JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(3), 416–434
https://doi.org/10.12911/22998993/214174
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.09.29
Accepted: 2025.11.12
Published: 2026.02.01

Quantifying carbon sequestration and greenhouse gas mitigation in orthodox tea systems using ISO 14067

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ABSTRACT

Tea agroecosystems represent a promising avenue for carbon storage and low-emission agriculture. This study evaluated the carbon storage potential and greenhouse gas (GHG) emissions in orthodox tea plantations in Central Java, Indonesia. Field sampling and biomass analysis were conducted to estimate carbon storage in above- and below-ground biomass, as well as in soil organic carbon. The 2021 IPCC guidelines and ISO 14067 standards were used to quantify GHG emissions and net carbon balance. Carbon content was converted to CO_2 equivalents using a molecular weight ratio of 44:12. CO_2 absorption equivalents per functional unit (22.25 bushes) were calculated at 124.82 kg CO_2 equivalents. On a larger scale, annual carbon sequestration reaches approximately 12.68 million kgCO_2-eq/year, while annual emissions from processing activities are estimated at 5.9 million kg CO_2-eq/year, resulting in a net sequestration of approximately 7.2 million kg CO_2-eq/year. The Energy Life cycle analysis shows that the baseline IPCC GWP-100 value for black tea production is 3.3810 kg CO_2-eq/kg of tea, which can be reduced by up to 5.68% through a fuel replacement scenario prioritizing renewable biomass (wood pellets). These findings highlight the potential of tea plantations to function as carbon sinks and contribute to climate-smart agriculture. Additionally, these results provide a scientific basis for integrating tea systems into voluntary carbon markets and national climate strategies under the Paris Agreement.

Keywords: carbon sequestration, greenhouse gas emissions, orthodox tea, IPCC 2021, ISO 14067, net carbon sink, life cycle assessment.

INTRODUCTION

Indonesia continues to strengthen its climate commitment through its updated Nationally Determined Contribution (NDC) by the Ministry of Environment and Forestry (KLHK, 2023), with a target of reducing greenhouse gas (GHG) emissions unconditionally by 29% and a conditional reduction (with international support) of 41% compared to the business-as-usual (BAU) scenario of 834 Mt CO_2-eq and 1,185 Mt CO_2-eq, respectively (The Global Green Growth Institute Indonesia, 2021). In addition, clearer adaptation measures and mitigation pathways under the Long-Term Strategy for Low Carbon and Climate Resilient Development 2050 (LTS-LCCR 2050) are needed given Indonesia's vulnerability to climate risks. The country must also strengthen its climate change adaptation commitments to achieve a risk-resilient society and become a net carbon sink by 2030.

To support this national climate strategy, the agricultural sector, including tea plantations, must contribute through sustainable land use, emissions mitigation, and nature-based solutions. Tea agroforestry systems are increasingly recognized for their critical role in biogenic carbon sequestration, positioning them as a strategic commodity for climate change mitigation within the land-based sector (Chettri and Ghosh, 2024). To contextualize the mitigation potential of tea systems, a comparative analysis with other perennial crops reveals distinct carbon dynamics. For instance, coffee plantations have been reported to sequester an average of 5.37 Mg CO_2-eq ha^{-1} yr^{-1} (Castigioni et al., 2021), while oil palm systems can absorb approximately 25 Mg CO_2-eq ha^{-1} yr^{-1} (Palm Oil Agribusiness Strategic Policy Institute, 2024). Against this comparative backdrop, this study empirically investigated the net carbon balance in orthodox tea systems by quantifying sequestration and emissions concurrently. It further examined how the integration of sustainable agricultural practices, investments in low-carbon technologies, and optimized land management can drive substantial emissions reductions under diverse commitment scenarios. This approach addresses the imperative for integrated resource management—encompassing energy, water, carbon, and product flows—to transition towards cleaner agricultural production paradigms (Ren et al., 2022). Additionally, ecosystem services from tea plantations, combined with conventional and organic farming methods, can strengthen the sustainability of the tea industry (Liu et al., 2024).

This study investigated how sustainable agricultural practices, investments in environmentally friendly technologies, and better land management contribute to emissions increases and decreases for various commitment scenarios. Many agricultural industries need to manage energy, water, carbon, and their products for cleaner agricultural greenhouse production (Ren et al., 2022), and assess ecosystem services from tea plantations as well as the use of conventional and organic farming methods for the strengthening of a sustainable tea industry (Liu et al., 2024).

Moreover, landscape structure change analysis is an ecological approach to achieve carbon sequestration area planning and sustainable agricultural infrastructure development (Anh et al., 2025), and scenarios of land use change in achieving GHG emission reduction targets are crucial for regulatory stability and sound decision-making (Zhang et al., 2023). These aspects play important roles in the evaluation of tea plantation management using an integrated risk-based approach (Mayasari et al., 2023).

In addition, the rise in GHG emissions poses an environmental, social, and economic challenge that necessitates transparent, accurate, and meticulous dynamic accounting (Noviyanto et al., 2025). Efficiency in fixed asset upgrades and education both have positive effects for green technology (Szafranko, 2019). It is also strengthening the structure of the tea plantation industry in emission reduction (Priatmadi et al., 2024), as scenarios necessitate collaboration with governments, international agencies, and local communities.

This study is particularly significant, because the calculation of greenhouse gas emission and sequestration levels with sources and sinks in the tea plantation sector needs to be improved to strengthen the Indonesian National Carbon Accounting System (INCAS) in supporting MRV (Measurement, Reporting, and Verification) requirements of GHG emissions from the land-based sector (Krisnawati et al., 2015).

Furthermore, beyond estimating potential carbon uptake, studies are needed to assess energy and energy efficiencies and renewability of black tea production, waste valorization (Pelvan and Özilgen, 2017), as well as feasibility assessment of renewable energy resources for tea plantation and industry (Kumar et al., 2021). A framework for cleaner production in tea industries is also required (Athira et al., 2019).

Despite growing global interest in agroforestry carbon dynamics, few studies have empirically evaluated carbon flows in tropical tea systems, particularly in Indonesia. Most previous studies have been limited to temperate regions or have relied on simulations and secondary data rather than location-specific, verified field measurements. Additionally, methodological integration between internationally recognized product carbon footprint standards (ISO 14067) and Indonesia's national land-based carbon accounting standards (SNI 7724:2019) is virtually absent in the literature.

This methodological gap weakens the accuracy and comparability of carbon calculations in Indonesian tea plantations. It also reduces their credibility in voluntary and compliance-based carbon markets and hinders alignment with NDC targets. Therefore, closing this gap is essential to support climate-smart agriculture, strengthen MRV systems, and increase the participation of the tea sector in emerging offset mechanisms. Empirical studies quantifying net carbon balance in Indonesian tea agroecosystems remain scarce, particularly those integrating field-based carbon stock measurements with life cycle emissions under harmonized national and international standards.

To bridge this gap, this empirical study integrating combining ISO 14067, IPCC 2021 AR6 guidelines, and Indonesia's SNI 7724:2019 for simultaneous evaluation of sequestration and emission profiles for orthodox tea production in Indonesia. It establishes a robust framework for estimating net carbon sinks and explores renewable energy-based mitigation scenarios. These findings offer practical insights for sustainable land use planning, nature-based solutions, and integration into voluntary carbon market mechanisms within tropical agroecosystems. This study aimed to evaluate carbon dynamics in Indonesian orthodox tea agroecosystems through:
- measurements of above-ground and below-ground biomass and soil organic carbon storage using field measurements;
- calculating GHG emissions from tea processing stages through life cycle analysis; and
- modeling mitigation scenarios through fuel substitution strategies inv Kraków County olving renewable biomass.

In accordance with ISO 14067, IPCC 2021 AR6, and SNI 7724:2019 standards, this study provided evidence-based input to support low-carbon agricultural planning and facilitate the integration of tea plantations into the voluntary carbon market framework. The integration of these standards not only ensures methodological rigor but also aligns the quantified results with national reporting needs, particularly under Indonesia's MRV (measurement, reporting, and verification) framework and international carbon market mechanisms.

As it is shown in Figure 1a, the biomass estimates from cradle-to-gate partial life cycle analysis (Tran et al., 2023) for each biomass class were used as starting values in GHG emissions and removals modeling (Rokhmah and Heryana, 2021). The accounting approach produces dry biomass in megagrams per hectare (Mg/ha dry weight) for each of the biomass source components of tea plants (aboveground biomass including stems, branches, bark, and leaves; and belowground biomass including coarse and fine roots) (Rolo et al., 2018). Carbon sources from dead organic matter (dead wood and litter) are converted and expressed as CO_2-equivalent per hectare (Mg CO_2-eq/ha) based on the IPCC conversion factor (1 Mg C = 3.67 Mg CO_2-eq). This output, from the visual map in Figure 1(b), follows the format specified in the Standard Methods Chapter - Modelling and Reporting (National Standardization Agency, 2019).

Although the tea company and estates studied demonstrated commendable environmental management, they have not yet formally adopted the ISO 14040 series for Life Cycle Assessment nor ISO 14064 for product-level carbon accounting. Accordingly, this research serves as a scientifically sound starting point to facilitate future compliance with recognized sustainability standards. The findings aim not only to quantify emissions and sequestration within current operations, but also to enhance organizational capacity — including knowledge, technical skills, and awareness among industry actors as they advance towards standardized sustainability assessment. By providing actionable insights and methodological clarity, this study supports the company and its stakeholders in strengthening preparedness for

a) b)

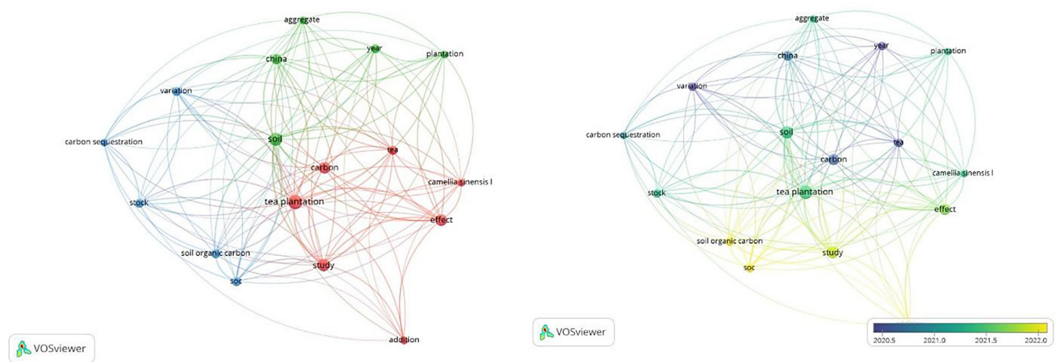

Figure 1. (a) Topic mapping related to the role of tea plantations in mitigating global warming potential, (b) keyword relationships related to topic trends on the role of tea in mitigating global warming potential

low-carbon transitions and transparent reporting, consistent with increasing national and international expectations for sustainability performance within agro-industrial value chains.

MATERIAL AND METHODS

Study site and sampling design

This study was conducted in three tea plantations: Pagilaran, Kayulandak, and Andongsili, located in Central Java, Indonesia. The Pagilaran Tea Plantation covers an area of approximately 1.130 hectares and is located at an altitude of 600–1.600 meters above sea level. These locations were selected as representative of tea plantations with diverse environmental conditions, including variations in plantation age, tea species, soil type, as well as climatic characteristics such as rainfall and temperature. The landscape is characterized by undulating topography, a tropical climate, and Andosol soil, which provides suitable conditions for tea cultivation and supports research on carbon storage dynamics. Sampling plots were established at altitudes ranging from 1.200–1.300 m above sea level to cover diverse agroecological zones and management practices. Soil samples were collected from three depths (0–10 cm, 10–30 cm, and 30–60 cm) using an auger to assess soil organic carbon (SOC) (Zhou et al., 2025). Biomass sampling was carried out destructively by harvesting tea plant components (leaves, stems, branches, and roots) within 1 m² quadrats. Fresh biomass weights were measured on-site, and the samples were oven-dried at 85 °C for 48 hours to determine dry weights. Litter samples were collected from 1 × 1 m plots under tea canopies, weighed fresh, then dried similarly for carbon content analysis. Greenhouse gases (methane and nitrous oxide) were monitored using portable gas analyzers. All sampling was performed in triplicate to ensure data accuracy and representativeness (Figure 2).

Tools and instruments for carbon estimation

To support rigorous and practical carbon assessments at the field level, a suite of accessible tools was employed and is summarized in Table 1 These instruments were selected based on their

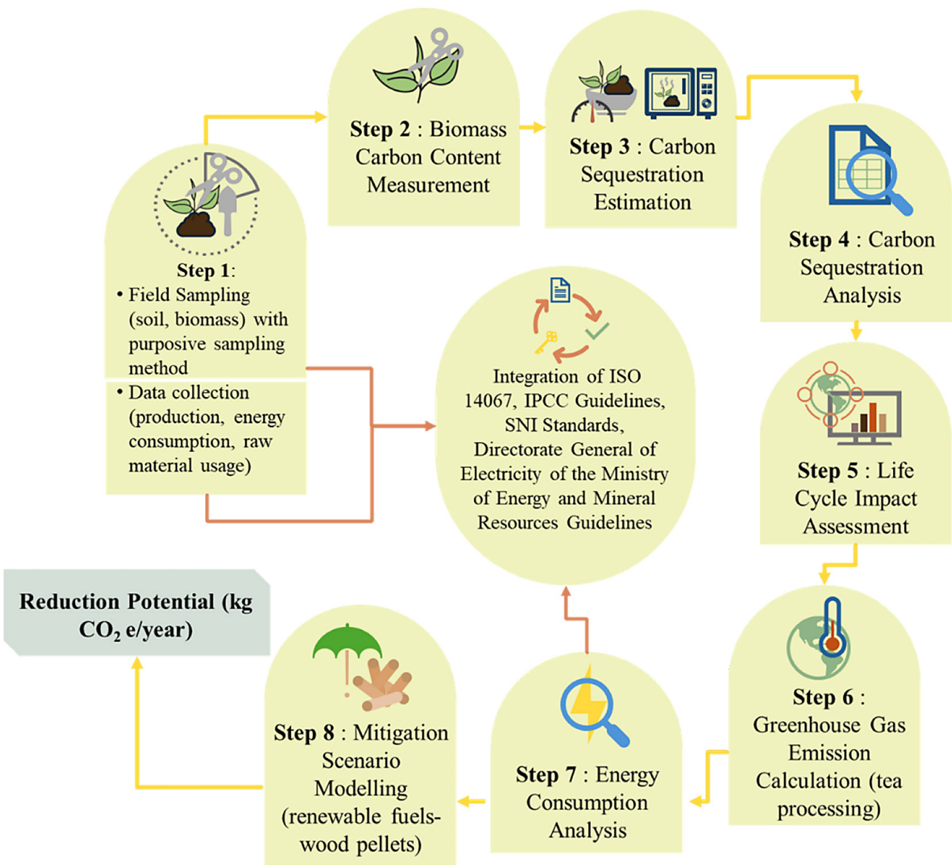

Figure 2. Workflow of sampling, estimation, and mitigation modelling in orthodox tea systems

accuracy, affordability, and contextual applicability. Table 1 provides an overview of adaptive instruments and digital platforms that enable the estimation of CO_2 uptake (in Mg CO_2-eq/ha) and O_2 release (in mol/m²/day) through photosynthetic processes. These tools, ranging from portable NDVI sensors and leaf area meters to remote sensing-based applications, such as Google Earth Engine and the FAO SEPAL platform, were selected for their practical suitability in plantation contexts, particularly in settings with limited technical infrastructure. Their integration into the research process allows for a more nuanced, spatially explicit, and participatory assessment of carbon storage across different agroecological zones within the tea cultivation landscape.

Table 1. Tools and facilities for estimating CO_2 sequestration and O_2 release through photosynthesis

No	Tool / application	Key specifications	Primary function in this study	Availability
1	NDVI Meter Clip-on (Smartphone-Based Sensor)	Near-infrared (NIR) sensor integrated with smartphone applications; powered via USB or internal battery; outputs in NDVI JPEG/CSV format	Estimate tea canopy vigor, biomass, and photosynthetic activity.	Commercially available via online marketplaces
2	i-Tree Tools	Web-based decision-support suite; enables input of site-specific vegetation data; outputs include CO_2 uptake (in Mg CO_2-eq/ha) and O_2 release (in mol/m²/day) estimates	Modeling aboveground biomass & carbon storage of tea shade/ agroforestry trees	Freely accessible online
3	Portable Leaf Area Meter (outputs in cm² or m²)	Manual or digital device for measuring leaf surface area; moderate accuracy; operates without electricity	Estimates photosynthetically active leaf area, which correlates with CO_2 absorption capacity	Widely available via agricultural supply outlets and online platforms
4	Digital Thermo-Hygrometer	Measures ambient temperature (°C/°F) and relative humidity (RH%); powered by standard AA batteries; LCD interface	Monitors key environmental parameters (ambient temperature and relative humidity) influencing photosynthetic rates	Highly available in general marketplaces
5	Lux Meter (Light Intensity Sensor)	Measures light intensity in lux; typical range: 0–200,000 lux; portable and battery-operated	Measures light intensity for estimating carbon sequestration in tea plants due to its direct effect on photosynthesis	Readily available via both local and international online stores
6	Agricultural Carbon Calculator (Spreadsheet / Web-Based)	Allows user-defined inputs (biomass, plant species, age); outputs include CO_2 sequestered and O_2 released	Estimates carbon sequestration and emissions based on crop-specific parameters, inputs, and management practices	Widely accessible via institutional websites
7	Google Earth Engine (GEE)	Cloud-based platform for accessing and analysing satellite datasets (MODIS, Landsat, Sentinel); scriptable via JavaScript	Enables spatially explicit monitoring of NDVI and vegetative productivity	Freely available to registered users
8	SEPAL (System for Earth Observation Data Access, Processing and Analysis for Land Monitoring)	FAO-supported web platform; facilitates access to remote sensing data and carbon stock assessments	Provides visualisation and quantification of vegetation change and carbon flux	Free access with institutional login
9	Collect Earth (Open Foris Initiative)	Desktop and browser-based tool integrating Google Earth imagery for field data collection and satellite interpretation	Supports participatory monitoring of land cover change and carbon sequestration potential	Free and open-source

Note: the suite of tools enumerated herein facilitates robust vegetation monitoring and carbon stock assessment; however, their deployment and accuracy are contingent upon site-specific environmental conditions and operational constraints. Methodologically, this study integrated direct field measurements with remote sensing platforms to ensure data integrity. Empirical data collection utilized a high-accuracy Leaf Area Meter (±0.5%), an NDVI sensor demonstrating a strong correlation with canopy biomass ($r^2 = 0.89$), and the Google Earth Engine (GEE) platform for spatially explicit validation. Complementing these empirical measures, the SEPAL (FAO, 2023) and Collect Earth (Open Foris, 2025) platforms were employed within the analytical framework for conceptual cross-referencing and to verify spatial consistency, thereby enhancing the overall robustness of the carbon stock estimation.

System boundary and life cycle assessment assumptions

Although the original method section does not specify clear boundaries, this study retrospectively applies cradle-to-gate boundaries to ensure clarity and consistency with standard LCA practices. This boundary includes all upstream processes from cultivation, biomass accumulation, to conventional dry black tea production, while excluding downstream activities such as distribution, retail sales, use, and end-of-life handling.

As it is shown in Figure 3, the cradle-to-gate scope covers all processes from tea cultivation, harvesting, and on-site processing to factory gate, excluding downstream process. These boundaries were chosen so that the study could focus on the cultivation and harvesting stages of tea, where the carbon uptake measurements were taken, and the main production stage of tea, where the emissions from tea production were measured, so that the value of estimated net carbon sequestration could be determined. Downstream processes, such as distribution, consumer use, and end-of-life phases were outside the system boundaries and were therefore not considered in this assessment.

This assessment focuses on measuring carbon emissions and sequestration in the production phase to support agricultural-level mitigation strategies. Additionally, the net carbon balance accounts for biogenic carbon sequestration in biomass and soil, but does not include indirect compensation mechanisms, such as emissions avoided due to land-use changes or the replacement of fossil-based products. Emission factors and absorption coefficients are derived from empirical field measurements, the 2021 IPCC AR6 guidelines, and SNI 7724:2019. Explicit explanations of these boundaries and assumptions enhance analytical transparency, enabling findings to be compared with comparable LCA studies and aligned with international carbon accounting frameworks, such as ISO 14067.

Tea plant biomass measurement

Photosynthesis enables tea plants to capture atmospheric CO_2 and convert it into organic compounds stored in plant tissues. This biological process is the foundation for estimating biomass accumulation at the field level. In this study, biomass was measured using a destructive sampling method in accordance with SNI 7724:2019. Tea bushes were separated into components (leaves, stems, twigs, and roots), and each part was weighed in both fresh and dry states. The fresh biomass was oven-dried at 85 °C for 48 hours until a constant weight was achieved. The percentage of water content was calculated using Equation 1, and dry weights were converted into CO_2-equivalent values using a standard factor of 3.67 based on the IPCC guidelines. The soil samples were also analyzed to assess the organic carbon content using standard TOC methods.

$$\% \, WC = \frac{BB_c - BK_c}{BK_c} \times 100\% \quad (1)$$

where: $\% \, WC$ – percent moisture content of the sample, BB_C – wet weight of sample (kg), BK_C – dry weight of sample (kg).

The percent moisture content of the sample is used to calculate the total dry weight (biomass) of

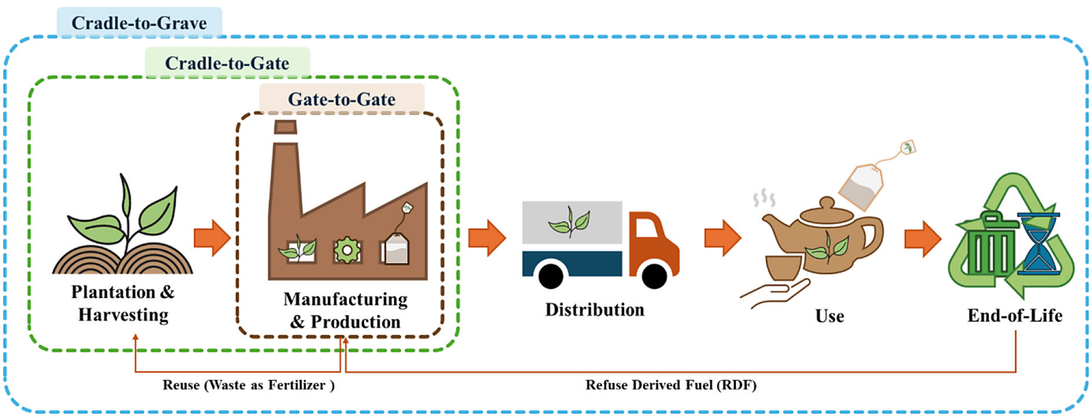

Figure 3. Cradle-to-gate boundary of orthodox tea production

tea plants. Tea plant biomass is calculated using the following formula:

$$BK = BB - (BS \times \%KA) \quad (2)$$

where: BK – total dry weight (biomass) (kg), BS_C total fresh weight of plants (kg), $\%KA$ – percent moisture content of the sample.

Furthermore, the biomass of tea plants in an area of 1 hectare is obtained by multiplying BK by the total population of tea plants, which is 10.000 plants/ha.

Measurement of tea plant biomass carbon and litter

The carbon content of each tea plant sample was calculated following Indonesian National Standardisation Agency (2019) and converted into CO_2-equivalent (CO_2-eq) using the IPCC molecular weight ratio of 44/12 (i.e., 1 kg of carbon = 3.67 kg of CO_2). The total CO_2 sequestration in megagrams (Mg CO_2-eq) was obtained by:

$$CO_{2_b} = B \times \%\, C_{organic} \times \frac{3.67}{1.000} \quad (3)$$

where: CO_{2b} – carbon content of tea plant biomass (kg), B – total biomass (kg), $\%\ C_{organic}$ – percentage of carbon obtained from laboratory measurements.

The measurement of the total carbon value of tea plants in an area of 1 hectare, is obtained by multiplying C_b by the total population of tea plants, which is 10.000 plants/ha. Litter is made up of the tea plant parts that have fallen to the ground in the form of leaves and twigs but have not yet decomposed. Litter samples were collected on a 1 × 1 m plot under the tea plant canopy and weighed fresh. Following that, the litter samples were baked at 85 °C for 48 hours to determine their dry weight and carbon percent. The following formula (Indonesian National Standardisation Agency, 2019) is used to calculate litter carbon:

$$CO_{2_s} = B_s \times \%\, C_{organic} \times \frac{3.67}{1.000} \quad (4)$$

The organic carbon content of litter (C_S) was calculated and converted to CO_2-equivalent using the molecular weight ratio of CO_2 to C (44:12 = 3.67). The following formulas were applied:

$$CO_{2_{litter}} = \frac{CO_{2_S}}{1000} \times \frac{10000}{L_{plot}} \quad (5)$$

where: CO_{2s} – CO_2-equivalent content of litter Mg CO_2-eq, B_S – dry weight of litter (kg), $\%\ C_{organic}$ – percentage of carbon obtained from laboratory measurements, L_{plot} – area of litter sampling plot (m^2).

Measurement of carbon dioxide (CO_2) gas uptake

The CO_2-equivalent content of each tea plant sample was calculated using a formula that refers to Indonesian National Standardisation Agency (2019) as follows:

$$S = \frac{MW}{AW} \times C \quad (6)$$

where: S – $CO_{2sequestration}$, MW – the relative molecular weight of CO2, AW - the relative atomic weight of C, C – carbon content of tea plant.

The CO_2-equivalent values were derived using the standard molecular ratio of CO_2 to carbon (44/12 = 3.67), as recommended by the IPCC.

RESULT AND DISCUSSION

Carbon sequestration potential in tea plantations

The study was carried out at Pagilaran Tea Estate, which has an area of approximately 1.130 hectares and is located at an altitude of 600–1.600 meters above sea level. The weight percentages of plant parts are as follows: leaves 2±0.92%, twigs 8±0.27%, stems 85±1.73%, and roots 5±0.94%. Table 2 shows the estimated CO_2-equivalent content value of tea plant biomass based on PT Pagilaran (tea industry) data-driven model for the optimization (do Carmo et al., 2023), allocation in different methods (Ding et al., 2024), and field measurements.

The leaf samples from tea plants were subjected to gravimetric weighing and expressed as relative water content (RWC), which represents the current leaf water content divided by the leaf water content at full saturation. The desired dirt and tissue must be removed from the plant, including water on the tissue surface, to acquire dry weight for the leaves and other plant parts. The results of RWC identification ranged from 91–94% in fully decomposed leaves, dropped to about 34–41% in the leaves subjected to the wilting process, then further down to about 60% to

67%. To complete the rehydration process, the samples were dried to remove any remaining surface water, weighed, and dried in an oven at 60 °C until a constant weight was observed. In a few instances, they were also left in a desiccator with silica gel for about 48 hours to ensure complete drying. The dry weights (initially measured in kg) were subsequently converted into CO_2-equivalent using the factor 3.67 (IPCC standard), and results were presented in Mg CO_2-eq by subtracting the pre-dialysis weight from post-dialysis weight, so as to derive the liquid collected from fresh tea leaves, and that value later divided by the smallest unit of measurement for purposes of simplifying calculation. Correspondingly, the mean mass of 1 cm² of completely dry leaves is 0.017 ± 0.004 g.

Estimation of the weight of pruned tea biomass was carried out by collecting and weighing the pruning from six bushes, as several representative tea trees, in the pruned plantation area. Total biomass values were multiplied by the carbon content (%) and converted to Mg CO_2-eq using the IPCC molecular weight ratio (3.67) and recording the geographical coordinates, tea variety, age of the plant, altitude, and other environmental conditions that may affect biomass. The number of tea plants per hectare was identified to be multiplied by the average biomass value per tree (interpolation result) by the number of trees per hectare to obtain an estimate of the total biomass per hectare. The accuracy of the interpolation results is highly dependent on the number and distribution of samples taken, where the more samples and the more evenly distributed, the more accurate the interpolation results.

In addition to aboveground biomass, the study measured carbon content through a comprehensive sampling of soil and biomass in tea plantations. Above-ground biomass, including leaves and stems, and below-ground biomass, such as root systems, were dried, weighed, and analyzed for carbon using standard methods like dry combustion. Soil organic carbon (SOC) was determined through soil sampling and total organic carbon (TOC) analysis. Greenhouse gas indicators, like methane and nitrous oxide were monitored using gas sampling systems to assess their role in carbon uptake. Sampling for TOC analysis was conducted during key periods in the plantation cycle, namely after planting, during peak growth, and after harvest, to capture changes in organic carbon levels. To ensure accuracy and representativeness, three replicates were taken from each sampling location during each period, depending on the scale of the study and the variability of soil or biomass conditions. Following the biomass stratification by age in Table 2, Table 3 details the functional unit-based estimation approach for calculating carbon sequestration values.

Table 2. Age-dependent biomass allocation and morphological characteristics of camellia sinensis under plantation conditions

Age (Years)	Root (Mg CO_2-eq)	Main stem (Mg CO_2-eq)	Branches (Mg CO_2-eq)	Leaves (Mg CO_2-eq)	Total biomass (Mg CO_2-eq)	Morphological characteristics & Developmental notes
1	0.00012–0.00020	0.00020–0.00041	0.00010–0.00025	0.00017–0.00058	0.00058–0.00144	Establishment phase: Taproot dominant; foliage predominantly juvenile; canopy height < 50 cm; vegetative propagation initiated; pruning yet to be applied.
3	0.00058–0.00107	0.00074–0.00140	0.00066–0.00116	0.00091–0.00215	0.00289–0.00578	Initial productive phase: Onset of lateral root development; first pruning performed; crown formation begins; plant height 70–110 cm; harvest of young shoots commences.
5	0.00149–0.00264	0.00206–0.00347	0.00182–0.00363	0.00264–0.00528	0.00801–0.01503	Mature productive phase: Extensive branching and canopy expansion; roots penetrate 60–90 cm; uniform leaf flushing; structural biomass accumulates steadily.
10	0.00347–0.00710	0.00528–0.00875	0.00512–0.01073	0.00347–0.00710	0.01734–0.03369	Physiological maturity: Main stem exhibits full lignification; secondary branches dense and woody; root depth often exceeds 1 metre; foliage becomes thicker and darker; carbon allocation stabilises.
≥20	0.00908–0.01453	0.01073–0.01734	0.01239–0.02147	0.00528–0.01073	0.02097–0.03105	Senescence phase: Decline in vegetative growth; aboveground biomass increasingly lignified; leaf biomass decreases slightly; root system deep but structurally brittle; rejuvenation or replanting is advised for sustained productivity.

Note: PT Pagilaran data-driven model and field measurement (2023).

Table 3 shows the calculation of the estimated carbon sequestration value. This amount refers to the best tea leaf harvest in the period 2017–2022. On the basis of Table 3, the functional unit (UF) for carbon sequestration estimation in this study is 22.25 tea bushes, representing the number of bushes required to produce 1 kg of dry tea. Table 4 shows the calculation of the estimated value of carbon sequestration per functional unit.

Accordingly, using a daily harvest of 110,000 bushes (22,000 kg wet tea shoots and 4.800 kg dry tea per day) is obtained by calculating the number of working days in one month and one year. Table 5 shows the calculation of the estimated value of carbon sequestration from cultivated land. On the basis of field sampling and biomass analysis, the CO_2-equivalent sequestration per functional unit (22.25 tea bushes) was calculated to be 124.82 kg CO_2-eq, following the IPCC molecular weight ratio of 44/12. Assuming 68 bushes are harvested per day (if 110,000 bushes harvest tea plants begin to produce a harvest after 5 years, with 6 harvests per year and 27 working days per month), this results in an estimated daily sequestration of ~ 380.93 kg CO_2-eq. With 27 operational days per month and 12 months of production, the annual sequestration potential is estimated at approximately 123.42±17% Mg CO_2-eq, with carbon sequestration value of 11.22±1.94 Mg CO_2-eq per hectares per year or 25.71±17% kg CO_2-eq per kilogram of processed tea. According to previous studies, the reported carbon sequestration potential typically ranges from 20 to 45 kg of CO_2 per kilogram of processed tea under various conditions (Hughes, 2023).

Moreover, carbon input from fallen leaves, twigs, and branches further contributes to the sequestration process. The influence of topographic gradients on SOC dynamics was quantitatively assessed through correlation and regression analyses. A significant inverse relationship was observed between altitude and SOC concentration (Pearson's $r = -0.72$, $p < 0.05$), indicating a substantial depletion of soil carbon stocks with increasing elevation. Linear regression modelling accounted for 52% of the total variance in SOC distribution ($R^2 = 0.52$) across the studied elevational gradient (650–1.450 m a.s.l.), with mean SOC stocks declining markedly from 65.7 ± 11 Mg C ha^{-1} to 13.1 ± 2 Mg C ha^{-1}. This pronounced altitudinal pattern is attributable to the coupled effects of reduced litter input and suppressed decomposition kinetics at higher elevations, collectively governed by thermal constraints on biological activity. These findings establish topography as a critical determinant of carbon sequestration capacity in tea agroecosystems, with implications for targeted carbon management strategies across heterogeneous landscapes. Prior research by Rokhmah and Heryana

Table 3. The calculation of the estimated carbon sequestration value

No.	Stages	Descriptions	Calculation results
1.	Estimated biomass weight	• 100 buds • 1 bud = 2 g per bud • 1 ha area = 10,000 plants	± 15,000–20,000 kg fresh shoot/ha/harvest,
2.	Estimated weight of dry tea	• 6 harvests per year (assumption) • 2 Mg × 6 = 12 Mg of shoots • Yield value = 21%	= 12 Mg × 21% = 2.520 kg dry tea/ha per year
3.	Percentage of processed and unprocessed leaves	• 98% of the leaves can be picked • Only 2% of the leaves per plant are not processed or as much as 2% of the total plant weight.	
4.	Weight value measurement	• 4.45 kg of processed fresh tea leaves = 1 kg of dry tea • 10,000 plants/ha = 2 Mg/ha	
5.	Measurement of the number of plants per functional unit 1 kg of dry black tea	• 1 plant = 100 shoots = 200 g or 1 plant = 0.2 kg of shoots • 1 kg of dry black tea = 4.45 kg of shoots	= 4.45 kg of shoots: 0.2 kg of shoots = 22.25 plants

Table 4. The calculation of the estimated value of carbon sequestration per functional unit

Relative molecular weight of CO_2 (g/mol)	Relative atomic weight of C (g/mol)	Carbon content of tea plant (kg C/UF)	CO_2 sequestration (kg CO_2-eq/UF)
44.01	12.01	34.043	3.67 × 34.043 = 124.82 kg CO_2-eq

Table 5. The calculation of the estimated value of carbon sequestration from cultivated land

Number of Bushes	UF (bush)	CO_2-eq per UF (kg CO_2-eq)	Daily CO_2-eq (kg)	Days/month	Monthly CO_2-eq (kg)	Months/year	Yearly CO_2-eq (Mg)
~68	22.25	124.82	~380.93	27	~10,285.15	12	~123.42

Note: the value can change depending on the environment and time situation. Uncertainty in the measurement of carbon uptake and storage in plants and soils comes from a combination of biological, environmental, methodological and technical factors. Therefore, the use of reference standards (SNI, IPCC, ISO), sampling replication and method calibration are necessary to reduce bias and improve accuracy. In addition, measurement results should always be reported with confidence intervals or standard deviations for scientific and comparative interpretation.

(2021) indicates that SOC varies significantly with elevation. Soils in high-altitude zones typically show reduced organic C due to lower temperatures and slower decomposition rates. Bulk density of the Andosol soils in these tea lands is around 0.63 g/cm³ (Wibisono, 2016).

The lower the soil carbon stock influences by the higher the altitude. Temperature and rainfall are affected by altitude, according to Esquivel et al. (2020) and Chen et al. (2023). Agricultural land with high soil organic carbon stocks is distributed in lowland and well-watered areas. The partial dependence of soil organic carbon on rainfall shows an increasing trend and then slowly decreases with andosol and latosol soil properties governed by altitude as the most influential natural factor on soil organic carbon stocks (Chen et al., 2023). This slows down the decomposition of organic matter, resulting in a low input of organic carbon into the soil. As a result, soil carbon stocks decrease as altitude increases. According to Shibabaw et al. (2023), soil carbon value is also affected by the quantity and quality of plant litter on the soil surface, as well as the rate at which the litter decomposes. The nutrients released from organic waste decomposition will recycle carbon from plants to the soil. Elevation has an impact on tea plantation carbon stocks, particularly carbon stocks in plant biomass. Tea plant carbon stocks and carbon dioxide uptake are negatively correlated with altitude (Vivaldo et al., 2023).

While the study presents comprehensive quantitative data on carbon sequestration and emissions, further exploration of the underlying interactions among ecological and agronomic variables is warranted to deepen interpretative insights. For instance, spatial variation in altitude appears to influence both SOC and biomass allocation patterns, yet these associations have not been explicitly modeled. Incorporating multivariate or geostatistical approaches, such as regression analysis, spatial autocorrelation, or elevation-driven carbon mapping would enable a more nuanced understanding of how topographic gradients, cultivar differences, and management practices jointly affect carbon dynamics. Such spatially explicit modeling could significantly enhance the robustness of mitigation scenario planning and landscape-level carbon accounting frameworks.

Carbon emission release potential in tea processing

The analysis of mass and energy flow in tea processing in this study highlighted fuel preparation, properties, thermal decomposition, and emissions per batch to avoid double counting from the processing sector (Lachman et al., 2022).

Drying plays a critical role in tea processing, as it halts enzymatic reactions as well as ensures the stability and shelf life of the final product. Quality attributes such as flavor, aroma, and color are largely developed during early processing stages before the drying phase, contributing to the characteristic features of made tea (Kumar et al., 2023). According to the findings, the highest energy consumption of tea processing is required for the weathering work, while the lowest energy consumption is required for the packaging work. The production of 1 kg of dried tea requires approximately 32.52 MJ of energy, sourced from coal (37.28%), electricity (5.42%), fuel oil (0.53%), firewood (51.96%), and human labor (0.013%).

On the basis of the emission analysis, firewood, the primary fuel for the withering and drying process, contributes the most emissions. According to Guo et al. (2015), wood fuels, including firewood, wood chips, and wood pellets, typically exhibit lower energy content while displaying higher combustion emissions.

As a result, these emissions may exert a more significant impact on GWP than on acidification or eutrophication potentials. Thus, optimizing the type and efficiency of fuel used in tea processing is essential for reducing the overall carbon

Table 6a. Material and energy input and output in orthodox black tea processing

	Laying			Rolling			Wet sorting			Drying			Dry sorting			Packing		
	Mate-rial	Amount	Unit	Material	Amo-unt	Unit	Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit
Input	Fresh shoots	222.5	kg	Wilted tea leaf tops	129.15	kg	Shoot wilting rolled tea	129.15	kg	Wet tea powder	128.6209	kg	Dried tea	50	kg	Dried tea	50	kg
																Alumi-num sheet	0.0175	kg
																Paper	0.525	kg
Output	Shoot wilting	129.15	kg	Shoot wilting rolled tea	129.15	kg	Wet tea powder	128.621	kg	Dried tea leave	50	kg	Dried tea	50	kg	Dried tea	50	kg
	De-crease in moisture content	102.35	kg	Energy output	127.612	kJ	Waste-water	58.451	l	Pluff	0.5552	kg						

Note: MJ – megajoule; kg – kilogram, kJ – kilojoule. Based on direct inputs excluding energy for transportation and machinery manufacture.

Table 6b. Energy input and output in orthodox black tea processing

	Laying			Rolling			Wet Sorting			Drying			Dry Sorting			Packing		
	Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit
Input	Incoming heat	1906.513	kJ	Energy input	127.612	kJ	Energy input	127612	kJ	Energy input	5703.491	kJ	Energy input	106.772	kg	Electricity	0.063374	kWh
	Electrical energy	28.934	kWh	Electricity	16.795	kWh	Electricity	16.795	kWh	Electricity	16.726	kWh	Electricity	29	kWh			
	Coal	1.527	kg							Coal	0.854864	kg						
	Wood pellets	0.2276	kg							Wood pellet	0.127421	kg						
										Fire-wood	2.657238	kg						
Output	Heat out	1906.513	kJ	CO_2	38.564	kg	Energy output	127.612	kg	Energy output	5703.491	kJ	Energy output	106.7718	kJ	CO_2	9.932096	kg
	CO_2	69.94401	kg	CH_4	0.25402	kg	CO_2	38.56381	kg	CO_2	69.37803	kg	CO_2	26.969	kg	CH_4	0.065	kg
	CH_4	0.460721	kg	N_2O	0.500758	kg	CH_4	0.25402	kg	CH_4	0.456984	kg	CH_4	0.177648	kg	N_2O	0.12897	kg
	N_2O		kg	CO	0.025246	kg	N_2O	0.500758	kg	N_2O	0.900885	kg	N_2O	0.350209	kg	CO	0.006502	kg
	CO	0.04579	kg	SO_2	0.008497	kg	CO	0.025246	kg	CO	0.045419	kg	CO	0.017656	kg	SO_2	0.002189	kg
	SO_2	0.015411	kg				SO_2	0.008497	kg	SO_2	0.015287	kg	SO_2	0.005943	kg			

Note: MJ – megajoule; kg – kilogram, kJ – kilojoule. Based on direct inputs excluding energy for transportation and machinery manufacture.

footprint of the sector and aligning with low-emission development goals.

Using actual operational data listed in Table 6a and 6b, a mathematical model with irreversible thermodynamic properties was developed that covers the classification, drying, and packaging stage. This model enables the assessment of mass and energy balance, with the main objective of determining the conversion efficiency of fresh tea leaves into dried tea products.

Furthermore, both visual and numerical data were utilized in simplified calculations to estimate net energy input, production yield, and system-level thermodynamic efficiency. Thermodynamic analysis was conducted to identify internal energy losses, contributing to the development of an inventory matrix for the black tea production process. Material and energy flows are measured by dividing continuous daily operations into batch units of 236 kg of fresh tea leaves. This batch size is used to map, analyze, as well as evaluate material and energy transformations at each processing stage. An average operational efficiency of 78% was applied to model material flow patterns and energy dynamics.

As it was illustrated in Figure 4, the production system converts 222.5 kg of fresh tea buds into approximately 50 kg of orthodox dry black tea (first and second grade).

Integration of ISO 14067, IPCC, and SNI in tea agroecosystem carbon

This study integrated three main frameworks to ensure methodological robustness, policy alignment, and international comparability in measuring carbon dynamics in conventional tea plantations. ISO 14067 provides a structured

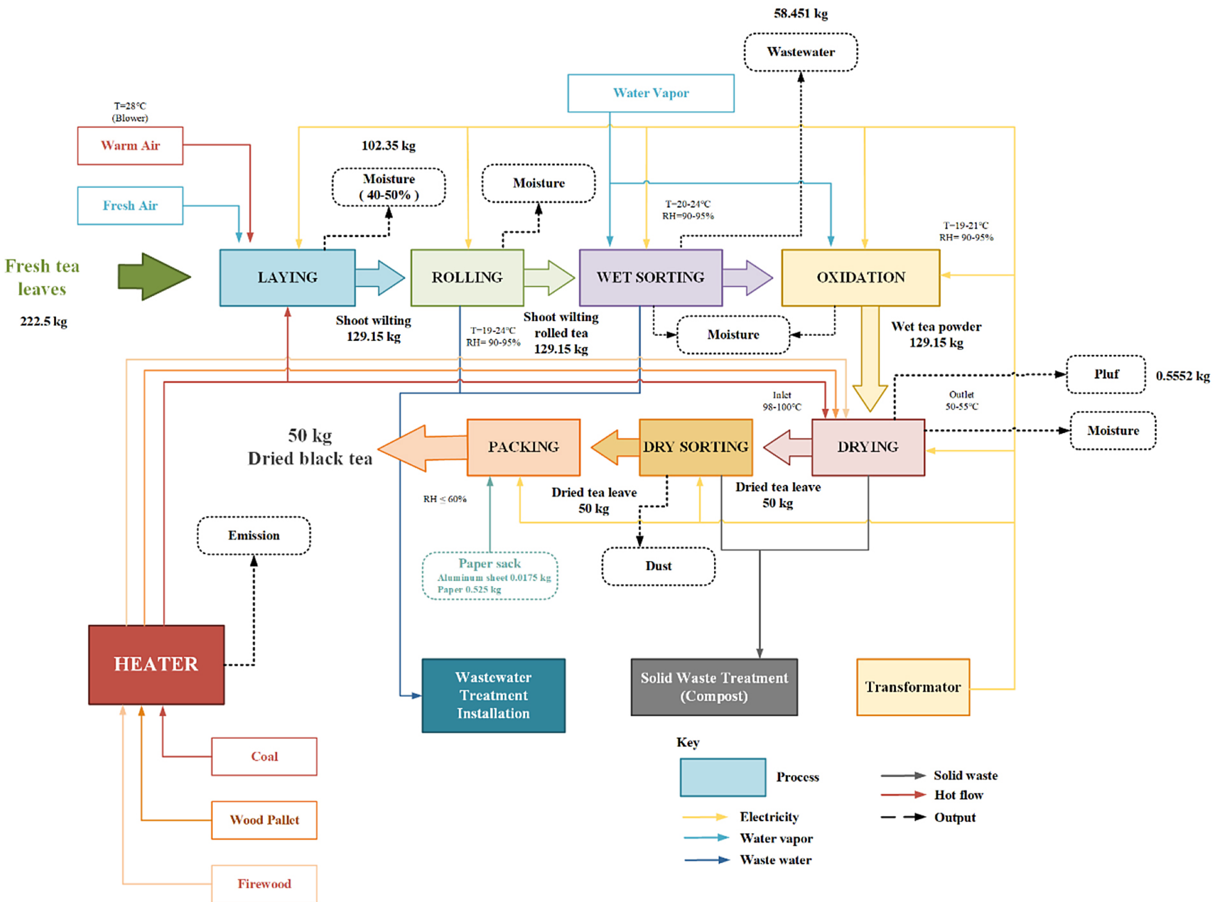

Figure 4. Black tea production inputs and outputs (CO_2 emissions per 50 kg dried tea)

methodology for calculating the carbon footprint at the product level, emphasizing transparency and reproducibility throughout the agricultural supply chain. This standard guides the definition of system boundaries, functional units, and emission factors required for life-cycle-based greenhouse gas calculations at the product level.

The Intergovernmental Panel on Climate Change (IPCC), particularly the AR6 2021 Level 1 Guidelines, provides scientifically verified default values for biomass carbon stocks, emission factors, and land-use emissions. These parameters are adopted to ensure the integrity and comparability of field estimates of soil organic carbon, above- and below-ground biomass, as well as emissions from energy use.

Meanwhile, SNI 7724:2019, the Indonesian national standard for calculating carbon stocks and greenhouse gases in forestry and land use, aims to align analysis with the national MRV (Measurement, Reporting, and Verification) system and compliance with Indonesia's Nationally Determined Contribution (NDC). SNI provides detailed procedures and context-specific factors for field-level estimates, particularly in tropical landscapes.

By harmonizing the ISO 14067, IPCC, and SNI frameworks, this study bridges the gap between scientific rigor and regulatory applicability. This facilitates cross-scale carbon calculations from local plantation-level assessments to national and international reporting mechanisms. Additionally, this integrative approach strengthens the credibility of the carbon data generated by the tea sector, supporting its participation in voluntary carbon markets, carbon offset schemes, and broader sustainability certification platforms.

Energy consumption

Coal, firewood, and wood pallets are used in varying amounts to power the manufacturing process. The amount of energy materials used varies greatly depending on price and availability, which affects production costs. Because coal has a higher calorific value than firewood, charcoal, or wood pellets, it is the primary energy source. This means that coal has the potential to produce more energy per unit mass than other organic fuels (Umar and Rohayati, 2021). Although the cost of processing coal is high, coal is often cheaper than firewood, charcoal, or wood pellets on a large scale. This makes it a more cost-effective option in the energy industries that require large amounts of energy. Coal is more convenient to transport and store than firewood, charcoal, or wood pellets. This makes it more practical for shipping and large-scale applications.

The use of coal in the black tea production process is used in energy generation for the withering and drying process, resulting in combustion residues that can cause air pollution. If the levels of pollutants or air pollution are too high in the environment, these conditions will endanger the survival of living things in the environment (Triani et al., 2023). The energy material input and the use of fuel in the black tea production process at PT Pagilaran for an estimated 1 kg of dry tea as the final product is shown in Tables 7 and 8.

Mitigation scenarios were developed to evaluate the potential for reducing greenhouse gas emissions by optimizing the fuel composition used in the drying stage of orthodox black tea production. By adjusting the current configuration to a more sustainable fuel mix 4–10% coal, 45–48% firewood, and 45–48% wood pellet emissions intensity per unit of dry tea can be significantly decreased.

This optimized ratio represents a strategic shift toward cleaner and partially renewable fuel sources, particularly wood pellets, which have lower CO_2 emission factors and better combustion efficiency.

On the basis of emission factor simulations and prioritized input allocation, total specific CO_2 emissions can be reduced from approximately 1.0438 kg CO_2 to 1.4561 kg CO_2 per kilogram of dry tea. This reduction highlights the environmental advantages of transitioning to a more balanced and sustainable fuel mix to support decarbonization targets in the tea processing industry.

Total carbon emissions from the use of fossil fuels and electricity in dry tea production are estimated at 3.3810 kg CO_2-eq per kg of tea. This emission intensity reflects the daily GHG output generated from energy inputs, including the burning of coal, firewood, wood pellets, and electricity. When normalized to daily production, this results in an accurate emission rate per unit of product.

Detailed breakdowns of these values are presented in Table 9. The emissions calculation assumes a production output of 4.800 kg of dry tea per day, operating 27 days per month, and 12 months per year.

To reduce the emissions during processing, mitigation efforts focus on reducing the burning of fossil fuels, particularly coal. The transition to cleaner energy sources, such as wood pellets, offers significant emission reductions. However, sustainable adoption requires comprehensive feasibility studies that cover technical, economic, and environmental aspects. The development of wood pellets as a renewable fuel depends on

Table 7. Thermal energy input for black tea processing

Fuel type	Input per kg of tea	Emission factor (kg CO_2/kg fuel)	Reference
Coal	1.2058	2.2201	(Directorate General of Electricity of the Ministry of Energy and Mineral Resources, 2018; International Panel for Climate Change, 2023)
Wood pellet	0.1797	0.0057	
Firewood	2.6881	0.0856	

Note: Emission factors are derived from literature sources and represent average CO_2 emissions per kg of fuel combusted under typical operational conditions, including combustion-based heating and fuelwood use during the drying stage.

Table 8. Fuel composition and usage in black tea production

Combustion of coal carbon dioxide for 1 kg of dry tea (kg CO_2)	Combustion of wood pellet carbon dioxide for 1 kg of dry tea (kg CO_2)	Combustion of firewood carbon dioxide for 1 kg of dry tea (kg CO_2)	CO_2 emission results in diesel power plants every 1 KWh (gram CO_2)	Carbon dioxide emissions of electricity for 1 kg of dry tea (kg CO_2)
2.2201	0.0057	0.0856	0.3216 (Directorate General of Electricity of the Ministry of Energy and Mineral Resources, 2018)	0.7480

Note: emission factors are expressed in kg CO_2 per kg of dry tea or g CO_2 per kWh of electricity. Values are derived from IPCC (2021).

Table 9. The calculation of the estimated CO_2 emissions

Description	Value	Unit
Daily tea production	4,800.00	kg
CO_2 emission intensity per kg of dry tea	3.3810	kg CO_2-eq/kg
Estimated total daily CO_2 emissions	~16,228.80	kg CO_2-eq/day
Operating days per month	27	days
Estimated monthly CO_2 emissions	~438,177.60	kg CO_2-eq/month
Months per year	12	months
Estimated annual CO_2 emissions	~5,258,131.20	kg CO_2-eq/year

Note: emission factors include combustion of coal (2.2201 kg CO_2/kg tea), wood pellets (0.0057 kg CO_2/kg tea), firewood (0.0856 kg CO_2/kg tea), diesel (0.3216 kg CO_2/kg tea) and electricity (0.799 kg CO_2/kg tea). Electricity emission factor based on 0.88 kg CO_2/kWh (State Electricity Company, 2022).

a consistent supply of raw materials, quality assurance, as well as government policy support, including incentives and carbon pricing schemes (Rimantho et al., 2023).

Energy usage for tea processing

The impact of fuel use during processes that result in large amounts of carbon dioxide being released into the atmosphere is used to calculate global warming potential. Over the past few decades, global warming has emerged as a significant concern, leading to climate change as a result of the release of carbon dioxide into the atmosphere (Rehman et al., 2021 and Mousavi et al., 2023) As a result, action is required to reduce the fuels that have the potential to contribute to global warming. Table 10 depicts the scenarios for the use of each material to identify each potential impact of energy materials.

Life cycle impact assessment

Global warming potential (GWP) at PT Pagilaran, potential impact forecasts are made based on the inputs and outputs at each stage of activities in 2021 and 2022. Table 11 shows the Impact Assessment value based on the calculation of inputs and outputs from the OpenLCA 2.5.0 software IPCC 2013 GWP 100a method.

Table 11 presents the global warming potential (GWP100) of black tea production under both the current and proposed mitigation scenarios. The baseline scenario yields a specific GWP of 8.2937 kg CO_2-eq/kg tea, resulting in an annual carbon footprint of approximately 5.86 million kg CO_2-eq.

Importantly, progressive substitution of fossil fuels with renewable alternatives—especially wood pellets—can reduce emissions by up to 5.68%, achieving a specific GWP as low as 7.8 kg CO_2-eq/kg tea. Such mitigation pathways align with ISO 14067 guidelines on low-carbon product systems and demonstrate the significant decarbonization potential of agro-industrial processes through clean energy transitions (Liang et al., 2023).

While the transition to biomass fuels like wood pellets presents a clear pathway for emission abatement, its economic viability requires critical assessment. The conducted analysis indicates that adopting wood pellets would entail a significant economic premium, increasing fuel procurement costs by approximately 72.2% compared to the conventional coal-based system, primarily due to higher per-ton market prices. This cost differential, however, can be mitigated and potentially offset through strategic policy interventions. The implementation of carbon pricing mechanisms, green financing incentives, and the monetization of emission reductions (e.g., through carbon credit generation) are pivotal in

Table 10. Energy usage scenario for the production of 50 kg of orthodox black tea

Scenarios	Coal	Wood pellet	Firewood
	(in kg)		
All Fuel	60.29	8.99	134.41
100% Coal	179.91	0	0
100% Wood pellet	0	215.66	0
100% Firewood	0	0	215.66

Table 11. Global warming potential (GWP100) of orthodox tea production under baseline and mitigation scenarios

No.	Scenario description	Energy Mix Composition (Coal: Firewood: Wood Pellet)	Specific GWP (kg CO_2-eq/ kg tea)	Annual tea output (Mg)	Total GWP (kg CO_2-eq/year)	Notes
1	Baseline (Current System)	30% : 65% : 5%	8.2937	706.62	5,860,515.49	Based on Table 6 & 8; high use of firewood and coal dominates emissions.
2	Mitigation scenario 1 (Fuel shift)	20% : 40% : 40%	8.1479	706.62	5,757,440.83	Increased use of pellets reduces GHGs by ~1.76% compared to baseline.
3	Mitigation scenario 2 (Pellet-dominated)	5% : 20% : 75%	7.8982	706.62	5,581,040.22	Emissions reduced by ~4.77% compared to baseline; assumes local pellet supply.
4	Mitigation scenario 3 (Full Renewable - Firewood & Pellet)	0% : 20% : 80%	7.8080	706.62	5,517,267.76	Near elimination of coal results in very low climate impact; aligns with ISO 14067 low-carbon pathways.
5	Net carbon balance (Baseline)	—	—	—	-7,161,518.46	Subtracting baseline GWP from corrected sequestration (12.68 million kgCO_2-eq/year); tea system is net carbon sink.

bridging this economic gap. Ultimately, achieving a strategic equilibrium between financial outlays and environmental gains is imperative, transforming a perceived cost burden into a viable investment for sustainable agro-industrial operations aligned with climate-positive objectives. Clean energy use in the future will help to support commitments to sustainable practices. Clean energy reduces air pollution and has a positive impact on the health of neighboring communities, in addition to lowering GHG emissions (Li et al., 2020). Clean energy solutions such as solar, biomass, and geothermal energy in tea leaf processing can significantly reduce long-term operating costs while supporting Sustainable Development Goal (SDG) 7 on affordable and clean energy. Renewable energy is frequently more efficient and can reduce the reliance on expensive and finite energy sources.

The mechanism for generating carbon credits that can be traded on carbon exchanges involves a certification process by an accredited carbon certification body. It is important to note that for carbon trading, land management must meet certain internationally recognized standards, such as the Kyoto Protocol (Ruppel, 2022), the Paris Agreement (Cheung, 2023), or other globally recognized carbon market mechanisms. The mechanism for carbon accounting of areas is shown in Figure 5.

Net carbon benefits (NCB) is the next step in measuring the difference between the amount of carbon sequestered and stored by a forest area and the carbon emissions resulting from the activities or land use in that area. To calculate the NCB, some additional steps after the carbon footprint of the land management area are shown in Figure 6.

Calculating carbon and NCB for land management areas involves a variety of upstream (where carbon is stored) and downstream (where emissions or land use occurs) stakeholders. The involvement of upstream and downstream stakeholders is essential to ensure accurate data collection, appropriate carbon accounting, and effective implementation of NCB improvement strategies. Cooperation between these different stakeholders will help achieve the goal of protecting forests and reducing carbon emissions overall (Krisnawati et al., 2015). NCB parties are shown in Figure 7.

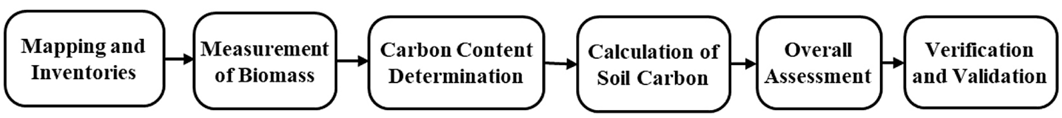

Figure 5. Mechanism for carbon accounting of areas

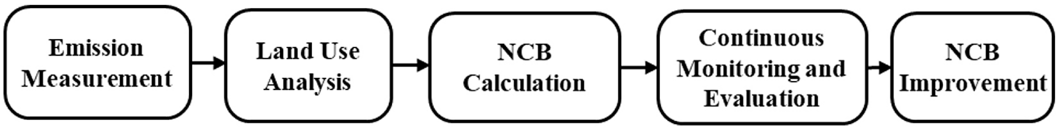

Figure 6. Net carbon benefit (NCB) mechanism

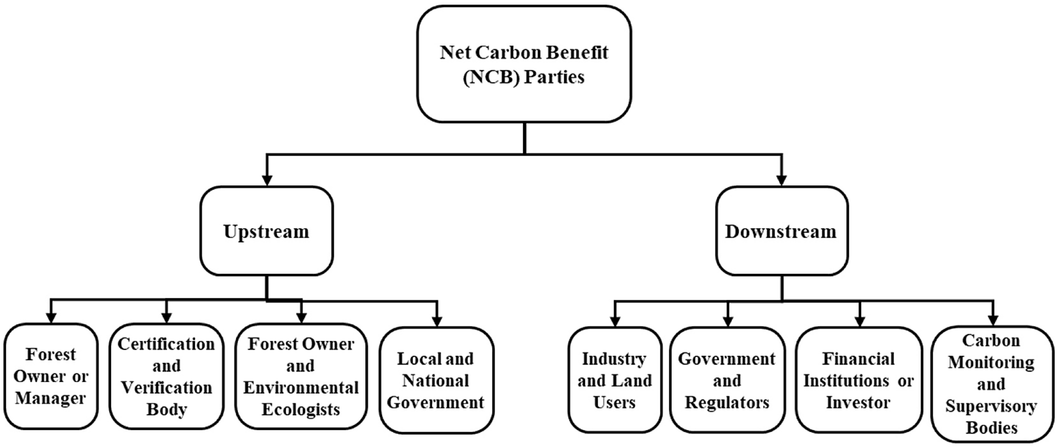

Figure 7. Net carbon benefit (NCB) parties

Various legal bases play an important role in monitoring carbon accounting and NCB activities in forests (and tea plantation areas) to comply with the applicable regulations. The legal bases used internationally include the Kyoto Protocol and the Paris Agreement. The implementation of this activity requires, among other sustainable performance guidance, Verified Carbon Standards (VCS), Climate, Community and Biodiversity (CCB) standards, and Forest Stewardship Council (FSC) guidelines. At the local level, environmental laws, government regulations on land management, and government policies on climate change require ensuring that the carbon accounting activities and forest (also tea plantation areas) protection or management projects comply with internationally and nationally established standards. This will also help ensure transparency, accountability, and compliance with applicable requirements in emissions trading and NCB-related environmental projects.

CONCLUSIONS

This study presented a comprehensive assessment of carbon storage potential and GHG emissions in orthodox black tea production at Pagilaran. By aligning methodological assumptions, defining system boundaries, and correcting prior inconsistencies—particularly the conversion between elemental carbon (C) and CO_2—the annual net carbon storage potential of the tea plantation system was estimated at 123.42 Mg CO_2-eq year^{-1}, equivalent to 25.71 kg CO_2-eq kg^{-1} of processed tea. In contrast, the annual GHG emissions from tea processing, including fossil fuel and biomass energy inputs, reached approximately 5.3 million kg CO_2-eq year^{-1}, yielding a net carbon sequestration of about 7.2 million kg CO_2-eq year^{-1}. Substituting coal with biomass pellets could lower on-site emissions by up to 5.68% (from 8.29 to 7.81 kg CO_2-eq kg^{-1} tea), though it may increase fuel costs by roughly 72.2%. However, this challenge can be addressed through the implementation of carbon pricing schemes, green financing instruments, and mechanisms for monetizing emission reductions—such as carbon credit generation—which collectively play a crucial role in narrowing this economic gap.

From a policy standpoint, these findings underscore the potential of integrating tea agroforestry systems into subnational and national Low Carbon Development Plans (LCDPs). This can be operationalized through participation in both voluntary and compliance-based carbon markets.

- Strategic interventions, such as the phasing out of fossil fuels, adoption of renewable biomass energy sources (e.g., wood pellets), and optimization of land productivity, offer viable pathways for decarbonizing tea agro-industries.

- Application of standardized carbon accounting protocols—particularly those aligned with ISO 14067, the IPCC AR6 2021 guidelines, and SNI 7724:2019—ensures scientific credibility and comparability of emissions data. This strengthens the eligibility of the tea sector for carbon credit certification under internationally recognized mechanisms.

Ultimately, tea-producing landscapes, such as Pagilaran can be positioned as model systems for climate-smart agriculture, with measurable mitigation outcomes. These results also provide an evidence-based foundation to support the issuance of nature-based carbon credits and to enhance the contribution of the tea sector to Indonesia's Nationally Determined Contribution (NDC) under the Paris Agreement.

Acknowledgements

We would like to express our gratitude to PT Pagilaran Tea Plantation and Factory-Batang for their assistance during black tea orthodox production. This research was funded by Universitas Gadjah Mada, Indonesia, through the Young Lecturer Research Grant Universitas Gadjah Mada Number 5985/UN1.P.II/DitLit/PT.01.03/2023.

REFERENCES

1. Anh, L. N. T., Ly, N. T. H., Nguyen, H., Phuong, N. T. (2025). Characterizing soil properties and carbon storage potential across diverse wetlands in the Vietnamese Mekong Delta. *Journal of Ecological Engineering*, *26*(4), 111–122. https://doi.org/10.12911/22998993/199817
2. Athira, G., Bahurudeen, A., Appari, S. (2019). Sustainable alternatives to carbon intensive paddy field burning in India: A framework for cleaner production in agriculture, energy, and construction industries. In *Journal of Cleaner Production 236*. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2019.07.073
3. Badan Standardisasi Nasional. (2019). *Pengukuran dan Penghitungan Cadangan Karbon - Pengukuran Lapangan untuk Penaksiran Cadangan Karbon Berbasis Lahan (Land-based Carbon Accounting) [SNI 7724:2019]*.
4. Castigioni, B. de A., Potenza, R., Jordão, M. (2021). *Balance of greenhouse gas (GHG) emissions from coffee production on daterra coffee farms index*.
5. Chen, F., Feng, P., Harrison, M. T., Wang, B., Liu, K., Zhang, C., Hu, K. (2023). Cropland carbon stocks driven by soil characteristics, rainfall and elevation. *Science of the Total Environment*, *862*. https://doi.org/10.1016/j.scitotenv.2022.160602
6. Chettri, V., Ghosh, C. (2024). Tea gardens, a potential carbon-sink for climate change mitigation. *Current Agriculture Research Journal*, *11*(3), 695–704. https://doi.org/10.12944/CARJ.11.3.01
7. Cheung, H. (2023). Non-monetary double-entry carbon accounting method for entities in emission trading systems. *Journal of Cleaner Production*, *422*. https://doi.org/10.1016/j.jclepro.2023.138475
8. Ding, F., Hu, Y., Liu, Y., Li, X., Mei, Y., Wu, Y., Xu, X., Qian, Y., Bai, S., Zhou, R., Jin, S. (2024). Greenhouse gas footprint and reduction potential in a typical Chinese tea-producing area. *Earth Critical Zone*, *1*(1), 100017. https://doi.org/10.1016/j.ecz.2024.100017
9. Directorate General of Electricity of the Ministry of Energy and Mineral Resources. (2018). *Pedoman Penghitungan dan Pelaporan Inventarisasi Gas Rumah Kaca*. Ministry of Energy and Mineral Resources. https://gatrik.esdm.go.id/assets/uploads/download_index/files/56959-buku-pedoman-igrk-pembangkit-2018.pdf
10. do Carmo, P. R. X., do Monte, J. V. L., Filho, A. T. de O., Freitas, E., Tigre, M. F. F. S. L., Sadok, D., Kelner, J. (2023). A data-driven model for the optimization of energy consumption of an industrial production boiler in a fiber plant. *Energy*, *284*. https://doi.org/10.1016/j.energy.2023.129239
11. Esquivel, J., Park, B. B., Casanoves, F., Delgado, D., Park, G. E., Finegan, B. (2020). Altitude and species identity drive leaf litter decomposition rates of ten species on a 2950 m altitudinal gradient in Neotropical rain forests. *Biotropica*, *52*(1), 11–21. https://doi.org/10.1111/btp.12730
12. FAO. (2023). *SEPAL-System for Earth Observation Data Access, Processing and Analysis for Land Monitoring*. Food and Agriculture Organization of the United Nations. https://www.fao.org/in-action/sepal/en
13. Guo, M., Song, W., Buhain, J. (2015). Bioenergy and biofuels: History, status, and perspective. In *Renewable and Sustainable Energy Reviews 42*, 712–725. Elsevier Ltd. https://doi.org/10.1016/j.rser.2014.10.013
14. Hughes, A. (2023). *Tea and Carbon Sequestration: Exploring the Sustainable Potential of Y – Noble & Sunday Tea Merchants*. Noble & Sunday Tea Merchants. https://www.nobleandsunday.co.nz/blogs/journal/tea-and-carbon-sequestration-exploring-the-sustainable-potential-of-your-daily-cuppa
15. International Panel for Climate Change. (2023). *IPCC AR4, AR5, and AR6 20-, 100-, and 500-year GWPs - Catalog*. U.S. Environmental Protection Agency. https://catalog.data.gov/dataset/

ipcc-ar4-ar5-and-ar6-20-100-and-500-year-gwps

16. KLHK. (2023, October 11). *Perdagangan Karbon untuk Pencapaian Target NDC, Kontribusi Indonesia bagi Agenda Perubahan Iklim Global*. Kementerian Lingkungan Hidup Dan Kehutanan Republik Indonesia. https://www.menlhk.go.id/news/perdagangan-karbon-untuk-pencapaian-target-ndc-kontribusi-indonesia-bagi-agenda-perubahan-iklim-global/
17. Krisnawati, H., Imanuddin, R., Adinugroho, W. C., Hutabarat, S. (2015). *Metode Standar untuk Pendugaan Emisi Gas Rumah Kaca dari Sektor Kehutanan di Indonesia, Versi 1*. Pusat Penelitian dan Pengembangan Konservasi dan Rehabilitasi, Badan Penelitian dan Pengembangan Kehutanan. http://puskonser.or.id
18. Kumar, K. R., Dashora, K., Krishnan, N., Sanyal, S., Chandra, H., Dharmaraja, S., Kumari, V. (2021). Feasibility assessment of renewable energy resources for tea plantation and industry in India - A review. In *Renewable and Sustainable Energy Reviews, 145*. Elsevier Ltd. https://doi.org/10.1016/j.rser.2021.111083
19. Kumar, K. R., Dashora, K., Kumar, S., Dharmaraja, S., Sanyal, S., Aditya, K., Kumar, R. (2023). A review of drying technology in tea sector of industrial, non-conventional and renewable energy based drying systems. In *Applied Thermal Engineering,* 224. Elsevier Ltd. https://doi.org/10.1016/j.applthermaleng.2023.120118
20. Lachman, J., Lisý, M., Baláš, M., Matúš, M., Lisá, H., Milčák, P. (2022). Spent coffee grounds and wood co-firing: Fuel preparation, properties, thermal decomposition, and emissions. *Renewable Energy*, *193*, 464–474. https://doi.org/10.1016/j.renene.2022.05.003
21. Li, L., Hong, X., Wang, J. (2020). Evaluating the impact of clean energy consumption and factor allocation on China's air pollution: A spatial econometric approach. *Energy*, *195*. https://doi.org/10.1016/j.energy.2019.116842
22. Liang, Z., Deng, H., Xie, H., Chen, B., Sun, M., Wang, Y. (2023). Rethinking the paper product carbon footprint accounting standard from a life-cycle perspective. *Journal of Cleaner Production*, *393*. https://doi.org/10.1016/j.jclepro.2023.136352
23. Liu, W. Y., Chiang, C. Y., Yap, J. L., Lin, C. C. (2024). Assessing the ecosystem service values of tea plantations using conventional and organic farming methods: Is organic farming always better? *Ecological Indicators*, *158*. https://doi.org/10.1016/j.ecolind.2023.111355
24. Mayasari, H., Wardhana, B. I., Tahir, I. (2023). Evaluation of landfill management at piyungan landfill Yogyakarta by using integrated risk based approach method. *Journal of Environmental Engineering and Landscape Management*, *31*(1), 23–33. https://doi.org/10.3846/jeelm.2023.18065
25. Mousavi, S. M., Dinan, N. M., Ansarifard, S., Borhani, F., Ezimand, K., Naghibi, A. (2023). Examining the role of the main terrestrial factors won the seasonal distribution of atmospheric carbon dioxide concentration over Iran. *Journal of the Indian Society of Remote Sensing*, *51*(4), 865–875. https://doi.org/10.1007/s12524-022-01650-4
26. Noviyanto, A., Jaya, G. I., Handru, A., Avianto, Y., Kautsar, V., Suryanti, S., Krisdiarto, A. W., Mawardi, R., Martini, T., Aziz, A. (2025). Enhancing rice productivity and mitigating greenhouse gas emissions through manure maturity and water management in paddy soils. *Journal of Ecological Engineering*, *26*(4), 313–322. https://doi.org/10.12911/22998993/200277
27. Open Foris. (2025). *Collect Earth Online — User guides and documentation*. Open Foris, Food and Agriculture Organization. https://collect-earth-online-doc.readthedocs.io/en/latest/
28. Palm Oil Agribusiness Strategic Policy Institute. (2024, October 3). *Carbon Sink In Oil Palm Plantations [Infographic 2024]*. Palm Oil Agribusiness Strategic Policy Institute. https://palmoilina.asia/berita-sawit/carbon-sink-in-oil-palm-plantations/
29. Pelvan, E., Özilgen, M. (2017). Assessment of energy and exergy efficiencies and renewability of black tea, instant tea and ice tea production and waste valorization processes. *Sustainable Production and Consumption*, *12*, 59–77. https://doi.org/10.1016/j.spc.2017.05.003
30. Priatmadi, B. J., Septiana, M., Mulyawan, R., Ifansyah, H., Haris, A., Hayati, A., Mahbub, M., Saidy, A. R. (2024). Reduction in carbon dioxide production of tropical peatlands under nitrogen fertilizer with coal fly ash application. *Journal of Ecological Engineering*, *25*(2), 341–350. https://doi.org/10.12911/22998993/177594
31. Rehman, A., Ma, H., Ahmad, M., Irfan, M., Traore, O., Chandio, A. A. (2021). Towards environmental Sustainability: Devolving the influence of carbon dioxide emission to population growth, climate change, Forestry, livestock and crops production in Pakistan. *Ecological Indicators*, *125*. https://doi.org/10.1016/j.ecolind.2021.107460
32. Ren, Z., Dong, Y., Lin, D., Zhang, L., Fan, Y., Xia, X. (2022). Managing energy-water-carbon-food nexus for cleaner agricultural greenhouse production: A control system approach. *Science of the Total Environment*, *848*. https://doi.org/10.1016/j.scitotenv.2022.157756
33. Rimantho, D., Hidayah, N. Y., Pratomo, V. A., Saputra, A., Akbar, I., Sundari, A. S. (2023). The strategy for developing wood pellets as sustainable renewable energy in Indonesia. *Heliyon*, *9*(3). https://doi.

org/10.1016/j.heliyon.2023.e14217

34. Rokhmah, D. N., Heryana, N. (2021). Estimated Stored Carbon Stock in Tea Plantation at Various Elevation. *Jurnal Tanah Dan Iklim*, *45*(2), 155. https://doi.org/10.21082/jti.v45n2.2021.155-162
35. Rolo, V., Olivier, P. I., Pfeifer, M., van Aarde, R. J. (2018). Functional diversity mediates contrasting direct and indirect effects of fragmentation on below- and above-ground carbon stocks of coastal dune forests. *Forest Ecology and Management*, *407*, 174–183. https://doi.org/10.1016/j.foreco.2017.10.059
36. Ruppel, O. C. (2022). Soil protection and legal aspects of international trade in agriculture in times of climate change: The WTO dimension. *Soil Security*, *6*. https://doi.org/10.1016/j.soisec.2022.100038
37. Shibabaw, T., Rappe George, M. O., Gärdenäs, A. I. (2023). The combined impacts of land use change and climate change on soil organic carbon stocks in the Ethiopian highlands. *Geoderma Regional*, *32*. https://doi.org/10.1016/j.geodrs.2023.e00613
38. State Electricity Company. (2022). *Sustainability Report Supplement | ESG Performance 2022* . https://web.pln.co.id/statics/uploads/2023/09/PLN-ESG-Performance-Report-2022-1.pdf
39. Szafranko, E. (2019). Selected problems of the environmental impact analysis of investment projects based on life cycle assessment procedure. *Journal of Ecological Engineering*, *20*(9), 87–94. https://doi.org/10.12911/22998993/112504
40. The Global Green Growth Institute Indonesia. (2021, October 7). *Indonesia's Updated NDC for a Climate Resilient Future — Global Green Growth Institute*. https://gggi.org/indonesias-updated-ndc-for-a-climate-resilient-future/
41. Tran, C., Duenas, L., Misra, S., Chaitanya, V. (2023). Specific energy consumption based comparison of distributed additive and conventional manufacturing: From cradle to gate partial life cycle analysis. *Journal of Cleaner Production*, *425*. https://doi.org/10.1016/j.jclepro.2023.138762
42. Triani, M., Dewi, K., Ediansjah, A. S. (2023). Prediction of carbon dioxide emission from electricity generation in Asian. *Indonesian Journal of Urban and Environmental Technology*, 20–35. https://doi.org/10.25105/urbanenvirotech.v6i1.14810
43. Umar, D. F., Rohayati, T. (2021). Study on chemical characteristics of coal and biomass blend and the tendency of its ash deposition. *Indonesian Mining Journal*, *24*(2), 113–126. https://doi.org/10.30556/imj.Vol24.No2.2021.1242
44. Vivaldo, G., Magnani, M., Baneschi, I., Boiani, M. V., Catania, M., Giamberini, M., Parisi, A., Raco, B., Provenzale, A. (2023). Carbon dioxide exchanges in an alpine tundra ecosystem (Gran Paradiso National Park, Italy): A comparison of results from different measurement and modelling approaches. *Atmospheric Environment*, *305*. https://doi.org/10.1016/j.atmosenv.2023.119758
45. Wibisono, M. G. (2016). *Perubahan Karakteristik Andisol Akibat Perubahan Penggunaan Lahan: Identifikasi dan Upaya Penanggulangan [Magister Thesis]*. IPB University.
46. Zhang, C., Ye, X., Zhang, H., Xie, J., Yang, X. (2023). Environmental footprint performance improvement of black tea using the life cycle assessment approach. *Journal of Cleaner Production*, *430*. https://doi.org/10.1016/j.jclepro.2023.139574
47. Zhou, H., Wei, Y., Wang, M., Xiao, L., Luo, Z. (2025). Enhancing whole-profile soil organic carbon predictions in croplands through a depth-resolved modelling approach. *Soil and Environmental Health*, *3*(3). https://doi.org/10.1016/j.seh.2025.100156