantly practiced in the Global North and is closely associated with growing consumer preference for organically and sustainably produced food (Besky, 2025). Comparative studies indicate that biodynamic farming systems generally exhibit superior soil quality compared with conventional systems, despite producing relatively lower crop yields, while maintaining comparable or higher economic returns on a per-hectare basis (Reganold, 1995). Although biodynamic agriculture currently occupies a niche position within global farming systems, its continued expansion and demonstrated environmental benefits suggest that it represents a promising pathway towards more integrated and sustainable agricultural production.

Conclusion

The present study demonstrated that long-term adoption of different farming systems significantly influenced soil health, microbial diversity, and tea productivity. Organic and biodynamic farming practices contributed to consistent improvements in soil physicochemical properties, indicating their potential to enhance soil fertility and long-term sustainability. Among the three farming systems evaluated, biodynamic management supported the highest abundance and diversity of beneficial soil microorganisms, followed by organic farming, whereas conventional farming consistently recorded the lowest microbial populations. In contrast, conventional farming achieved the highest tea yield, followed by biodynamic and organic farming. Although conventional management maximized productivity, its reliance on synthetic agrochemicals may have contributed to reduced soil biological activity. Biodynamic farming, on the other hand, provided a more balanced production system by improving soil physicochemical properties, sustaining beneficial microbial communities, and maintaining yields substantially higher than those obtained under organic management and closer to those of conventional farming. These findings suggest that biodynamic farming represents a promising and sustainable alternative for tea cultivation by balancing productivity with long-term soil health and ecological resilience.

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Author contributions

S. Ranjithkumar: Investigation, Conceptualization, Data curation, Software, Writing – original draft. P. Nepolean: Supervision, Validation, Writing – review and editing. Francis Lijo Mendez: Data curation, Software, Writing – review and editing. Azariah Babu: Validation, Writing – review and editing.

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