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ORIGINAL PAPER

Long Term Effects of Integrated Management Practices on Soil Chemical and Biological Properties in Tea Cultivation

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Abstract
This study evaluated the long-term effects of integrated soil rehabilitation practices on soil chemical, biological, and productivity indicators in strongly acidic tea plantations in Türkiye. The objective of this study was to evaluate the effectiveness of the integrated TEMA model (15 t ha^{-1} tea-waste compost + 2 t ha^{-1} dolomite + hoeing) in restoring degraded soils compared to single-input conventional or organic management practices. Between 2018 and 2022, two tea gardens, one conventionally fertilized and one organically managed, were monitored under field conditions. The TEMA treatment was compared with chemical fertilization and farmyard manure-only systems. Fresh tea yield was recorded each year. Soil samples from 0 to 10 and 10–20 cm were analyzed for pH, EC, $CaCO_3$, soil organic matter, qCO_2, fungal to bacterial ratio, β-glucosidase, and catalase. Principal component analysis was used to evaluate relationships. Yield declined under chemical fertilization (17650–15200 kg ha^{-1}), whereas TEMA maintained stable yields (20100–20130 kg ha^{-1}). In the organic system, manure-only plots produced 6600–8800 kg ha^{-1}, while TEMA increased yields from 27,500 to 35,400 kg ha^{-1}. Soil pH increased to 5.6–5.7 under TEMA, with soil organic matter reaching 3.79% and higher enzyme activities. Principal component analysis identified soil organic matter, pH, $CaCO_3$, and enzyme activities as the main drivers of system differentiation. Integrated soil management improved strongly acidic tea soils through coordinated chemical buffering and biological functioning. The TEMA model provides a practical approach for sustainable soil rehabilitation and long-term productivity.

Keywords Acid soil restoration · Soil health · Microbial activity · Carbon-mediated stabilization · Long-term field evaluation

1 Introduction

Tea (*Camellia sinensis* L.) is the second most consumed beverage worldwide after water. It is cultivated on approximately 5.27 million hectares (Bania et al. 2025) mainly in China, India, Kenya, Sri Lanka, and Vietnam. Türkiye also holds a significant position in global tea production, ranking sixth worldwide. In Türkiye, where tea has been intensively cultivated in the Eastern Black Sea Region for the past seven decades, it has become both the most important beverage and the national drink, representing a vital source of income for producers and a deeply rooted cultural habit for consumers (Turumtay et al. 2022). Currently, tea is grown on nearly 79,000 hectares in the provinces of Rize, Trabzon, Artvin, Giresun, and Ordu. Türkiye ranks sixth in global tea cultivation and contributes substantially to the regional economy and rural development (Haciimamoglu et al. 2025).

Tea plants thrive optimally in soils with organic matter content above 2% and a pH between 4.5 and 5.5. However, since the 1970s, the intensive application of ammonium sulfate and ammonium nitrate fertilizers has accelerated soil acidification in tea plantations, resulting in a pH decline of 0.47–1.43 units over the past 20–30 years (Gao et al. 2024; Jia et al. 2023), while studies conducted in the Eastern Black Sea region of Türkiye indicate that tea soils are generally strongly acidic, with pH values commonly ranging between 4 and 5 and in some cases falling below 4 (Dengiz et al. 2020). This acidification negatively affects root

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development, plant biomass, and nutrient uptake efficiency, ultimately leading to yield losses and deterioration of tea quality (Ye et al. 2022a). Moreover, the long-term reliance on chemical fertilizers has been associated with organic matter depletion and nutrient imbalances, further reducing soil fertility (Xing et al. 2025b).

To mitigate soil degradation, various sustainable practices have been explored. Organic amendments such as farmyard manure or tea-waste compost improve soil fertility, increase enzymatic activity, and support beneficial microbial communities (Lin et al. 2019; Liu et al. 2023). These amendments also enhance soil enzymatic activities including urease, phosphatase, and β-glucosidase, thereby strengthening nutrient cycling and soil health (Xing et al. 2025b; Xu et al. 2025). In addition, organic inputs contribute to higher microbial diversity and the proliferation of beneficial microorganisms such as nitrogen-fixing bacteria and mycorrhizal fungi (Bebber and Richards 2022; Shu et al. 2022). Nevertheless, when applied individually, these practices are often insufficient to fully rehabilitate degraded and acidified soils in conventional tea plantations. Liming has long been used to buffer soil acidity and restore pH to levels suitable for root growth (Wenyika et al. 2025). Similarly, hoeing reduces soil compaction, improves aeration, and enhances both root development and nutrient cycling (Xing et al. 2025a). However, like organic inputs, these single practices frequently provide only limited benefits over the long term and cannot adequately sustain productivity under acidic soil conditions. In this context, the integration of composting, liming, and hoeing, referred to in this study as the TEMA (15 t ha^{-1} tea-waste compost + 2 t ha^{-1} dolomite + hoeing) treatment, a term used solely as a study-specific designation to describe the combined application of these practices, rather than a predefined management model, represents a diversified management strategy designed to overcome the limitations of single-input practices in tea plantations.

In recent years, integrated management approaches have attracted growing attention. The combined use of organic and inorganic inputs has been shown to buffer soil acidity, enhance microbial diversity, and improve both yield and tea quality more effectively than single-input strategies (Mjanja et al. 2025; Wang et al. 2025). For instance, combining rapeseed cake or biochar with mineral fertilizers has reduced heavy metal accumulation in tea leaves, improved nutrient cycling, and promoted more stable microbial communities (Lin et al. 2019). Organic fertilizers have also been reported to increase antioxidant compounds such as polyphenols and amino acids while reducing caffeine content, thereby improving tea quality and offering consumer health benefits (Manzoor et al. 2024; Raza et al. 2024). Excessive use of chemical fertilizers also raises environmental concerns. High nitrogen inputs accelerate nitrate leaching into groundwater and increase greenhouse gas emissions such as N_2O and NO, thereby disrupting soil ecological balance (de Vries et al. 2024; Rashidabad et al. 2025). In contrast, combined applications of organic fertilizers with soil amendments such as biochar have been found to reduce these emissions while maintaining or even increasing tea yield (Luo et al. 2023). However, long-term field evaluations of combined practices such as composting, liming, and hoeing in tea plantations remain very limited, particularly under the conditions of Türkiye's Eastern Black Sea Region. Against this background, the present study addresses the following research question: How does integrated soil management combining composting, liming, and hoeing influence soil chemical buffering capacity, biological functioning, and tea yield stability in strongly acidic tea plantation soils? Based on these considerations, we hypothesized that integrated management would improve soil chemical properties, particularly soil pH stabilization and $CaCO_3$ accumulation, and that these improvements would subsequently enhance soil biological functioning and sustain yield performance compared to single-input management.

Accordingly, to test this hypothesis, this study was conducted in Türkiye's Eastern Black Sea Region to evaluate the effects of sustainable management practices on soil health and tea yield in both organic and conventional plantations. Specifically, the objectives were (i) to assess the effects of hoeing, liming, and composting on soil chemical, biological, and enzymatic properties; (ii) to compare the effectiveness of the integrated TEMA treatment (15 t ha^{-1} tea-waste compost + 2 t ha^{-1} dolomite + hoeing) with conventional and organic single-input practices.

2 Material and Methods

2.1 Study Area

The experimental sites were located in Rize province, Türkiye (Conventional: 41°03'51.7"N 40°43'56.7"E; Organic: 40°59'32.3"N 40°47'44.5"E) (Fig. S1). Long-term (1927–2025) climatological records indicate that the region has a mean annual temperature of 14.5 °C and an average annual precipitation of 2291.7 mm, with recorded temperatures ranging from −7 °C to 38.7 °C (Turkish State Meteorological Service 2025). The climate is classified as Cfa according to the Köppen–Geiger climate classification system, indicating a humid subtropical climate with year-round precipitation and hot summers (Kottek et al. 2006). Detailed climatic parameters are presented in Table S2. Climatic conditions during the study period (2018–2022), including annual mean temperature and total precipitation, are presented in Table S3. Both tea gardens each covered

an area of 600 m² and represented two distinct valleys, one managed conventionally and the other organically. Within each garden, the experimental area was divided into two treatments (standard practice and TEMA), each consisting of three replicated plots. Each plot measured 100 m², and plots were arranged in a completely randomized design to ensure independent replicates under field conditions. 50% of the total area in each garden was subjected to the TEMA treatment from 2018 to 2022.

Treatments Two tea garden management systems, conventional and organic, were evaluated. In both systems, standard practices were compared with TEMA-supported treatments.

2.1.1 Conventional Treatment

The treatment was conducted in the Sabuncular village tea garden of Senoz Valley, Çayeli, Rize. This tea garden has been managed under conventional cultivation for five years, with an annual application of 1.3 t ha^{-1} of 25–5–10 fertilizer. The treatments applied between 2018 and 2022 in this garden are as follows:

- Chemical treatment: 1.3 t ha^{-1} of 25–5–10 fertilizer
- TEMA treatment: 15 t ha^{-1} tea-waste compost + 2 t ha^{-1} dolomite + hoeing

2.1.2 Organic Treatment

The organic treatment was applied in the tea garden located in Buzlupınar Village, Senoz Valley, Çayeli, Rize. This garden has been managed organically for five years prior to the experiment, with the annual application of 5 t ha^{-1} farmyard manure. Between 2018 and 2022, the following treatments were implemented:

- Organic treatment: 5 t ha^{-1} farmyard manure
- TEMA treatment: 15 t ha^{-1} tea-waste compost + 2 t ha^{-1} dolomite + hoeing

The chemical properties of tea-waste compost and farmyard manure used in the study are presented in Table S1. These materials were applied in 2018, 2020, and 2022 and exhibited relatively stable chemical characteristics across years. Tea-waste compost was characterized by high OC contents (48.50–49.95%) and total N concentrations (2.24–2.53%). The material was slightly acidic (pH 6.25–6.30) and had electrical conductivity (EC) values ranging from 2.24 to 2.44 dS m^{-1}. Macronutrient contents ranged from 0.47% to 0.60% for P_2O_5 and from 1.44% to 1.70% for K_2O. Micronutrient concentrations also showed limited variation, with Fe ranging between 0.31% and 0.47%, Cu between 11.50 and 21.03 mg kg^{-1}, Zn between 51.58 and 64.98 mg kg^{-1}, and Mn between 858.80 and 935 mg kg^{-1}. Farmyard manure exhibited organic carbon contents ranging from 31.85% to 34.12% and total N contents between 1.69% and 1.85%. The material showed an alkaline reaction (pH 7.98–8.45) and EC values of 2.77–2.91 dS m^{-1}. Macronutrient contents ranged from 1.13% to 1.47% for P_2O_5 and from 1.91% to 2.10% for K_2O. Micronutrient concentrations varied slightly across years, with Fe ranging between 0.22% and 0.44%, Cu between 17.45 and 32.23 mg kg^{-1}, Zn between 346.30 and 410.96 mg kg^{-1}, and Mn between 412.00 and 504.30 mg kg^{-1}. The initial soil physicochemical and biological properties of the experimental sites are presented in Table 1. A representative image of the tea-waste application is shown in Fig. S3a. Liming practices are widely recommended in tea plantations to regulate soil acidity and enhance nutrient availability under strongly acidic conditions. Although tea plants are adapted to acidic soils (optimal pH range 4.0-5.5), excessive acidification can reduce the availability of essential nutrients and disrupt soil chemical balance (Kavitha 2016). Therefore, soil pH adjustment through lime or dolomite applications represents an important management strategy in tea cultivation systems. In the present study, ground agricultural dolomite containing 54% $CaCO_3$ and 45% $MgCO_3$ was applied at a rate of 2 t ha^{-1} to moderate soil acidity and improve soil reaction. A representative image of the dolomite application is presented in Fig. S3b. Hoeing in tea plants was carried out as a shallow mechanical tillage practice to remove weeds in the root zone and to improve soil aeration. A representative image of the hoeing practice is presented in Fig. S3c.

2.2 Data Collection and Measurement

This study investigated tea yield and associated soil properties in the experimental tea gardens. Within each management system, the plot was divided into two treatment zones (standard practice and TEMA), each consisting of three independent replicated plots. Each garden 600 m^2 was divided into two treatment zones, and each treatment consisted of three replicated plots, each covering approximately 100 m^2. These plots were maintained consistently throughout the study period (2018–2022) and served as experimental units for statistical analysis. Each year, three distinct harvesting periods (first, second, and third flush) were observed. Fresh tea leaves were harvested separately from each replicate plot, and the fresh weight was recorded to determine plot-level yield.

For each site, treatment, and soil depth (0–10 cm and 10–20 cm), soil sampling was conducted independently within each replicate plot. Within each plot, three randomly

Table 1 Initial physicochemical and biological properties of soils in the conventional and organic treatments

Parameters	Conventional Treatment				Organic Treatment			
	Chemical		TEMA		Organic		TEMA	
	Depth (cm)		Depth (cm)		Depth (cm)		Depth (cm)	
	0–10	10–20	0–10	10–20	0–10	10–20	0–10	10–20
Soil Texture	SCL		SCL		SCL		SCL	
pH (1:2.5 w/v)	3.72 ± 0.07	4.27 ± 0.08	3.63 ± 0.02	3.77 ± 0.04	4.46 ± 0.15	4.13 ± 0.07	4.06 ± 0.02	4.03 ± 0.04
EC (1:2.5 w/v) (dS m^{-1})	0.08 ± 0.005	0.07 ± 0.004	0.14 ± 0.007	0.10 ± 0.006	0.13 ± 0.03	0.07 ± 0.003	0.22 ± 0.007	0.20 ± 0.009
$CaCO_3$ (%)	0.06 ± 0.004	0.003 ± 0.001	0.07 ± 0.003	0.07 ± 0.002	0.14 ± 0.01	0.03 ± 0.003	0.22 ± 0.005	0.08 ± 0.01
SOM (%)	0.84 ± 0.06	0.65 ± 0.07	2.15 ± 0.02	1.85 ± 0.01	3.36 ± 0.18	2.57 ± 0.5	3.83 ± 0.08	2.23 ± 0.03
qCO_2 (μg CO_2 μg^{-1} Cmic 24 h^{-1})	0.80 ± 0.19	1.00 ± 0.47	0.81 ± 0.06	0.69 ± 0.03	1.08 ± 0.06	1.37 ± 0.15	0.69 ± 0.02	0.77 ± 0.02
Soil catalase enzyme activity (mL O_2 g^{-1} 3 min^{-1})	73.11 ± 2.36	71.66 ± 3.51	153.28 ± 2.37	75.08 ± 5.12	157.66 ± 3.51	110.49 ± 7.83	236.70 ± 4.85	205.72 ± 14.08
Soil β-glucosidase enzyme activity (μg pNP g^{-1} dry soil)	0.68 ± 0.03	0.70 ± 0.01	0.65 ± 0.01	0.63 ± 0.02	0.64 ± 0.04	0.59 ± 0.01	0.7 ± 0.02	0.63 ± 0.03
Fungal to Bacterial Ratio (mg C kg^{-1})	0.07 ± 0.002	0.06 ± 0.005	0.12 ± 0.002	0.10 ± 0.002	0.12 ± 0.005	0.11 ± 0.002	0.14 ± 0.007	0.13 ± 0.003

Values represent mean ± standard error (SE) of three replicates. Chemical: 1.3 t ha^{-1} of 25–5–10 fertilizer; TEMA: 15 t ha^{-1} tea-waste compost + 2 t ha^{-1} dolomite + hoeing; Organic: 5 t ha^{-1} farmyard manure; SCL: sandy clay loam; SOM: soil organic matter; qCO_2: soil specific respiration rate; EC: electrical conductivity. Enzyme activities are expressed on a dry soil basis

distributed subsamples were collected from the root zone and composited to obtain one representative sample per replicate. After thorough homogenization, approximately 2 kg of fresh soil was transferred into polyethylene bags and transported to the laboratory. Samples for biological analyses were stored at 4 °C, whereas samples for physicochemical analyses were air-dried, and sieved (<2 mm) prior to analysis. The soil texture of both experimental sites where the trials were conducted was sandy clay loam (SCL). According to (Soil Taxonomy 2022), the tea-growing soils in the Çayeli region are classified as Typic Hapludults.

2.3 Physicochemical Analysis of Soils and Organic Amendments

2.3.1 Organic Amendment Analysis

Chemical parameters of tea-waste compost and farmyard manure were analyzed to characterize their physicochemical properties. Organic matter (OM) content was determined by the loss-on-ignition method after oven drying at 105 °C and ignition at 550 °C (Nelson and Sommers 1996). Total nitrogen (N) was determined using the Kjeldahl digestion–distillation method (Bremner 1996). Total phosphorus (P_2O_5) and potassium (K_2O) contents were determined following wet acid digestion using an HNO_3–$HClO_4$ mixture (Jones et al. 1991). Phosphorus concentration was measured calorimetrically by the molybdenum blue method (Murphy and Riley 1962), whereas potassium was quantified using flame photometry (Jones et al. 1991). Compost reaction (pH) and electrical conductivity (EC) were measured in a compost-to-water suspension (1:10 w/v) after 1 h of shaking (Thomas 1996). Micronutrient contents (Fe, Cu, Zn, and Mn) were determined after acid digestion and quantified using inductively coupled plasma–optical emission spectrometry (ICP–OES) according to standard procedures (Jones et al. 1991). All analyses were performed in triplicate, and analytical grade reagents were used throughout the study.

2.3.2 Soil Analysis

Chemical and biological parameters were analyzed in the collected soil samples to characterize their properties. Soil particle distribution was determined using the Bouyoucos hydrometer method (Bouyoucos 1951). Soil reaction (pH) and electrical conductivity (EC) were measured in a soil-to-water suspension (1:2.5 w/v) (Richards 1954). Soil carbonate content was determined by the calcimeter method (Richards 1954). Soil organic matter was measured using the modified Walkley–Black wet oxidation procedure (Nelson and Sommers 1996). Soil basal respiration was determined under controlled incubation conditions (25 °C), and CO_2 was quantified using standard alkali trap method. The metabolic quotient (qCO_2) was calculated as the ratio of basal respiration (CO_2–C) to microbial biomass carbon (Cmic), expressed as μg CO_2–C μg^{-1} Cmic 24 h^{-1}. Catalase

enzyme activity was measured according to (Beck 1971) by quantifying the oxygen released during the breakdown of hydrogen peroxide. β-glucosidase activity was determined following the method described by (Naseby and Lynch 1997). Briefly, 1.5 g of soil sample was shaken with acetate buffer solution in a rotary shaker for 1 h and then centrifuged at 4000 rpm for 15 min. The substrate of the enzyme (4-nitrophenyl β-D-glucopyranoside) was added to the resulting extract, and enzyme activity was quantified spectrophotometrically at 400 nm. The fungal to bacterial ratio was calculated as the proportion of total fungal biomass to total bacterial biomass. Total fungal biomass was extracted according to the method of (Bloem 1995). Total bacterial extraction and biomass determination were carried out using a protocol similar to that applied for fungal hyphae (Bloem 1995); however, the fluorescent protein dye 5-(4,6-dichlorotriazin-2-yl) aminofluorescein (DTAF) was used for staining bacterial cells. All analyses were performed in triplicate, and analytical grade reagents were used throughout the study.

2.4 Statistical Analysis

The Kolmogorov Smirnov test was employed to assess whether the data followed a normal distribution, and Levene's test was used to evaluate the homogeneity of variances. All results are expressed as mean ± standard error (SE). The experiment was set up in a completely randomized design and each treatment contained three replicates. For soil parameters, a three-way analysis of variance (ANOVA) was applied with treatment (conventional and organic), year (2018, 2020, and 2022), and soil depth (0–10 and 10–20 cm). For tea yield, a two-way ANOVA including treatment and year was performed. Significant differences among treatments were determined using Tukey's HSD test at $p < 0.05$. Principal component analysis (PCA) was employed to investigate multivariate relationships among soil chemical and biological variables. The sampling sites were mapped using ArcGIS software (version 10.5). All statistical analyses, including normality and homogeneity tests, ANOVA, Tukey's HSD, multivariate analysis (PCA), and graphical outputs, were performed using OriginPro 2025 software (OriginLab, Northampton, MA, USA).

3 Results

3.1 Effects of Treatments on Tea Yield

In the conventionally managed tea plantation, the effects of the treatments on fresh tea leaf yield (sum of three harvest periods) are shown in Fig. 1a. Across all evaluated years (2018, 2020, and 2022), the TEMA treatment consistently produced significantly higher yields than conventional fertilization ($p < 0.05$), with fresh leaf yields of 20,100, 19,900, and 20,130 kg ha^{-1}, respectively. In contrast, yields under conventional fertilization were lower (17650–15200 kg ha^{-1}) and exhibited a declining trend over time, whereas TEMA showed a consistent increase, reaching the highest yield in the final year. In the organically managed tea plantation (Fig. 1b), TEMA similarly resulted in substantially higher fresh leaf yields (27500, 32200, and 35400 kg ha^{-1}) compared to organic fertilization alone (6600–8800 kg ha^{-1}). Although yields under organic management increased slightly over the years, they remained markedly lower than those obtained with TEMA, which showed a pronounced and consistent upward trend. Differences among years and treatments were statistically significant ($p < 0.05$).

3.2 Effects of Treatments on Soil pH

In the conventionally managed tea plantation, soil pH values as affected by treatments and soil depth are presented in Fig. 2a–b. Across all sampling years (2018, 2020, and 2022), soils receiving the TEMA treatment exhibited significantly higher pH values than those under conventional fertilization. Surface soil pH under chemical fertilization remained strongly acidic (3.72–4.33) and did not show a significant temporal change. In contrast, surface soils under TEMA application showed a marked increase in pH over time, rising from 3.63 in 2018 to 5.65 in 2022. In both treatments, surface soils exhibited higher pH values than subsurface soils, and differences among years and soil depths were statistically significant ($p < 0.05$). Similarly, in the organically managed tea plantation (Fig. 2c–d), TEMA-treated soils consistently showed higher pH values than soils receiving farmyard manure alone. Soil pH under organic management remained relatively stable across years, whereas TEMA application resulted in a clear temporal increase, with surface soil pH reaching 5.71 in 2022. As observed in the conventional system, surface soils exhibited higher pH values than subsurface layers, and differences among treatments, years, and soil depths were statistically significant ($p < 0.05$).

3.3 Effects of Treatments on Soil EC

Soil EC values as affected by treatments and soil depth under conventional and organic management systems are shown in Fig. 3. In the conventionally managed tea plantation, EC values under TEMA application were slightly higher than those under conventional fertilization in 2018, while the highest EC values were recorded in 2020 under conventional management; by 2022, EC values under both treatments were comparable (Fig. 3a). Differences among

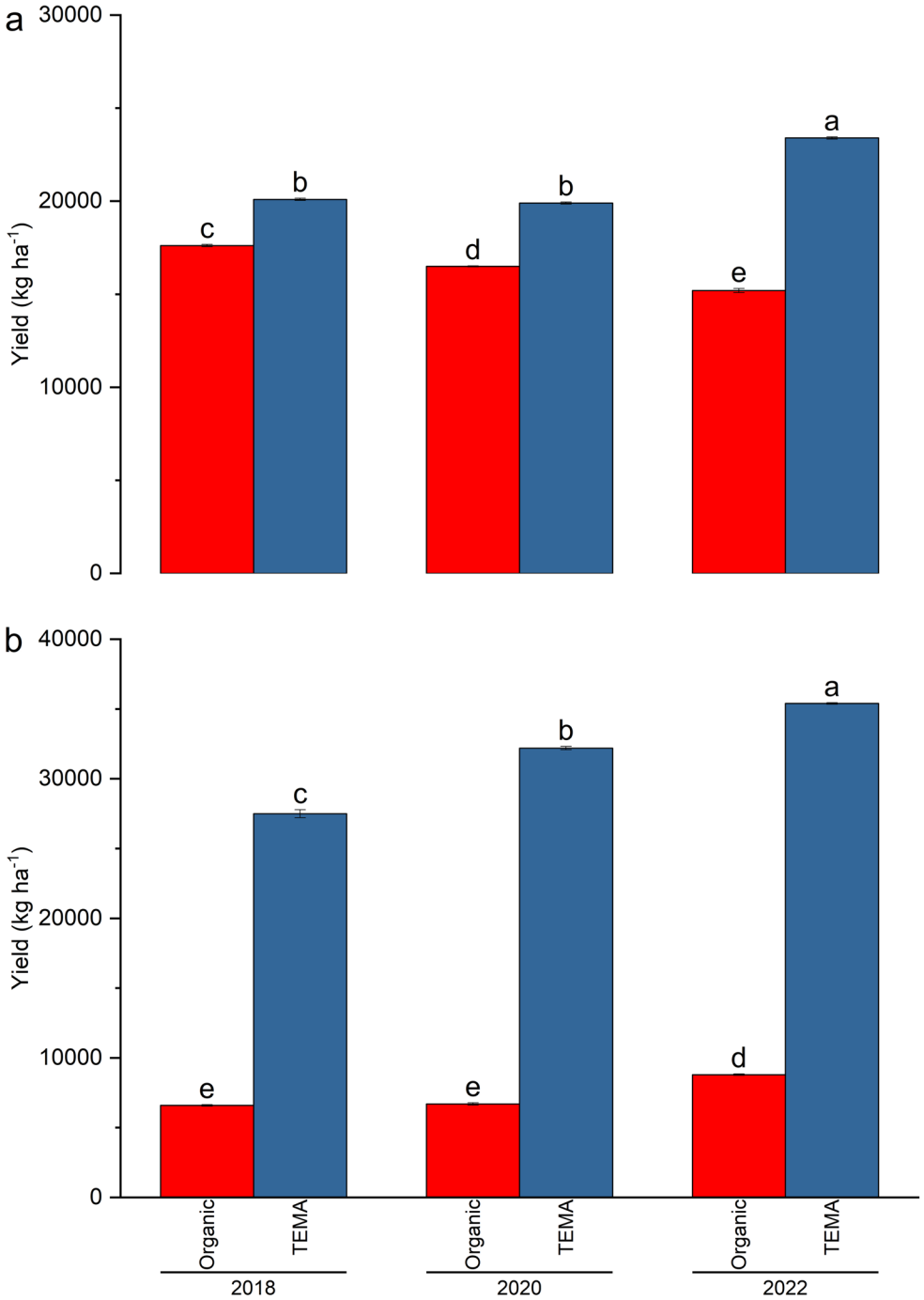


Fig. 1 Annual tea yield (kg ha^{-1}) under conventional (**a**) and organic (**b**) management systems as affected by treatment across years (2018, 2020, and 2022). Values represent mean ± standard error (SE) of three replicates. Different letters above the bars indicate significant differences among treatments based on two-way ANOVA, with comparisons among treatments performed within each year using Tukey's HSD test ($p < 0.05$). TEMA: 15 t ha^{-1} tea waste compost + 2 t ha^{-1} dolomite + hoeing

sampling years were statistically significant ($p < 0.05$), whereas variations related to soil depth were not significant (Fig. 3b). In the organically managed tea plantation, soils receiving the TEMA treatment consistently exhibited higher EC values than soils under organic management alone across all sampling years. Surface soil EC under TEMA increased from 0.118 dS m^{-1} in 2018 to 0.210 dS m^{-1} in 2022, indicating a clear temporal increase (Fig. 3c). Differences associated with both sampling year and soil depth were statistically significant ($p < 0.05$) (Fig. 3d).

3.4 Effects of Treatments on Soil Lime

Soil lime ($CaCO_3$) contents as affected by treatments and soil depth under conventional and organic systems are presented in Fig. 4. In the conventional tea plantation, soils receiving the TEMA treatment exhibited consistently higher lime contents than those under conventional conditions across all sampling years (2018, 2020, and 2022). While surface soil lime content under conventional management remained relatively stable (0.060–0.069%),

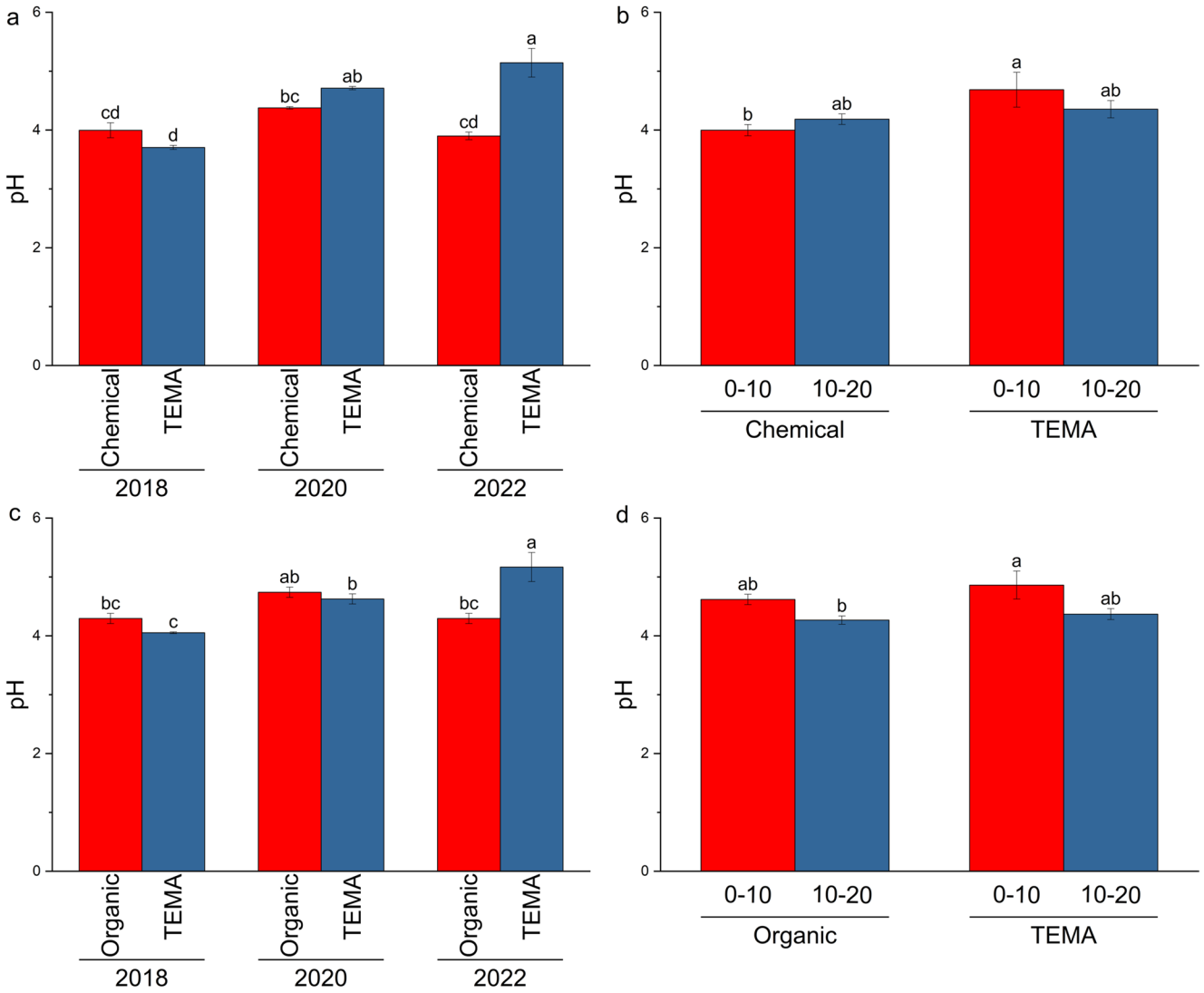


Fig. 2 Effects of treatment, year (2018, 2020, and 2022), and soil depth (0–10 and 10–20 cm) on soil pH under conventional (**a**, **b**) and organic (**c**, **d**) management systems. Values represent mean ± standard error (SE) of three replicates. Different letters above the bars indicate significant differences among treatments based on two-way ANOVA, with comparisons among treatments performed within each year using Tukey's HSD test ($p < 0.05$). TEMA: 15 t ha^{-1} tea waste compost + 2 t ha^{-1} dolomite + hoeing

TEMA application resulted in an increase over time, reaching 0.099% in 2022 (Fig. 4a). In both treatments, lime content decreased with increasing soil depth, and differences among years and soil depths were statistically significant ($p < 0.05$) (Fig. 4b). Similarly, in the organically managed tea plantation, TEMA-treated soils showed higher lime contents than soils receiving organic management alone. Surface soil lime content under organic management remained stable over time (0.142–0.149%), whereas TEMA application increased lime content up to 0.232% in 2022 (Fig. 4c). Although temporal changes in lime content were not statistically significant, differences related to soil depth were significant ($p < 0.05$), with lower values observed in subsurface soils (Fig. 4d).

3.5 Effects of Treatments on Soil Organic Matter

Soil organic matter (SOM) contents as affected by treatments and soil depth under conventional and organic management systems are presented in Fig. 5. In the conventionally managed tea plantation, SOM contents in TEMA-treated soils were consistently higher than those under conventional management across all sampling years (2018, 2020, and 2022) (Fig. 5a). In both treatments, SOM content decreased with increasing soil depth, and differences related to sampling year and soil depth were statistically significant ($p < 0.05$) (Fig. 5b).

In the organically managed tea plantation, SOM contents were higher in TEMA-treated soils than in soils

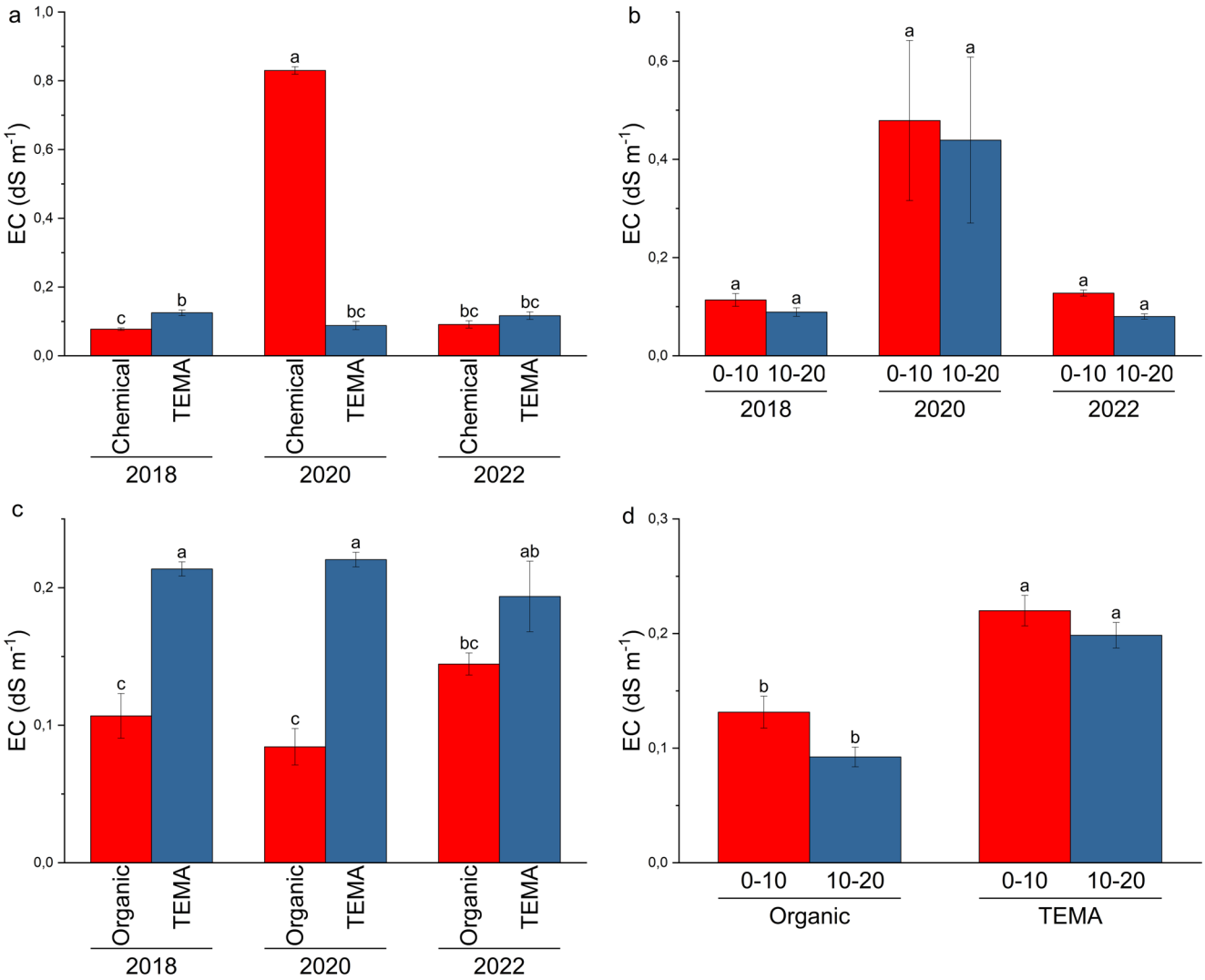


Fig. 3 Effects of treatment, year (2018, 2020, and 2022), and soil depth (0–10 and 10–20 cm) on soil electrical conductivity (EC, dS m^{-1}) under conventional (**a**, **b**) and organic (**c**, **d**) management systems. Values represent mean ± standard error (SE) of three replicates. Different letters above the bars indicate significant differences among treatments based on two-way ANOVA, with comparisons among treatments performed within each year using Tukey's HSD test ($p < 0.05$). TEMA: 15 t ha^{-1} tea waste compost + 2 t ha^{-1} dolomite + hoeing

under organic management alone; however, this difference was not statistically significant (Fig. 5c). The highest SOM values were observed in surface soils under TEMA application, and SOM content decreased with increasing soil depth in both treatments. Differences associated with soil depth were statistically significant ($p < 0.05$) (Fig. 5d).

3.6 Effects of Treatments on Soil Specific Respiration Rate (qCO_2)

Soil specific respiration rate (qCO_2) as affected by treatments and soil depth under conventional and organic management systems is shown in Fig. 6. In the conventionally managed tea plantation, surface soil qCO_2 values ranged from 0.81 to 1.79 µg CO_2 $µg^{-1}$ Cmic 24 h^{-1} under conventional management and from 0.74 to 1.29 µg CO_2 $µg^{-1}$ Cmic 24 h^{-1} under TEMA application. The highest qCO_2 value under conventional management was observed in 2020, while values in other years were statistically similar to those under TEMA (Fig. 6a). Temporal variations in qCO_2 were statistically significant ($p < 0.05$), whereas differences related to soil depth were not significant (Fig. 6b). In the organically managed tea plantation, surface soil qCO_2 values ranged from 1.08 to 1.44 µg CO_2 $µg^{-1}$ Cmic 24 h^{-1} under organic management and from 0.69 to 1.69 µg CO_2 $µg^{-1}$ Cmic 24 h^{-1} under TEMA application. Although qCO_2 values under TEMA were initially lower than those under organic management, they increased in 2020 and 2022 and reached

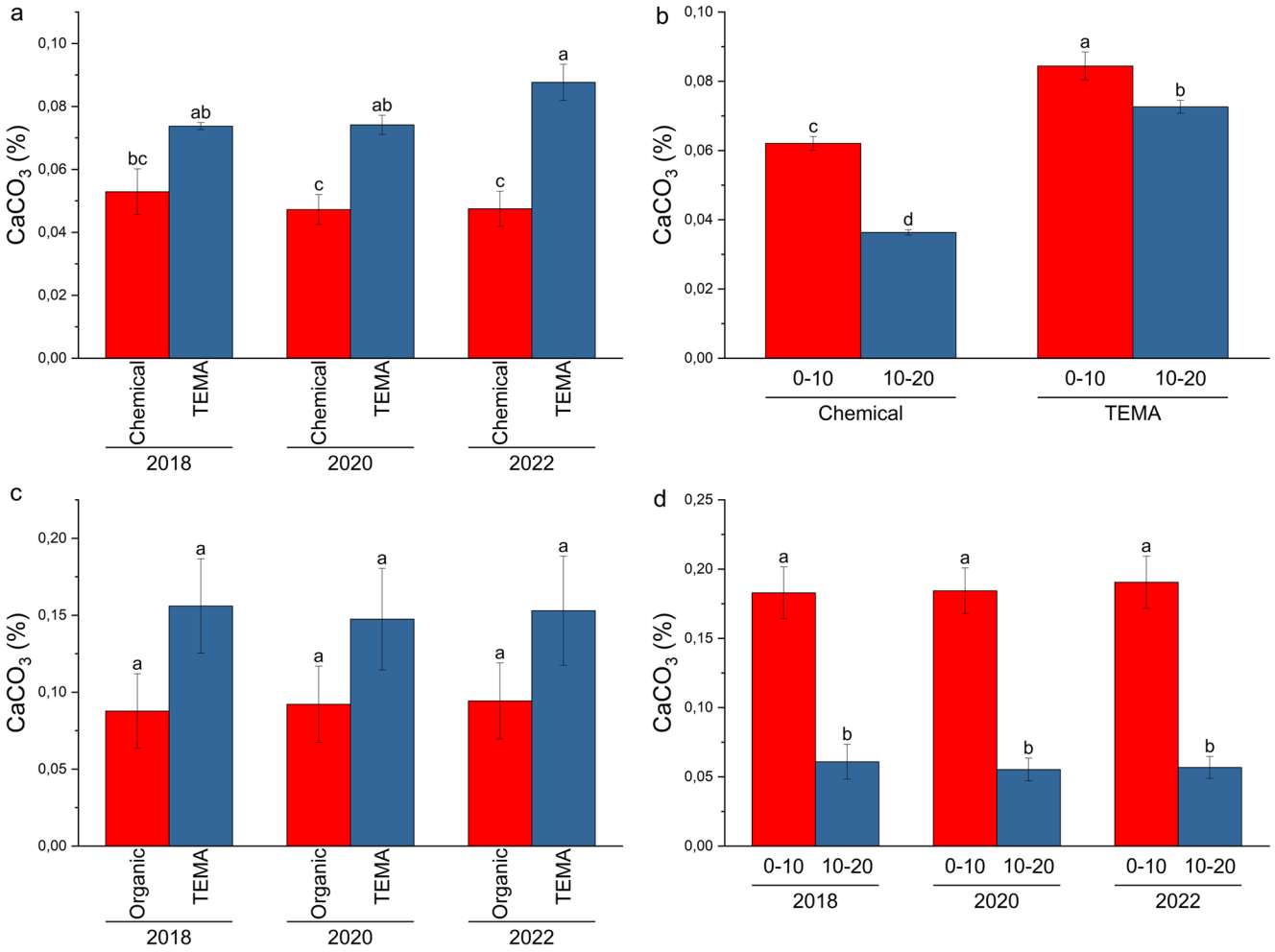


Fig. 4 Effects of treatment, year (2018, 2020, and 2022), and soil depth (0–10 and 10–20 cm) on soil calcium carbonate content ($CaCO_3$, %) under conventional (**a**, **b**) and organic (**c**, **d**) management systems. Values represent mean ± standard error (SE) of three replicates. Different letters above the bars indicate significant differences among treatments based on two-way ANOVA, with comparisons among treatments performed within each year using Tukey's HSD test ($p < 0.05$). TEMA: 15 t ha^{-1} tea waste compost + 2 t ha^{-1} dolomite + hoeing

significantly higher levels ($p < 0.05$) (Fig. 6c). Similar to the conventional system, variations related to soil depth were not statistically significant (Fig. 6d).

3.7 Effects of Treatments on Soil Catalase Enzyme Activity

Changes in soil catalase (CAT) enzyme activity as affected by treatments and soil depth under conventional and organic management systems are shown in Fig. 7a and d. In both management systems, CAT activity was consistently higher in TEMA-treated soils than in soils receiving single-input conventional or organic applications across all sampling periods. In both treatments, CAT activity decreased with increasing soil depth. Differences in CAT activity related to treatments and soil depth were statistically significant ($p < 0.05$).

3.8 Effects of Treatments on Soil β-Glukosidase Enzyme Activity

Changes in soil β-glucosidase (BG) activity as affected by treatments and soil depth under conventional management are shown in Fig. 8. BG activity showed similar values in 2018 and 2020, with no statistically significant differences between these years. In contrast, a significant increase in BG activity was observed in 2022 under the TEMA treatment ($p < 0.05$) (Fig. 8a). In addition, depth-related variations in BG activity under TEMA application were statistically significant ($p < 0.05$) (Fig. 8b). Changes in soil β-glucosidase (BG) activity as affected by treatments and soil depth under organic management. Similar to the conventional system, BG activity exhibited comparable values in 2018 and 2020, with no statistically significant differences between years. However, BG activity under the TEMA treatment increased

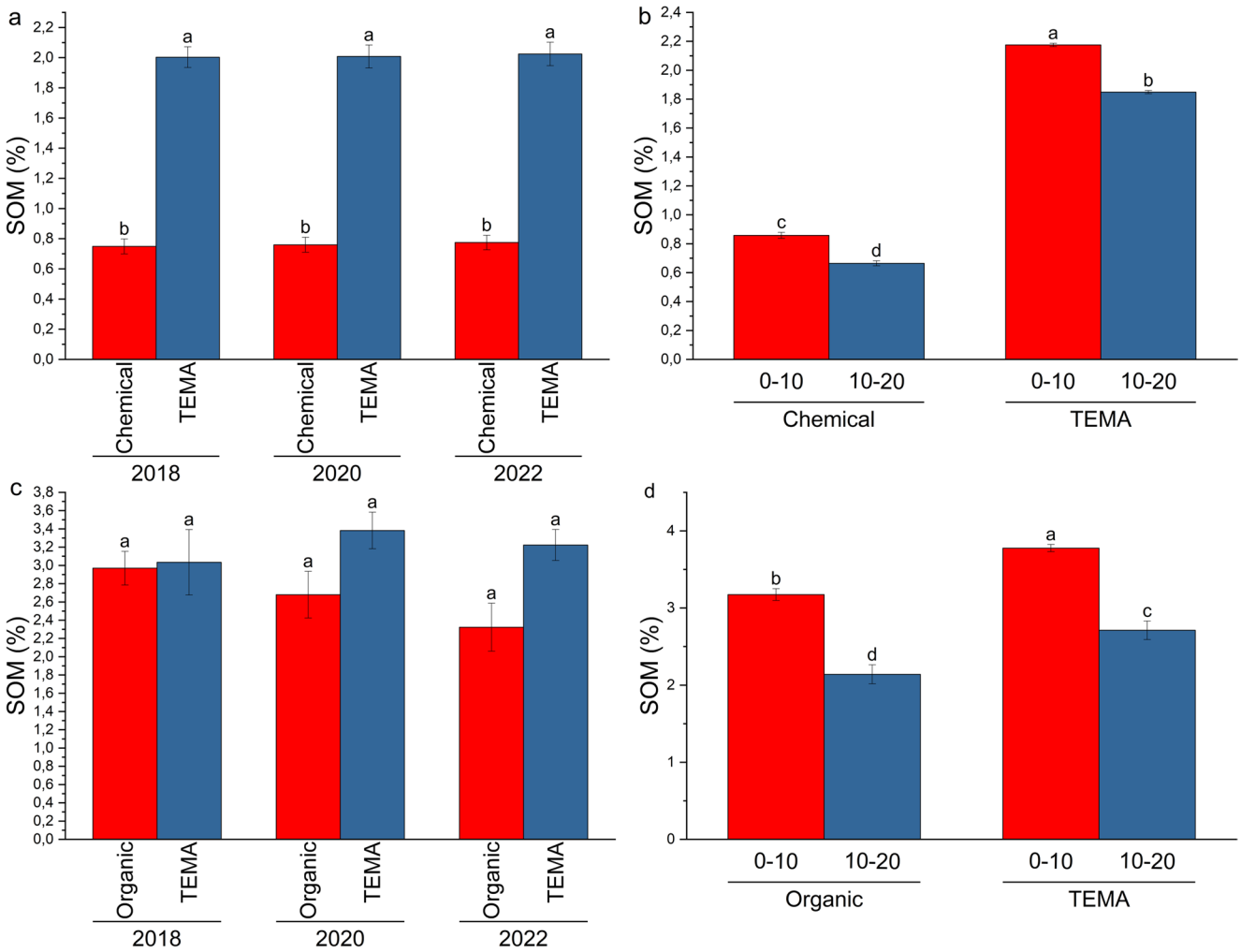


Fig. 5 Effects of treatment, year (2018, 2020, and 2022), and soil depth (0–10 and 10–20 cm) on soil organic matter (SOM, %) under conventional (**a**, **b**) and organic (**c**, **d**) management systems. Values represent mean ± standard error (SE) of three replicates. Different letters above the bars indicate significant differences among treatments based on two-way ANOVA, with comparisons among treatments performed within each year using Tukey's HSD test ($p < 0.05$). TEMA: 15 t ha^{-1} tea waste compost + 2 t ha^{-1} dolomite + hoeing

significantly in 2022 ($p < 0.05$) (Fig. 8c). Depth-related variations in BG activity were also statistically significant ($p < 0.05$) (Fig. 8d).

3.9 Effects of Treatments on Soil Fungal to Bacterial Ratio

Changes in the fungal to bacterial ratio as affected by treatments and soil depth under conventional management are shown in Fig. 9. Compared with chemical fertilization, TEMA application resulted in a significant increase in fungal to bacterial ratio over time ($p < 0.05$). Under TEMA, the fungal to bacterial ratio increased from 0.128 to 0.190 mg C kg^{-1} between 2018 and 2022, whereas under conventional fertilization the increase in surface soil fungal to bacterial ratio (0.074–0.092 mg C kg^{-1}) was not statistically significant (Fig. 9a). Depth-related variations fungal to bacterial ratio under TEMA application were statistically significant ($p < 0.05$) (Fig. 9b). Across all sampling periods, fungal to bacterial ratio Ratios were consistently higher in TEMA-treated soils than in soils receiving farmyard manure alone. While no significant temporal change was observed under organic management alone, the fungal to bacterial ratio under TEMA application increased significantly over time, rising from 0.147 to 0.193 mg C kg^{-1} (Fig. 9c). In both treatments, fungal to bacterial ratios were higher in surface soils, and differences related to treatments and soil depth were statistically significant ($p < 0.05$) (Fig. 9d).

3.10 10 Principal Component Analysis

The Principal Component Analysis (PCA) biplot for the conventionally managed tea plantation shows the distribution and influence of the selected soil variables on the first

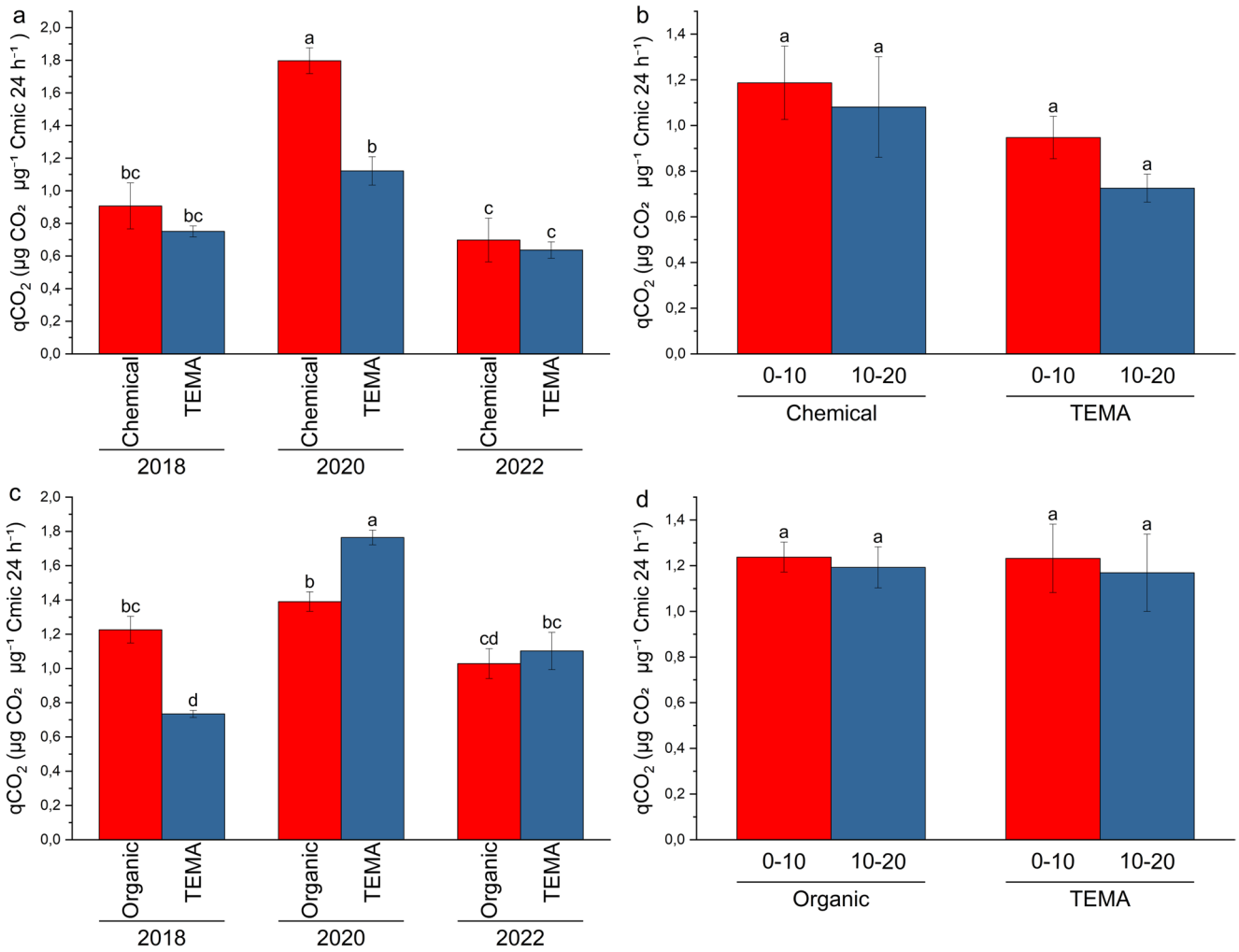


Fig. 6 Effects of treatment, year (2018, 2020, and 2022), and soil depth (0–10 and 10–20 cm) on soil specific respiration (qCO_2, mg CO_2–C g^{-1} microbial biomass C h^{-1}) under conventional (**a**, **b**) and organic (**c**, **d**) management systems. Values represent mean ± standard error (SE) of three replicates. Different letters above the bars indicate significant differences among treatments based on two-way ANOVA, with comparisons among treatments performed within each year using Tukey's HSD test ($p < 0.05$). TEMA: 15 t ha^{-1} tea waste compost + 2 t ha^{-1} dolomite + hoeing

two principal components, PC1 and PC2, which together explain 78.8% of the total variance, with 56.1% accounted for by PC1 and 22.7% by PC2 (Fig. S2A). PC1 is mainly associated with soil organic matter (SOM), $CaCO_3$, fungal to bacterial ratio, β-glucosidase, catalase, and pH, as indicated by their longer vectors oriented along the positive direction of this component. In contrast, electrical conductivity (EC) and specific respiration rate (qCO_2) show negative loadings on PC1. PC2 is primarily associated with EC and qCO_2, whereas β-glucosidase and catalase show weak to negative associations with this component. Clear temporal separation among sampling years is evident in the PCA biplot. Samples from 2018 are mainly distributed around the central and slightly negative regions of PC1, while samples from 2020 are predominantly clustered on the negative side of PC1 and the positive side of PC2, where EC and qCO_2 are more influential. In contrast, samples from 2022 are distinctly separated along the positive side of PC1, closely associated with SOM, pH, $CaCO_3$, catalase, β-glucosidase, and fungal to bacterial ratio. Overall, the PCA biplot for the conventionally managed system demonstrates a clear temporal shift in soil properties, with later sampling years showing stronger associations with soil chemical and biological indicators represented along PC1.

The Principal Component Analysis (PCA) biplot for the organically managed tea plantation shows the distribution and influence of the selected soil variables on the first two principal components, PC1 and PC2, which together explain 73.3% of the total variance, with 54.9% accounted for by PC1 and 18.4% by PC2 (Fig. S2B). PC1 is mainly associated with soil organic matter (SOM), $CaCO_3$, fungal to bacterial ratio, β-glucosidase, catalase, and pH, as indicated by their longer vectors oriented

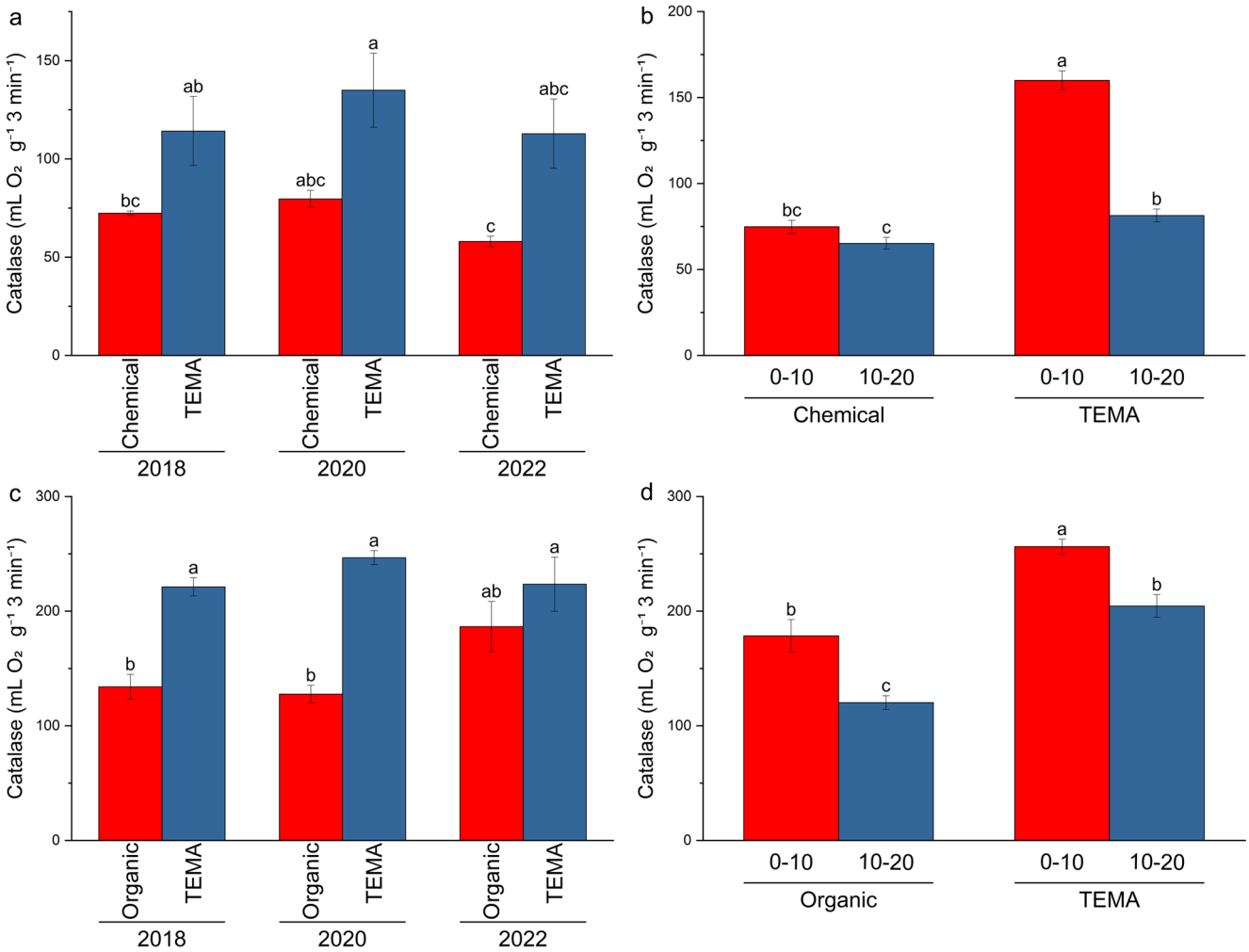


Fig. 7 Effects of treatment, year (2018, 2020, and 2022), and soil depth (0–10 and 10–20 cm) on soil catalase activity (mL O_2 g^{-1} 3 min^{-1}) under conventional (**a**, **b**) and organic (**c**, **d**) management systems. Values represent mean ± standard error (SE) of three replicates. Different letters above the bars indicate significant differences among treatments based on two-way ANOVA, with comparisons among treatments performed within each year using Tukey's HSD test ($p < 0.05$). TEMA: 15 t ha^{-1} tea waste compost + 2 t ha^{-1} dolomite + hoeing

along the positive direction of this component. In contrast, electrical conductivity (EC) shows a negative loading on PC1. PC2 is primarily associated with specific respiration rate (qCO_2), whereas catalase and $CaCO_3$ display negative associations with this component. Clear temporal separation among sampling years is evident in the PCA biplot. Samples from 2018 are mainly distributed on the negative side of PC1 and PC2, indicating lower associations with SOM, enzymatic activities, and $CaCO_3$. Samples from 2020 are more centrally distributed, reflecting intermediate conditions. In contrast, samples from 2022 are distinctly clustered on the positive side of PC1 and PC2, closely associated with SOM, pH, $CaCO_3$, β-glucosidase, catalase, and fungal to bacterial ratio. Overall, the PCA biplot for the organically managed system demonstrates a clear temporal shift in soil properties, with later sampling years showing stronger associations with soil chemical and biological indicators represented along PC1.

4 Discussion

Long-term soil acidification poses a persistent constraint in tea plantation systems, particularly under intensive fertilization regimes. This study evaluated whether integrated soil rehabilitation practices can simultaneously restore chemical buffering capacity, enhance biological functioning, and sustain tea productivity under strongly acidic conditions. The significant increase in fresh tea shoot yield under the TEMA treatment demonstrates that long-term productivity in acidic tea systems depends on integrated soil rehabilitation rather than single-input fertilization. In the conventional plantation, yield under chemical fertilization declined from 17,650 to 15,200 kg ha^{-1} over the study period, whereas TEMA maintained consistently higher and relatively stable yields (20100, 19900, and 20130 kg ha^{-1} in 2018, 2020, and 2022 respectively). This decline under fertilizer-only management

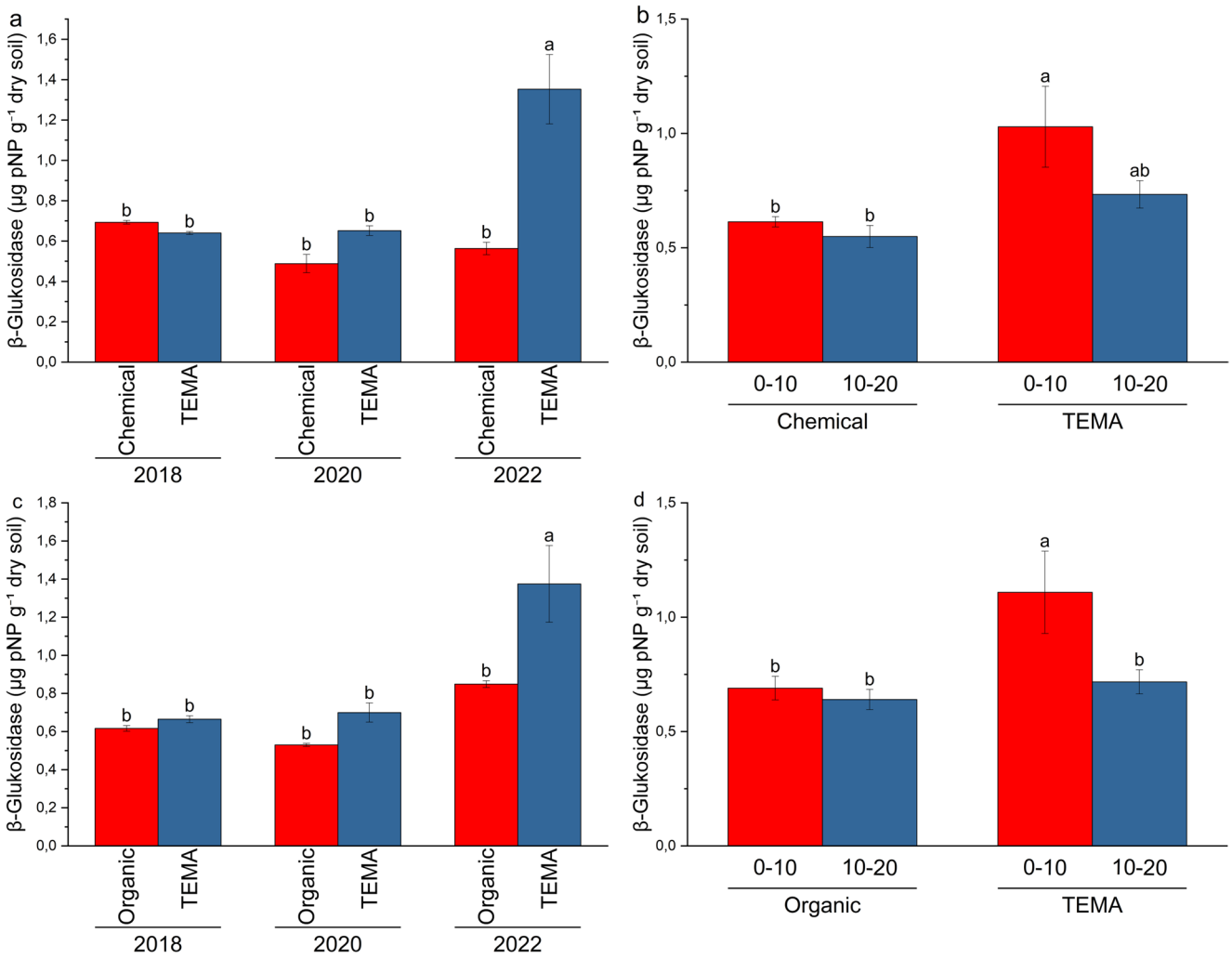


Fig. 8 Effects of treatment, year (2018, 2020, and 2022), and soil depth (0–10 and 10–20 cm) on soil β-glucosidase activity (µg p-nitrophenol g^{-1} soil h^{-1}) under conventional (**a**, **b**) and organic (**c**, **d**) management systems. Values represent mean ± standard error (SE) of three replicates. Different letters above the bars indicate significant differences among treatments based on two-way ANOVA, with comparisons among treatments performed within each year using Tukey's HSD test ($p < 0.05$). TEMA: 15 t ha^{-1} tea waste compost + 2 t ha^{-1} dolomite + hoeing

aligns with documented acidification processes in tea monocultures subjected to prolonged ammonium-based fertilization (Rebello et al. 2022). Repeated NH_4^+ fertilization promotes nitrification-driven proton release, accelerating soil acidification, depleting base cations, and increasing Al^{3+} and Mn^{2+} solubility. In already acidic tea soils, further pH decline intensifies Al toxicity, restricts root elongation, reduces nutrient uptake, and limits shoot productivity (Jahan et al. 2022; Sun et al. 2009). Acidification additionally constrains phosphorus availability through fixation by Al and Fe oxides and reduces exchangeable Ca and Mg pools, exacerbating nutrient imbalance (Jahan et al. 2022; Ye et al. 2022b). In contrast, the integrated TEMA treatment mitigated these constraints through combined liming and organic inputs. Dolomite buffered acidity and restored Ca^{2+} and Mg^{2+} availability (Zhao et al. 2025), while compost increased soil organic matter and nutrient retention capacity (Mjanja et al. 2025), and potentially complexed Al under acidic conditions (Rebello et al. 2022). In the organic plantation, manure alone resulted in low yields (6600–8800 kg ha^{-1}), whereas TEMA increased yields progressively from 27,500 to 35,400 kg ha^{-1}, indicating that organic inputs alone cannot overcome severe acidity without pH correction (Zhao et al. 2025). The temporal yield pattern suggests cumulative soil rehabilitation effects rather than short-term fertilization responses (Jahan et al. 2022). Interannual variation in climatic conditions may have also contributed to the observed variability in yield and soil responses. Differences in rainfall distribution and temperature regimes can influence plant growth dynamics, nutrient cycling, and microbial activity in tea plantation systems (Li et al. 2023; Zhang et al. 2020). Therefore, although all treatments were exposed to the same environmental conditions, year-to-year climatic variability may have partially influenced the magnitude of

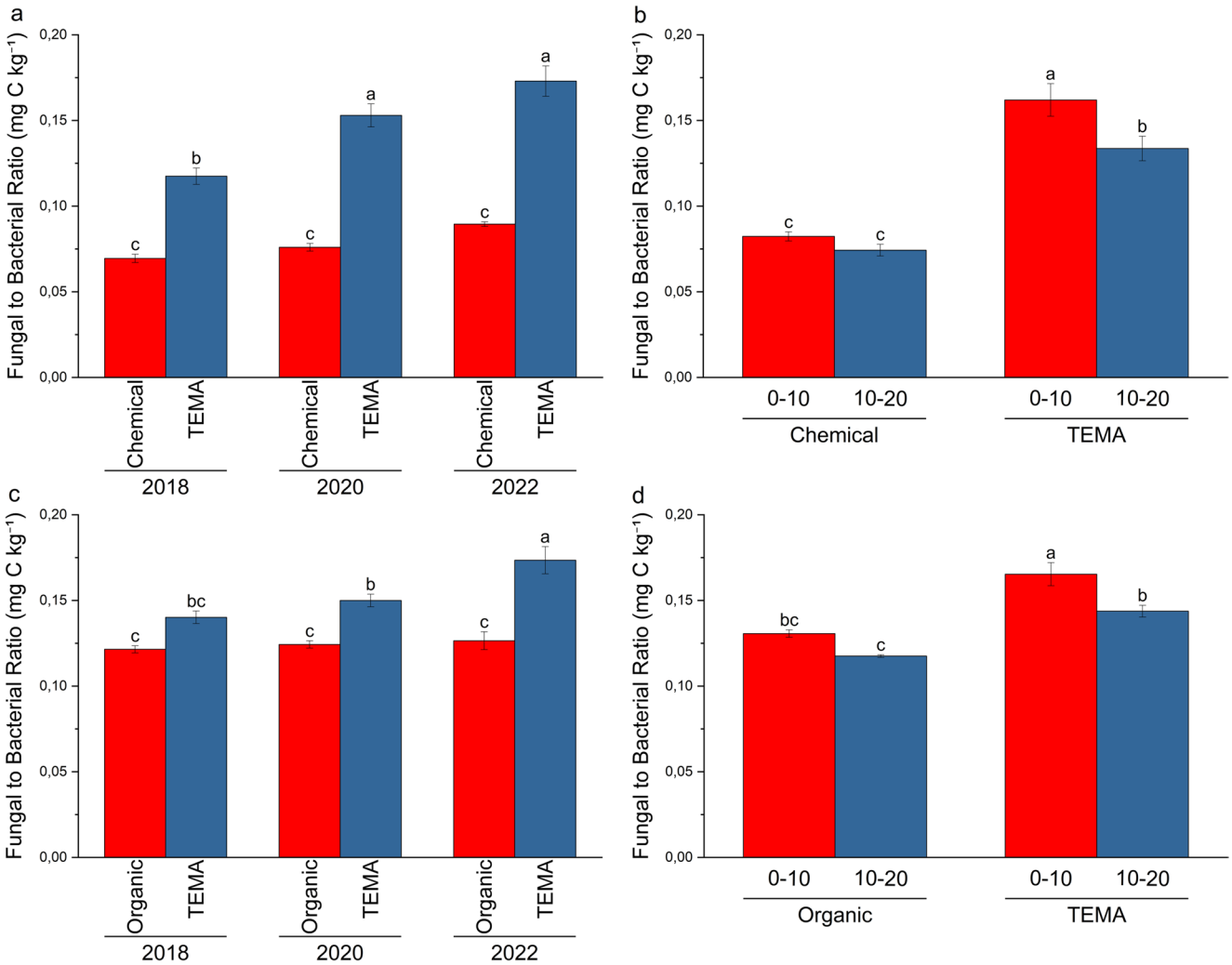


Fig. 9 Effects of treatment, year (2018, 2020, and 2022), and soil depth (0–10 and 10–20 cm) on the fungal-to-bacterial ratio (F/B) under conventional (**a**, **b**) and organic (**c**, **d**) management systems. Values represent mean ± standard error (SE) of three replicates. Different letters above the bars indicate significant differences among treatments based on two-way ANOVA, with comparisons among treatments performed within each year using Tukey's HSD test ($p < 0.05$). TEMA: 15 t ha^{-1} tea waste compost + 2 t ha^{-1} dolomite + hoeing

observed responses. Nevertheless, the consistent differences between treatments indicate that the primary drivers of yield and soil improvement were related to the integrated management practices rather than climatic fluctuations alone.

After establishing the productivity response, the underlying chemical drivers of yield variation require closer examination, particularly soil pH as the primary regulator of acidity in tea systems. Long-term soil acidification remains a primary constraint in tea cultivation, and our results show that management determines whether this constraint persists or is progressively alleviated. In the conventional plantation, soil pH remained strongly acidic under chemical fertilization with no meaningful rehabilitation over time, consistent with nitrification-driven proton release under repeated ammonium inputs (Gao et al. 2024; Ye et al. 2022b). In contrast, the TEMA treatment produced a clear temporal increase in pH, reaching ~ 5.6–5.7 in surface soil by the final year. Dolomite likely neutralized acidity through carbonate reactions while supplying Ca^{2+} and Mg^{2+}, thereby enhancing buffering capacity and reducing the solubility of phytotoxic Al species (Das et al. 2023; Gao et al. 2024). Such pH improvement creates a more favorable chemical environment for root growth and nutrient uptake. In the organic plantation, manure alone produced limited pH improvement, whereas the integrated treatment resulted in stronger buffering effects, indicating that combining organic inputs with liming enhances soil chemical stabilization more effectively than organic amendments alone (Chen et al. 2021; Dai et al. 2025; Liyanage et al. 2021). Greater pH changes in surface soil reflect amendment incorporation within the root-active zone (Gao et al. 2024). In addition to these pH-mediated effects, the integrated nature of the

TEMA treatment introduces important physicochemical and biological processes beyond simple nutrient supply. Dolomite application plays a critical role in buffering soil acidity by increasing soil pH and enhancing the availability of exchangeable Ca^{2+} and Mg^{2+}, while simultaneously reducing Al toxicity in acidic soils. These effects have been widely documented in both tea systems and comparable acidic agroecosystems, where liming improves soil buffering capacity and promotes more favorable root zone conditions (Arrobas et al. 2023). Moreover, soil mechanical practices such as hoeing can improve soil aeration, enhance root development, and facilitate nutrient cycling processes. Previous studies have shown that interactions between liming and soil physical management can further influence microbial activity, enzyme dynamics, and soil structural properties, indicating a synergistic relationship between chemical and mechanical interventions (Pacola et al. 2023). Therefore, the observed responses in this study should be interpreted as the combined outcome of amendment type, application rate, and integrated management practices rather than as a direct function of nutrient equivalence alone. Beyond acidity, changes in soil chemical status are also reflected in soluble ion dynamics, as captured by electrical conductivity (EC). Soil EC in humid tea-growing regions primarily reflects soluble nutrient dynamics rather than salinity risk, and all values remained below the 1 dS m^{-1} threshold considered safe for tea (Le et al. 2023; Sahu et al. 2023). Temporal EC variation in the conventional plantation likely reflected transient fertilizer-derived ionic peaks (Das et al. 2020), whereas convergence over time suggests stabilization through plant uptake and leaching (Ma et al. 2025). In the organic plantation, higher EC under TEMA reflected sustained nutrient release from compost mineralization and dolomite-derived Ca^{2+} and Mg^{2+} (Le et al. 2023; Shen and Lin 2021), consistent with gradual nutrient stabilization under integrated management (Tseng and Lai 2022).

While EC reflects short-term ionic fluctuations, longer-term buffering capacity is more directly represented by soil $CaCO_3$ dynamics. In the conventional plantation, low and stable $CaCO_3$ levels indicated limited buffering under fertilizer-only practice (Li et al. 2020b), whereas TEMA increased carbonate content through dolomite addition and enhanced base saturation via Al^{3+} displacement (The et al. 2006). In the organic plantation, TEMA further increased $CaCO_3$, reinforcing carbonate-mediated buffering in surface soil (Awopegba et al. 2017; Pędziwiatr et al. 2024).

In addition to carbonate buffering, organic carbon accumulation plays a central role in stabilizing soil chemical conditions. SOM increased more strongly under integrated management across both systems, particularly in the organic plantation where values reached 3.64–3.79%. This aligns with evidence that organic amendments enhance soil carbon stocks and microbial transformation processes (Hazarika et al. 2021; Mohammed et al. 2023). Increased SOM supports nutrient retention and reinforces chemical–biological feedback mechanisms (Gao et al. 2023; Khadim et al. 2024).

Given the key role of SOM in regulating microbial substrates, it is essential to evaluate how management influenced microbial metabolic efficiency, as indicated by qCO_2. Although temporal fluctuations occurred, all qCO_2 values remained below stress thresholds (Anderson 2003), indicating stable microbial functioning. Variations under TEMA likely reflected intensified metabolic activity associated with improved substrate availability and pH correction rather than stress-driven inefficiency (De Nobili et al. 2016; Pratamaningsih et al. 2023).

While qCO_2 reflects metabolic intensity, extracellular enzyme activities provide more direct insight into functional microbial processes. Soil enzyme activities responded clearly to long-term management, with consistently higher β-glucosidase and catalase activities under the integrated TEMA treatment. β-Glucosidase, which catalyzes the hydrolysis of cellobiose into glucose and regulates labile carbon release (Miao et al. 2024), was significantly stimulated under TEMA, indicating enhanced carbon turnover. Similar responses to compost and integrated nutrient management have been reported in acidic agroecosystems where organic inputs increase microbial biomass and enzyme synthesis (Zhang et al. 2023).

In strongly acidic soils, enzyme activity is often constrained by low pH and Al toxicity. Liming improves enzyme stability and microbial proliferation by alleviating acid stress (Liu et al. 2018). The elevated β-glucosidase activity under TEMA likely reflects combined effects of increased substrate supply and improved chemical conditions. Temporal variation further indicates dynamic responses to substrate availability and environmental fluctuations (Paradelo and Barral 2017; Pastor-Jáuregui et al. 2021).

Catalase, which decomposes hydrogen peroxide generated during aerobic metabolism (Mench et al. 2009), followed a similar trend, with higher activity under integrated management. Enhanced catalase activity suggests improved microbial resilience and oxidative stress regulation under buffered pH and increased organic inputs (Liu et al. 2018; Miao et al. 2024; Zhang et al. 2023). The coordinated increase in enzyme activities alongside higher SOM and stabilized pH provides a coherent mechanistic pattern: improved chemical conditions enhance substrate availability and microbial functioning. Interpreted together with sub-threshold qCO_2 values, elevated enzyme activities indicate intensified but stable biochemical functioning rather than stress-induced instability. Thus, integrated management strengthened the biological foundations of tea soil systems beyond fertilizer-only or manure-only practices.

Beyond enzyme responses, shifts in microbial community structure further clarify biological restructuring. In strongly acidic tea soils, elevated Fungal to Bacterial ratios generally reflect fungal dominance, which is associated with decomposition of complex substrates and improved structural stability. Organically managed soils exhibited consistently higher Fungal to Bacterial ratios than conventionally fertilized systems, consistent with evidence that organic inputs enhance fungal biomass through increased SOM and reduced chemical disturbance (Guo et al. 2020; Yang et al. 2022). Soil pH is a major driver of microbial composition, with acidic conditions suppressing bacteria more strongly than fungi (Han et al. 2021; Li et al. 2021). Management practices modulated this inherent fungal dominance over time. Under TEMA, compost-derived complex substrates likely stimulated fungal proliferation (Zhang et al. 2024), while partial pH correction contributed to a more balanced microbial structure rather than extreme dominance. The relationship between Fungal to Bacterial ratio, enzyme activity, and qCO_2 provides additional ecological insight. Higher Fungal to Bacterial ratios coincided with elevated β-glucosidase activity (Dai et al. 2025; Pu et al. 2025), indicating coordinated shifts in community composition and biochemical functioning. Combined with sub-threshold qCO_2 values, these results suggest active yet metabolically stable microbial systems rather than stress-driven imbalance. In perennial tea systems, fungal dominance contributes to aggregate formation and soil structural stability (Dai et al. 2025; Li et al. 2020a), reinforcing long-term ecosystem resilience. Overall, integrated management promoted a biologically structured and functionally robust microbial community.

The magnitude of the observed changes in this study can be better understood in the context of previous long-term tea soil research. Under conventional fertilization, long-term tea systems are often characterized by decreasing soil pH and limited improvements in soil organic matter and biological activity (Manzoor et al. 2024). In contrast, organic amendments have been reported to increase SOM and enzyme activities, although these effects are generally gradual and not always accompanied by simultaneous improvements in multiple soil functions (Hazarika et al. 2021). More importantly, studies on integrated nutrient management indicate that combining organic inputs with inorganic fertilization and/or liming leads to greater and more consistent improvements in soil pH, SOM, and biological indicators compared to single-input practices(Manzoor et al. 2024). However, even in these studies, the magnitude of change is often reported for individual parameters rather than a coordinated system-wide response. In this context, the results of the present study suggest a more pronounced and simultaneous improvement across chemical (pH, $CaCO_3$), organic (SOM), and biological (enzyme activities) indicators. This coordinated response indicates that the TEMA approach may enhance not only the magnitude but also the integration of soil improvements compared to previously reported management strategies in tea systems.

Across most soil parameters, the effects of the TEMA treatment were more pronounced in the surface layer (0–10 cm) than in the subsurface (10–20 cm). This pattern is consistent with findings from long-term studies in acidic soils, where integrated amendment practices such as compost application and liming primarily affect the upper soil layer due to direct application and limited downward movement of materials (Carmeis et al. 2017; Jakšić et al. 2020). In the present study, increases in soil pH, $CaCO_3$, and soil organic matter were generally stronger in surface soils, reflecting the localized impact of amendments within the root-active zone. In contrast, weaker or slower responses observed in the subsurface layer suggest that the vertical propagation of these effects is constrained by factors such as limited percolation, soil structure, and amendment mobility. Similar depth-dependent patterns have been widely reported, where chemical improvements, organic matter accumulation, and microbial activity are most pronounced in the topsoil, while subsoil responses are more variable and develop over longer timescales (Jat et al. 2024; Sandén et al. 2019). From a functional perspective, the stronger biological responses observed in surface soils can also be attributed to higher root density, greater organic inputs, and more favorable conditions for microbial activity. In contrast, subsurface layers receive fewer organic inputs and exhibit reduced biological activity, which may limit the magnitude of treatment effects. Overall, these findings indicate that the impact of integrated management is initially concentrated in the upper soil layer and gradually propagates downward over time.

The temporal evolution of soil responses suggests that the effects of integrated management did not occur simultaneously across all parameters but instead followed a gradual and sequential pattern. While increases in soil pH and $CaCO_3$ were already evident in the earlier years, and soil organic matter accumulated progressively over time, biological indicators including enzyme activities, qCO_2, and the Fungal to Bacterial ratio became more clearly differentiated only in the later stages of the study. In particular, β-glucosidase activity did not show significant differences in 2018 and 2020, but increased markedly in 2022, indicating a delayed response to management. This pattern suggests that improvements in chemical conditions preceded and progressively enabled biological responses, rather than triggering them immediately (Breugem et al. 2024; Lellei-Kovács et al. 2025; Maenhout et al. 2024).

In strongly acidic soils, increases in pH and base cations alleviate chemical limitations associated with low pH conditions and improve nutrient availability; however, these changes alone are not sufficient to induce immediate shifts in microbial functioning. Instead, the gradual accumulation of soil organic matter, supported by improved plant inputs under integrated management, provides the substrate necessary for microbial growth and enzyme production. As a result, biological responses tend to emerge only after sufficient SOM has accumulated and soil conditions have stabilized. This explains why enzyme activities and other biological indicators remained relatively unchanged in the early years despite improvements in soil chemical properties and only became significant once threshold conditions were reached. Similar delayed responses have been reported in long-term and perennial systems, where microbial activity and enzyme dynamics follow progressive improvements in SOM rather than short-term chemical changes (Alarcón Gutiérrez et al. 2021; Jinger et al. 2023; Tian 2012). This interpretation is consistent with previous studies showing that microbial biomass, enzyme activities, and even yield responses often lag behind initial improvements in soil chemical properties, reflecting the time required for SOM stabilization and microbial community adaptation (Berardi et al. 2020; Zhou et al. 2022). Therefore, the stronger biological differentiation observed in the final sampling year should be interpreted as the cumulative outcome of progressive soil improvement, rather than as a direct short-term response to treatment. This gradual transition is also evident in the PCA results, where samples from 2022 are clearly separated along the axis associated with soil chemical and biological indicators, indicating that system-level differentiation becomes more pronounced only after sustained co-development of chemical and biological processes over time.

To integrate these chemical and biological responses into a system-level framework, multivariate analysis was employed. The combined interpretation of soil chemical and biological indicators through PCA revealed coordinated changes in soil chemical and biological functioning in tea plantation soils under long-term management. PCA is commonly used to identify dominant gradients among soil chemical and biological indicators under contrasting management strategies (Dungan et al. 2025; Stellacci et al. 2021). In this study, SOM, pH, $CaCO_3$, β-glucosidase, catalase, and the fungal to bacterial ratio clustered along the primary axis of variation, whereas EC and qCO_2 were positioned along an opposing or secondary gradient. This multivariate structure indicates that long-term system differentiation was primarily associated with integrated improvements in chemical buffering capacity and biological functioning, rather than short-term fluctuations in soluble salts or transient respiratory responses. The strong alignment of enzymatic activities and microbial structure indicators with soil chemical buffering variables along the primary gradient suggests that improvements in SOM accumulation, pH stabilization, and carbonate buffering collectively enhanced biological functioning. These results support the interpretation that long-term soil rehabilitation in tea systems is driven by coordinated chemical stabilization and biological activation rather than isolated or short-term management effects. In this context, soil rehabilitation is evidenced by consistent improvements in key soil indicators, including increased pH, $CaCO_3$ content, SOM, enzyme activities (β-glucosidase and catalase), and the fungal to bacterial ratio. While these results provide strong evidence of coordinated functional changes in soil chemical and biological processes, the underlying microbial mechanisms were not directly resolved. Therefore, the findings should be interpreted at the level of functional indicators rather than detailed microbial community composition.

5 Conclusion

This long-term field study demonstrates that sustained soil rehabilitation in strongly acidic tea plantations cannot be achieved through single-input fertilization strategies alone. As hypothesized, continued reliance on fertilizer-only management maintained severe soil acidity and was associated with reduced yield performance. In contrast, the combined application of tea-waste compost, dolomite, and hoeing alleviated soil acidity and supported long-term productivity. The treatment significantly increased soil pH, enhanced $CaCO_3$ levels, and promoted the accumulation of soil organic matter. These chemical improvements were accompanied by higher β-glucosidase and catalase activities and a more balanced fungal tobacterial ratio, indicating improved biological functioning under less acidic conditions. The results support the hypothesis that coordinated chemical buffering and biological functioning are key components of long-term rehabilitation of acidic tea soils. Soil pH stabilization appears to play a central role in regulating these processes. The combined use of organic inputs and liming therefore represents a practical and context-specific strategy for restoring degraded tea-growing soils, although its broader applicability requires further validation under different environmental conditions. These findings provide practical implications for sustainable tea cultivation, particularly for farmers, land managers, and policymakers working in acidic soil environments, and contribute long-term field-based evidence from strongly acidic soils under Türkiye conditions.

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Authors' contributions A. Namli: Conceptualization, Investigation, Writing – original draft, Writing – review and editing; M. O. Akca: Visualization, Writing – original draft, Writing – review and editing; S. Farasat: Writing – original draft, N. Özer: determination of application areas, cooperation with farmers and field studies.

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Data availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Alarcón Gutiérrez E, Hernández C, Gardner T, García Pérez JA, Caballero M, Perroni Y, Farnet da Silva AM a, Gaime Perraud I, Barois I (2021) Soil bioindicators associated to different management regimes of *Cedrela odorata* plantations. Madera y Bosques 27:. https://doi.org/10.21829/myb.2021.2711912

Anderson T-H (2003) Microbial eco-physiological indicators to asses soil quality. Agric Ecosyst Environ 98:285–293. https://doi.org/10.1016/S0167-8809(03)00088-4

Arrobas M, Conceição N, Pereira E, Martins S, Raimundo S, Brito C, Correia CM, Rodrigues MÂ (2023) Dolomitic limestone was more effective than calcitic limestone in increasing soil pH in an untilled olive orchard. Soil Use Manag 39:1437–1452. https://doi.org/10.1111/sum.12948

Awopegba M, Oladele S, Awodun M (2017) Effect of mulch types on nutrient composition, maize (*Zea mays* L.) yield and soil properties of a tropical Alfisol in Southwestern Nigeria. Eur J Soil Sci 6:121–121. https://doi.org/10.18393/ejss.286546

Bania JK, Deka JR, Paul A, Nath AJ, Sileshi GW, Das AK (2025) Highly suitable areas for tea (*Camellia sinensis*) production will decline under future climate change scenarios. Environ Sustain Indic 26:100720. https://doi.org/10.1016/j.indic.2025.100720

Bebber DP, Richards VR (2022) A meta-analysis of the effect of organic and mineral fertilizers on soil microbial diversity. Appl Soil Ecol 175:104450. https://doi.org/10.1016/j.apsoil.2022.104450

Beck T (1971) Die Messung der Kataloseaktivität von Böden. Z für Pflanzenernährung und Bodenkunde 130:68–81. https://doi.org/10.1002/jpln.19711300108

Berardi D, Brzostek E, Blanc-Betes E, Davison B, DeLucia EH, Hartman MD, Kent J, Parton WJ, Saha D, Hudiburg TW (2020) 21st-century biogeochemical modeling: Challenges for Century-based models and where do we go from here? GCB Bioenergy 12:774–788. https://doi.org/10.1111/gcbb.12730

Bloem J (1995) Fluorescent staining of microbes for total direct counts. Molecular Microbial Ecology Manual. Springer Netherlands, Dordrecht, pp 367–378

Bouyoucos GJ (1951) A Recalibration of the Hydrometer Method for Making Mechanical Analysis of Soils 1. Agron J 43:434–438. https://doi.org/10.2134/agronj1951.00021962004300090005x

Bremner JM (1996) Nitrogen-Total. pp 1085–1121

Breugem A, Kros H, de Vries W (2024) Impacts of pH on mechanisms and rates of carbon and nitrogen mineralisation: a review. Wageningen Environmental Research, Wageningen, The Netherlands

Carmeis FA, Penn CJ, Crusciol CAC, Calonego JC (2017) Lime and phosphogypsum impacts on soil organic matter pools in a tropical Oxisol under long-term no-till conditions. Agric Ecosyst Environ 241:11–23. https://doi.org/10.1016/j.agee.2017.02.027

Chen Y-P, Tsai C-F, Rekha PD, Ghate SD, Huang H-Y, Hsu Y-H, Liaw L-L, Young C-C (2021) Agricultural management practices influence the soil enzyme activity and bacterial community structure in tea plantations. Bot Stud 62:8. https://doi.org/10.1186/s40529-021-00314-9

Dai C, Xiang F, Liu H, Zhou L, Li W (2025) The Prolonged Application of Organic Fertilizers Increases the Quality and Yield of Tea Crops. Plants 14:1317. https://doi.org/10.3390/plants14091317

Das RS, Rahman M, Sufian NP, Rahman SMA, Siddique MAM (2020) Assessment of soil salinity in the accreted and non-accreted land and its implication on the agricultural aspects of the Noakhali coastal region. Bangladesh Heliyon 6:e04926. https://doi.org/10.1016/j.heliyon.2020.e04926

Das S, Das A, Idapuganti RG, Layek J, Thakuria D, Sarkar D, Bhupenchandra I, Lal R, Chowdhury S, Babu S, Debbarma K (2023) Liming and micronutrient application improves soil properties and productivity of the groundnut-rapeseed cropping system in an acidic Inceptisol of India's eastern Himalayas. Land Degrad Dev 34:3681–3699. https://doi.org/10.1002/ldr.4713

De Nobili M, Brookes PC, Sánchez-Monedero MA, Contin M (2016) The complexity of soil biological sustainability. Acta Hortic 69–78. https://doi.org/10.17660/ActaHortic.2016.1146.9

de Vries W, Posch M, Simpson D, de Leeuw FAAM, van Grinsven HJM, Schulte-Uebbing LF, Sutton MA, Ros GH (2024) Trends and geographic variation in adverse impacts of nitrogen use in Europe on human health, climate, and ecosystems: A review. Earth Sci Rev 253:104789. https://doi.org/10.1016/j.earscirev.2024.104789

Dengiz O, İç S, Saygın F, İmamoğlu A, Mihalikova M (2020) Assessment of Soil Quality Index for Tea Cultivated Soils in Ortaçay

Micro Catchment in Black Sea Region. https://doi.org/10.15832/ankutbd.468900. Tarım Bilimleri Dergisi

Dungan RS, Acosta-Martinez V, Lehman RM, Manter DK, Mikha MM, Reardon CL, White PM Jr (2025) Short-term effects of a heavy dairy manure application on soil chemical and biological indicators in an irrigated semiarid cropping system. Agron J 117:e21737. https://doi.org/10.1002/agj2.21737

Gao S, Harrison BP, Thao T, Gonzales ML, An D, Ghezzehei TA, Diaz G, Ryals RA (2023) Biochar co-compost improves nitrogen retention and reduces carbon emissions in a winter wheat cropping system. GCB Bioenergy 15:462–477. https://doi.org/10.1111/gcbb.13028

Gao X, Liu C, Guo C, Duan X, Zhang Y, Ma C (2024) Soil Acidification and Its Temporal Changes in Tea Plantations of Guizhou Province, Southwest China. Land Degrad Dev 35:5648–5658. https://doi.org/10.1002/ldr.5321

Guo J, Ling N, Chen Z, Xue C, Li L, Liu L, Gao L, Wang M, Ruan J, Guo S, Vandenkoornhuyse P, Shen Q (2020) Soil fungal assemblage complexity is dependent on soil fertility and dominated by deterministic processes. New Phytol 226:232–243. https://doi.org/10.1111/nph.16345

Haciimamoglu T, Bulbul G, Yildirim K, Kartal B (2025) Assessing climate change effects on Turkish tea farming through a dual approach using MMQR and machine learning. Sci Rep 16:122. https://doi.org/10.1038/s41598-025-29358-8

Han Z, Wang J, Xu P, Li Z, Liu S, Zou J (2021) Differential responses of soil nitrogen-oxide emissions to organic substitution for synthetic fertilizer and biochar amendment in a subtropical tea plantation. GCB Bioenergy 13:1260–1274. https://doi.org/10.1111/gcbb.12842

Hazarika S, Sohliya B, Thakuria D, Kataki S, Rangappa K (2021) Influence of organic amendments on acidic soil responsive crop groundnut (*Arachis hypogaea* L). Environ Prog Sustain Energy 40. https://doi.org/10.1002/ep.13592

Jahan I, Shopan J, Rahman MM, Sarkar A, Baset MA, Zhang Z, Li X, Ahammed GJ, Hasan MK (2022) Long-Term Traditional Fertilization Alters Tea Garden Soil Properties and Tea Leaf Quality in Bangladesh. Agronomy 12:2128. https://doi.org/10.3390/agronomy12092128

Jakšić S, Ninkov J, Milić S, Vasin J, Banjac D, Jakšić D, Živanov M (2020) The State of Soil Organic Carbon in Vineyards as Affected by Soil Types and Fertilization Strategies (Tri Morave Region, Serbia). Agronomy 11:9. https://doi.org/10.3390/agronomy11010009

Jat RS, Singh HV, Dotaniya ML, Choudhary RL, Meena MK, Rai PK (2024) Biological and chemical vicissitudes in soil rhizosphere arbitrated under different tillage, residues recycling and oilseed brassica-based cropping systems. Sustainability 16:2027. https://doi.org/10.3390/su16052027

Jia X, Zhang Q, Wang Y, Zhang Y, Li M, Cheng P, Chen M, Lin S, Zou J, Ye J, Wang H (2023) Changes of physiological characteristics, element accumulation and hormone metabolism of tea leaves in response to soil pH. Front Plant Sci 14. https://doi.org/10.3389/fpls.2023.1266026

Jinger D, Kaushal R, Kumar R et al (2023) Degraded land rehabilitation through agroforestry in India: Achievements, current understanding, and future prospectives. Front Ecol Evol 11. https://doi.org/10.3389/fevo.2023.1088796

Jones JB, Wolf B, Mills HA (1991) Plant analysis handbook: a practical sampling, preparation, analysis, and interpretation guide. Micro-Macro Pub

Kavitha S (2016) Nutrient Availability of tea growing soil influenced by different rates of dolomite. J Tea Sci Res 6:1–7. https://doi.org/10.5376/jtsr.2016.06.0001

Khadim MD, Wesal AB, Peezhand AW (2024) Overview of the impact of compost on bulk density, aggregate consistency and cation exchange capacity of soils and its consequential effect on crop productivity. CJMS 4:344–359. https://doi.org/10.47760/cognizance.2024.v04i06.021

Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World Map of the Köppen-Geiger climate classification updated. Meteorol Z 15:259–263. https://doi.org/10.1127/0941-2948/2006/0130

Le VS, Herrmann L, Bräu L, Lesueur D (2023) Sustainable green tea production through agroecological management and land conversion practices for restoring soil health, crop productivity and economic efficiency: Evidence from Northern Vietnam. Soil Use Manag 39:1185–1204. https://doi.org/10.1111/sum.12885

Lellei-Kovács E, Botta-Dukát Z, Ónodi G, Mojzes A, Kröel-Dulay G (2025) The negative legacy effect of extreme drought on soil respiration is unaffected by post-drought precipitation regime in a temperate grassland. Glob Chang Biol 31. https://doi.org/10.1111/gcb.70083

Li J, Luo Z, Zhang C, Qu X, Chen M, Song T, Yuan J (2020a) Seasonal variation in the rhizosphere and non-rhizosphere microbial community structures and functions of *Camellia yuhsienensis* Hu. Microorganisms 8:1385. https://doi.org/10.3390/microorganisms8091385

Li J, Xue Y, Chen M, Su H, Wu Z, Duan T (2020b) improving effects of different calcium-magnesium conditioners on latosol. Am J Biochem Biotechnol 16:473–481. https://doi.org/10.3844/ajbbsp.2020.473.481

Li M, Hu J, Lin X (2021) Profiles and interrelationships of functional soil microbiomes involved in phosphorus cycling in diversified agricultural land-use systems. Food Energy Secur 10:e315. https://doi.org/10.1002/fes3.315

Li Y, Zhang J, Qiu Q, Zhou Y, You W (2023) Changes in soil properties and enzyme stoichiometry in three different forest types changed to tea plantations. Forests 14:2043. https://doi.org/10.3390/f14102043

Lin W, Lin M, Zhou H, Wu H, Li Z, Lin W (2019) The effects of chemical and organic fertilizer usage on rhizosphere soil in tea orchards. PLoS ONE 14:e0217018. https://doi.org/10.1371/journal.pone.0217018

Liu XY, Rashti MR, Esfandbod M, Powell B, Chen CR (2018) Liming improves soil microbial growth, but trash blanket placement increases labile carbon and nitrogen availability in a sugarcane soil of subtropical Australia. Soil Res 56:235–243. https://doi.org/10.1071/SR17116

Liu W, Cui S, Wu L, Qi W, Chen J, Ye Z, Ma J, Liu D (2023) Effects of bio-organic fertilizer on soil fertility, yield, and quality of tea. J Soil Sci Plant Nutr 23:5109–5121. https://doi.org/10.1007/s42729-023-01195-6

Liyanage LRMC, Sulaiman MF, Ismail R, Gunaratne GP, Dharmakeerthi RS, Rupasinghe MGN, Mayakaduwa AP, Hanafi MM (2021) Carbon mineralization dynamics of organic materials and their usage in the restoration of degraded tropical tea-growing soil. Agronomy 11:1191. https://doi.org/10.3390/agronomy11061191

Luo Y, Zhang Y, Wang Y, Sun Y, Xia X, Su Y, Liao W (2023) Combined application of biochar and pruned tea plant litter benefits nitrogen availability for tea and alters microbial community structure. Agronomy 13:1465. https://doi.org/10.3390/agronomy13061465

Ma X, Ou X, Chen D, Li Y, McMillan C, Ge T, Liu J, Xue M, Wang C, Shen W (2025) Shifts in fungal communities and potential functions under masson pine forest-to-tea plantation conversion in subtropical China. Microorganisms 13:1614. https://doi.org/10.3390/microorganisms13071614

Maenhout P, Di Bene C, Cayuela ML, Diaz-Pines E, Govednik A, Keuper F, Mavsar S, Mihelic R, O'Toole A, Schwarzmann A, Suhadolc M, Syp A, Valkama E (2024) Trade-offs and synergies of soil carbon sequestration: Addressing knowledge gaps related to soil management strategies. Eur J Soil Sci 75:e13515. https://doi.org/10.1111/ejss.13515

Manzoor ML, Ni K, Ruan J (2024) Influence of organic and inorganic fertilizers on tea growth and quality and soil properties of tea orchards' top rhizosphere soil. Plants 13:207. https://doi.org/10.3390/plants13020207

Mench M, Schwitzguébel J-P, Schroeder P, Bert V, Gawronski S, Gupta S (2009) Assessment of successful experiments and limitations of phytotechnologies: contaminant uptake, detoxification and sequestration, and consequences for food safety. Environ Sci Pollut Res 16:876–900. https://doi.org/10.1007/s11356-009-0252-z

Miao P, Pang X, Zhang M, Cheng W, Zhou Z, Li Y, Wang H, Jia X, Ye J, Zhang Q (2024) Enhancing soil health and tea plant quality through integrated organic and chemical fertilization strategies. Horticulturae 10:1311. https://doi.org/10.3390/horticulturae10121311

Mjanja BE, Shitindi MJ, Massawe BH, Mulashani GR (2025) Driving sustainability in tea farming: insights on organo-mineral fertilizers. Fronti Soil Sci 5:1629846. https://doi.org/10.3389/fsoil.2025.1629846

Mohammed I, Kodaolu B, Zhang T, Wang Y, Audette Y, Longstaffe J (2023) Analysis of molecular structure changes in humic acids from manure-amended soils over 17 years using elemental analysis and solid-state 13 C nuclear magnetic resonance spectroscopy. Soil Syst 7:76. https://doi.org/10.3390/soilsystems7030076

Murphy J, Riley JP (1962) A modified single solution method for the determination of phosphate in natural waters. Anal Chim Acta 27:31–36. https://doi.org/10.1016/S0003-2670(00)88444-5

Naseby DC, Lynch JM (1997) Rhizosphere soil enzymes as indicators of perturbations caused by enzyme substrate addition and inoculation of a genetically modified strain of Pseudomonas fluorescens on wheat seed. Soil Biol Biochem 29:1353–1362. https://doi.org/10.1016/S0038-0717(97)00061-8

Nelson DW, Sommers LE (1996) Total Carbon, Organic Carbon, and Organic Matter. pp 961–1010

Pacola M, Guimarães TM, Rigon JPG, Jacomassi LM, Bossolani JW, Viveiros J, de Siqueira GF, Dias PP, Calonego JC, Crusciol CAC (2023) Soil tillage systems and forms of lime application on soil attribute enhancements in ratoon sugarcane. Soil Use Manag 39:1388–1402. https://doi.org/10.1111/sum.12924

Paradelo R, Barral MT (2017) Availability and fractionation of Cu, Pb and Zn in an acid soil from Galicia (NW Spain) amended with municipal solid waste compost. Span J Soil Sci 7:31–39. https://doi.org/10.3232/SJSS.2017.V7.N1.03

Pastor-Jáuregui R, Paniagua-López M, Aguilar-Garrido A, Martín-Peinado F, Sierra-Aragón M (2021) Long-term assessment of remediation treatments applied to an area affected by a mining spill in Spain. Land Degrad Dev 32:2481–2492. https://doi.org/10.1002/ldr.3911

Pędziwiatr A, Kierczak J, Potysz A, Pietranik A (2024) Effect of soil additives on biogeochemistry of ultramafic soils—an experimental approach with *Brassica napus* L. Environ Monit Assess 196:744. https://doi.org/10.1007/s10661-024-12897-4

Pratamaningsih MM, Hati DP, Erwinda E, Muslim RQ, Kricella P, Subandiono RE, Mulyani A (2023) Potential development of tropical fruits on Kundur Island, Riau Islands Province, Indonesia. IOP Conf Ser Earth Environ Sci 1266:012096. https://doi.org/10.1088/1755-1315/1266/1/012096

Pu T, Tan Y, Zhao Y, Zhao Z, Zhang N, Li C, Song Y (2025) Effect of seasonal variations on soil microbial, extracellular enzymes, and ecological stoichiometry in tea plantations. Ecol Evol 15:e71362. https://doi.org/10.1002/ece3.71362

Rashidabad NN, Hashemi M, Keiser AD, Farhangi-Abriz S, Siller A (2025) The impact of soil covering on nitrogen losses from agroecosystems. pp 29–99

Raza A, Chaoqun C, Luo L, Asghar MA, Li L, Shoaib N, Yin C (2024) Combined application of organic and chemical fertilizers improved the catechins and flavonoids biosynthesis involved in tea quality. Sci Hortic 337:113518. https://doi.org/10.1016/j.scienta.2024.113518

Rebello R, Burgess PJ, Girkin NT (2022) Identifying sustainable nitrogen management practices for tea plantations. Nitrogen 3:43–57. https://doi.org/10.3390/nitrogen3010003

Richards LA (1954) Diagnosis and improvement of saline and alkali soils. Soil Sci 78:154. https://doi.org/10.1097/00010694-195408000-00012

Sahu N, Das P, Saini A, Varun A, Mallick SK, Nayan R, Aggarwal SP, Pani B, Kesharwani R, Kumar A (2023) Analysis of tea plantation suitability using geostatistical and machine learning techniques: A case of Darjeeling Himalaya, India. Sustainability 15:10101. https://doi.org/10.3390/su151310101

Sandén T, Zavattaro L, Spiegel H, Grignani C, Sandén H, Baumgarten A, Tiirola M, Mikkonen A (2019) Out of sight: Profiling soil characteristics, nutrients and bacterial communities affected by organic amendments down to one meter in a long-term maize experiment. Appl Soil Ecol 134:54–63. https://doi.org/10.1016/j.apsoil.2018.10.017

Shen F-T, Lin S-H (2021) Priming effects of cover cropping on bacterial community in a tea plantation. Sustainability 13:4345. https://doi.org/10.3390/su13084345

Shu X, He J, Zhou Z, Xia L, Hu Y, Zhang Y, Zhang Y, Luo Y, Chu H, Liu W, Yuan S, Gao X, Wang C (2022) Organic amendments enhance soil microbial diversity, microbial functionality and crop yields: A meta-analysis. Sci Total Environ 829:154627. https://doi.org/10.1016/j.scitotenv.2022.154627

Soil Taxonomy (2022) Soil Survey Staff Keys to Soil Taxonomy, 13th ed.U.S. Department of Agriculture, Natural Resources Conservation Service: Washington, DC, USA, 2022

Stellacci AM, Castellini M, Diacono M, Rossi R, Gattullo CE (2021) Assessment of soil quality under different soil management strategies: combined use of statistical approaches to select the most informative soil physico-chemical indicators. Appl Sci 11:5099. https://doi.org/10.3390/app11115099

Sun T, Liu P, Xie Z-L, Luo H (2009) Forms and Accumulation of aluminum in tea plant (*Camellia sinensis*). Acta Agron Sin 35:1909–1915. https://doi.org/10.3724/SP.J.1006.2009.01909

The C, Calba H, Zonkeng C, Ngonkeu ELM, Adetimirin VO, Mafouasson HA, Meka SS, Horst WJ (2006) Responses of maize grain yield to changes in acid soil characteristics after soil amendments. Plant Soil 284:45–57. https://doi.org/10.1007/s11104-006-0029-9

Thomas GW (1996) Soil pH and Soil Acidity. pp 475–490

Tian Y (2012) Soil microbiological properties and enzyme activities in ginkgo-tea agroforestry compared to monoculture. For Res 1:2. https://doi.org/10.4172/2168-9776.1000107

Tseng W-Y, Lai H-Y (2022) Comprehensive analysis revealed the specific soil properties and foliar elements respond to the quality composition levels of tea (*Camellia sinensis* L). Agronomy 12:670. https://doi.org/10.3390/agronomy12030670

Turkish State Meteorological Service (2025) General Directorate of State Meteorology Affairs Rize Official Climate Statistics

Turumtay H, Tombuloglu H, Havva Er, Sandalli C, Akyuz Turumtay E (2022) Elucidation of bioactive compounds in flower extracts of *Camellia sinensis* by HPLC-DAD-MS/MS and their inhibitory effects on replicative bacterial DNA polymerases. Ind Crops Prod 188:115528. https://doi.org/10.1016/j.indcrop.2022.115528

Wang B, Wang S, Li G, Fu L, Chen H, Yin M, Chen J (2025) Reducing nitrogen fertilizer usage coupled with organic substitution improves soil quality and boosts tea yield and quality in tea plantations. J Sci Food Agric 105:1228–1238. https://doi.org/10.1002/jsfa.13913

Wenyika P, Enesi RO, Gorim LY, Dyck M (2025) Effects of liming on soil physical and chemical properties in Europe and North

America: A review. Agrosyst Geosci Environ 8:e70175. https://doi.org/10.1002/agg2.70175

Xing Y, Wang X, Mustafa A (2025a) Exploring the link between soil health and crop productivity. Ecotoxicol Environ Saf 289:117703. https://doi.org/10.1016/j.ecoenv.2025.117703

Xing Y, Xie Y, Wang X (2025b) Enhancing soil health through balanced fertilization: a pathway to sustainable agriculture and food security. Front Microbiol 16:1536524. https://doi.org/10.3389/fmicb.2025.1536524

Xu J, Li Y, Li L (2025) A comprehensive review of the effects of organic amendments on soil health and fertility: mechanisms, greenhouse gas emissions, and implications for sustainable agriculture. Agronomy 15:2705. https://doi.org/10.3390/agronomy15122705

Yang G, Zhou D, Wan R, Wang C, Xie J, Ma C, Li Y (2022) HPLC and high-throughput sequencing revealed higher tea-leaves quality, soil fertility and microbial community diversity in ancient tea plantations: compared with modern tea plantations. BMC Plant Biol 22:239. https://doi.org/10.1186/s12870-022-03633-6

Ye J, Wang Y, Kang J, Chen Y, Hong L, Li M, Jia Y, Wang Y, Jia X, Wu Z, Wang H (2022a) Effects of long-term use of organic fertilizer with different dosages on soil improvement, nitrogen transformation, tea yield and quality in acidified tea plantations. Plants 12:122. https://doi.org/10.3390/plants12010122

Ye J, Wang Y, Wang Y, Hong L, Jia X, Kang J, Lin S, Wu Z, Wang H (2022b) Improvement of soil acidification in tea plantations by long-term use of organic fertilizers and its effect on tea yield and quality. Front Plant Sci 13. https://doi.org/10.3389/fpls.2022.1055900

Zhang W, Yao Z, Zheng X, Liu C, Wang R, Wang K, Li S, Han S, Zuo Q, Shi J (2020) Effects of fertilization and stand age on N 2 O and NO emissions from tea plantations: a site-scale study in a subtropical region using a modified biogeochemical model. Atmos Chem Phys 20:6903–6919. https://doi.org/10.5194/acp-20-6903-2020

Zhang Q, Zhang Y, Miao P, Chen M, Du M, Pang X, Ye J, Wang H, Jia X (2023) Effects of pruning on tea tree growth, soil enzyme activity and microbial diversity. Agronomy 13:1214. https://doi.org/10.3390/agronomy13051214

Zhang S, Lv J, Li Y, Zhang L, Hu Q, Li Z, Yang X, Li J, Wu T, Mao Y, Zhang L, Han W, Yan P, Li X (2024) Changes in soil organic carbon stocks and mineralization following the replacement of secondary evergreen broadleaf forests with tea (*Camellia sinensis* L.) plantations. Soil Use Manag 40:e13125. https://doi.org/10.1111/sum.13125

Zhao C, He X, Jiang H, Wang X, Gao J, Hu C (2025) Liming alters microbial communities affecting nitrification in the rhizosphere of *Camellia sinensis*. Agronomy 16:77. https://doi.org/10.3390/agronomy16010077

Zhou Z, Tian F, Zhao X, Zhang K, Han S (2022) Short-term but not long-term perennial mugwort cropping increases soil organic carbon in Northern China Plain. Front Plant Sci 13:975169. https://doi.org/10.3389/fpls.2022.975169

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