**Carbon Footprint of Tea: A Lifecycle Assessment from Cultivation to Consumption**

**ABSTRACT**

Tea is one of the most consumed beverages globally and plays a significant role in agriculture-driven economies like India. However, its production chain involves processes that emit considerable greenhouse gases (GHGs). This research analyses the carbon footprint of tea across its entire lifecycle from cultivation and processing to distribution and consumption. The study employs a descriptive and exploratory approach using secondary data sourced from peer-reviewed journals, government publications, and technical reports. Key findings highlight that plucking and transportation account for approximately 47% of field emissions, while drying in factories contributes the highest emissions in processing, estimated at 2762.28 kg CO₂ per 1000 kg of made tea. Despite tea bushes sequestering up to 5134.4 kg CO₂/ha/year, total emissions surpass this capacity, indicating a net carbon-positive balance. The research emphasizes the urgent need for mitigation strategies such as renewable energy use, improved agronomic practices, and carbon audits to enhance sustainability in tea production.

*Keywords​: Tea, Carbon dioxide, Carbon, Footprint, production, consumption*

**1. INTRODUCTION**

In recent years organizations worldwide have become increasingly concerned about carbon credits, focusing on carbon emissions, the amount of carbon emitted by organizations, and the climate resilience of various systems. While there is considerable discussion about carbon sequestration, the topic of carbon footprints, which has become crucial, is often overlooked. It is very important for tea sector also to maintain a balance sheet in tea factories to measure the amount of carbon emitted and sequestered. Additionally, no carbon audits have been conducted. Although literature on carbon sequestration is available, studies on carbon footprints are limited. Some research has been conducted in China and other regions, but there has been no research on carbon footprints in Assam's tea industry to date. The concentration of CO2 has increased significantly, rising from an annual average of 280 ppm in the late 1700s to 424 ppm in May 2023 (Aditya *et al.,* 2023). The agricultural sector contributes 15-20% of annual global greenhouse gas (GHG) emissions (FAOSTAT, 2018), with tea being an important agricultural product worldwide. The total planting area and yield of tea have been increasing in recent decades (Liang *et al.,* 2021). Tea production contributes to GHG emissions at various stages, from cultivation to consumption (Cichorowski *et al.,* 2015). The tea industry is considered to have high energy consumption due to its complex life cycle system (Zhang *et al.,* 2023). The production stage accounts for 57% of the environmental burden compared to other steps in the entire tea life cycle (Soheili-Fard *et al.,* 2018). In tea packaging, two-layer packaging is the most polluting scenario, while in terms of consumption, stoves are more environmentally friendly than electric kettles (Soheili-Fard *et al.,* 2018). Different farming management and processing techniques significantly impact the carbon footprint and primary energy demand of various tea products (Xu *et al.,* 2019). The carbon footprint of tea production and consumption is critical as it has substantial effects on the environment, economy, and society.

**2. OBJECTIVES**

1. To evaluate carbon emissions across the tea production lifecycle using secondary data
2. To identify emission hotspots and suggest mitigation strategies for sustainable tea production
3. To assess carbon balance by comparing emissions with sequestration in tea systems

**Lack of Methodology Section**:

**3. METHODOLOGY**

This article employs a descriptive and exploratory research approach, based entirely on secondary data. The information was gathered from a diverse range of credible sources, including peer-reviewed journal articles, technical bulletins, government databases such as FAOSTAT, and industry reports. The research specifically focuses on carbon emissions associated with black and green tea production, with particular emphasis on tea-growing regions in Northeast India. The scope of the research encompasses the entire lifecycle of tea cultivation, processing, packaging, distribution, and consumption. To ensure relevance and reliability, only sources published from 2005 onwards were included, provided they contained quantifiable data on energy use or greenhouse gas (GHG) emissions. Studies lacking detailed lifecycle stages or unrelated to tea production were excluded. Emissions data were categorized according to major lifecycle stages and standardized where possible using units such as kilograms of CO₂-equivalent per hectare or per 1000 kilograms of made tea. Furthermore, estimates of carbon sequestration by tea bushes and associated shade tree systems were reviewed and compared against total emission figures to assess the net carbon balance of tea production systems. This methodological framework enabled the identification of emission hotspots and opportunities for mitigation within the tea value chain.

**4. UNDERSTANDING THE CARBON FOOTPRINT**

A carbon footprint refers to the total amount of greenhouse gases (GHGs), primarily carbon dioxide, emitted directly or indirectly by an individual, product, company, or country, typically expressed in tonnes of CO₂-equivalents per year. It helps quantify the environmental impact of various activities and is essential for comparing emissions across sectors. A product’s carbon footprint includes emissions throughout its entire life cycle from raw material extraction and production to usage, transportation, and disposal (Wiedemann & Minx, 2008). There are three main types of carbon footprints: individual, product

and corporate. The individual carbon footprint encompasses emissions from personal activities such as transportation choices, household electricity use, food consumption habits, and recycling behaviours (Bai *et al.,* 2019). The product carbon footprint accounts for emissions during all stages of a product’s life, including material extraction, manufacturing, energy use, packaging, distribution, usage, and disposal (Pandey *et al.,* 2011). Lastly, the corporate carbon footprint measures the GHG emissions produced by a company’s operations, serving as a vital tool for assessing energy efficiency and identifying opportunities for emission reductions across industrial and organizational systems (Jeswani & Azapagic, 2016).

**5. SIGNIFICANCE OF ASSESSING TEA’S CARBON FOOTPRINT**

Tea is one of the most widely consumed beverages and is cultivated on more than 3,691.89 hectares of land worldwide. As demand for tea continues to rise, the production chain consumes significant amounts of energy and materials to achieve higher yields in both cultivation and processing. This increased consumption of resources leads to unfavourable impacts on greenhouse gas emissions and contributes to climate change. Therefore, it is essential to assess the tea production system to identify its carbon footprint throughout its entire life cycle, from cultivation and processing to waste disposal.

**Different stages of tea**

* Production
* Processing
* Consumption

**6. CARBON EMISSIONS ACROSS THE TEA VALUE CHAIN**

**6.1 Cultivation stage**

Tea cultivation involves several stages, each contributing to greenhouse gas (GHG) emissions in varying degrees.

* **Land Preparation:** During **land preparation**, especially in virgin areas, extensive clearing of trees and levelling is required, while uprooted areas undergo repeated ploughing using tractors. These operations consume large amounts of diesel, releasing significant quantities of CO₂ into the atmosphere (FAO, 2013).
* **Planting:** In **planting**, the manual digging of pits by laborers adds to indirect emissions, primarily through energy use in associated activities such as tool manufacturing and transportation (Pandey *et al.,* 2011).
* **Pruning: Pruning**, essential for developing a well-structured bush frame, involves repeated manual or mechanical cutting. While mechanized pruning can reduce labour, it increases fuel use, thereby contributing to higher emissions (Tao *et al.,* 2018).
* **Fertilizer & Pesticide use**: The **application of fertilizers**, particularly nitrogen-based synthetic types, is a major source of nitrous oxide (N₂O), a potent greenhouse gas, through processes like volatilization, leaching, and surface runoff (IPCC, 2006). In addition, **plant protection** practices that involve the use of synthetic pesticides also contribute to emissions, both through their chemical breakdown and the energy involved in their production and application (Roy *et al.,* 2014).
* **Plucking:** The **plucking** stage is highly labour-intensive, with frequent harvesting cycles requiring a large workforce. Although it involves limited mechanical input, the sheer scale of human involvement contributes to indirect emissions (Bai *et al.,* 2019).
* **Transportation**: Finally, **transportation**, which occurs in multiple stages from gardens to factories, then to warehouses, auction centres, and consumers relies heavily on fossil fuels. This stage is considered one of the most carbon-intensive due to the burning of diesel and petrol across long distances (Jeswani & Azapagic, 2016).

Overall, each activity in the tea value chain plays a role in contributing to the total carbon footprint, warranting sustainable intervention strategies.

**Table 1. Operation wise fuel consumption & CO2 produced in tea gardens** (Aditya *et al.,* 2023)

|  |  |  |
| --- | --- | --- |
| **Farming Operations** | **Fuel used (kg/ha)** | **kg CO2 eq/ha** |
| Land development and planting | 0.69 | 1.83 |
| Irrigation | 0.45 | 1.20 |
| Fertilizer and chemical application | 0.70 | 1.85 |
| Pruning | 0.89 | 2.35 |
| Plucking and transportation | 2.42 | 6.38 |

Table 1. provides a breakdown of the fuel usage and associated carbon dioxide emissions across various farming operations in tea cultivation. Land development and planting consume 0.69 kg/ha of fuel, leading to 1.83 kg CO₂ equivalent per hectare. Irrigation uses 0.45 kg/ha of fuel, resulting in 1.20 kg CO₂ equivalent per hectare. Fertilizer and chemical application utilize 0.70 kg/ha of fuel, contributing to 1.85 kg CO₂ equivalent per hectare. Pruning operations use 0.89 kg/ha of fuel, emitting 2.35 kg CO₂ equivalent per hectare. The most fuel-intensive activity is plucking and transportation, which uses 2.42 kg/ha of fuel, resulting in the highest emissions at 6.38 kg CO₂ equivalent per hectare. Overall, plucking and transportation contribute significantly more to carbon emissions compared to other operations.

**6.2 Processing stage**

Different operations in tea processing

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**Fig 1.Steps involved in production of various varieties of tea** (Aditya *et al.,* 2023)

Different operations in tea processing & their energy consumption

* **Withering**: The withering process, which involves temporarily storing harvested shoots to partially remove moisture, results in changes to the shoots' texture, making the leaves flaccid. This stage contributes to the tea's flavour, aroma, colour, and taste through chemical changes. Factories typically use equipment such as centrifugal fans, heaters, coal stoves, axial fans, and withering troughs. According to Dutta *et al.,* (2019), energy consumption for withering per 1,000 kg of made tea was estimated at 20.27 L of diesel, 43.93 kg of coal, and 87.17 kWh of electricity. For 100 kg of tea production, Sharma *et al.,* (2019) found that withering required 5.54 kWh of electricity and 179.11 MJ of thermal energy.
* **Rolling:** The rolling process shapes and sizes the withered tea leaves, making the product acceptable to consumers. There are two types of black tea produced based on the rolling method: Orthodox tea and CTC tea. Factories use rotor vanes for rolling CTC tea and table rollers for Orthodox tea. For every 1,000 kg of made tea, the estimated energy consumption is 190 kWh of electrical energy and 574.63 MJ of thermal energy (Aditya *et al.,* 2023). Additionally, tea-processing units often rely on diesel generators for electricity during power cuts.
* **Fermentation:** The fermentation process involves the oxidation of tea leaves, which determines the type of tea, such as green, white, oolong, or black, based on the level of oxidation. Factories use equipment like CFM machines, humidifiers, floor fermentation, fermenting troughs, electric fans, and blowers for this process. The energy consumption for fermenting 1,000 kg of tea is estimated at 0.79 litters of diesel and 89.65 kWh of electricity (Aditya *et al.,* 2023). For producing 100 kg of tea, the required electrical consumption for fermentation was 8.63 kWh (Sharma *et al.,* 2019).
* **Drying:** The drying process reduces the moisture content of tea leaves to 2.8%–3%, halting enzymatic reactions and creating a stable product. It is one of the most energy-intensive stages in tea production. For every 1,000 kg of tea, the estimated energy consumption is 16.08 litters of diesel, 630.22 kg of coal, and 103.41 kWh of electricity (Sharma *et al.,* 2019). The drying process requires 8.41 times more thermal energy compared to withering (Sharma *et al.,* 2019; Aditya *et al.,* 2023).
* **Sorting and Packaging:** After drying, tea leaves undergo sorting to remove fibres and stalky substances, followed by sieving and grading based on particle size. The final step in tea manufacturing is packaging, which is essential for protecting the tea from moisture and contaminants. These processes together require 61.72 kWh of electricity and 161.48 MJ of thermal energy per 1,000 kg of tea (Aditya *et al.,* 2023). Energy consumption in these stages is relatively lower compared to other stages of tea processing.

**Table 2. Thermal and electrical energy requirements per 1000 kilogram of made tea & corresponding CO2 emissions in tea factories at various stages of tea processing**

|  |  |  |  |
| --- | --- | --- | --- |
| **Operations** | **Thermal energy (MJ)** | **Electrical energy (kWh)** | **kg CO2 eq per 1,000 kg**  **of tea made** |
| Withering | 2837.16 | 87.17 | 475.39 |
| Rolling | 574.63 | 190.00 | 41.52 |
| Fermentation | 29.30 | 89.65 | 2.08 |
| Drying | 23868.68 | 103.41 | **2762.28** |
| Sorting | 134.00 | 53.15 | 9.52 |
| Packaging | 27.48 | 8.57 | 1.95 |

(Aditya *et al.,* 2023)

Table 2 shows the highest carbon footprint in drying process which is 2762.28 kg CO2 eq per 1,000 kg of tea made.

**6.3 Consumption stage**

Factors influencing carbon emission in tea consumption are

* **Brewing Method**

*1. Electric Kettle vs. Stovetop:* The energy source and efficiency of the appliance used to boil water can significantly impact the carbon footprint. Electric kettles are generally more efficient than stovetop kettles (Murray *et al.,* 2016).

*2. Quantity of Water:* Boiling more water than necessary increases the energy consumption and, consequently, the carbon footprint (Akash *et al.,* 2024).

* **Energy Sour**

Carbon intensity of the energy source used for boiling water (e.g., coal, natural gas, renewable energy) plays a significant role. Regions with cleaner energy grids will have a lower carbon footprint for the same activity (Gielen *et al.,* 2019).

* **Tea Type and Preparation**

Different types of tea (e.g., loose leaf, tea bags, instant tea) have different carbon footprints. Tea bags and instant tea often involve additional processing and packaging, which increase their overall carbon footprint (Sun *et al.,* 2024).

* **Packaging and Disposal**

The type of packaging (biodegradable vs. non-biodegradable) and the disposal method (recycling, composting, landfill) affect the carbon footprint. Packaging materials that are not biodegradable or recyclable contribute to higher emissions (Islam *et al.,* 2024).

* **Additives**

Adding milk, sugar, honey, or other ingredients increases the carbon footprint. For example, dairy milk has a higher carbon footprint compared to plant-based alternatives (Craig *et al.,* 2023)

* **Frequency of Consumption**

The frequency with which an individual consumes tea affects the cumulative carbon footprint.

Regular, heavy consumption will have a higher overall impact (He *et al.,* 2022).

* **Waste Management**

The disposal of used tea leaves, bags, and any associated waste contributes to the carbon footprint. Proper composting or recycling can mitigate some of these impacts (Morita *et al.,* 2024)

**6.4 GREEN TEA SPECIFIC LIFECYCLE OF CARBON FOOTPRINT**

A diagram of a cradle to grave

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**Fig 2. Release and utilization of carbon in green tea production**

**The specific considerations for each stage are as follows**: (He *et al.,* 2023)

**Cultivation**: Emissions from the upstream production of fertilizer and pesticide, as well as emissions from fertilizer application in the field and the use of agricultural machinery in the pruning and harvesting period  
**Processing**: Emissions from electricity, coal, and pellets consumed by mechanical equipment in the processing stage

**Packaging and transportation**: Emissions from the production of packaging materials and energy consumption during transportation  
**Consumption and disposal**: Emissions from boiling water and tea residue treatments

**7. RESULTS & DISCUSSION**

Plucking and transportation are the most significant sources of emissions during the cultivation stage, which is clearly indicates in Table 1, primarily due to frequent harvesting cycles and the extensive use of diesel-powered transport. Similarly, Table 2 identifies drying as the most emission-intensive stage in tea processing, accounting for over 80% of total factory related emissions. When comparing black and green tea systems, black tea generally exhibits a higher carbon footprint due to its energy demanding oxidation and prolonged drying processes. Although green tea requires energy for steaming, its overall processing time and post-harvest energy use are relatively lower. However, variations in cultivation practices such as fertilizer application rates and shade management may offset or exacerbate green tea’s environmental impact, depending on regional conditions. Supporting figures, including lifecycle stage diagrams and energy flow charts, visually emphasize the distribution of energy use across different stages, reinforcing that the greatest opportunities for carbon mitigation lie in post-harvest transportation and drying processes. These trends highlight the importance of targeted strategies, such as adopting biodiesel or electric vehicles for transport, implementing solar-powered drying systems, and improving field operations through optimized pruning and harvesting schedules. To effectively reduce the carbon footprint of tea production, policy interventions and factory-level carbon audits should concentrate on these high-emission stages.

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| --- | --- |
| **A graph of blue rectangular bars with text  Description automatically generated with medium confidence**  (i) | **A graph of different colored lines  Description automatically generated with medium confidence**  (ii) |
| **A graph of different colored bars  Description automatically generated with medium confidence**  (iii) | **A graph of a graph showing the number of carbon dioxide  Description automatically generated with medium confidence**  (iv) |

(He *et al.,* 2023)

**8. CARBON SEQUESTRATION POTENTIAL OF TEA SYSTEMS**

Tea bushes exhibit significant CO2 absorption potential, ranging from 1,243.8 to 2,526.7 kg CO2 per hectare annually (Phukan et al., 2018). Higher-yielding cultivars are more efficient at assimilating CO2 compared to quality-focused varieties. Approximately 50% of the absorbed atmospheric CO2 is sequestered in their biomass (Pramanik & Phukan, 2020), while organic carbon is released through roots, equivalent to 5.9%–8.6% of the CO2 they assimilate. Mature tea bushes (25–30 years old) can sequester about 5,134.4 ± 831.6 kg CO2/ha annually (Phukan et al., 2018). The tea-albizzia plantation system shows significant carbon offset potential, at 61.2 kg per plant (Alom et al., 2021). Organic tea cultivation leads to 43% higher above-ground biomass production (194.4 t/ha) compared to conventional methods (136 t/ha), with below-ground carbon accumulation at 135 t/ha in organic versus 125 t/ha in conventional systems (Subramanian *et al.,* 2013). For every ton of tea produced, factories emit approximately 3,292 ± 493.91 kg of CO2, while tea gardens contribute about 13.61 kg CO2 per hectare (Kalita *et al.*, 2018). In July 2021, North-Eastern tea production reached 157.23 million kgs, resulting in total CO2 emissions of 514,032.38 tonnes from cultivation and production, while the atmospheric CO2 sequestration was approximately 410,491.3 tonnes, leading to a discrepancy of 103,541.1 tonnes between emissions and sequestration (Aditya *et al.,* 2023).

**9. CONCLUSION**

This research article highlights that major carbon emissions in tea production originate from transportation, fuel-intensive field operations, and factory-level drying processes. While tea plantations demonstrate a substantial capacity for carbon sequestration, the current emission levels often exceed the amount sequestered, leading to a net positive carbon balance and contributing to climate change. Addressing this imbalance is essential for achieving environmental sustainability in the tea sector. Future research should focus on the adoption of low-carbon technologies in processing, the development of region-specific carbon auditing frameworks, and the implementation of policy incentives to support sustainable cultivation practices. Mitigation strategies such as deploying solar-powered drying systems, switching to biodiesel or electric transport options, and promoting organic farming can significantly reduce the industry’s carbon footprint. These approaches, combined with strategic planning and regulatory support, are vital for transitioning the tea industry toward a more climate-resilient and ecologically responsible future.

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