

Linking soil biological restoration with crop quality and ecosystem functions in organic Oolong tea agroecosystems

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Research Article

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Abstract

Sustainable management of perennial agroecosystems requires strategies that maintain crop productivity while enhancing soil health and ecosystem functions. However, the interactions among soil biological processes, crop performance, and quality formation remain insufficiently understood in tropical tea production systems.

This study evaluated the effects of organic and conventional management on soil–plant interactions in Oolong tea (*Camellia sinensis* L.) agroecosystems in the Central Highlands of Vietnam. A two-season field experiment using a randomized complete block design was conducted to assess crop productivity, soil properties, microbial biomass, phytochemical quality, and ecological pest regulation.

Organic management resulted in a moderate reduction in fresh tea yield (– 9.2%) but improved soil ecosystem indicators, including soil organic carbon (+ 33.0%), total nitrogen (+ 33.3%), microbial biomass carbon (+ 45.3%), and soil moisture retention (+ 24.6%). These improvements were accompanied by increased polyphenol content (+ 18.1%), catechin concentration (+ 15.6%), and antioxidant activity (+ 15.2%).

Correlation and multivariate analyses showed strong associations between soil biological indicators and tea quality traits, suggesting that improved belowground functioning contributes to enhanced ecosystem performance.

These findings demonstrate that organic management can strengthen soil biological functions while maintaining productive and high-quality tea agroecosystems. The results provide insights into sustainable management strategies for perennial tropical cropping systems.

1. Introduction

Tea (*Camellia sinensis* L.) is an economically important perennial crop cultivated across diverse tropical and subtropical agroecosystems. As a long-lived production system, tea cultivation strongly depends on the maintenance of soil fertility, biological processes, and ecological stability to sustain both productivity and product quality. In addition to yield performance, tea value is influenced by biochemical attributes, including catechins, polyphenols, flavonoids, and antioxidant compounds, which determine sensory characteristics and functional properties (Ahmed et al., 2014; Zhang et al., 2019; Li et al., 2022). The accumulation of these secondary metabolites is regulated by interactions among environmental conditions, soil nutrient availability, and agricultural management practices (Ahmed et al., 2014; Chen et al., 2023).

The increasing need for sustainable management of perennial cropping systems has stimulated interest in organic production approaches that enhance soil health and ecosystem functions. Compared with conventional intensive farming systems, organic management emphasizes organic matter recycling, biological nutrient cycling, and reduced dependence on synthetic agrochemical inputs. Previous studies

have demonstrated that organic practices can increase soil organic carbon, improve microbial abundance and activity, and enhance agroecosystem multifunctionality (Reganold and Wachter, 2016; Lori et al., 2017). Nevertheless, organic systems may experience short-term productivity constraints due to slower nutrient release and differences in nutrient availability compared with conventional management (Seufert et al., 2012; Ponisio et al., 2015; Seufert and Ramankutty, 2020).

In perennial tea agroecosystems, soil biological processes represent a key component connecting management practices with crop performance and ecosystem sustainability. Organic amendments provide carbon resources that support soil microbial communities involved in nutrient cycling, organic matter transformation, and plant–soil interactions (Bender et al., 2016; Trivedi et al., 2020). Increasing evidence suggests that belowground biological processes may influence aboveground plant responses, including growth regulation, stress adaptation, and secondary metabolite formation through microbial-associated pathways (Banerjee et al., 2021; Pang et al., 2021).

Despite increasing recognition of the importance of soil health in sustainable agriculture, most studies on tea production have examined soil properties, crop productivity, and biochemical quality independently. The integrated relationships among soil biological functioning, microbial activity, ecosystem performance, and crop quality remain insufficiently quantified, particularly in tropical highland perennial tea systems. Understanding these interactions is essential for developing management strategies that balance productivity, quality improvement, and long-term agroecosystem sustainability.

This knowledge gap is particularly relevant for tropical highland regions such as Lâm Đồng, Vietnam, where Oolong tea production represents an important perennial agricultural system. Intensive conventional management based on repeated fertilizer and pesticide applications may affect soil biological processes and reduce ecosystem resilience over time (Khan et al., 2018). Therefore, integrated evaluations combining soil indicators, microbial activity, crop performance, and quality attributes are needed to support the transition toward more sustainable tea agroecosystems.

This study investigated the soil–microbe–plant interactions underlying productivity and quality responses in organic and conventional Oolong tea agroecosystems under tropical highland conditions. Specifically, the objectives were to:

- (i) evaluate the effects of organic management on tea productivity and quality-related traits;
- (ii) quantify changes in soil properties and microbial biomass as indicators of ecosystem functioning; and
- (iii) determine relationships among soil biological indicators, crop performance, and quality attributes using multivariate and exploratory pathway analyses.

We hypothesized that organic management improves soil biological functioning and ecosystem performance, thereby supporting enhanced crop quality while maintaining productivity in tropical perennial tea agroecosystems.

2. Materials and Methods

2.1. Study site and agroecosystem characteristics

The field experiment was conducted in Lâm Đồng Province, Central Highlands of Vietnam (11°45'–12°30' N, 107°15'–108°00' E), a major tea-producing region characterized by high-altitude tropical conditions. The experimental sites were located at elevations between 800 and 1,500 m above sea level.

The region has a subtropical highland climate, with an annual mean temperature of approximately 18–22°C and annual rainfall ranging from 1,800 to 2,500 mm, mainly occurring from May to October. According to the FAO soil classification system, the dominant soil type is classified as Ferralsols, characterized by acidic conditions and moderate organic matter content.

The study sites represented typical commercial Oolong tea production systems in the region and were selected to evaluate the influence of contrasting management practices on soil biological properties, crop productivity, and tea biochemical quality.

2.2. Experimental design and management treatments

A two-season field experiment (2023–2024) was conducted to compare organic and conventional Oolong tea (*Camellia sinensis* L.) production systems.

The experiment followed a randomized complete block design (RCBD) consisting of two management treatments:

1. organic management
2. conventional management

Each treatment was replicated four times ($n = 4$), resulting in eight experimental plots. Each plot covered an area of 100 m², and buffer zones were maintained between plots to minimize potential interference among treatments.

Experimental plots consisted of mature Oolong tea plants aged 8–10 years. The plots were selected based on similar cultivar, plant age, elevation, slope, and initial soil conditions to reduce environmental variation.

2.3. Organic and conventional tea management practices

Organic management was based on ecological nutrient management principles without the application of synthetic fertilizers or chemical pesticides.

Soil fertility in organic plots was maintained through compost application (10–15 t ha⁻¹ yr⁻¹), incorporation of organic residues, and biofertilizer supplementation to enhance soil organic matter and microbial activity.

Pest management in organic plots relied on integrated ecological approaches, including biological control practices and botanical-based pest management strategies.

Conventional plots were managed according to standard local farming practices. Synthetic NPK fertilizer (16–16–8) was applied at a rate of 300–400 kg ha⁻¹ yr⁻¹. Chemical pesticides were applied when necessary according to common farmer management practices.

2.4. Assessment of tea productivity and quality attributes

Tea yield was determined by measuring the cumulative fresh shoot biomass harvested from each experimental plot during the growing seasons. Yield data were converted and expressed as kg ha⁻¹.

Tea biochemical quality was evaluated based on major secondary metabolites associated with tea quality.

Total polyphenol content was determined using the Folin–Ciocalteu colorimetric method (Singleton et al., 1999).

Catechin concentration was quantified using high-performance liquid chromatography (HPLC) with catechin standards for calibration.

Antioxidant capacity was determined using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay and expressed as percentage inhibition activity.

All biochemical measurements were performed using replicated samples collected independently from each experimental plot.

2.5. Soil sampling and biological property analysis

Soil samples were collected from the surface layer (0–20 cm depth) at the beginning and end of each growing season.

For each plot, composite soil samples were obtained by mixing multiple subsamples collected randomly within the plot area. Samples were air-dried, sieved, and prepared for physicochemical analysis.

The following soil indicators were measured:

- soil organic carbon (SOC)
- total nitrogen (TN)
- microbial biomass carbon (MBC)
- soil moisture content

SOC was determined using the Walkley–Black oxidation method.

TN concentration was measured using the Kjeldahl digestion method.

MBC was determined using the chloroform fumigation–extraction method as an indicator of soil microbial activity.

2.6. Pest monitoring and ecological indicators

Pest incidence and natural predator abundance were monitored throughout the experimental period using standardized field observations.

Pest incidence was calculated as:

$$\text{Pest incidence (\%)} = (\text{affected plants} / \text{total observed plants}) \times 100$$

Natural predator abundance was recorded within each experimental plot to evaluate biological regulation responses under different cultivation systems.

2.7. Statistical and multivariate analyses

All statistical analyses were conducted using R software (version 4.3.0).

Data were examined for normality and homogeneity of variance before statistical analysis.

The effects of management systems on measured variables were evaluated using linear mixed-effects models:

$$Y_{ij} = \mu + T_i + B_j + \epsilon_{ij}$$

where:

Y_{ij} = observed response variable

μ = overall mean

T_i = fixed effect of cultivation system

B_j = random effect of block

ϵ_{ij} = residual error term

The model was implemented using the **lme4 package** in R.

When significant treatment effects were detected, mean comparisons were performed using Tukey's HSD test at **$p < 0.05$** .

Pearson correlation analysis was conducted to evaluate relationships among soil indicators, microbial biomass, and tea biochemical quality parameters.

Principal component analysis (PCA) was performed to visualize multivariate relationships among cultivation systems, soil properties, yield, and phytochemical traits.

2.8. Exploratory soil–plant pathway assessment

An exploratory pathway assessment was conducted to examine potential relationships among management practices, soil biological properties, and tea quality responses.

Due to the experimental scale and sample size, a component-based approach using standardized regression coefficients was applied instead of covariance-based structural equation modelling.

The hypothesized pathway was:

Management system → soil properties → microbial biomass → soil biological functions → ecosystem performance → crop quality

This analysis was used to support mechanistic interpretation and identify potential associations among variables rather than to establish direct causal relationships.

3. Results

3.1 Productivity and quality responses under contrasting management systems

Organic and conventional management systems showed significant differences in both productivity and tea quality parameters (Table 1).

Table 1
Effects of organic and conventional cultivation on yield and tea quality

Parameter	Conventional	Organic	% Change	p-value
Yield (kg ha ⁻¹)	12,500 ± 520	11,350 ± 480	-9.2%	< 0.05
Polyphenols (%)	18.2 ± 0.6	21.5 ± 0.8	+ 18.1%	< 0.01
Catechins (mg g ⁻¹)	85.4 ± 3.2	98.7 ± 3.8	+ 15.6%	< 0.01
Antioxidant activity (%)	62.3 ± 2.1	71.8 ± 2.5	+ 15.2%	< 0.01
Note: Values are presented as mean ± standard deviation (SD). Different significance levels are indicated as follows: *p < 0.05, **p < 0.01.				

Organic cultivation resulted in a moderate but significant reduction in fresh tea yield compared with conventional management. Yield decreased from 12,500 ± 520 kg ha⁻¹ under conventional cultivation to 11,350 ± 480 kg ha⁻¹ under organic management, representing a reduction of 9.2% (p < 0.05).

In contrast, organic management significantly enhanced major biochemical quality indicators. Total polyphenol concentration increased by 18.1%, while catechin content increased by 15.6% compared with conventional tea. Similarly, antioxidant activity was significantly improved by 15.2% under organic cultivation ($p < 0.01$).

These results indicate a clear shift between biomass production and phytochemical accumulation in response to contrasting management strategies.

Figure 2. Relationship between yield performance and phytochemical quality attributes under organic and conventional management.

3.2 Soil biological responses and ecosystem indicators

Organic management significantly improved soil physicochemical and biological properties (Table 2).

Table 2
Soil properties under organic and conventional systems

Parameter	Conventional	Organic	% Change	p-value
Soil organic carbon (%)	2.15 ± 0.12	2.86 ± 0.15	+ 33.0%	< 0.01
Total nitrogen (%)	0.18 ± 0.01	0.24 ± 0.02	+ 33.3%	< 0.01
Microbial biomass C (mg kg ⁻¹)	320 ± 25	465 ± 30	+ 45.3%	< 0.001
Soil moisture (%)	21.5 ± 1.2	26.8 ± 1.5	+ 24.6%	< 0.05
Note: SOC: soil organic carbon; TN: total nitrogen; MBC: microbial biomass carbon. Values represent mean ± SD. Statistical significance is indicated at * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.				

Soil organic carbon increased from 2.15 ± 0.12% in conventional plots to 2.86 ± 0.15% under organic management, representing a 33.0% improvement ($p < 0.01$).

Total nitrogen showed a similar response, increasing by 33.3% under organic cultivation. The strongest response was observed for microbial biomass carbon (MBC), which increased by 45.3% compared with conventional management ($p < 0.001$).

Figure 3. Effects of organic and conventional management on soil physicochemical and biological properties in Oolong tea systems.

Soil moisture content was also significantly higher in organic plots (+ 24.6%), suggesting improved soil water retention capacity associated with organic amendments.

3.3. Pest dynamics and natural regulation

Management practices influenced pest occurrence and predator abundance during the experimental period (Table 3).

Table 3
Pest incidence under different management systems

Parameter	Conventional	Organic (Year 1)	Organic (Year 2)
Pest incidence (%)	12.5 ± 1.5	18.7 ± 2.1	13.2 ± 1.6
Predator abundance (no./plot)	8.2 ± 1.1	10.5 ± 1.3	15.8 ± 1.8
<i>Note: Values are mean ± SD.</i>			

Organic plots showed higher pest incidence during the first year of conversion ($18.7 \pm 2.1\%$) compared with conventional plots ($12.5 \pm 1.5\%$).

However, pest incidence declined to $13.2 \pm 1.6\%$ during the second year, approaching the level observed in conventional management.

At the same time, predator abundance increased from 10.5 ± 1.3 individuals plot⁻¹ in the first year to 15.8 ± 1.8 individuals plot⁻¹ in the second year.

These results indicate progressive ecological stabilization under organic management.

3.4. Relationships between soil properties and tea quality

Pearson correlation analysis revealed strong relationships between soil biological indicators and tea phytochemical characteristics (Table 4).

Table 4
Pearson correlation analysis between soil biological properties and phytochemical quality attributes of Oolong tea (*Camellia sinensis* L.)

Soil indicator	Total polyphenols (%)	Catechins (mg g ⁻¹)	Antioxidant activity (%)
Soil organic carbon (SOC)	0.82**	0.78**	0.75*
Total nitrogen (TN)	0.74*	0.69*	0.71*
Microbial biomass carbon (MBC)	0.88***	0.85***	0.83**
Soil moisture content	0.65*	0.62*	0.60*
Notes: Values indicate Pearson correlation coefficients (<i>r</i>) between soil parameters and tea phytochemical quality traits across experimental treatments.			

SOC = soil organic carbon; TN = total nitrogen; MBC = microbial biomass carbon.

Significance levels: $p < 0.05$ (), $p < 0.01$ (), and $p < 0.001$ ().

Microbial biomass carbon showed the strongest positive correlations with:

- polyphenol content ($r = 0.88$, $p < 0.001$)
- catechin concentration ($r = 0.85$, $p < 0.001$)
- antioxidant activity ($r = 0.83$, $p < 0.01$)

Soil organic carbon and total nitrogen were also positively associated with tea quality indicators.

These relationships suggest that improved soil biological activity may contribute to enhanced secondary metabolite accumulation.

3.5 Integrated soil–plant–ecosystem relationships

Principal component analysis demonstrated a clear separation between organic and conventional production systems.

Organic management was associated with higher soil organic carbon, microbial biomass, polyphenols, catechins, and antioxidant capacity.

In contrast, conventional management was primarily associated with higher yield performance.

Pathway analysis further indicated that microbial biomass represented an important intermediate factor linking soil improvement with phytochemical responses.

4. Discussion

4.1. Organic management influences productivity–quality trade-offs in tea agroecosystems

The present study demonstrates that organic management substantially modifies the balance between productivity and biochemical quality formation in Oolong tea (*Camellia sinensis* L.) cultivated under tropical highland conditions. Although organic cultivation resulted in a moderate yield reduction (– 9.2%), significant improvements were observed in major quality-related metabolites, including total polyphenols (+ 18.1%), catechins (+ 15.6%), and antioxidant activity (+ 15.2%).

The reduction in yield under organic management is consistent with previous meta-analyses reporting productivity gaps between organic and conventional agricultural systems, mainly due to differences in nutrient availability and mineralization dynamics (Seufert et al., 2012; Ponisio et al., 2015). However, the magnitude of yield reduction observed in this study was relatively moderate, suggesting that perennial tea systems under favorable tropical highland conditions may partially compensate for reduced external inputs through improved soil biological processes.

The enhancement of tea phytochemical quality under organic cultivation can be explained by changes in plant carbon allocation and secondary metabolism. According to the carbon–nutrient balance hypothesis, relatively lower availability of rapidly accessible nitrogen may shift plant metabolism toward

carbon-based secondary compounds, including phenolics and flavonoids (Ahmed et al., 2014). Similar increases in tea secondary metabolites under altered environmental and cultivation conditions have also been reported by Zhang et al. (2019) and Li et al. (2022).

Therefore, the observed response indicates that organic management does not simply reduce productivity but modifies plant physiological processes, resulting in a trade-off between biomass accumulation and biochemical quality improvement (Fig. 2).

4.2. Soil biological restoration as a driver of ecosystem functioning

The significant increases in soil organic carbon, total nitrogen, and microbial biomass carbon demonstrate that organic management enhanced belowground ecosystem functioning.

Organic amendments provide continuous carbon inputs that improve soil structure, nutrient retention, and microbial habitat conditions. The 33% increase in SOC observed in this study agrees with previous evidence showing that organic farming practices promote soil carbon accumulation and biological activity (Reganold and Wachter, 2016; Lori et al., 2017).

Among soil indicators, microbial biomass carbon showed the strongest response (+ 45.3%), suggesting that soil microorganisms represent a sensitive biological indicator of management-induced changes. Soil microbial communities are recognized as important regulators of nutrient cycling, organic matter transformation, and plant nutrient acquisition (Bender et al., 2016; Trivedi et al., 2020).

The improvement of microbial activity observed under organic management may therefore represent an important mechanism linking soil restoration with enhanced crop quality.

4.3. Linking belowground processes with aboveground crop performance

One of the key findings of this study is the strong association between microbial biomass and phytochemical quality traits. Microbial biomass carbon showed significant positive correlations with polyphenols ($r = 0.88$), catechins ($r = 0.85$), and antioxidant activity ($r = 0.83$), indicating a close relationship between belowground biological processes and aboveground biochemical responses.

Recent studies have demonstrated that soil microbial communities can influence plant secondary metabolism through multiple mechanisms, including nutrient regulation, phytohormone production, and activation of plant defense-related pathways (Trivedi et al., 2020; Banerjee et al., 2021).

The PCA analysis (Fig. 4) further supported this relationship by showing a clear association among organic management, soil biological indicators, and phytochemical traits. Organic systems were primarily characterized by higher SOC, microbial biomass, and bioactive compound accumulation, whereas conventional systems were associated with greater yield performance.

These findings support the proposed soil–microbe–plant quality framework, in which improved soil biological conditions contribute to enhanced secondary metabolite accumulation in tea plants.

4.4. Ecological regulation during organic transition

The transition from conventional to organic production was associated with temporary changes in pest dynamics. Higher pest incidence during the first year of organic management indicates an initial adjustment phase following the reduction of synthetic pesticide inputs.

However, the decline in pest pressure during the second year, accompanied by increased predator abundance, suggests gradual restoration of ecological regulation mechanisms.

Greater biodiversity and natural enemy activity have been shown to improve biological control functions in agricultural ecosystems (Letourneau et al., 2011; Crowder and Jabbour, 2014).

These findings indicate that evaluating organic systems requires consideration of temporal dynamics because short-term assessments may underestimate long-term ecological benefits.

4.5. Implications for sustainable perennial agroecosystem management

The integration of correlation analysis, PCA, and pathway analysis provides evidence of interconnected relationships among management practices, soil biological properties, and tea quality formation.

The proposed conceptual pathway (Fig. 5) suggests the following mechanism:

Organic management → increased soil organic carbon → enhanced microbial biomass → regulation of secondary metabolism → improved phytochemical quality

Rather than acting independently, soil properties and plant biochemical responses appear to function as an integrated biological network. This supports the concept that soil health management can be used as a strategy to improve both sustainability and product quality in high-value horticultural crops.

For premium tea production systems, improvements in biochemical quality may provide economic advantages that partially offset moderate yield reductions. Therefore, organic management represents a promising approach for developing sustainable and climate-resilient tea production systems in tropical highlands.

4.6. Limitations and future perspectives

Although this study provides mechanistic evidence linking soil biological processes with tea quality responses, several limitations should be considered.

First, the experiment covered two growing seasons; therefore, longer-term monitoring is required to evaluate the stability of organic management effects.

Second, microbial biomass was used as an indicator of soil biological activity, but detailed microbial community composition was not characterized.

Future studies integrating metagenomic sequencing, metabolomics, and long-term field trials will be valuable for identifying specific microbial groups and biochemical pathways involved in tea quality regulation

5. Conclusions

This study provides an integrated assessment of the effects of organic management on yield performance, soil biological functioning, and phytochemical quality of Oolong tea (*Camellia sinensis* L.) under tropical highland conditions. The results demonstrate that organic cultivation induced a moderate yield reduction (– 9.2%) but significantly enhanced tea quality attributes, including total polyphenols, catechins, and antioxidant activity.

The improvement in tea biochemical quality was associated with substantial increases in soil organic carbon, total nitrogen, and microbial biomass carbon, highlighting the important role of soil biological processes in regulating plant secondary metabolism. Strong positive relationships between microbial biomass and phytochemical traits suggest that soil microbial activity may act as a key biological mediator linking organic management practices with quality formation in tea plants.

Multivariate and pathway analyses further supported the existence of an integrated soil–microbe–plant quality relationship, where enhanced soil biological functioning contributed to improved secondary metabolite accumulation. These findings indicate that soil health improvement represents an important strategy for enhancing the quality and sustainability of high-value perennial tea production systems.

Although organic management involves short-term productivity trade-offs, its benefits for soil fertility, ecological regulation, and product quality support its potential application in sustainable tea cultivation. Future long-term studies incorporating soil microbiome profiling and metabolomic approaches are recommended to further clarify the biological mechanisms underlying soil-mediated regulation of tea quality.

Declarations

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Author Contributions

Tao Anh Khoi conceived and designed the study, conducted field experiments, performed data analysis, and wrote the manuscript. The author has read and approved the final version of the manuscript.

Conflicts of Interest

The author declares no conflict of interest.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethical Approval

Not applicable.

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Figures

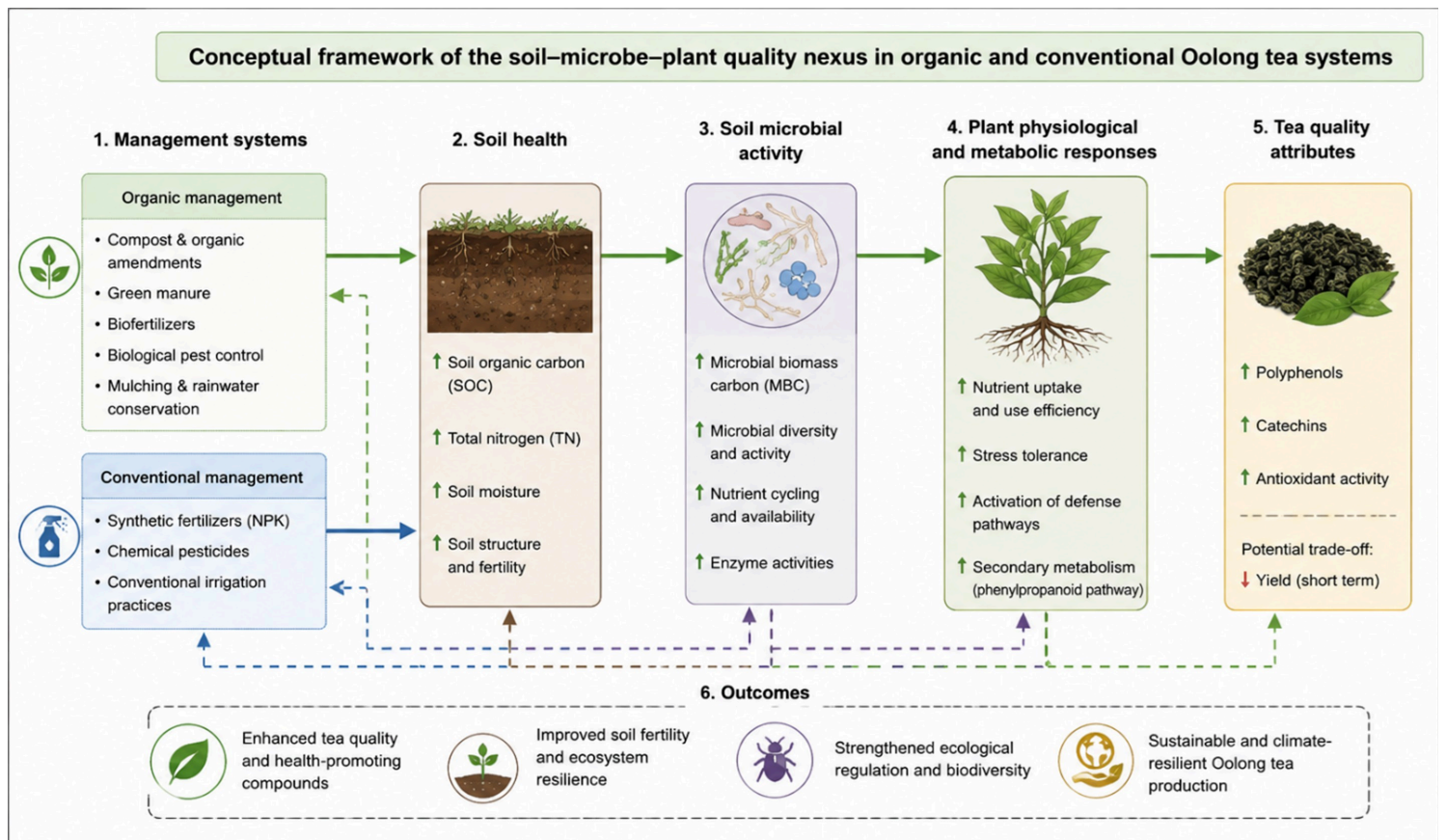


Figure 1

Conceptual framework linking organic management, soil biological restoration, ecosystem functions, and crop quality in tropical tea agroecosystems.

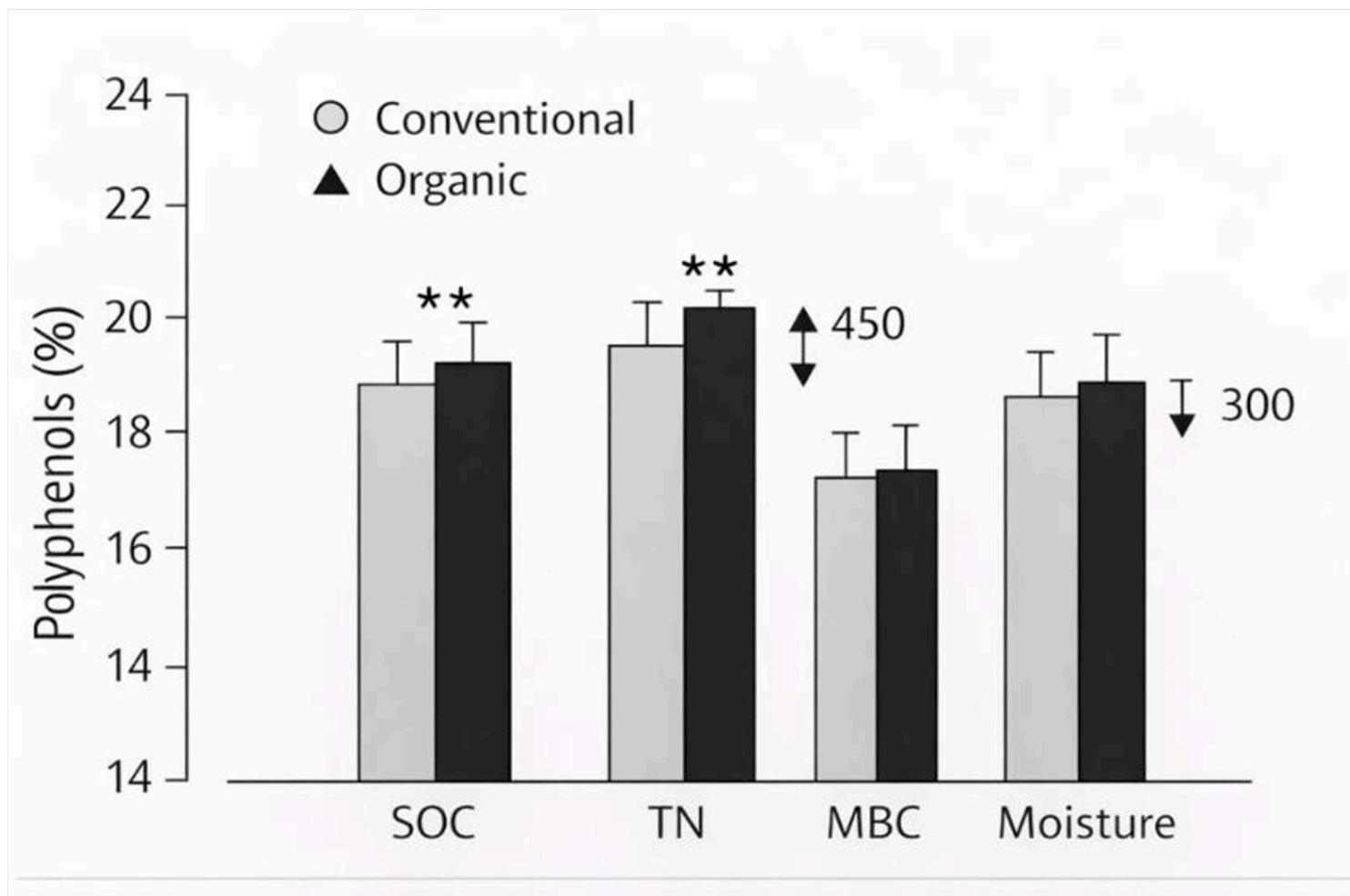


Figure 2

Relationship between yield performance and phytochemical quality attributes under organic and conventional management

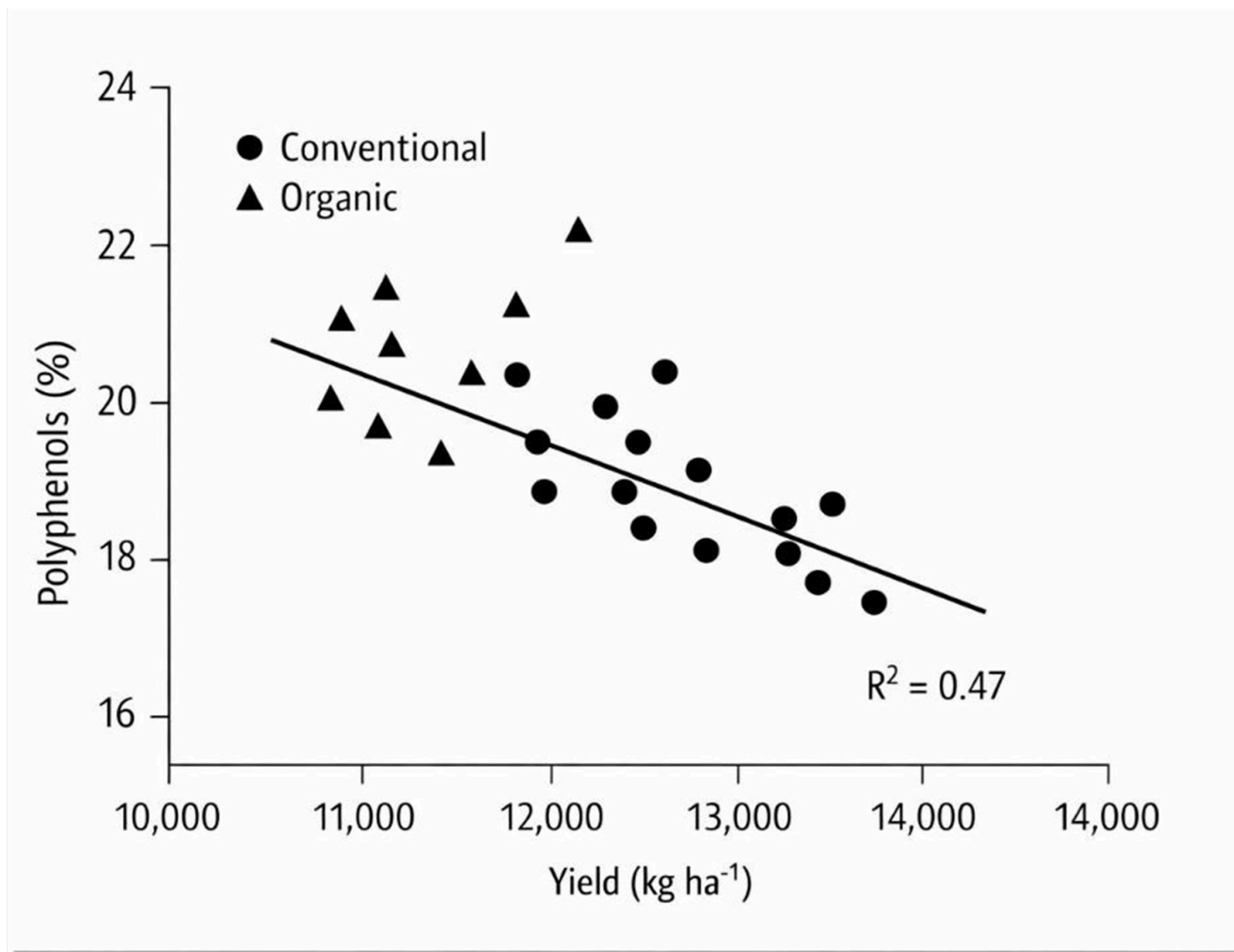


Figure 3

Effects of organic and conventional management on soil physicochemical and biological properties in Oolong tea systems

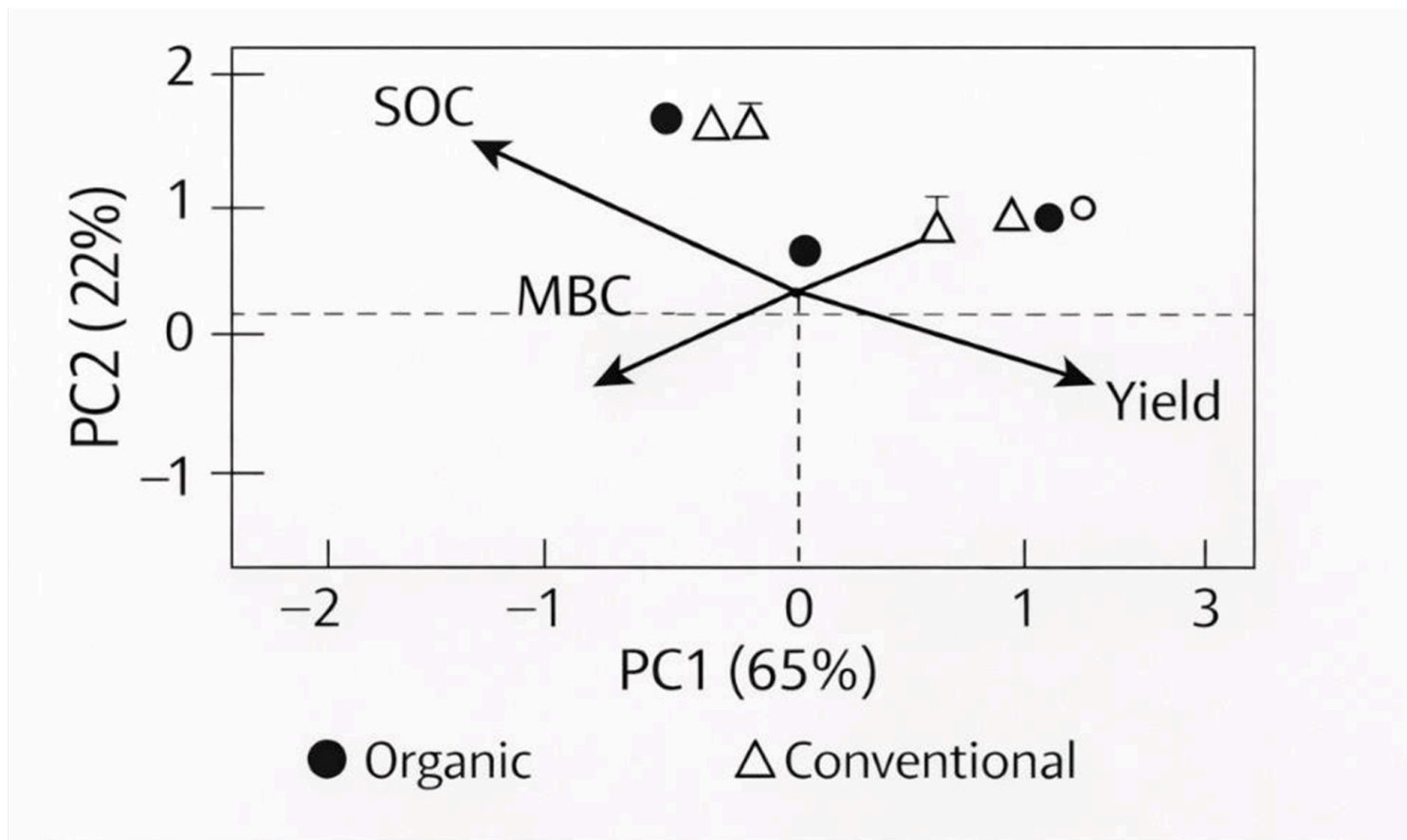


Figure 4

Principal component analysis (PCA) showing relationships among management systems, soil properties, yield, and tea biochemical quality.

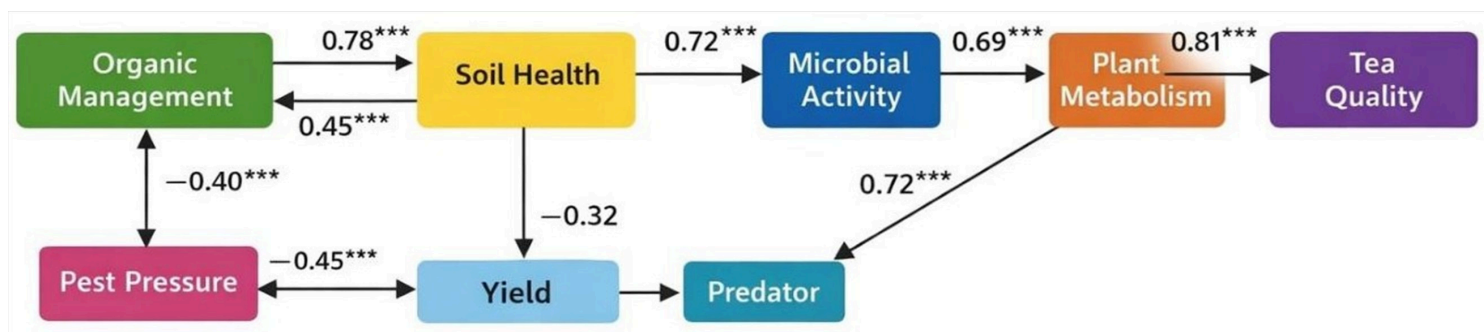


Figure 5

Proposed soil-mediated pathway supporting sustainable Oolong tea agroecosystem functioning.