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Enhancing Soil Resilience to Climate Change: Long-Term Effects of Organic Amendments on Soil Thermal and Physical Properties in Tea-Cultivated Ultisols

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Abstract: This study examined the impact of the long-term application (25 years) of tea waste (TW), compost (COM), and neem oil cake (NOC) compared to conventional synthetic fertilizers (CONV) on soil thermal and physical properties of a tea-cultivated Ultisol. Soil samples were collected from 0–15 cm and 15–30 cm depths of an experimental site of the Tea Research Institute in Sri Lanka. These samples were analyzed for soil thermal conductivity (k), volumetric heat capacity (C), thermal diffusivity (D), bulk density (BD), aggregate stability, soil organic carbon (SOC), and volumetric water contents at 0 kPa (θ_0) and 10 kPa (θ_{10}). TW and COM significantly ($p < 0.05$) increased surface SOC, leading to better aggregation, lower BD, and, consequently, a substantial reduction in k and D compared to CONV plots. Further, TW and COM amendments slightly increased C compared to CONV plots due to elevated SOC and water content. However, NOC had no impact on soil thermal and physical properties compared to CONV. The reduced thermal conductivity and thermal diffusivity indicated an improved soil capacity to buffer extreme temperature fluctuations. Moreover, soils treated with TW and COM exhibited greater water retention and improved soil resistance to erosion. The findings suggest that the long-term application of tea waste and compost could be a sustainable soil management strategy for improving soil health and enhancing resilience to climate change in tea-cultivated Ultisols.

Keywords: soil thermal properties; organic amendments; tea cultivation

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1. Introduction

Tea is the second most consumed beverage in the world [1,2] and global consumption was nearly 5 million tons in 2013 [3]. Tea cultivation holds significant socio-economic importance for rural development and poverty alleviation in developing countries including Sri Lanka, given its status as one of the most vital cash crops. Black tea serves as Sri Lanka's principal source of foreign revenue, contributing to 15% of its net foreign income and 1.2% of its Gross Domestic Product (GDP). With a workforce of 2.2 million, the tea industry in Sri Lanka has established a longstanding reputation internationally, notably for producing Ceylon tea, renowned for its unique flavor and aroma. As a woody perennial crop cultivated in rain-fed monocultures, tea (*Camellia sinensis* (L.) O. Kuntze) heavily relies on agro-climatic factors such as sunlight, temperature, rainfall, soil, and topography. Global warming is anticipated to significantly affect tea production, likely influencing both the quantity and quality of tea.

In Sri Lanka, it is considered that a monthly mean temperature exceeding 22 °C may decrease tea productivity [4]. Since the 1850s, the average global surface temperature has increased by 1.09 °C, primarily due to the heightened levels of greenhouse gases (GHGs), notably CO_2, CH_4, and N_2O [5]. This warming trend impacts more than just air temperature, as it can also alter soil temperature regimes. Rising soil temperatures driven by anthropogenic climate change exacerbate global warming by stimulating microbial respiration, leading to enhanced CO_2 emissions, a potent greenhouse gas [6]. Additionally, higher soil temperatures increase the metabolic activity of fungal decomposers, which accelerate the breakdown of organic matter. This could result in faster soil organic matter mineralization, potentially impacting soil fertility and structure. For optimal tea growth, soil temperatures should remain within the range of 18–25 °C. Deviations from this range, particularly increases, can hinder tea plant growth, reducing both yield and quality. For instance, Mallik and Ghosh [7] observed that elevated soil temperatures in deeper soil layers led to reduced tea yields. Moreover, an elevation in soil temperature within cultivated soils could accelerate the proliferation of diseases. For instance, *Pratylenchus loosi*, the predominant nematode species responsible for significant economic losses in tea cultivation in Sri Lanka, Japan, Iran, Bangladesh, China, and Korea, was observed to modify its population and distribution under higher soil temperatures [8,9]. In addition, extreme weather events pose challenges to tea cultivation. For example, prolonged droughts can dry out soils, reducing yields and quality, while heavy rains may cause waterlogging, soil erosion, and significant nutrient leaching [4]. Thus, maintaining a healthy and thermally stable soil ecosystem is crucial for achieving higher tea yield and ensuring quality under a changing climate.

Soil thermal properties, including thermal conductivity (k), volumetric heat capacity (C), and thermal diffusivity (D), play a critical role in governing the transfer and storage of heat in soil. These properties collectively regulate the dynamics of soil temperature, influencing processes such as plant growth [10,11], microbial activity [12,13], and root growth [14]. Soil thermal conductivity quantifies the rate of heat transfer through the soil due to a temperature gradient [15]. Soil volumetric heat capacity quantifies the amount of heat a volume of soil stores or releases with a unit change in temperature. Therefore, soil volumetric heat capacity governs how rapidly the change in soil temperature occurs in response to an absorption or dissipation of heat in soil. Soil thermal diffusivity, on the other hand, characterizes the heating and cooling rate accompanying a change in soil temperature profile. It is defined as the ratio of thermal conductivity to volumetric heat capacity [16]. A higher thermal diffusivity value indicates a more rapid diffusion of heat within the soil. Knowledge of soil thermal properties is essential for elucidating heat transfer mechanisms and predicting thermal regimes within the soil profile. Soil thermal properties exert a fundamental control over the rate and extent of soil warming and cooling, thereby influencing a multitude of critical ecosystem processes. In the context of a changing climate, a thorough understanding and targeted management of soil thermal properties become increasingly crucial for regulating soil temperature regimes.

It underscores the need for developing sustainable soil management strategies to mitigate and adapt to the effects of climate change on agriculture. The application of organic amendments to soils is a common practice for improving soil physical, chemical, and biological properties. These practices contribute to the United Nations Sustainable Development Goals (SDGs), particularly those related to sustainable agriculture (SDG 2) and climate action (SDG 13). However, the impacts of the long-term application of organic amendments on soil thermal and physical properties have not been fully understood. Studies have explored the potential changes in soil thermal properties resulting from tillage [17], cover crops [18], organic manure [19], and biochar application [20–23]. A critical knowledge gap exists regarding the influence of the long-term use of organic amendments on thermal properties within tropical Ultisols used for tea cultivation, which could serve a potential sustainable soil management strategy for climate smart agriculture. This study used the organic amendments such as tea waste, compost, and neem oil cake which were derived from materials within the tea cultivation system. Therefore, elucidating these impacts is paramount for the development of sustainable soil management practices tailored to tea perennial cropping systems in tropical regions. This study investigated the long-term effects of organic amendments on soil thermal and physical properties of an Ultisol used for tea cultivation. By examining these impacts, we aim to understand how various organic amendments applied over extended periods affect soil thermal and physical properties. This knowledge can reveal the suitability of organic amendments as a sustainable soil management strategy to improve soil health and enhance resilience to climate change.

2. Materials and Methods

2.1. Experimental Site

The experimental site was the Tea Research Institute Organic Conventional (TRIORCON) trial which was located at St. Coombs Estate of the Tea Research Institute (TRI) in Talawakelle, Sri Lanka (Figure 1). The impact of organic agriculture on tea has been studied since 1997 at the TRIORCON site, which was located at 1382 m altitude on Rhodudults soils (USDA soil taxonomy) with a mean annual temperature of 18 °C and mean annual rainfall of 2550 mm. The geographic central coordinates of the site were 6°54′53.7″ N 80°42′20.7″ E. The soil textures of the surface and sub-surface soil of the study area were Sandy clay loam and Sandy loam, respectively (Table 1).

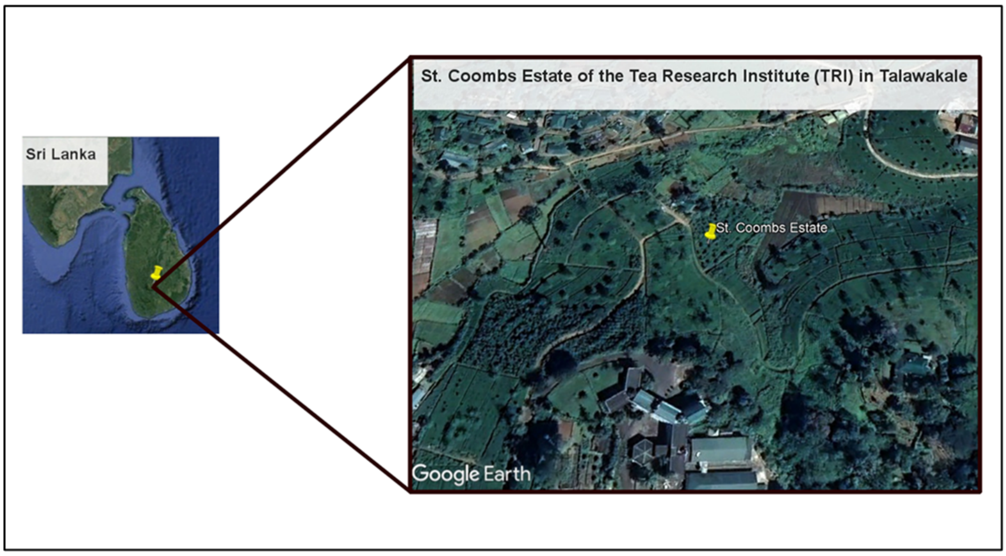

Figure 1. St. Coombs Estate of the Tea Research Institute in Talawakalle, Sri Lanka (TRISL).

Table 1. Percentage of soil textural separates and soil textural class of surface (0–15 cm) and sub-surface (15–30 cm) soil.

Depth (cm)	Clay%	Silt%	Sand%	Textural Class (USDA)
0–15	33.25	15.86	50.89	Sandy clay loam
15–30	39.13	15.68	45.19	Sandy clay

2.2. Experimental Design

The total area of the site was 1.2 ha and consisted of 4 treatments: 3 organic amendments and 1 conventional inorganic fertilizer. One received tea waste (TW: 2 kg fresh weight (FW) plant^{-1} split^{-1}, 2 times year^{-1}), another received neem oil cake (NOC: 250 g FW plant^{-1} split^{-1} 2 times year^{-1}), and the other received a 4-month-old compost made of miscellaneous green shoots, predominantly *Tithonia diversifolia*, tea waste, and cow dung (COM: 2 kg FW plant^{-1} split^{-1}, 2 times year^{-1}). These three organic amendments were included in the TRIORCON because they were locally available, traceable, and acceptable by growers (TW is waste from a tea factory, NOC is waste from neem oil mills, and COM is mostly made from materials available on farms). The conventional treatment (CONV) was fertilized according to the TRISL recommendations, consisting of 270 kg N ha^{-1} year^{-1} as urea plus 35 kg P_2O_5 ha^{-1} year^{-1} as rock phosphate and 120 kg K_2O ha^{-1} year^{-1} as muriate of potash. The TRIORCON experimental site comprised three blocks, with each block featuring four main plots, each assigned with a specific treatment. Within each main plot of a block, two minimally disturbed subplots were established (Figure 2).

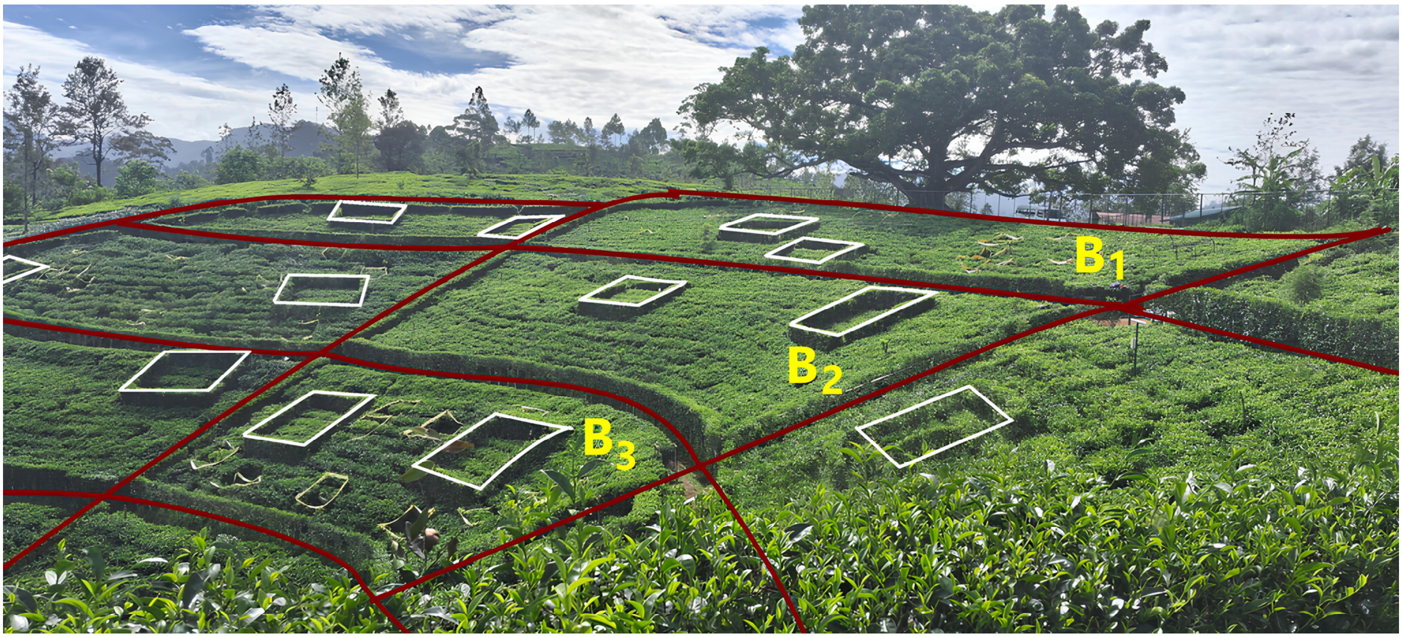

Figure 2. The TRIORCON trial site located in St. Coombs estate of the Tea Research Institute, Talawakelle, Sri Lanka. The red rectangles represent the blocks (B1–B3), which were developed perpendicular to the slope of the land. Each block contains four main plots assigned to specific treatments. The white rectangles indicate the minimally disturbed subplots established within the main plots in each block.

2.3. Soil Sampling and Processing

A total of ninety-six (96) soil samples were collected, consisting of both intact core samples and minimally disturbed soil samples. These samples were collected from three experimental blocks, each containing four main plots with two subplots per main plot. Within each main plot, one sample was collected from each of the two subplots, resulting in a total of eight samples per block. Soil was sampled at two depth intervals, 0–15 cm and 15–30 cm, with 48 samples collected at each depth interval (24 intact core samples and 24 minimally disturbed samples).

Minimally disturbed soil samples were carefully placed in airtight Ziplock bags to preserve their natural structure. Intact soil core samples were extracted using a core sampler and secured with plastic caps at both ends, and then placed in individual Ziplock bags. The samples were transported to the laboratory and stored at 4 °C until analysis.

Minimally disturbed soil samples were air-dried before undergoing aggregate stability analysis.

2.4. Determination of Soil Water Content

Soil water contents at 0 and 10 kPa were determined using the sandbox apparatus [24]. A cheesecloth, fastened with rubber bands, covered the base of the soil core rings, which were then positioned in a water-filled plastic tray for 48 h. This facilitated the saturation of intact soil core samples through capillary rise action. Following saturation, the samples were placed in a sandbox apparatus. The samples were kept in contact with the filter cloth for one hour, the water level was then raised 1 cm below the top of the sample core ring, and the suction regulator was adjusted to 0 kPa (pF 0). After the samples had reached saturation, they were weighed again using a top loading balance. The samples were then replaced in the same places in the sandbox and the suction regulator was adjusted to 10 kPa (pF 2) to allow for drainage. After the samples had reached equilibrium at 10 kPa, they were weighed. Volumetric water contents (θ) at 0 and 10 kPa pressures were determined and the corresponding values denoted as θ_0 and θ_{10}.

2.5. Measurement of Soil Thermal Properties

Soil thermal properties were measured using the KD2 Pro thermal property sensor (Decagon devices, Pullman, USA) on intact soil core samples at θ_0 and θ_{10}. A dual-needle sensor (SH-1) of the KD2 Pro thermal property sensor was calibrated and its accuracy was verified using performance verification standards. At each suction level, the dual-needle sensor (SH-1) was vertically inserted into each soil core sample (Figure 3) and kept for 10 min to equilibrate with soil temperature. Two readings were recorded on the same soil sample while keeping a 10 min time interval between them. All the measurements were carried out under controlled temperature conditions in the Soil Physics Research Laboratory of the Department of Soil Science, University of Peradeniya.

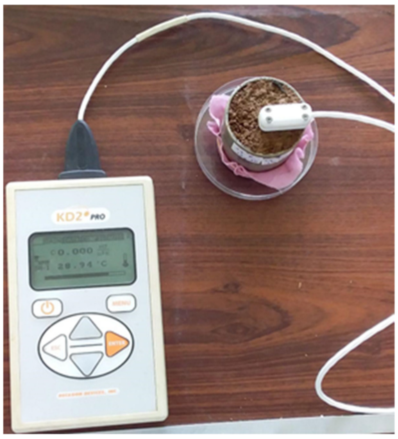

Figure 3. Measuring soil thermal properties in a soil core sample using SH-1 dual-needle sensor.

2.6. Measurement of Soil Bulk Density, Soil Organic Carbon, and Texture

After measurement of the soil thermal properties, soil in each core was dried at 105 °C in the oven for 48 h and the bulk density was determined by the core sample method [25]. Soil porosity was estimated using Equation (1), where ρ_b was the bulk density and ρ_p was the particle density, with the latter assumed to be 2.65 g cm^{-3}.

$$Porosity = 1 - \left(\frac{\rho_b}{\rho_p}\right) \quad (1)$$

The soil was then ground and passed through a 2 mm sieve prior to soil texture and organic carbon analysis. Fifty grams of the <2 mm particles were used for soil texture determination by the Pipette method [26]. Ten grams of finely ground (<0.5 mm) particles were used to determine soil organic carbon by the loss-on-ignition (LOI) method as described by [27].

2.7. Determination of Aggregate Stability

The standard dry sieving method was used to evaluate the mechanical stability of aggregates and their size distribution [28]. From each sample, 500 g of air-dried, undisturbed soil was separated and mechanically sieved for 10 min at constant oscillation using the rotary sieve shaker, which consisted of a nest of sieves with apertures of 5, 3, 2, 1, 0.425, and 0.106 mm and the bottom pan. Accordingly, seven aggregate size classes were obtained (0.00–0.106, 0.106–0.425, 0.425–1.00, 1.00–2.00, 2.00–3.00, 3.00–5.00, and >5.00 mm) and soil dry weights of the individual size classes were determined. The mean weight diameter (*MWD*) was calculated using Equation (2).

$$\boldsymbol{MWD} = \sum_{i=1}^{n} (\boldsymbol{X_i W_i}) \quad (2)$$

X_i = mean diameter of *i*th size fraction;
W_i = the proportion of the total sample weight occurring in the *i*th size fraction;
n = total number of size fractions.

The single sieve method was used to measure the wet aggregate stability using the wet sieving apparatus [28]. The apparatus had eight 60 mesh sieves such that eight samples were oscillating in eight separate dispersion solution containers at one time. The apparatus had a vertical stroke of 1.3 cm to allow the dispersing solution, which was placed in a container below each sieve to cover the sample at an immersion frequency of 34 cycles min^{-1}. Four grams of 1–2 mm aggregates was placed on each sieve and two dispersion processes were performed.

2.8. Data Analysis

The experiment followed a Randomized Complete Block Design (RCBD). A one-way analysis of variance (ANOVA) was conducted using SigmaPlot 14.5 [29]. Before performing ANOVA, the Shapiro–Wilk test was used to assess data normality ($p < 0.05$). Duncan's method was applied for pairwise multiple comparisons to identify specific group differences when ANOVA indicated significant treatment effects ($p < 0.05$). Principal component analysis (PCA) was performed using the Scikit-learn library in Python [30]. Prior to applying PCA, the dataset was standardized using the StandardScaler tool from the Scikit-learn library 1.6. This ensured that all variables contributed equally to the analysis, regardless of their original scales. A PCA model was then applied to reduce dimensionality, retaining 12 principal components for initial analysis. Principal components with eigenvalues more than one were retained based on the scree plot (Figure 4). The correlation coefficient between each principal component and the original soil properties was calculated using the Pandas library in Python. A heatmap was then generated to visualize these correlations between the principal components and the original soil properties, utilizing the Seaborn library.

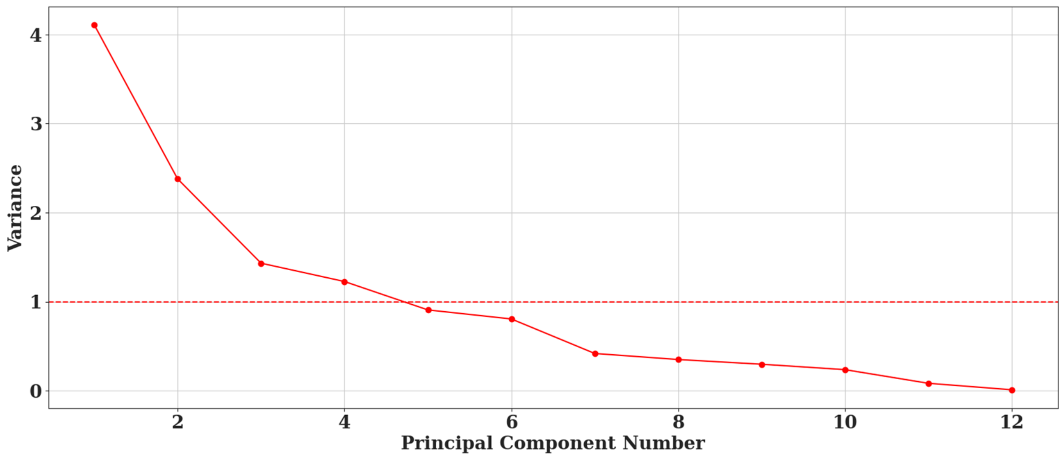

Figure 4. The scree plot indicating the eigenvalues of each principal component in descending order. Each eigenvalue corresponds to the amount of variance explained by its associated principal component.

3. Results

3.1. Soil Organic Carbon

There was a statistically significant ($p < 0.05$) increase in soil organic carbon (SOC) content within manure-amended plots compared to the control plots that solely received inorganic fertilizer (CONV) (Figure 5). This effect was particularly pronounced for treatment with TW, which exhibited the highest measured SOC content (2.52%). Notably, TW application resulted in a substantial increase in SOC content within the 0–15 cm depth layer, exceeding that of CONV plots by 25.79%. Similarly, plots amended with COM displayed a significantly greater SOC content compared to CONV. Interestingly, no significant difference in surface layer (0–15 cm) SOC content was observed between plots treated with NOC and CONV. Furthermore, the analysis revealed no significant variation in SOC content across all plots for the sub-surface layer (15–30 cm).

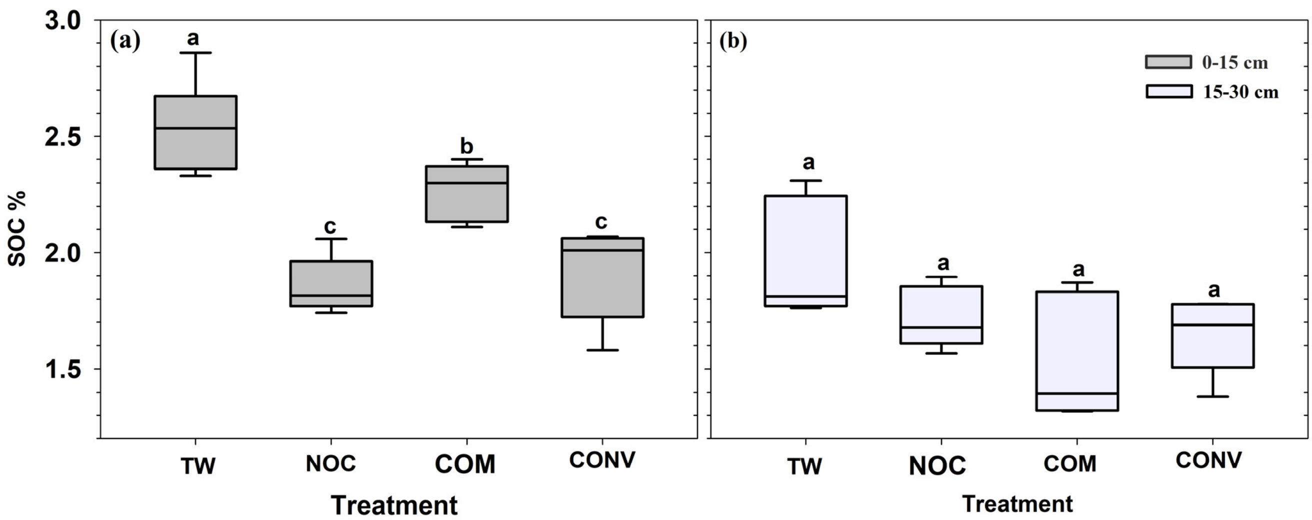

Figure 5. Mean soil organic carbon percentage in various amendments applied to surface (**a**) and sub-surface (**b**) soil. Different letters within each depth indicate a significant ($p < 0.05$) difference among the treatments within that depth.

3.2. Bulk Density and Porosity

The TW- and COM-applied plots exhibited significantly ($p < 0.05$) lower bulk densities for the surface (0–15 cm) soil compared to NOC- and CONV-added plots, with reductions of 9.32% and 6.78% compared to the CONV plots. The porosity of TW- and COM-applied plots exceeded that of CONV (inorganic fertilizer)-applied plots by 8.33% and 5.45%, respectively (Table 2). Moreover, no significant disparity was noted in the bulk density and porosity of sub-surface (15–30 cm) soil between the plots treated with organic amendments and those treated with inorganic fertilizers only (Table 2).

Table 2. Means (±SD) of bulk density (BD), porosity, mean weight diameter (MWD), and water-stable aggregate (WSA) percentage of surface (0–15 cm) and sub-surface (15–30 cm) based on different soil amendments. Different letters within a column indicates a significant ($p < 0.05$) difference in the soil property among the treatments within that depth.

Treatments	BD (g/cm^3)	Porosity (%)	MWD	WSA (%)
0–15 cm				
TW	1.07 ± 0.03 ^{c}	0.60 ± 0.01 ^{a}	2.61 ± 0.15 ^{a}	97.77 ± 0.54 ^{a}
NOC	1.14 ± 0.03 ^{ab}	0.57 ± 0.01 ^{bc}	2.28 ± 0.17 ^{b}	98.07 ± 0.25 ^{a}
COM	1.10 ± 0.01 ^{bc}	0.58 ± 0.01 ^{ab}	2.13 ± 0.36 ^{bc}	98.11 ± 0.38 ^{a}
CONV	1.18 ± 0.03 ^{a}	0.55 ± 0.02 ^{c}	2.22 ± 0.09 ^{b}	97.36 ± 0.45 ^{a}
15–30 cm				
TW	1.08 ± 0.03 ^{a}	0.60 ± 0.01 ^{a}	1.85 ± 0.64 ^{a}	96.38 ± 0.88 ^{a}
NOC	1.08 ± 0.05 ^{a}	0.60 ± 0.01 ^{a}	1.82 ± 0.55 ^{a}	97.38 ± 0.42 ^{a}
COM	1.07 ± 0.04 ^{a}	0.60 ± 0.02 ^{a}	1.66 ± 0.32 ^{a}	97.90 ± 0.42 ^{a}
CONV	1.12 ± 0.03 ^{a}	0.59 ± 0.01 ^{a}	1.83 ± 0.41 ^{a}	96.39 ± 0.42 ^{a}

3.3. Aggregate Stability and Aggregate Size Distribution

The application of TW resulted in the highest MWD at 2.61 mm, whereas plots treated with compost exhibited the lowest MWD value at 2.13 mm (Table 2). There was no significant difference in MWD observed between NOC and CONV plots (Table 2). Additionally, the MWD of sub-surface soil (15–30 cm) showed no notable differences among the various treatments ($p < 0.05$). In contrast to the observed variations in MWD across different manure-treated plots, the WSA percentage remained consistent among both surface and sub-surface soils, as shown in Table 2. Across all treatments, a predominance of the 5–3 mm aggregate size fraction was evident in both surface and sub-surface soils (Figure 6). There was no significant difference in the percentage of the 5–3 mm aggregate size fraction among the different manure-applied plots in the surface as well as sub-surface soil. However, it was apparent that the 5–3 mm aggregate size fraction in surface soil (0–15 cm) treated with TW exhibited a slight elevation compared to the other treatments (Figure 5a). The θ_0 in TW-applied surface soil (0–15 cm) was significantly higher than that of all other plots treated with manure or inorganic fertilizer ($p < 0.05$). Nonetheless, there were no notable differences in θ_{10} among the treatments in the surface soil (0–15 cm), as shown in Table 2. Additionally, there were no significant differences observed among the treatments of the sub-surface soil (15–30 cm) for both θ_0 and θ_{10}.

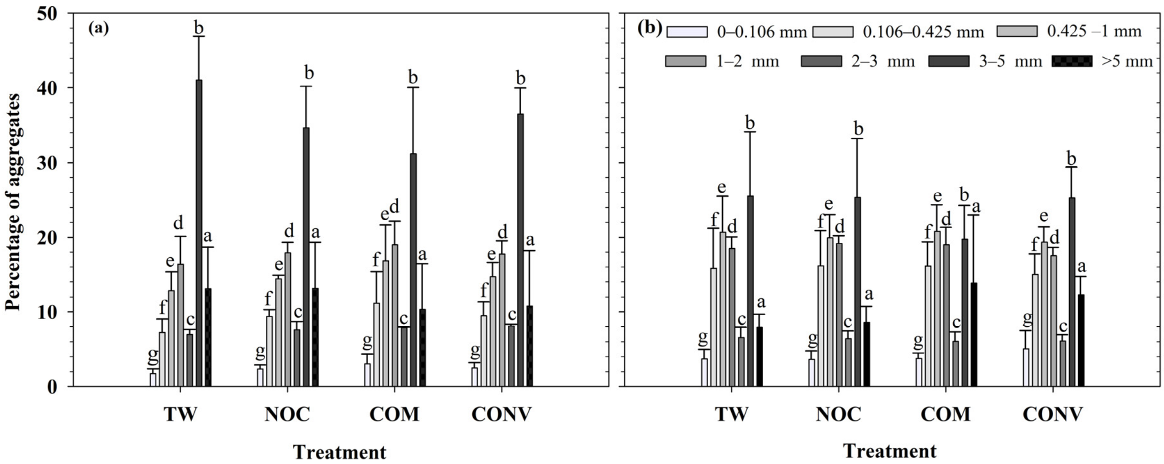

Figure 6. Percentage distribution of aggregate size fractions in soils treated with various amendments (TW: tea waste, NOC: neem oil cake, COM: compost, and CONV: recommended inorganic fertilizers only), depicted for two depths—(**a**) 0–15 cm and (**b**) 15–30 cm. Data presented as mean ± standard deviation (n = 3). Different letters within each depth for the same size fraction indicate a significant ($p < 0.05$) difference in that fraction among treatments within that depth.

3.4. Soil Thermal Properties

The results showed that plots amended with inorganic fertilizer only (CONV) exhibited the greatest k at both saturation (0 kPa) and 10 kPa matric suction. In contrast, plots receiving TW and COM displayed the lowest k values at these same matric suctions. Soil thermal conductivity (k) was significantly reduced by the application of organic amendments compared to inorganic fertilizer alone (CONV) (Table 3). Notably, k in plots treated with TW was 17% lower than in CONV plots at both saturation and 10 kPa suction. Similarly, COM application resulted in a decrease in k by 17% at saturation and 14% at 10 kPa suction, compared to CONV. These findings are consistent with [31], who reported a 17% and 12% reduction in k for cover crop treatments at 0 kPa and 33 kPa water tensions, respectively. In contrast, no significant difference in k was observed between NOC-applied plots and CONV, suggesting that not all organic amendments have the same effect. Additionally, the results showed no notable discrepancies in k at saturation among treatments within the 15–30 cm depth. However, the k value measured at 10 kPa water suction in the sub-surface soil treated with COM was the lowest among all treatments.

Table 3. Means (±SD) of volumetric water content (VWC), thermal conductivity (k), volumetric heat capacity (C), and thermal diffusivity of surface (0–15 cm) and sub-surface (15–30 cm) based on different soil amendments. Different letters within a column indicate a significant ($p < 0.05$) difference in the soil property among the treatments within that depth.

Treatments	VWC_sat (cm^3/cm^3)	VWC_10 kPa (cm^3/cm^3)	K_sat (W/mK)	K_10 kPa (W/mK)	C_sat (MJ/m^3K)	C_10 kPa (MJ/m^3K)	D_sat (mm^2/s)	D_10 kPa (mm^2/s)
0–15 cm								
TW	0.62 ± 0.03 ^{a}	0.55 ± 0.02 ^{ab}	1.01 ± 0.03 ^{b}	0.92 ± 0.04 ^{b}	3.43 ± 0.19 ^{a}	3.39 ± 0.13 ^{a}	0.31 ± 0.02 ^{a}	0.28 ± 0.01 ^{b}
NOC	0.59 ± 0.01 ^{ab}	0.56 ± 0.01 ^{a}	1.15 ± 0.05 ^{ab}	1.11 ± 0.05 ^{a}	3.43 ± 0.09 ^{a}	3.56 ± 0.22 ^{a}	0.34 ± 0.02 ^{a}	0.32 ± 0.02 ^{ab}
COM	0.61 ± 0.01 ^{ab}	0.55 ± 0.01 ^{ab}	1.02 ± 0.03 ^{b}	0.95 ± 0.03 ^{b}	3.50 ± 0.09 ^{a}	3.24 ± 0.13 ^{a}	0.29 ± 0.01 ^{a}	0.30 ± 0.02 ^{ab}
CONV	0.57 ± 0.01 ^{b}	0.51 ± 0.02 ^{b}	1.23 ± 0.02 ^{a}	1.11 ± 0.03 ^{a}	3.29 ± 0.08 ^{a}	3.15 ± 0.05 ^{a}	0.38 ± 0.01 ^{a}	0.35 ± 0.01 ^{a}
15–30 cm								
TW	0.58 ± 0.01 ^{a}	0.53 ± 0.02 ^{a}	1.11 ± 0.02 ^{a}	0.99 ± 0.04 ^{ab}	3.41 ± 0.12 ^{a}	2.84 ± 0.11^{a}	0.33 ± 0.01 ^{a}	0.33 ± 0.01 ^{a}
NOC	0.62 ± 0.01 ^{a}	0.56 ± 0.03 ^{a}	1.09 ± 0.03 ^{a}	1.01 ± 0.02 ^{ab}	3.37 ± 0.13 ^{a}	3.35 ± 0.10 ^{a}	0.33 ± 0.01 ^{a}	0.31 ± 0.01 ^{a}
COM	0.58 ± 0.01 ^{a}	0.51 ± 0.01 ^{a}	1.08 ± 0.05 ^{a}	0.86 ± 0.02 ^{b}	3.18 ± 0.07 ^{a}	2.99 ± 0.06 ^{a}	0.34 ± 0.02 ^{a}	0.33 ± 0.01 ^{a}
CONV	0.59 ± 0.01 ^{a}	0.51 ± 0.02 ^{a}	1.13 ± 0.04 ^{a}	1.06 ± 0.05 ^{a}	3.29 ± 0.12 ^{a}	3.04 ± 0.11 ^{a}	0.34 ± 0.01 ^{a}	0.35 ± 0.01 ^{a}

At saturation (0 kPa), no statistically significant differences ($p < 0.05$) in D were observed between treatments. However, compared to CONV plots with inorganic fertilizer, COM and TW applications reduced D values by 23.68% and 18.42%, respectively. The trend continued at 10 kPa suction within the 0–15 cm depth. Here, a significant difference ($p < 0.05$) in D was observed between TW and CONV plots. Specifically, D in TW plots was 20% lower than in CONV plots. This finding suggests that TW application may have a more pronounced effect on reducing D under unsaturated conditions, especially in the top soil layer. Interestingly, no significant differences in D were observed between treatments at 10 kPa and saturation within the 15–30 cm layer. This likely parallels the observations for thermal conductivity and can be attributed to the limited incorporation depth of organic amendments, which are typically concentrated in the top soil layer.

Volumetric heat capacity (C) represents the amount of heat required to elevate the temperature of a unit volume of soil by one degree Kelvin. In simpler terms, C indicates how much thermal energy a unit of soil can absorb or release when its temperature fluctuates. Our study revealed no statistically significant differences ($p < 0.05$) in C between treatments at either saturation (0 kPa) or 10 kPa suction for both the surface (0–15 cm) and sub-surface (15–30 cm) soil layers. Interestingly, however, C exhibited a slight upward trend in plots treated with organic amendments compared to CONV plots at both water suction levels. While these differences were not statistically significant, they suggest a potential influence of organic amendments on soil heat storage capacity.

4. Discussion

Tea waste was a by-product from tea processing facilities while the compost was made from green shoots (*Tithonia diversifolia*), tea waste, and cow dung. The plots applied with TW and COM significantly increased SOC accumulation compared to NOC and control plots receiving only inorganic fertilizer. This enhanced SOC accumulation in TW and COM treatments may be attributed to their higher C:N ratios compared to NOC. A study by Liyanage, Sulaiman [32] suggests that TW exhibits lower carbon mineralization rates than other soil amendments, making it a promising candidate for improving soil quality. As TW is also a component of COM, it likely contributes to the elevated SOC content observed in COM-amended plots relative to NOC and CONV. Interestingly, the study revealed a more pronounced impact on surface soil (0–15 cm) compared to the sub-surface layer (15–30 cm), which was a result of the surface incorporation of amendments.

A growing body of research underscores the positive impact of long-term organic amendment application on soil health [33,34]. Specifically, these practices elevate SOC levels, which is a well-established driver of both reduced bulk density and increased soil porosity [35,36]. The incorporation of organic materials with denser mineral soil fractions leads to a reduction in bulk density. This phenomenon can be attributed to two key mechanisms. Firstly, organic matter inherently possesses a lower density compared to mineral particles. Consequently, mixing these materials dilutes the overall density of the soil matrix. Secondly, the decomposition of organic matter within the soil facilitates the formation of pores and aggregates, further decreasing bulk density. Mean weight diameter (MWD) is an indicator of the predominance of larger, more stable aggregates over smaller and less stable fractions [37,38]. A higher MWD indicates a high resistance to wind erosion and the predominance of macro-aggregates. SOC plays a key role in forming soil aggregates and stabilizing soil structure [39]. Plots treated with TW exhibited higher MWDs, which indicates the formation of larger macro-aggregates, which in turn facilitated greater water drainage at a matric potential of 10 kPa suction compared to CONV plots.

The significant decrease in bulk density and increase in porosity in TW and COM plots have caused a significant decrease in k. Several factors influence soil k: the proportions of different soil particles (fractions), the contact between solid particles themselves, and the contact between solids and water [17,23,40]. Additionally, the size and arrangement of the solid particles play a role. As expected, k was consistently higher at saturation compared to measurements taken at 10 kPa suction for all treatments. This is because saturated soil has a greater water content, and water conducts heat more efficiently than air. The larger decrease in thermal conductivity (k) observed in TW and COM plots can be primarily attributed to the increased pore space following drainage at 10 kPa suction. This suggests the formation of more macropores in these treatments compared to the control (CONV). Our results align with previous studies by Haruna and Anderson [41] and Miller, Beasley [19] who also reported lower k values in soils cultivated with cover crops and applied with long-term feedlot manures, respectively. The volumetric heat capacity is influenced by the water content and SOC in soil [42]. While we anticipated a significant increase in C with organic amendments, this effect was masked by a substantial decrease in bulk density of the manure-amended surface soils. This decrease is likely due to the higher porosity associated with the amendments. Similar findings were reported by Miller, Beasley [19] in their study on the thermal properties of feedlot-manure-amended soils. Previous research by Haruna and Anderson [41] and Haruna, Anderson [18] observed a decrease in thermal diffusivity (D) in cover crop grown soils. Our results also indicated a significant reduction in D at unsaturated soil conditions (i.e., 10 kPa) in TW-applied plots as compared to CONV, which is influenced by reduced bulk density [19]. The reduction in D was more pronounced under unsaturated conditions possibly due to increased macroporosity in TW-applied plots.

Soil thermal properties are mainly influenced by a suite of other soil properties such as bulk density, soil texture, SOC, soil water content, and porosity. Principal component analysis (PCA) revealed a strong correlation between PC1 and several soil properties, including k, D, bulk density, SOC, and soil water content (Figure 7). This indicated that these properties were interrelated, suggesting that they may be influenced by similar underlying factors. For example, increased SOC content led to higher porosity, which can in turn decrease bulk density and influence k, D, and water holding capacity. Further analysis of the PCA loadings (the contribution of each variable to the principal components) could provide more specific insights into these relationships. A strong negative correlation (−0.68) between C at 10 kPa and PC2 indicated that PC2 captured the interplay between volumetric heat capacity and soil organic carbon.

This study suggested that the long-term application of TW and COM alters soil thermal properties, particularly k and D. This decrease in k results from the reduction in soil bulk density observed in TW and COM plots. Interestingly, the increased soil water content at saturation in these plots did not negate the k reduction, suggesting a more pronounced effect of BD on k. The D measures the soil's capacity to conduct heat relative to its ability to resist rapid temperature fluctuations. The highest D observed in CONV plots indicates that these plots facilitate greater heat transfer while providing less buffering against rapid temperature changes. Our findings suggest that TW and COM treatments may buffer tea plantation soils against extreme temperature fluctuations in warmer tropical climates. This is due to the reduced heat transfer rate in these plots compared to soils receiving only inorganic fertilizers. Conversely, k under CONV management (i.e., using only conventional synthetic fertilizers) can result in a rapid increase in soil temperature, extending to greater depths. This can enhance the vulnerability of stored carbon by accelerating mineralization, which may, in turn, elevate atmospheric CO_2 levels and contribute to greater variability in global climate. Additionally, the higher k, combined with reduced organic amendment levels, can exacerbate surface water evaporation and diminish moisture availability for the tea crop. This implies that applying more persistent organic amendments like TW can offer a dual benefit, enhancing soil water retention and promoting thermal stability, both of which are crucial for root growth and microbial activity.

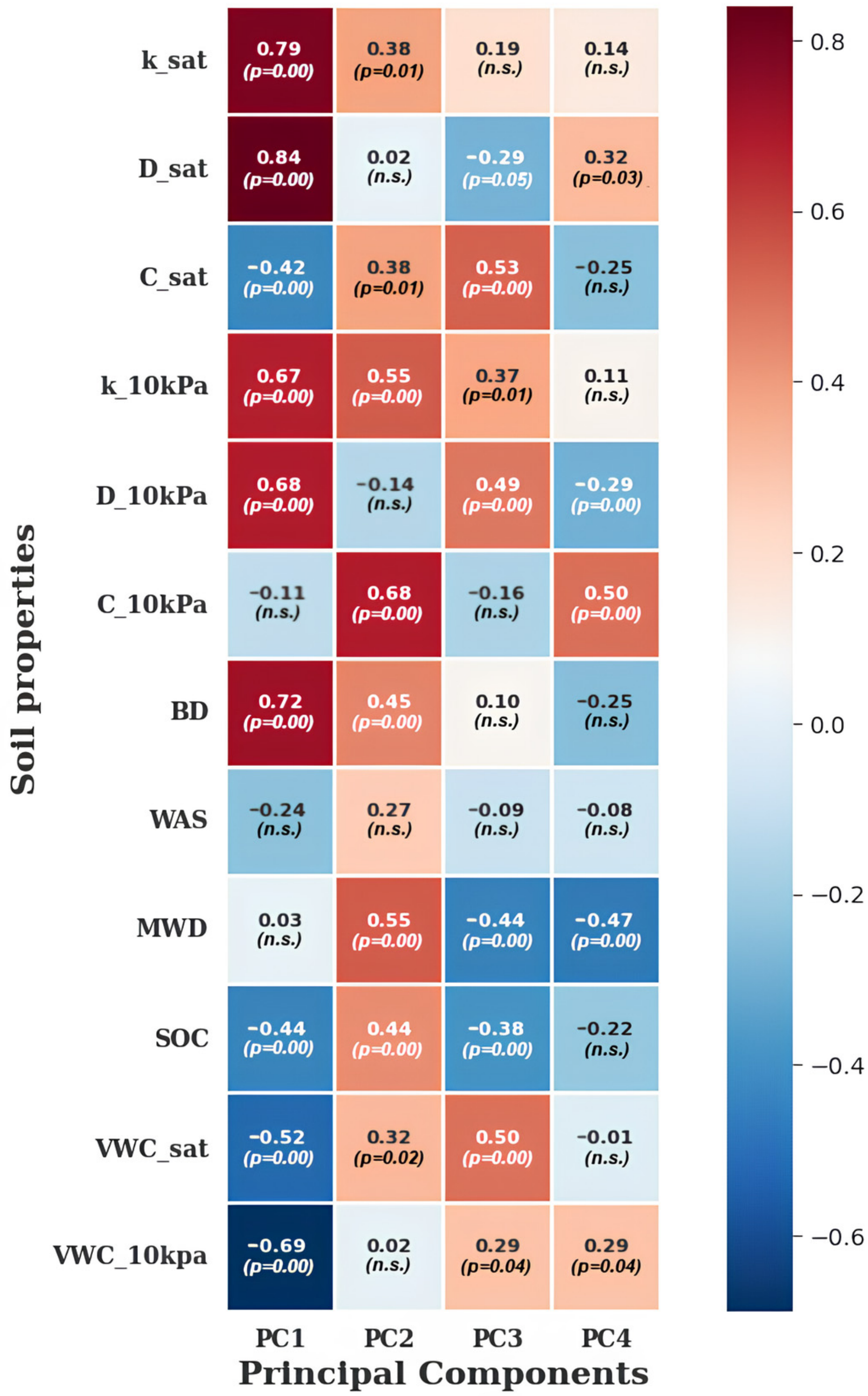

Figure 7. Correlation between soil properties and principal components (PC1–PC5). Strong correlations indicate an effective representation of soil properties in a principal component, while weak correlations suggest inadequate representation. Probability values for each correlation are indicated in brackets, where "n.s." denotes no significant probability values. Soil properties include k_sat, D_sat, and C_sat (thermal conductivity, diffusivity, and volumetric heat capacity at 0 kPa, respectively); k_10 kPa, D_10 kPa, and C_10 kPa (thermal conductivity, diffusivity, and volumetric heat capacity at 10 kPa, respectively); BD (bulk density); WSA (water-stable aggregate); MWD (mean weight diameter); SOC (soil organic carbon); and SWC_sat and SWC_10 kPa (soil water content at 0 and 10 kPa, respectively).

Soil erosion in tea plantations in Sri Lanka remains a significant environmental challenge, as it not only depletes fertile topsoil but also results in the loss of applied fertilizers, reducing agricultural productivity [43]. Furthermore, the United Nations factsheet highlights that Sri Lanka is likely to experience more intense rainfall events and higher temperatures in the future as a consequence of climate change [44]. Results from this study showed that the long-term application of TW and compost (COM) emerges as a sustainable soil management strategy to mitigate the adverse impacts of climate change such as accelerated soil erosion and damages from extreme droughts. For example, TW and COM amendments reduce BD and enhance soil porosity and aggregate stability, thereby improving the soil's resistance to erosion. Additionally, soils treated with TW and COM exhibit greater water retention capacity and improved thermal properties, enabling them to store more water and heat in soil. This contributes to increased soil resilience, helping to buffer against extreme temperature fluctuations, conserving water and supporting the sustainable production of tea under changing climatic conditions.

Pratylenchus loosi is a major economic threat to tea cultivation in Sri Lanka, as well as in other tea-growing regions like Japan, Iran, Bangladesh, China, and Korea. Studies suggest that rising soil temperatures may significantly alter nematode populations and distribution [15,16]. Therefore, by improving soil thermal buffering capacity, the application of TW has the potential to not only enhance soil health but also indirectly contribute to the overall health of the tea ecosystem by mitigating potential negative effects of nematode communities.

The application of TW and COM in tea plantations presents a sustainable soil management practice that improves soil water retention and aggregate stability within the tea ecosystem. TW, a waste byproduct of tea processing, is readily available, making it a valuable resource for enhancing soil health. Similarly, the materials used to produce compost, such as green shoots of Tithonia diversifolia, are sourced from shade trees within the tea ecosystem, contributing to the recycling of organic matter. By incorporating these locally available materials, TW and COM can not only improve soil physical and thermal properties but also support the natural nutrient cycle. The application of TW and COM supports sustainability and improves soil health, making it an effective strategy for enhancing the resilience of tropical tea ecosystems in a changing climate.

5. Conclusions

This study demonstrated that the long-term application of tea waste and compost significantly enhanced the soil physical and thermal properties of a tea-cultivated Ultisol compared to synthetic fertilizers and neem oil cake. Tea waste and compost increased soil organic carbon, improved aggregation, reduced bulk density, and enhanced porosity, which collectively improved thermal buffering capacity. These findings underscore the potential of tea waste and compost as sustainable soil management strategies to improve soil health and resilience against rising soil temperatures in tea ecosystems. Neem oil cake, however, showed no significant effect on the measured soil properties compared to synthetic fertilizers, highlighting the importance of amendment selection. Future research should focus on investigating the effects of these amendments on daily and seasonal variations in soil temperature, providing a detailed understanding of how they influence thermal dynamics and energy fluxes over time. Furthermore, long-term studies should evaluate their impact on soil water balance, with a particular focus on seasonal water depletion patterns within the root zone, to enhance our understanding of water availability and its implications for plant growth and ecosystem sustainability.

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References

1. Boehm, R.; Cash, S.B.; Anderson, B.T.; Ahmed, S.; Griffin, T.S.; Robbat, A.; Stepp, J.R.; Han, W.; Hazel, M.; Orians, C.M. Association between Empirically Estimated Monsoon Dynamics and Other Weather Factors and Historical Tea Yields in China: Results from a Yield Response Model. *Climate* **2016**, *4*, 20. https://doi.org/10.3390/cli4020020.
2. Marx, W.; Haunschild, R.; Bornmann, L. Global Warming and Tea Production—The Bibliometric View on a Newly Emerging Research Topic. *Climate* **2017**, *5*, 46. https://doi.org/10.3390/cli5030046.
3. Chang, K. *World Tea Production and Trade: Current and Future Development*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2015; pp. 3–4.
4. Wijeratne, M.; Anandacoomaraswamy, A.; Amarathunga, M.; Ratnasiri, J.; Basnayake, B.; Kalra, N. Assessment of impact of climate change on productivity of tea (Camellia sinensis L.) plantations in Sri Lanka. *J. Natl. Sci. Found. Sri Lanka* **2007**, *35*, 119. https://doi.org/10.4038/jnsfsr.v35i2.3676.
5. Cambridge University Press. *Intergovernmental Panel on Climate, C., Climate Change 2021—The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2023
6. Bond-Lamberty, B.; Bailey, V.L.; Chen, M.; Gough, C.M.; Vargas, R. Globally rising soil heterotrophic respiration over recent decades. *Nature* **2018**, *560*, 80–83. https://doi.org/10.1038/s41586-018-0358-x.
7. Mallik, P.; Ghosh, T. Impact of surface-net solar radiation and soil temperature on tea production in India: a study of the Dooars region in West Bengal. *Reg. Environ. Chang.* **2021**, *21*, 1–14. https://doi.org/10.1007/s10113-021-01844-5.
8. Amarasena, P.G.D.S.; Mohotti, K.M.; De Costa, D.M. Effects of changing rainfall and soil temperature on population density of Pratylenchus loosi in tea lands at different elevations. *Trop. Agric. Res.* **2016**, *27*, 265. https://doi.org/10.4038/tar.v27i3.8205.
9. Mohotti, K.M. Marked shift in damage caused by parasitic nematode species in tea with long term climate change in Sri Lanka. In: Proceedings of first national conference on *Climate Change and Its Impacts on Agriculture, Forestry and Water*; Kandy, Sri Lanka, 2017.
10. Toselli, M.; Flore, J.A.; Marangoni, B.; Masia, A. Effects of root-zone temperature on nitrogen accumulation by non-bearing apple trees. *J. Hortic. Sci. Biotechnol.* **1999**, *74*, 118–124. https://doi.org/10.1080/14620316.1999.11511083.
11. Weih, M.; Karlsson, P.S. The nitrogen economy of mountain birch seedlings: implications for winter survival. *J. Ecol.* **1999**, *87*, 211–219. https://doi.org/10.1046/j.1365-2745.1999.00340.x.
12. Kaiser, C.; Meyer, H.; Biasi, C.; Rusalimova, O.; Barsukov, P.; Richter, A. Conservation of soil organic matter through cryoturbation in arctic soils in Siberia. *J. Geophys. Res. Biogeosci.* 2007, *112*. https://doi.org/10.1029/2006jg000258.
13. Wallenstein, M.; Allison, S.D.; Ernakovich, J.; Steinweg, J.M.; Sinsabaugh, R. Controls on the temperature sensitivity of soil enzymes: A Key Driver of In Situ Enzyme Activity Rates. In *Soil Enzymology*; Shukla, G., Varma, A., Eds.; Springer: Berlin/Heidelberg, Germany, 2010; Volume 22, pp. 245–258.
14. Lahti, M.; Aphalo, P.J.; Finer, L.; Lehto, T.; Leinonen, I.; Mannerkoski, H.; Ryyppo, A. Soil temperature, gas exchange and nitrogen status of 5-year-old Norway spruce seedlings. *Tree Physiol.* **2002**, *22*, 1311–1316. https://doi.org/10.1093/treephys/22.18.1311.
15. Zhang, N.; Wang, Z. Review of soil thermal conductivity and predictive models. *Int. J. Therm. Sci.* 2017, *117*, 172–183. https://doi.org/10.1016/j.ijthermalsci.2017.03.013.
16. Carslaw, H.S.; Jaeger, J.C. *Conduction of Heat in Solids*; Oxford University Press: Oxford, UK, 1959; p. 262.
17. Abu-Hamdeh, N.H. Effect of tillage treatments on soil thermal conductivity for some Jordanian clay loam and loam soils. *Soil Tillage Res.* **2000**, *56*, 145–151.
18. Haruna, S.I.; Anderson, S.H.; Nkongolo, N.V.; Reinbott, T.; Zaibon, S. Soil Thermal Properties Influenced by Perennial Biofuel and Cover Crop Management. *Soil Sci. Soc. Am. J.* **2017**, *81*, 1147–1156. https://doi.org/10.2136/sssaj2016.10.0345.

19. Miller, J.; Beasley, B.; Drury, C.; Larney, F.; Hao, X.; Chanasyk, D. Influence of long-term feedlot manure amendments on soil hydraulic conductivity, water-stable aggregates, and soil thermal properties during the growing season. *Can. J. Soil Sci.* **2018**, *98*, 421–435.
20. Khaledi, S.; Delbari, M.; Galavi, H.; Bagheri, H.; Chari, M.M. Effects of biochar particle size, biochar application rate, and moisture content on thermal properties of an unsaturated sandy loam soil. *Soil Tillage Res.* **2022**, *226*, 105579. https://doi.org/10.1016/j.still.2022.105579.
21. Usowicz, B.; Lipiec, J.; Łukowski, M.; Marczewski, W.; Usowicz, J. The effect of biochar application on thermal properties and albedo of loess soil under grassland and fallow. *Soil Tillage Res.* **2016**, *164*, 45–51. https://doi.org/10.1016/j.still.2016.03.009.
22. Liu, Z.; Xu, J.; Li, X.; Wang, J. Mechanisms of biochar effects on thermal properties of red soil in south China. *Geoderma* **2018**, *323*, 41–51. https://doi.org/10.1016/j.geoderma.2018.02.045.
23. Zhao, J.; Ren, T.; Zhang, Q.; Du, Z.; Wang, Y. Effects of Biochar Amendment on Soil Thermal Properties in the North China Plain. *Soil Sci. Soc. Am. J.* **2016**, *80*, 1157–1166. https://doi.org/10.2136/sssaj2016.01.0020.
24. Romano, N.; Hopmans, J.; Dane, J. Water retention and storage: Suction table. In *Methods of Soil Analysis*; Part 4. Physical Methods; Dane, J.H., Topp, C.G., Eds.; Soil Science Society of America Madison: Madison, MI, USA, 2002; pp. 692–698.
25. Black, G.; Hartge, K. Bulk density. In *Methods of Soil Analysis*; Part; Wiley: Hoboken, NJ, USA, 1986; Volume 1, pp. 347–380.
26. Gee, G.W.; Or, D. 2.4 Particle-Size Analysis. In *Methods of Soil Analysis: Part 4 Physical Methods*; Dane, J.H., Topp, C.G., Eds.; Soil Science Society of America: Madison, MI, USA, 2002; pp. 255–293.
27. Ben-Dor, E.; Banin, A. Determination of organic matter content in arid-zone soils using a simple "loss-on-ignition" method. *Commun. Soil Sci. Plant Anal.* **1989**, *20*, 1675–1695.
28. Kemper, W.D.; Rosenau, R.C. Aggregate Stability and Size Distribution1. In *Methods of Soil Analysis: Part 1—Physical and Mineralogical Methods*; Klute, A., Ed.; Soil Science Society of America, American Society of Agronomy: Madison, MI, USA, 1986; pp. 425–442.
29. *SigmaPlot for Windows*, Version 14.5; Systat Software, Inc.: San Jose, CA, USA, 2020.
30. Pedregosa, F.; Varoquaux, G.; Gramfort, A.; Michel, V.; Thirion, B.; Grisel, O.; Blondel, M.; Prettenhofer, P.; Weiss, R.; Dubourg, V.; Vanderplas, J. Scikit-learn: Machine learning in Python. *J. Mach. Learn. Res.* **2011**, *12*, pp. 2825–2830.
31. Haruna, S.I.; Ward, Z.A.; Cartwright, A.L.; Wunner, A.A.; Jackson, C.A.; Berry, C.R. No-till cover crop effects on the thermal properties of a Paleudult. *Soil Tillage Res.* **2023**, *231*. https://doi.org/10.1016/j.still.2023.105717.
32. Liyanage, L.R.M.C.; Sulaiman, M.F.; Ismail, R.; Gunaratne, G.P.; Dharmakeerthi, R.S.; Rupasinghe, M.G.N.; Mayakaduwa, A.P.; Hanafi, M.M. Carbon Mineralization Dynamics of Organic Materials and Their Usage in the Restoration of Degraded Tropical Tea-Growing Soil. *Agronomy* **2021**, *11*, 1191.
33. Gupta, R.K.; Sraw, P.K.; Kang, J.S.; Kaur, J.; Sharma, V.; Pathania, N.; Kalia, A.; Al-Ansari, N.; Alataway, A.; Dewidar, A.Z.; et al. Interactive effects of long-term management of crop residue and phosphorus fertilization on wheat productivity and soil health in the rice–wheat. *Sci. Rep.* **2024**, *14*, 1–12. https://doi.org/10.1038/s41598-024-51399-8.
34. Matisic, M.; Dugan, I.; Bogunovic, I. Challenges in Sustainable Agriculture—The Role of Organic Amendments. *Agriculture* **2024**, *14*, 643. https://doi.org/10.3390/agriculture14040643.
35. Celik, I.; Gunal, H.; Budak, M.; Akpinar, C. Effects of long-term organic and mineral fertilizers on bulk density and penetration resistance in semi-arid Mediterranean soil conditions. *Geoderma* **2010**, *160*, 236–243. https://doi.org/10.1016/j.geoderma.2010.09.028.
36. Luna, L.; Vignozzi, N.; Miralles, I.; Solé-Benet, A. Organic amendments and mulches modify soil porosity and infiltration in semiarid mine soils. *Land Degrad. Dev.* **2017**, *29*, 1019–1030. https://doi.org/10.1002/ldr.2830.
37. Le Bissonnais, Y. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology Stabilité structurale et évaluation de la sensibilité des sols à la battance et à l'érosion: I: Théorie et méthologie. *Eur. J. Soil Sci.* **1996**, *47*, 425–437.
38. Amézketa, E. Soil Aggregate Stability: A Review. *J. Sustain. Agric.* **1999**, *14*, 83–151
39. Onweremadu, E.U.; Onyia, V.N.; Anikwe, M. Carbon and nitrogen distribution in water-stable aggregates under two tillage techniques in Fluvisols of Owerri area, southeastern Nigeria. *Soil Tillage Res.* 2007, *97*, 195–206.
40. Noborio, K.; McInnes, K.; Heilman, J. Measurements of soil water content, heat capacity, and thermal conductivity with a single TDR probe. *Soil Sci.* **1996**, 161, 22–28.
41. Haruna, S.I.; Anderson, S.H. Influence of no-till cover crop management on soil thermal properties. *Soil Res.* **2022**, *60*, 580–589. https://doi.org/10.1071/sr21197.
42. Hillel, D. *Applications of Soil Physics*; Academic Press: New York, NY, USA, 1980.

43. Ananda, J.; Herath, G.; Chisholm, A. Determination of yield and erosion damage functions using subjectively elicited data: application to smallholder tea in Sri Lanka. *Aust. J. Agric. Resour. Econ.* **2001**, *45*, 275–289.
44. United Nations Sri Lanka. Fact Sheet: Climate Impact in Sri Lanka; United Nations Sri Lanka: Colombo, Sri Lanka, 2023.