

Article

Short-Term Effects of Biochar on Soil Fluxes of Methane, Carbon Dioxide, and Water Vapour in a Tea Agroforestry System

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Abstract

Tea (*Camellia sinensis*) cultivation is a major global industry that faces sustainability challenges due to soil degradation and greenhouse gas (GHG) emissions from intensive management. Biochar—charcoal designed and used as a soil amendment—has emerged as a potential tool to improve soil health, enhance carbon sequestration, and mitigate GHG fluxes in agroecosystems. However, field-scale evidence of its effects on GHG dynamics in woody crops like tea remains limited, particularly regarding methane (CH₄). Here, we present, to our knowledge, the first field assessment of biochar impacts on CO₂, CH₄, and H₂O vapour fluxes in a subtropical tea agroforestry system with and without shade trees in northeastern Bangladesh. Using a closed dynamic chamber and real-time gas analysis, we found that biochar application (at 7.5 t·ha^{−1}) significantly enhanced average soil methane (CH₄) uptake by 84%, while soil respiration (CO₂ efflux) rose modestly (+18%) and water-vapour fluxes showed a marginal increase. Canopy conditions modulated these effects: biochar strongly enhanced CH₄ uptake under both shaded and open canopies, whereas biochar effects on water-vapour flux were detectable only when biochar was combined with a shade-tree canopy. Structural equation modelling suggests that CH₄ flux was primarily governed by biochar-induced changes in soil pH, moisture, nutrient status, and temperature, while CO₂ and H₂O fluxes were shaped by organic matter availability, temperature, and phosphorus dynamics. These findings demonstrate that biochar can promote CH₄ uptake and alter soil carbon–water interactions during the dry season in tea plantation systems and support operational biochar use in combination with shade-tree agroforestry.

Keywords: biochar; agroforestry; tea; shade tree; climate change



Academic Editor: Yam Kanta Gaihre

Received: 2 October 2025

Revised: 21 January 2026

Accepted: 21 January 2026

Published: 24 January 2026

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1. Introduction

As one of the world's most consumed beverages, tea (*Camellia sinensis*) is a globally significant crop cultivated across 5.7 million hectares, underpinning rural economies and livelihoods throughout Asia, Africa, and Latin America [1–3]. Globally, the tea trade is valued at over USD 9 billion annually, making its sustainability a priority in international agricultural policy [1]. However, the environmental footprint of tea production poses a substantial challenge to its long-term viability. Intensive cultivation, characterized by heavy nitrogenous fertilizer application, frequently leads to soil degradation, including acidification and nutrient depletion, which compromises soil fertility [4,5]. Consequently, tea

plantations have become notable sources of soil greenhouse gas (GHG) emissions, particularly nitrous oxide (N_2O) and carbon dioxide (CO_2) [6]. Addressing these interconnected challenges is now critical as the global community strives to meet sustainability targets for carbon neutrality and land restoration [7–9]. This creates a critical tension necessitating innovative management practices that can align tea production with global climate and land restoration goals.

Two primary approaches to enhancing the sustainability of tea plantations have been the implementation of agroforestry practices and the addition of organic soil amendments. Shade-tree tea agroforestry—a management system integrating tea bushes with an over-story of diverse trees—provides a structural framework that enhances carbon sequestration, optimizes nutrient cycling and soil fertility, moderates the soil microclimate, and influences the microbial processes that drive GHG fluxes [10–13]. Organic soil amendments may also be used to enhance tea plantation sustainability by acting as both a direct source of nutrients and by enhancing soil physicochemical properties, including the capacity of the soil to retain water and nutrients. The primary organic soil amendments used in this context have been manures (e.g., [14,15]), composts [16], mulches [17], and bacterial inoculants [18]. Together, shade trees and organic inputs form an integrated management strategy in many estates, yet their combined effects on soil GHG and water-vapour fluxes remain poorly quantified.

Biochar has recently emerged as a key soil amendment for climate-smart agriculture [19]. Produced from the pyrolysis of biomass, biochar is a stable, carbon-rich material whose unique properties—including a highly porous structure, large specific surface area, and chemical recalcitrance—distinguish it from rapidly decomposing organic amendments like composts or manures [20,21]. Its application has been shown to influence soil processes through three main pathways: (i) physical changes in soil structure and aeration; (ii) chemical effects on pH, sorption, and nutrient availability; and (iii) shifts in microbial habitat and community composition [3,22–25].

The intensive management required for tea production often leads to a cascade of soil health issues, including degradation from high nutrient demand, soil acidification, and compaction, which in turn drive inefficient water use and elevate emissions of GHGs [4,6]. Biochar application potentially offers a multifaceted approach to address these interconnected challenges. In tea gardens, biochar applications have been shown to ameliorate soil acidity, improve soil aggregate stability, and increase soil organic carbon stocks over multiple years [23,26,27]. Beyond these direct soil health benefits, biochar is increasingly recognized for its potential to mitigate climate change by altering the biogeochemical pathways governing GHG fluxes. For instance, several studies in tea plantations have documented significant reductions in N_2O emissions following biochar application [28,29]. By contrast, almost all biochar studies in tea have focused on soil physicochemical properties, N_2O emissions, and yield responses, with little or no direct measurement of CH_4 or soil water-vapour fluxes. These combined characteristics establish biochar as a promising tool for sustainable soil management, yet its specific impacts on GHG fluxes, particularly CH_4 , CO_2 , and water-vapour flux within tea agroecosystems, remain poorly understood.

CH_4 fluxes in tea agroecosystems have often been considered negligible due to the general notion that tea soils are typically well-drained and aerobic [30], and integrated analyses have not considered CH_4 [6]. This perspective, however, may overlook the effects of common management practices, such as soil compaction from human traffic or heavy machinery and altered soil chemistry from agrochemical inputs, which can create conditions favourable to methanogenesis. Biochar applications can alter these conditions. By increasing soil porosity and aeration, biochar may enhance the activity of methanotrophic bacteria, thereby increasing the soil's capacity to act as a CH_4 sink. Conversely, certain

biochars can release phenolic compounds that inhibit methane oxidation [31] or create anaerobic microsites within aggregates that could potentially support methanogenesis. Laboratory incubations of acidic tea soils have shown inconsistent results, with some studies reporting no significant effect of biochar on CH₄ fluxes [32]. The interactive effects of biochar with shade-tree canopies, which alter soil temperature and moisture, remain entirely unexplored, leaving a critical gap in predicting field-scale CH₄ dynamics.

The impact of biochar on soil respiration (CO₂ flux) in tea plantations is equally unresolved. While the primary benefit of biochar is the addition of recalcitrant carbon for long-term sequestration, its immediate effect on native soil organic carbon (SOC) mineralization is debated. The addition of labile carbon from fresh biochar can trigger a positive priming effect, stimulate microbial activity, and temporarily increase CO₂ emissions [29,33]. In contrast, other studies suggest biochar can stabilize native SOC within newly formed aggregates, leading to a negative priming effect and reduced overall respiration [26]. Field studies in tea gardens have yielded conflicting results: for instance, Wang et al. [32] observed a decrease in CO₂ emissions from an acidic tea garden soil amended with biochar, whereas Han et al. [34] found that manure application stimulated respiration far more than biochar did.

Potential interactions between biochar, GHG fluxes, and soil moisture dynamics have been almost entirely overlooked. Biochar is widely recognized for its ability to improve soil water retention [24]. Studies have also generally found that biochar reduces soil evaporation [35,36]. However, prior studies have focused on agricultural systems, and field measurements of soil water-vapour (H₂O) flux in response to biochar application in woody crops appear to be non-existent. Soil moisture is a key variable that controls the redox conditions governing CH₄ cycling and modulates microbial and root respiration, directly influencing CO₂ emissions [37]. Understanding how biochar-induced changes in soil water flux interact with the microclimate modifications from shade trees is essential for assessing impacts on water-use efficiency and the coupled C and water cycles.

The present study provides the first field assessment of biochar's effects on soil CO₂, CH₄, and H₂O fluxes within a subtropical tea agroforestry system, utilizing a high-resolution, closed-dynamic chamber system and real-time gas analysis for flux measurements. The primary objectives were to: (1) quantify how biochar treatment influences the fluxes of soil CH₄, CO₂, and H₂O vapour; (2) determine the extent to which soil physicochemical properties, such as pH, bulk density, moisture content, temperature, organic matter, and macronutrient concentrations (N, P, and K), mediate these flux responses; (3) assess whether shade trees interact with biochar treatment to modulate soil CH₄, CO₂, and H₂O vapour fluxes; and (4) evaluate the relative contributions of drivers (e.g., edaphic factors and the presence of shade trees) in shaping flux patterns. We hypothesized that biochar application would significantly reduce net CH₄ emissions (increase net CH₄ sink) by improving soil aeration while having a negligible effect on total soil respiration (CO₂), reduce H₂O vapour fluxes, and that the presence of shade trees would modulate these responses by creating cooler, moister soil conditions conducive to CH₄ oxidation and by reducing soil respiration and evaporation.

2. Materials and Methods

2.1. Study Sites

The field experiment was carried out in the Lakkatura Tea Garden (24.90° N, 91.905° E; hereafter "LTG"), on the outskirts of Sylhet, northeastern Bangladesh. LTG is one of the largest estates administered by the Bangladesh National Tea Board and covers approximately 1293 ha of undulating, low-elevation terrain (Figure 1). Monoculture stands of tea (*Camellia sinensis*) dominate the estate. Permanent shade is provided mainly by

Albizia odoratissima (L.f.) Benth. (Leguminosae) and *Melia azedarach* L. (Meliaceae) planted between tea rows at ~ 100 trees ha^{-1} ; leguminous *Albizia* also enriches soil N through litter and root turnover [38]. In this study, ‘agroforestry’ (tea + shade-tree) plots were located in tea rows with this established shade-tree overstorey, whereas ‘agricultural’ (tea only) plots were located in adjacent tea-only rows lacking shade trees, so that the presence or absence of the shade-tree canopy constituted one factor in the experimental design. The shade-tree system was installed in 2007–2008, and in May 2016, 20 m $\times$ 20 m “agricultural” and “agroforestry” plots were replicated for the present study, nine years after co-planting.

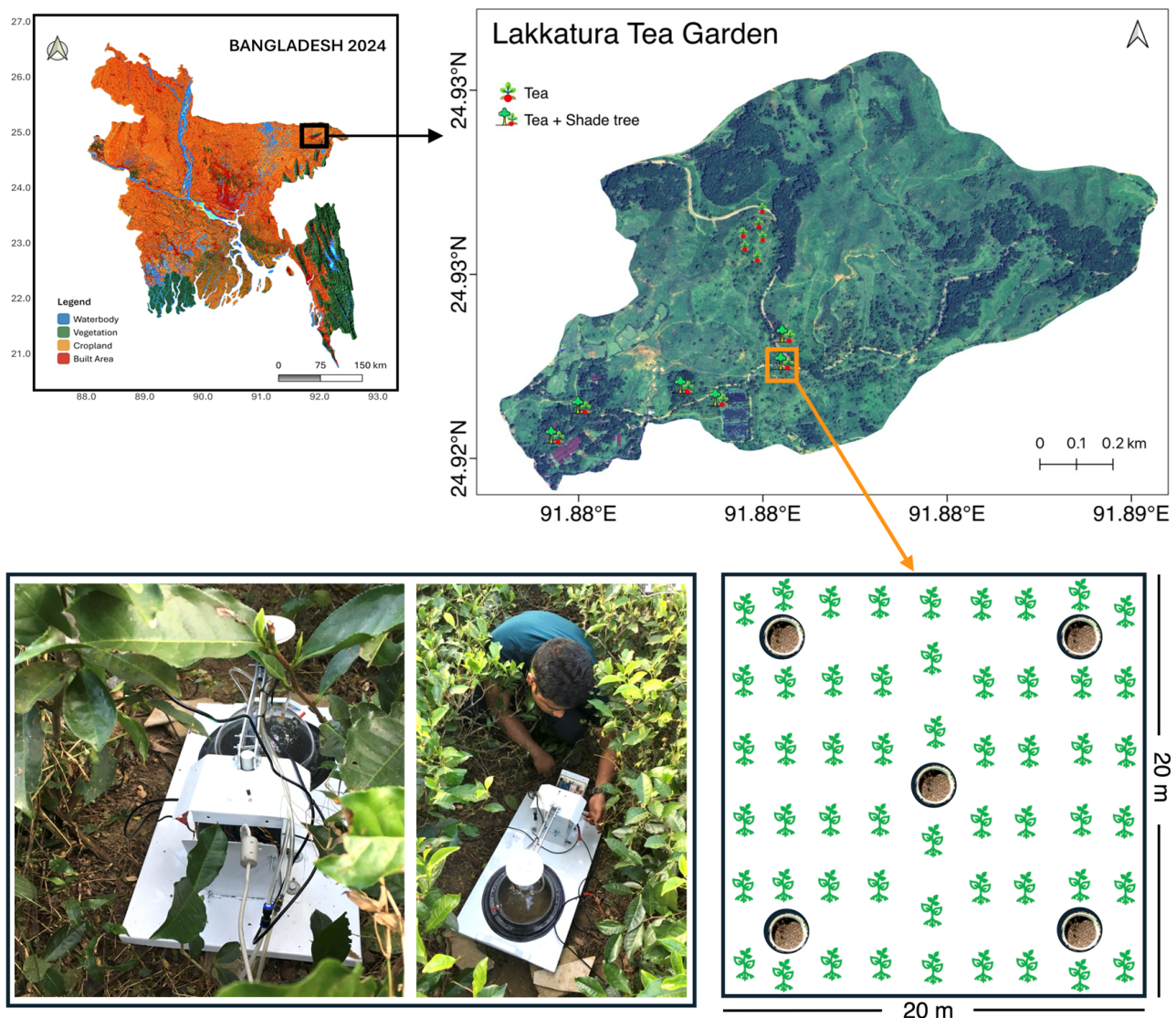


Figure 1. Location of Lakkatura Tea Garden (Sylhet, northeastern Bangladesh) and layout of the two experimental land-use systems. Monoculture tea plots (*Camellia sinensis*) and tea-based agroforestry plots (tea interplanted with *Albizia odoratissima* and *Melia azedarach*) that each received $7.5 \text{ t} \cdot \text{ha}^{-1}$ biochar are delineated.

LTG lies on the eastern Surma-Kushiyara floodplain (Agro-ecological Zone 20) [39]. Parent material is Holocene alluvium deposited by the Surma River system; the resulting soils are young Entisols and weakly developed Inceptisols that are typically sandy-to-silty loams. Profiles are strongly acidic (field pH ~ 5.5) and low in organic matter, reflecting intense leaching and decades of ammonium fertilizer use in tea gardens [23,38]. Nutrient status is therefore heterogeneous and closely linked to land-use history and topographic

position. These strongly acidic, low-organic-matter, sandy-to-silty loam soils are typical of intensively managed tea estates in the region and provide conditions under which relatively small changes in aeration and moisture—such as those induced by biochar addition and shade-tree canopies—can have disproportionate effects on GHG fluxes.

The estate experiences a humid subtropical monsoon climate. Mean daily maxima reach 31–32 °C in late summer (August), while mean minima fall to ~13–15 °C in January (source: <https://weatherspark.com>). Long-term records indicate 4100 ± 300 mm of rain per year, with 75–80% falling during the southwest monsoon (May–September) when orographic uplift against the Meghalaya Plateau intensifies convection. The cool, comparatively dry season extends from December to early February, providing a brief respite from perennial humidity.

2.2. Sampling Design

Twelve square plots (20 m × 20 m; 400 m² each) were established on level ground at Lakkatura Tea Garden in May 2016. A full two-factor randomized complete-block design was employed, with land-use system (tea monoculture versus tea + shade-tree agroforestry) crossed with biochar dose (0 t·ha^{−1} control versus 7.5 t·ha^{−1}). This 7.5 t·ha^{−1} rate was selected as a conservative, field-realistic dose at the lower end of rates commonly used in agricultural biochar trials and shown to elicit measurable soil and crop responses in field studies, and it corresponded to the maximum amount that could be realistically produced on-site and uniformly applied across the experimental area without disrupting estate operations. Each of the four treatment combinations was replicated three times, giving 12 plots in total. Plots were spatially dispersed across the garden to the extent possible to minimize treatment carryover and edge effects. Biochar was broadcast evenly across the soil surface and incorporated to a depth of ~2 cm during routine cultivation immediately after application.

2.3. Biochar Production and Characterization of Physicochemical Properties

Biochar was prepared exactly as described by Karim et al. [23]. Air-dried mill offcuts from the commonly planted tree *Acacia auriculiformis* A. Cunn. ex Benth. were pyrolyzed for 3.5 h in a locally fabricated open “flame-curtain” kiln of the Kon-Tiki design [40]. Kiln-wall thermocouples recorded an average pyrolysis temperature of about 450 °C, with brief peaks up to 550 °C. As soon as the flame front collapsed, the incandescent char was quenched with water for 30 min to remove condensable volatiles [41], drained thoroughly, and sun-dried for three days before field application.

Biochar physicochemical characterization followed the same protocols as Karim et al. [23]. Total carbon and nitrogen were measured with a LECO TruSpec 628 CN analyzer (St. Joseph, MI, USA), whereas trace elements were determined after four-acid digestion by inductively coupled plasma mass spectrometry (ICP-MS) at Activation Laboratories (Ancaster, ON, Canada). Volatile matter and ash were quantified by proximate analysis (ASTM D1762-84). Assessments of volatile matter, ash content, pH, electrical conductivity, and bulk density were conducted in accordance with the standard methods previously described [23]. Detailed physicochemical properties of the biochar are provided in Table A1.

2.4. Greenhouse Gas Flux and Microenvironmental Variable Measurements

Five PVC collars (internal diameter = 20 cm; height ≈ 10 cm) were installed at equal distances from plot edges and treatment boundaries in each of the 12 plots at least seven days before the first sampling campaign. Collars were pushed ~5 cm into the soil to minimize leakage [42] and laid out to capture within-plot flux heterogeneity; any plants rooted inside a collar were clipped flush with the surface at installation to ensure soil-only flux measurements. Fluxes were measured twice—once in mid-December 2016 and again

in late January 2017 (7–8 months following biochar additions). These two campaigns were intentionally scheduled during the cool, dry winter, a period with minimal field-operation disturbance, to capture treatment effects on soil–atmosphere exchange under stable dry-season conditions.

Carbon dioxide, methane, and water-vapour mole fractions were measured with an ultraportable greenhouse-gas analyzer (Los Gatos Research model 915-0011, San Jose, CA, USA; off-axis integrated cavity ring-down spectroscopy). A transparent, custom respiration chamber (radius = 10 cm, volume = 2450 cm³; early prototype of CS-RC10, CredoSense Inc., Toronto, ON, Canada) was placed on each collar and connected to the gas analyzer in a closed dynamic configuration. Three consecutive runs of ~2.5 min were logged at 1 Hz. No precipitation occurred during either campaign, precluding “Birch-effect” post-precipitation increases in gas fluxes [43].

To minimize potential artefacts associated with transparent chambers (radiative heating and pressure disequilibrium), the chamber was equipped with a Venturi vent to maintain near-ambient pressure and limit heat accumulation during closure. Fluxes were estimated from a short, high-quality fitting window after excluding the initial “dead band” (see flux-processing procedure below), which constrains any transient greenhouse warming during the fitted interval. Chamber air temperature remained stable during measurements (typically within ± 0.5 °C). Gas temperature and pressure were recorded continuously by the analyzer and were explicitly incorporated into the ideal-gas conversion used to compute fluxes.

Immediately after each flux measurement, volumetric soil-water content and temperature in the upper 10 cm were recorded within 50 cm of the collar using a CS-SM2 probe ($\pm 2.5\%$ VWC, ± 0.5 °C; CredoSense Inc., Toronto, ON, Canada). Within-plot soil pH was measured on pooled cores with a handheld meter (HI98100, Hanna Instruments, Woonsocket, RI, USA).

Raw mole-fraction time series of CO₂, CH₄, and H₂O vapour were processed with the algorithm of Halim et al. [44], designed to accommodate both linear (low) and nonlinear (high) flux regimes. After excluding the “dead band,” the first 20–30 s of the gas concentration measurement [45,46], the routine searched the first 90 s for the window (~50 s) whose CO₂ concentration–time slope showed the highest Pearson correlation (*r*). This same window was then used to calculate the slope of CH₄ and H₂O vapour concentrations. For calculating concentration–time slope, if a polynomial test detected significant nonlinearity, data were fit to the following equation:

$$C'_t = C'_x + (C'_0 - C'_x)e^{\{-a \cdot x(t-t_0)\}}$$

where C'_t is the instantaneous H₂O vapour or water-corrected CH₄ or CO₂ mole fraction at the time *t*; C'_0 is the value of C'_t at *t* = 0; C'_x is an asymptote parameter; *a* is a curvature parameter; and *t*₀ is the time when the chamber is closed [45]. The initial slope for non-linear concentrations was then calculated as

$$\frac{dc}{dt} = a (C'_x - C'_t)$$

where $\frac{dc}{dt}$ = change in gas concentration with time (ppm·s^{−1}; interpreted as μmol·mol^{−1}·s^{−1}), and other parameters are as defined above. In the case of a linear concentration, the slope of the linear model was used as $\frac{dc}{dt}$. In either case, the gas flux rate was then determined as

$$F = \frac{P V}{R T A} \times \frac{dc}{dt}$$

where $F = \text{CO}_2$, CH_4 , or H_2O vapour flux, P = air pressure (1.01325 MPa); V = effective volume of chamber (m^3); R = ideal gas constant ($8.31 \text{ Pa} \cdot \text{m}^3 \cdot \text{K}^{-1} \cdot \text{mol}^{-1}$); T = gas temperature (K); A = chamber surface area (0.0346 m^2), and $\frac{dc}{dt}$ is the slope of CO_2 or CH_4 or H_2O vapour concentrations with time, as determined above.

The effective chamber volume (m^3) for each measurement was calculated as the sum of the chamber volume, the collar volume protruding above the soil surface, and the connecting tube plus analyzer cavity volume. Collar volume above the ground was determined from the mean collar height measured at four cardinal points inside each collar.

2.5. Determination of Soil Physicochemical Properties

Soil samples were collected during the final gas-flux campaign from the soils directly within each collar. Physicochemical properties were analyzed following the methods described by Karim et al. [23]. Gravimetric soil moisture content (%) was determined by oven-drying samples at 60°C for 48 h. Bulk density ($\text{g} \cdot \text{cm}^{-3}$) was calculated by dividing the dry mass of soil (105°C for 24 h) by the sample volume ($\pi \times r^2 \times h = 196.35 \text{ cm}^3$). Soil organic matter content (%) was assessed using the loss-on-ignition method, with samples combusted at 600°C for six hours [47]. Total nitrogen (N) was determined by the semi-micro Kjeldahl method [48], while available phosphorus (P, $\mu\text{g} \cdot \text{g}^{-1}$) was extracted using Bray and Kurtz-1 for acidic soils and quantified colorimetrically at 882 nm [49]. Available potassium (K, $\text{meq} \cdot 100 \text{ g}^{-1}$) was measured using ammonium acetate extraction and flame photometry at 766.5–769.5 nm [50].

2.6. Statistical Analysis

All statistical analyses were carried out in R 4.5.1 [51]. For every collar, the three consecutive flux runs were averaged, so each plot and sampling date provided five collar means. A preliminary linear mixed-effects model that treated sampling “campaign” (mid-December 2016 versus late January 2017) as a fixed effect revealed neither a main nor an interactive influence of date on any response variable (all $p > 0.20$). Data from the two campaigns were therefore pooled, yielding 60 collar-level means used in the statistical analyses.

Treatment effects on CH_4 , CO_2 , and H_2O vapour fluxes were evaluated with a hierarchical mixed-effects model of the form $Y \sim \text{land-use system} \times \text{biochar} + (1 | \text{plot/collar})$, in which tea monoculture versus tea-plus-shade-tree agroforestry constituted the land-use factor and biochar dose was control ($0 \text{ t} \cdot \text{ha}^{-1}$) or $7.5 \text{ t} \cdot \text{ha}^{-1}$. Random intercepts were assigned to collars nested within plots to partition collar- and plot-level variance. Models were fitted with lme4::lmer, and Satterthwaite-adjusted denominator degrees of freedom were supplied by lmerTest [52]. When the land-use $\times$ biochar interaction was significant at $\alpha = 0.05$, pairwise contrasts were performed with Tukey’s honestly significant difference test implemented in multcomp, and compact letter displays were generated with multcompView [53].

Bivariate relationships between individual gas fluxes and soil properties—bulk density, pH, organic-matter content, Bray-1 phosphorus, exchangeable potassium, and total nitrogen—were explored with ordinary least-squares regression using stats::lm. Model coefficients, R^2 values, and p -values were extracted, and fitted lines with 95% confidence envelopes were visualized with ggplot2 [54].

Finally, a covariance-based structural-equation model (SEM) was constructed in the R package “lavaan” and plotted with “semPlot” to disentangle direct and indirect controls on each gas flux [55]. Exogenous nodes comprised biochar application, shade-tree presence, and the eight soil variables; endogenous nodes were the three fluxes. Models were fitted by maximum likelihood with robust (Huber–White) standard errors, and the final path

diagram retained only links with $p \leq 0.10$. Standardized coefficients are reported to facilitate comparison of pathway strengths.

3. Results

Measurements indicated moderate rates of soil CO₂ efflux in the tea agroecosystem, with values ranging from 1.33 to 4.41 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (overall mean [$\pm\text{SE}$] $2.63 \pm 0.06 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). Soil evaporation rates were low to moderate, ranging from 10.2 to 276.4 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (overall mean $84.1 \pm 3.2 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), consistent with relatively low to moderate soil water content characteristic of the dry-season. Net CH₄ uptake was observed for all measurements, with values ranging from -3.55 to $-0.19 \text{ nmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (overall mean $-1.92 \pm 0.07 \text{ nmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$).

3.1. Biochar Effects on Soil CH₄, CO₂, and H₂O Fluxes

Biochar addition ($7.5 \text{ t}\cdot\text{ha}^{-1}$) significantly altered soil GHG exchange relative to the unamended control (Figure 2). Mean CH₄ uptake shifted from $-1.35 \pm 0.06 \text{ nmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in control soils to $-2.49 \pm 0.05 \text{ nmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ under the biochar addition treatment, an 84% increase in net uptake ($p < 0.001$) (Figure 2c). Carbon-dioxide effluxes rose, from 2.41 ± 0.08 to $2.84 \pm 0.09 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ —an 18% enhancement ($p < 0.001$) (Figure 2b). Water-vapour flux exhibited only a marginally significant 12% rise (77.9 ± 3.47 vs. $87.5 \pm 4.00 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$; $p = 0.07$) (Figure 2a).

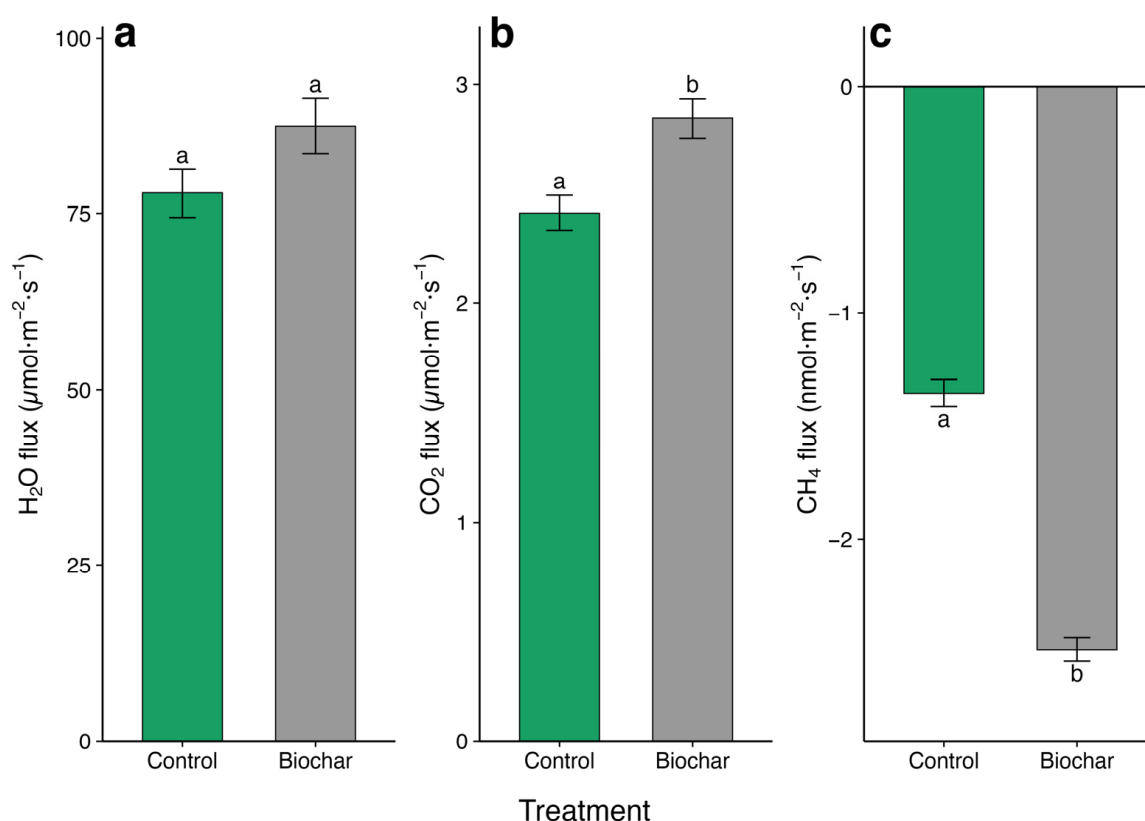


Figure 2. Effect of biochar addition ($7.5 \text{ t}\cdot\text{ha}^{-1}$) on soil GHG fluxes in a tea garden ecosystem. Bars show treatment means $\pm$ SE calculated from 30 collar measurements per treatment ($5 \text{ collars} \times 3 \text{ plots} \times \text{two campaigns}$) for (a) water vapour and (b) CO₂ fluxes expressed in $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and (c) CH₄ flux expressed in $\text{nmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Positive values indicate net emission; negative values indicate net uptake. Columns sharing the same lowercase letter do not differ significantly (Tukey HSD, $\alpha = 0.05$).

3.2. Interactive Effects of Biochar and Shade Trees on Soil GHG Exchange

A significant biochar $\times$ shade-tree interaction was detected overall for all three gases (mixed-effects model, $p < 0.01$), driven primarily by CH_4 and H_2O ; for CO_2 , post hoc comparisons indicated an additive pattern (i.e., shade lowered baseline flux but did not alter the biochar effect size) (Figure 3).

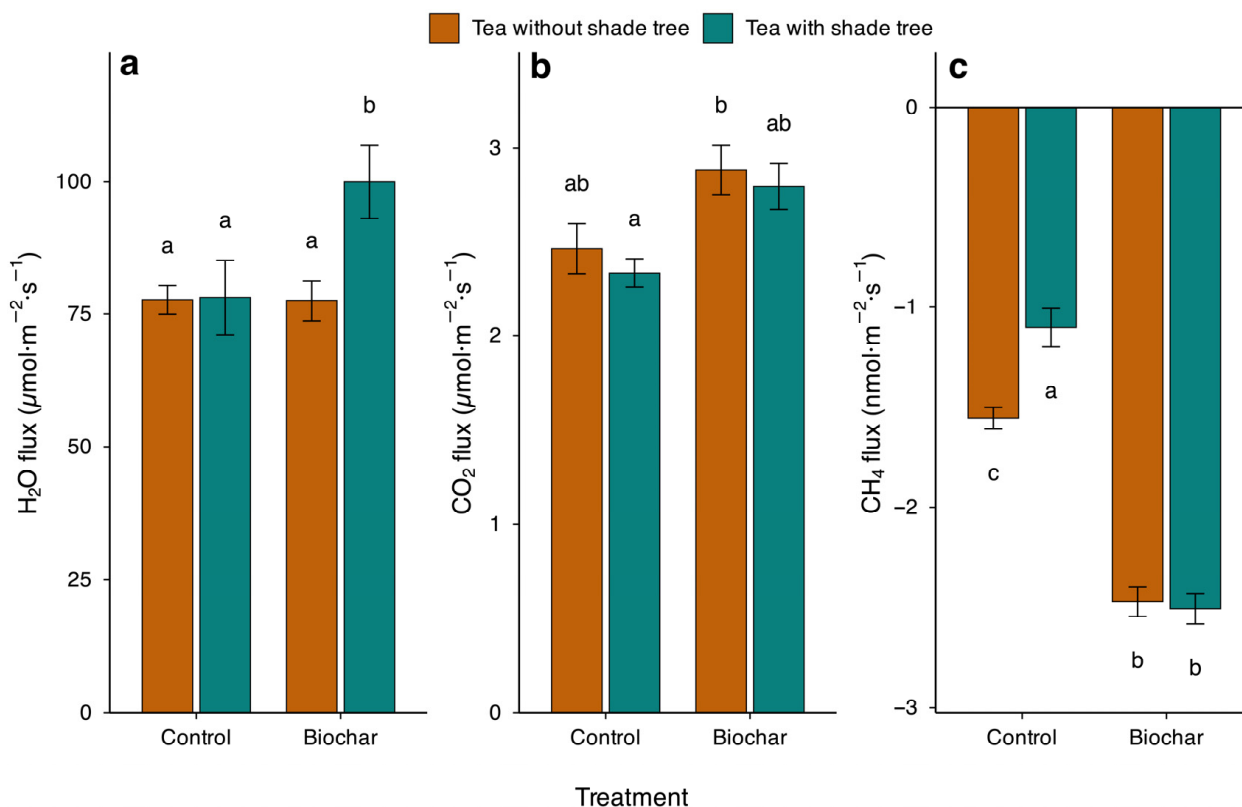


Figure 3. Interactive effect of biochar and shade-tree overstory on soil-atmosphere gas exchange. Bars show means $\pm$ SE for (a) H_2O vapour and (b) CO_2 fluxes ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and (c) CH_4 flux ($\text{nmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) in tea monoculture (brown) and tea + shade-tree agroforestry (teal) plots receiving either 0 $\text{t}\cdot\text{ha}^{-1}$ (control) or 7.5 $\text{t}\cdot\text{ha}^{-1}$ (biochar) amendments. Each mean is based on 30 collar measurements per treatment combination (five collars $\times$ three plots $\times$ two campaigns). Positive values denote net emission; negative values denote net uptake. Columns that share a lowercase letter do not differ significantly (mixed-effects model followed by Tukey HSD, $\alpha = 0.05$).

Net CH_4 uptake (Figure 3c) was somewhat higher in the control treatment without shade trees ($-1.55 \pm 0.05 \text{ nmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) than in the corresponding plots with shade trees ($-1.10 \pm 0.10 \text{ nmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). Soils under both canopy conditions showed marked increases in CH_4 uptake in response to biochar additions, exhibiting similar flux rates (-2.51 ± 0.08 and $-2.47 \pm 0.07 \text{ nmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), corresponding to increases of 62% and 125%, respectively.

Biochar addition increased CO_2 efflux (Figure 3b) under both canopy conditions, and shade did not modify the biochar effect size. Mean fluxes were highest in unshaded biochar plots ($2.88 \pm 0.13 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), followed by shaded biochar plots (2.80 ± 0.12), unshaded controls (2.47 ± 0.13), and shaded controls (2.34 ± 0.08). Post hoc tests showed that both biochar treatments had significantly higher CO_2 efflux than the shaded control ($p < 0.05$), whereas the difference between the two biochar treatments was not significant ($p > 0.2$). The shaded control remained the only treatment significantly lower than the others, indicating an additive—not synergistic—effect of shade and biochar.

Shade modified the direction of the biochar effect on H_2O vapour flux (Figure 3a). Shaded biochar plots exhibited the highest H_2O flux ($100 \pm 6.9 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), significantly exceeding unshaded biochar plots (77.6 ± 3.9 ; $p = 0.014$) and both control treatments (78.1 ± 7.1 and 77.7 ± 2.8 ; both $p < 0.03$). No significant differences were detected among unshaded biochar and the two control treatments ($p > 0.8$), indicating that shade enhanced biochar-induced moisture loss, contrary to the initially assumed pattern.

Together, these patterns indicate that biochar consistently enhances CH_4 uptake across canopy conditions, increases CO_2 efflux in an additive manner, and elevates H_2O vapour flux only when combined with shade, underscoring the role of canopy microclimate in mediating soil–biochar interactions.

3.3. Relations Among CH_4 , CO_2 and H_2O Fluxes

Bivariate analyses showed that methane uptake was weakly but significantly coupled to the exchange of both H_2O vapour and CO_2 (Figure 4). Across all collars and treatments, CH_4 flux became more negative (i.e., uptake increased) as H_2O flux rose (slope = $-0.006 \text{ nmol CH}_4\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ per $\mu\text{mol H}_2\text{O}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $R^2 = 0.05$, $p = 0.03$, Figure 4a). A steeper inverse relationship was detected between CH_4 and CO_2 (slope = $-0.333 \text{ nmol CH}_4\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ per $\mu\text{mol CO}_2\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $R^2 = 0.10$, $p < 0.001$; Figure 4b). Neither the slopes nor the intercepts differed between the biochar and control datasets (interaction terms, $p > 0.1$), so a single pooled regression is reported. These patterns suggest that conditions that stimulate soil respiration and water vapour loss—likely higher diffusivity and greater microbial activity—also favour methanotrophic CH_4 oxidation, reinforcing the fact that CH_4 dynamics are functionally integrated with broader carbon and moisture exchanges in this subtropical tea soil.

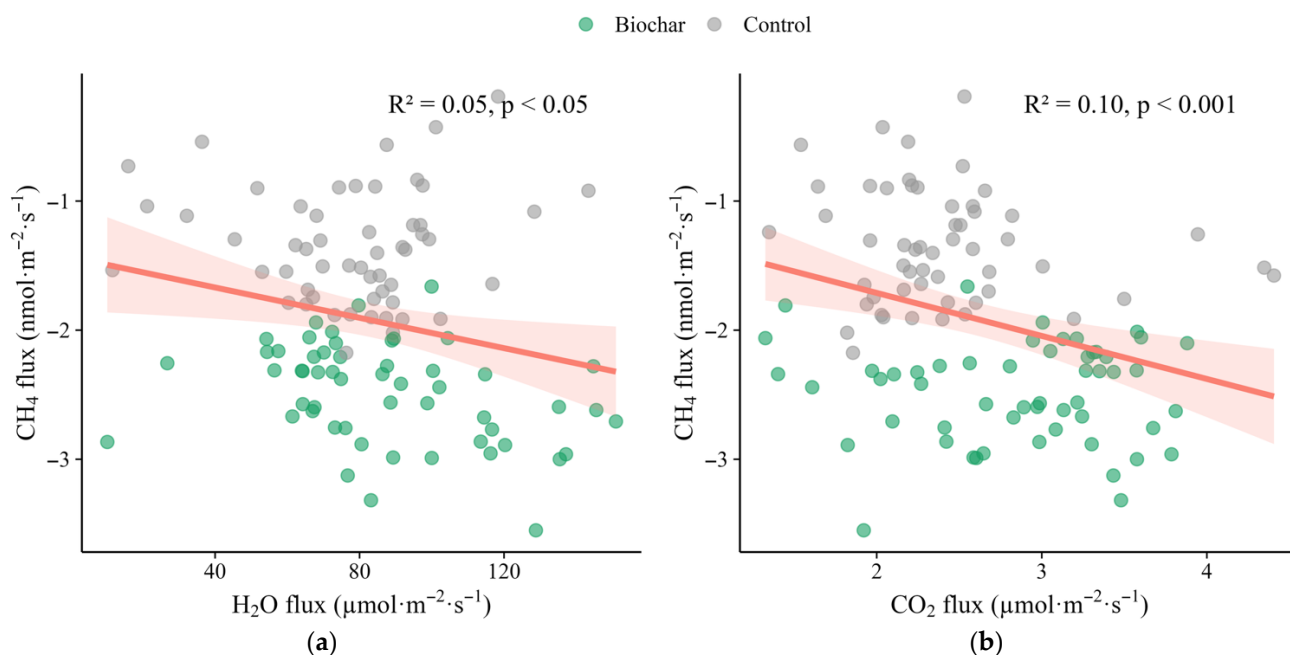


Figure 4. Bivariate relationships between methane uptake and co-emitted gases. (a) Relation between CH_4 flux ($\text{nmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and water-vapour flux ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$); and (b) relation between CH_4 and CO_2 flux ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). Grey symbols = control; green symbols = biochar ($7.5 \text{ t}\cdot\text{ha}^{-1}$). Each point is the mean of the three consecutive fluxes from a single collar ($n = 60$ per panel; average across campaigns per collar). The solid red line is the ordinary least-squares regression fitted to the pooled data; the shaded band is the 95% confidence envelope. Regression statistics (R^2 , p) refer to this overall fit. Negative CH_4 values denote net soil uptake.

3.4. Soil Drivers and Mechanistic Pathways Governing Gas Exchange

The multivariate picture that emerged from the combined regression and structural equation modelling (SEM) analyses (Figures 5 and 6) shows that each gas responds to a distinct but partially overlapping suite of soil and management factors.

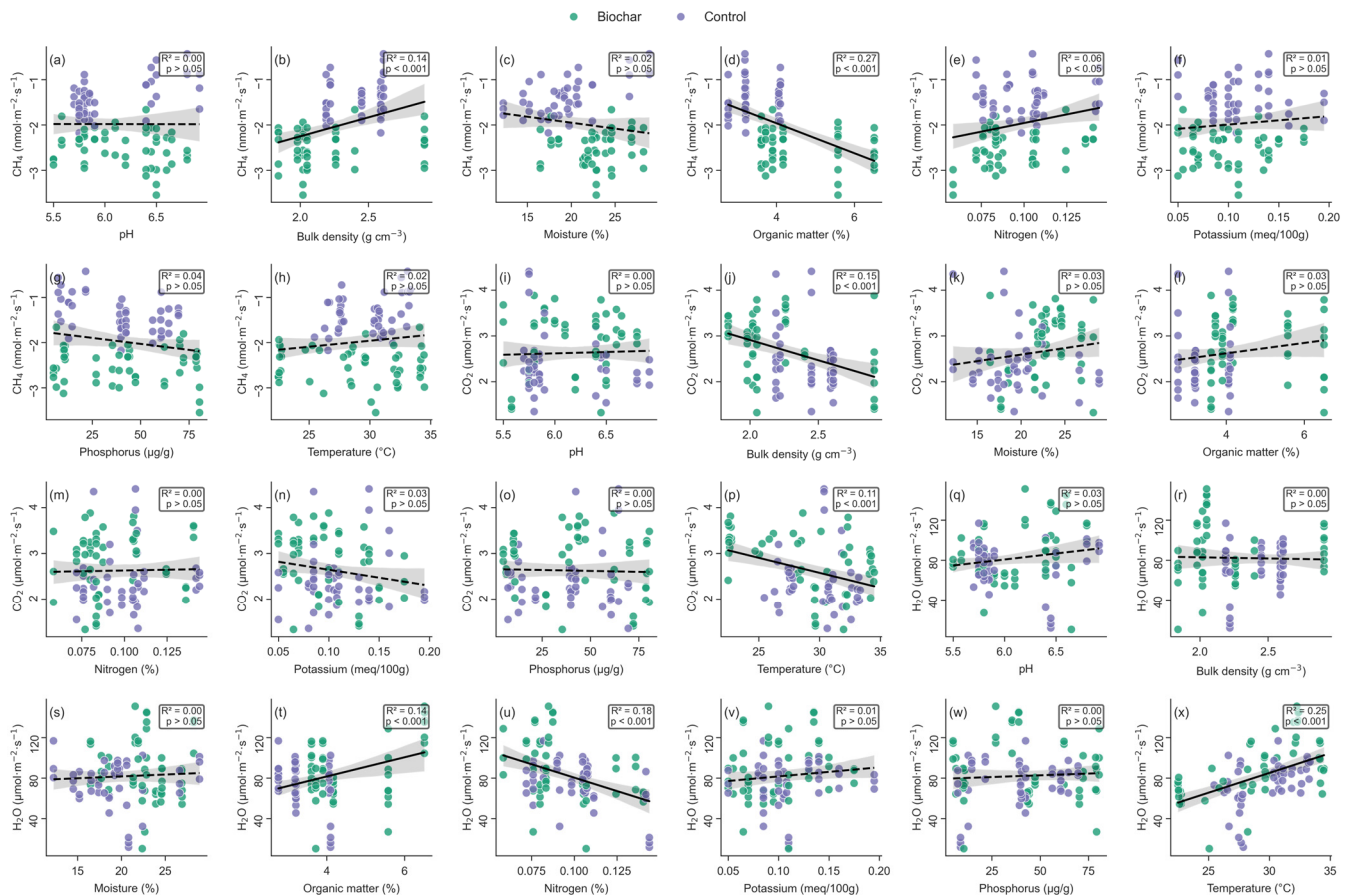


Figure 5. Bivariate relations between soil properties and gas fluxes in biochar-amended (green) and control (purple) tea plots. Columns show, from left to right, soil pH, bulk density (g cm^{-3}), gravimetric moisture (%), organic-matter content (%), total nitrogen (%), exchangeable potassium ($\text{meq} \cdot 100 \text{ g}^{-1}$), Bray-1 phosphorus ($\mu\text{g} \cdot \text{g}^{-1}$), and soil temperature ($^{\circ}\text{C}$). Rows give (a–h) CH_4 flux ($\text{nmol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$; negative values = net uptake), (i–p) CO_2 flux ($\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), and (q–x) H_2O -vapour flux ($\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$). Each symbol is the collar-level mean of three consecutive flux values ($n = 60$; average across campaigns per collar). Ordinary least-squares regressions were fitted to the pooled data; solid black lines indicate significant relationships ($p < 0.05$), and dashed lines denote non-significant trends. Shaded bands are 95% confidence envelopes, and inset boxes report model R^2 and two-tailed p values for each panel.

For CH_4 flux, the bivariate regressions indicated consistent associations with key soil properties. CH_4 uptake weakened as bulk density increased ($R^2 = 0.09$, $p = 0.004$; Figure 5b) and showed positive relationships with organic-matter content ($R^2 = 0.21$, $p < 0.001$; Figure 5d) and total nitrogen ($R^2 = 0.06$ and $p = 0.02$; Figure 5e), indicating that higher organic matter and nitrogen contents were associated with weaker net CH_4 uptake (negative fluxes closer to zero).

In the SEM (Figure 6), which explained 74.0% of the variance in CH_4 flux ($R^2 = 0.74$), biochar treatment emerged as the strongest single predictor ($\beta = -0.82$, $p < 0.001$), indicating a large enhancement of CH_4 uptake (more negative fluxes) in biochar-amended plots.

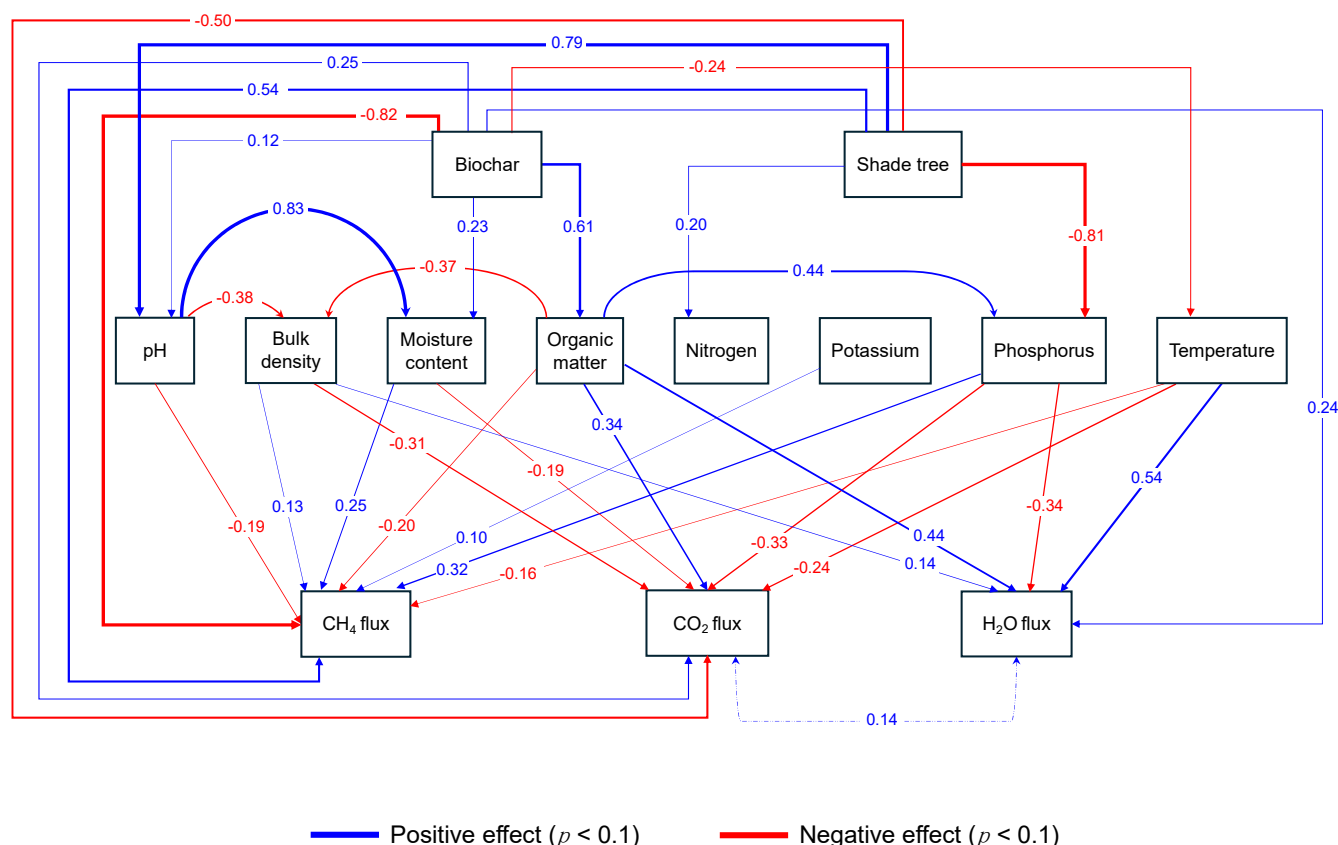


Figure 6. Covariance-based structural-equation model of controls on soil GHG exchange. Rectangles represent measured variables: biochar treatment, shade-tree presence, and eight soil properties (pH, bulk density, gravimetric moisture, organic matter, total N, exchangeable K, Bray-1 P, and soil temperature) are exogenous predictors; CH₄, CO₂, and H₂O-vapour fluxes are endogenous responses. Solid lines depict direct effects retained in the final model (standardized path coefficients printed alongside the arrows), whereas dashed lines indicate significant covariances between predictors. Blue arrows denote positive effects, and red arrows denote negative effects; only paths with $p \leq 0.10$ are shown. The model was based on 60 collar-level observations and provided an acceptable fit ($\chi^2 = 0.28$, $p = 0.60$; CFI = 1.0; RMSEA < 0.001; and SRMR = 0.004).

Positive paths from shade-tree presence ($\beta = 0.54$ and $p < 0.001$), bulk density ($\beta = 0.13$ and $p = 0.055$), gravimetric moisture ($\beta = 0.25$ and $p = 0.005$), exchangeable K ($\beta = 0.10$ and $p = 0.010$), and Bray-1 P ($\beta = 0.32$ and $p = 0.025$) indicate that higher values of these variables are associated with weaker net CH₄ uptake (i.e., negative flux closer to zero). In contrast, organic matter exerted a negative effect ($\beta = -0.20$ and $p = 0.023$), as did soil pH ($\beta = -0.19$ and $p = 0.081$) and temperature ($\beta = -0.16$ and $p = 0.061$), consistent with slightly stronger uptake at higher values of these variables. Taken together, these pathways indicate that biochar alters CH₄ flux both directly and via changes in soil structure, moisture, and nutrient status, with some co-varying soil properties (e.g., greater moisture, K, and P) partially offsetting the strong direct enhancement of the CH₄ sink.

The controls on CO₂ efflux were more diffuse. In the bivariate analysis, CO₂ declined with bulk density ($R^2 = 0.10$ and $p = 0.004$; Figure 5j), decreased slightly with temperature ($R^2 = 0.12$ and $p < 0.001$; Figure 5p), and showed only a marginal tendency to fall with K ($R^2 = 0.03$ and $p = 0.08$; Figure 5n). The SEM, which explained 31.5% of the variance ($R^2 = 0.315$), clarified these relationships and indicated that shade-tree presence ($\beta = -0.50$ and $p = 0.003$) and bulk density ($\beta = -0.31$ and $p = 0.008$) exerted the strongest suppressive effects. Bray-1 P ($\beta = -0.33$ and $p = 0.014$), temperature ($\beta = -0.24$ and $p = 0.039$), and

gravimetric moisture ($\beta = -0.19$ and $p = 0.042$) also contributed negatively. In contrast, biochar ($\beta = 0.25$ and $p = 0.038$) and organic matter ($\beta = 0.34$ and $p = 0.025$) exerted a direct positive effect on soil CO₂ flux. Overall, these results indicate that CO₂ efflux reflects a balance between physical structure, microclimatic conditions, and increases in soil organic content.

For water-vapour flux, the collar-level regressions suggested a positive link with organic matter ($R^2 = 0.11$ and $p = 0.006$; Figure 5t) and a pronounced negative link with total N ($R^2 = 0.18$ and $p < 0.001$; Figure 5u). In the SEM, temperature was the dominant driver ($\beta = 0.54$ and $p < 0.001$), followed by organic matter ($\beta = 0.44$ and $p < 0.001$). Bulk density showed a marginally positive effect ($\beta = 0.14$ and $p = 0.053$), while biochar ($\beta = 0.24$ and $p = 0.015$) had a significant direct influence on vapour fluxes. The model accounted for 34.7% of the variance, indicating that, during the dry-season campaigns, temperature and organic matter outweighed amendment-induced physical changes in controlling vapour exchange.

Overall, our statistical analyses provide the basis for the mechanistic interpretation developed below, namely that biochar-related changes in soil structure and associated nutrient pools are most closely linked to CH₄ flux, that CO₂ efflux co-varies with substrate availability and diffusional constraints imposed by canopy cover and soil compaction, and that H₂O flux appears more strongly associated with temperature and organic matter than with the amendment's physical legacy.

4. Discussion

Our study provides, to our knowledge, the first field assessment of biochar's effects on concurrent soil fluxes of methane, carbon dioxide, and water vapour within a tea agroforestry system, revealing a complex suite of responses. Taken together, CH₄ uptake, CO₂ efflux, and H₂O vapour efflux represent linked expressions of how biochar and shade trees reshape the soil–atmosphere interface by altering soil structure, moisture availability, and surface energy balance. The most pronounced effect was an average 84% enhancement of soil methane uptake following a 7.5 t·ha^{−1} biochar application. Concurrently, we observed a modest but significant average 18% increase in soil respiration (CO₂ efflux) and a marginal 12% rise in water-vapour flux. Crucially, the presence of a shade-tree canopy modulated these outcomes, with a significant biochar × shade-tree interaction detected for all three gases. While responses for CH₄ and CO₂ were qualitatively similar across canopy conditions, the increase in water-vapour flux occurred only in shaded conditions. These findings offer partial support for our initial hypotheses: although the prediction of enhanced methane uptake was confirmed, the observed increases in CO₂ and water-vapour fluxes contradict our expectation that biochar would have negligible or suppressive effects on these emissions.

4.1. Biochar Drives a Major Methane Sink Capacity via Competing Physical and Chemical Pathways

The average 84% increase in soil CH₄ uptake stands out as the most significant biogeochemical response to biochar application in this study, transforming the tea garden soil into a substantially stronger CH₄ sink. This finding is particularly noteworthy given that such well-drained upland tropical soils are not typically considered major players in the methane cycle. Our structural equation model (SEM), which explained 74.0% of the variance in CH₄ flux, provides strong evidence that this effect is complex, driven by both direct and indirect mechanisms.

The primary driver was the direct effect of the biochar application itself (path coefficient $\beta = -0.82$), indicating that the inherent physical properties of biochar were paramount.

The high porosity and large surface area typical of wood-derived biochars produced at similar temperatures likely improved soil aeration and gas diffusivity, creating optimal conditions for methanotrophic bacteria to oxidize atmospheric CH₄. This aligns with findings from other managed temperate and boreal forests where biochar application has been shown to increase CH₄ uptake [56–58]. A comprehensive review by Li et al. [37] confirms that enhanced aeration is the most commonly cited mechanism for increased CH₄ consumption in forest soils amended with biochar. Consistent with this, our findings indicate that biochar treatment exerts the strongest negative effect on CH₄ flux ($\beta = -0.82$), thereby enhancing CH₄ uptake.

However, our data also reveal a critical trade-off. Biochar's direct positive effect on moisture content ($\beta = 0.23$) had a suppressive effect ($\beta = 0.25$) on CH₄ uptake. This suggests that while the bulk soil becomes better aerated, the fine biochar particles can fill pore spaces and hold water, creating anaerobic microsites that may inhibit the activity of aerobic methanotrophs. Furthermore, the weak but significant relationships between CH₄ uptake and soil organic matter suggest that the addition of nutrient-rich biochar may alter microbial competition in ways that slightly temper the overall CH₄ sink strength. A similar weak relationship was also observed with temperature, likely because temperatures notably suppress methanotrophic activity in upland soils, possibly due to the inhibition of mesophilic methanotrophs [59]. However, since we did not directly measure methanotroph communities or CH₄ oxidation directly, this trade-off should be viewed only as a plausible mechanistic interpretation of the flux data. Taken together, these patterns indicate that soil structure, near-surface moisture, and associated organic matter and nutrient pools are the main soil properties through which biochar and shade trees regulate CH₄ uptake in this system.

This result contrasts sharply with other studies in acidic tea soils and tropical plantations where biochar had negligible or inconsistent effects on CH₄ fluxes [29,60], highlighting that the net impact is highly dependent on biochar properties, soil type, and ecosystem context. The powerful, multifaceted response observed in our study underscores that biochar's role in the CH₄ cycle is not simply a matter of adding porous material, but rather a complex interplay between enhanced gas exchange and the creation of inhibitory, water-saturated, and/or nutrient-rich microsites. At the bulk scale, reduced soil compaction and increased macroporosity expand the volume of well-aerated pore space, improving oxygen supply and diffusion pathways for methanotrophs, thereby tending to strengthen net CH₄ uptake. Superimposed on this are localized zones adjacent to biochar particles where high water-holding capacity and nutrient enrichment promote more reduced, heterotroph-dominated microsites that locally suppress methanotrophic activity. Our SEM results and flux patterns suggest that in this upland, well-drained tea soil, the structural gains in aeration more than compensate, at the plot scale, for these inhibitory microsites, yielding a net increase in CH₄ uptake even though some portions of the pore network become less favourable for methanotrophy.

4.2. Increased Soil Respiration Driven by an Indirect Substrate Priming Effect

The observed 18% increase in soil respiration (CO₂ efflux) following biochar application, while seemingly counterintuitive to the goal of carbon sequestration, is best explained as a short-term, indirect “positive priming effect”. The freshly pyrolyzed biochar, produced from *Acacia auriculiformis* offcuts, likely contained a fraction of labile organic compounds such as volatile fatty acids [61] that served as a readily available energy source for soil microbes. This infusion of new substrate can stimulate the microbial community, leading to accelerated decomposition of not only the labile biochar components but also of native soil organic matter [29,33].

Our SEM results support this interpretation, showing that CO₂ flux was strongly predicted by biochar treatment and organic matter content. This highlights soil organic matter as the key mediating property for CO₂ efflux, consistent with the idea that biochar chiefly influences respiration via changes in substrate availability rather than through direct physical alteration of gas diffusivity. Moreover, the SEM revealed another strong direct path from biochar to organic matter, implying biochar's direct influence on soil respiration is primarily controlled through its effect on the soil microbial community. While some studies have reported reduced CO₂ emissions with biochar through SOC stabilization [26], our findings align with others that show a transient increase in respiration due to substrate effects [34].

We interpret this as a short-term positive priming effect of labile biochar components on microbial activity. We cannot rule out contributions from increased root respiration and shifts in microbial biomass, and our short-term dry-season measurements do not resolve how long this elevation in CO₂ efflux persists. From a carbon management perspective, this initial pulse of CO₂ represents a short-term carbon cost. However, this is expected to be far outweighed by the long-term climate benefit derived from the much larger recalcitrant carbon pool within the biochar that will remain stable in the soil for centuries. In addition, increased microbial activity is expected to be associated with increased nutrient mineralization that can increase net primary productivity. Nevertheless, this priming effect must be considered in full life-cycle assessments of biochar as a climate mitigation tool.

4.3. Biochar's Contradictory Effect on Water-Vapour Flux: A Thermal Trade-Off

Our finding that biochar increased soil water-vapour flux by up to 12%, with the strongest and statistically significant increase occurring in shaded plots, is notable because it contrasts with the commonly reported pattern that biochar reduces soil evaporation [35,36]. Most reports of reduced evaporation come from annual row-crop systems where biochar is incorporated into the tilled layer, whereas our result reflects surface-applied biochar in a woody perennial agroforestry system, a context for which field data on H₂O fluxes are almost non-existent.

Our results strongly suggest that this unexpected outcome reflects an interaction between soil temperature, surface energy balance, and near-surface water availability rather than a purely hydraulic response. The structural equation model (SEM) identified soil temperature as one of the significant predictors of H₂O flux ($\beta = 0.54$), followed by organic matter and a direct positive path from biochar. We interpret this as evidence that the dark, surface-applied biochar layer likely altered the surface energy balance by absorbing more solar irradiation, modifying near-surface moisture storage and soil surface temperature [62], thereby accelerating evaporation. These SEM results therefore indicate that soil temperature and near-surface organic matter are the dominant soil properties through which biochar influences H₂O vapour flux in this tea agroforestry system, mainly via changes in surface energy balance and shallow moisture storage.

In our dry-season campaigns, that combination of warm surface conditions and higher near-surface moisture appears to have been most strongly expressed under the shade-tree canopy, where moderated microclimate and litter inputs likely maintained greater water availability close to the surface. This helps explain why the biochar-induced increase in water-vapour flux was statistically detectable only in shaded plots, whereas unshaded biochar plots—despite higher incident radiation—showed no increase relative to controls, presumably because rapid drying constrained vapour loss. This highlights a critical, context-dependent trade-off: while biochar is well known for improving water retention within the soil profile [36], our findings indicate that when applied at the surface in perennial systems, its thermal properties can enhance surface evaporation under certain canopy

configurations. The net effect on water-use efficiency may therefore depend strongly on biochar placement (e.g., surface vs. incorporated) and on how canopy structure shapes microclimates and soil moisture regimes within the agroecosystem.

4.4. An Integrated Strategy: Combining Agroforestry and Biochar for Optimal Climate and Soil Benefits

The most significant insight from this study is the powerful synergy created by combining biochar with shade-tree agroforestry, revealing an integrated and highly effective path toward climate-smart tea production. Our findings demonstrate that an agroforestry system does not just coexist with biochar application but fundamentally improves its performance by mitigating its undesirable effects while locking in its key climate benefits. This highlights that the full potential of a soil amendment like biochar is only realized when it is deployed within a resilient, well-managed ecological system.

While biochar application alone successfully transformed the soil into a potent methane sink, it also came with the costs of increased carbon dioxide and, in some canopy contexts, higher water vapour emissions. However, the presence of shade trees acted as a critical environmental buffer. Under shade, biochar-treated plots exhibited the highest H₂O vapour fluxes, consistent with our inference that moderated microclimate and greater near-surface moisture interacted with the darker, warmer biochar surface to sustain evaporation during the measurement campaigns. At the same time, shade trees had a strong suppressive effect on soil respiration ($\beta = -0.50$), partially offsetting the temporary increase in CO₂ caused by biochar. Crucially, these microclimatic effects did not compromise methane mitigation: CH₄ uptake in shaded biochar plots remained high and, in proportional terms, the biochar-induced enhancement of CH₄ uptake was at least as strong under shade as in open plots.

From a land management perspective, this integrated approach is a near-optimal strategy. Biochar additions maximize the net greenhouse gas benefit by sustaining high methane uptake and supporting broader soil health by enhancing carbon cycling while improving water retention within the soil profile, even where surface evaporation is locally enhanced, thus aligning with global goals for carbon neutrality and land restoration. By leveraging a biological solution (shade trees) to refine and enhance a technological one (biochar), this combined system provides a robust and actionable framework for building more sustainable and climate-resilient perennial cropping systems worldwide. In practical terms for tea estates, our results suggest that modest, surface-applied rates of biochar produced from on-site pruning are most effective when implemented in existing shade-tree blocks, where they can simultaneously strengthen the CH₄ sink and support soil moisture conservation during the dry season. At a policy level, the combination of enhanced CH₄ uptake demonstrated here and previously reported reductions in N₂O emissions [63] indicates that shaded tea plantations could be priority candidates for biochar-based climate-mitigation and soil-restoration initiatives, although full life-cycle and multi-season GHG budgets are still needed before formal accounting. Our results are consistent with, and add to, emerging evidence for strong benefits of biochar use in multi-species agroforestry systems [64,65].

All measurements were conducted during the cool, dry season; thus, while the dataset captures dry-season responses in an established tea agroforestry system, the results should not be interpreted as annual greenhouse-gas balances or definitive climate-mitigation estimates. Seasonal variation, biochar ageing, and N₂O fluxes—critical elements of a complete GHG budget—were not assessed, restricting our inferences to short-term, dry-season conditions. Long-term, multi-season trials that incorporate N₂O dynamics, biochar placement depth, and tea yield-quality metrics are essential to validate durability and agronomic viability. Future work should examine whether the strong dry-season enhancement of the

CH₄ sink we observed persists across wetter periods and inter-annual climate variability. It should also test deeper incorporation versus surface application of biochar—including sub-surface or mulched placements that decouple evaporation from soil warming—to determine whether similar synergies arise in other perennial crops (e.g., coffee, cocoa, rubber) across tropical and subtropical regions.

Author Contributions: Conceptualization, M.A.H., N.V.G. and S.C.T.; methodology, M.A.H., M.R.K., N.V.G. and S.C.T.; software, M.A.H. and M.R.K.; formal analysis, M.A.H. and M.R.K.; investigation, M.A.H., M.R.K. and N.V.G.; data curation, M.A.H. and M.R.K.; writing—original draft preparation, M.A.H.; writing—review and editing, M.A.H., M.R.K. and S.C.T.; supervision, S.C.T.; funding acquisition, M.A.H., N.V.G. and S.C.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Centre for Global Change Science, University of Toronto, Canada, with additional generous support from 48 backers through [Experiment.com](https://experiment.com/projects/combating-climate-change-with-biochar-in-beautiful-bangladesh?s=search), a crowdfunding platform for science (<https://experiment.com/projects/combating-climate-change-with-biochar-in-beautiful-bangladesh?s=search> (accessed on 1 October 2025)).

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author (abdul.halim@mail.utoronto.ca) upon reasonable request.

Acknowledgments: We gratefully acknowledge the support of the managing team of the Lakkatura Tea Garden. We also thank the Department of Forestry and Environmental Science, Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh, in particular Narayan Saha and Romel Ahmed, for their valuable assistance. Additional thanks are extended to Md Abuzar Gifari, Mahabud Rana Tarun, and several other students from Shahjalal University for their help during the study.

Conflicts of Interest: Author Md Abdul Halim is an employee of CredoSense Inc. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Physicochemical properties of the kiln-derived *Acacia auriculiformis* wood biochar used in this experiment. Previously characterized in Karim et al. [23].

Properties	Unit	Mean ± SE (n = 3)
Al	%	0.083 ± 0.003
As	ppm	1.000 ± 0.000
Ba	ppm	17.667 ± 0.333
Total C	%	72.1 ± 0.073
Ca	%	1.820 ± 0.031
Cd	ppm	0.150 ± 0.041
Ce	ppm	1.000 ± 0.000
Co	ppm	0.467 ± 0.033
Cr	ppm	11.000 ± 2.517
Cu	ppm	16.200 ± 0.208
Fe	%	0.900 ± 0.015
K	%	2.060 ± 0.038
La	ppm	0.533 ± 0.033
Li	ppm	0.433 ± 0.033
Total N	%	1.8 ± 0.014

Table A1. Cont.

Properties	Unit	Mean $\pm$ SE (n = 3)
Na	%	0.051 $\pm$ 0.002
Nb	ppm	1.067 $\pm$ 0.033
Ni	ppm	4.333 $\pm$ 0.133
P	%	0.235 $\pm$ 0.002
Rb	ppm	25.000 $\pm$ 0.404
Pb	ppm	3.167 $\pm$ 0.067
Mg	%	0.120 $\pm$ 0.000
Mn	ppm	131.667 $\pm$ 2.728
Mo	ppm	1.767 $\pm$ 0.033
Sb	ppm	0.100 $\pm$ 0.000
Sn	ppm	1.467 $\pm$ 0.088
Sr	ppm	70.333 $\pm$ 1.453
Th	ppm	0.133 $\pm$ 0.033
Tl	ppm	<0.05
W	ppm	0.200 $\pm$ 0.000
Y	ppm	0.333 $\pm$ 0.033
Zn	ppm	799.667 $\pm$ 35.751
Zr	ppm	2.233 $\pm$ 0.393
Volatile matter	%	70.2 $\pm$ 0.89
Ash content	%	7.9 $\pm$ 0.12
pH	–	7.6 $\pm$ 0.11
EC	$\mu\text{S}\cdot\text{cm}^{-1}$	532.3 $\pm$ 17.6
Bulk density	$\text{g}\cdot\text{cm}^{-3}$	0.141 $\pm$ 0.005

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