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

**ABSTRACT**

Tea is one of the most widely consumed beverages in the world and plays a vital role in agricultural economies like India. However, its production process contributes significantly to greenhouse gas (GHG) emissions. This study aims to assess the carbon footprint of tea throughout its entire lifecycle from cultivation and processing to distribution and consumption using a descriptive and exploratory research approach. Secondary data were obtained from peer-reviewed journals, government publications and industry reports. The methodology includes categorizing emissions by lifecycle stages and estimating emissions in CO₂-equivalent units. Key findings reveal that plucking and transportation contribute approximately 47% of cultivation emissions, while factory drying is the most emission-intensive processing stage, generating around 2762.28 kg CO₂ per 1000 kg of made tea. Although tea plantations sequester carbon up to 5134.4 kg CO₂/ha/year the net balance remains carbon-positive due to high processing and transport emissions. The study highlights the need for mitigation strategies such as adoption of renewable energy, improved agronomic practices, and implementation of carbon auditing 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

**3. METHODOLOGY**

This study adopts a descriptive and exploratory research design grounded entirely in secondary data. Data were systematically collected from peer-reviewed scientific articles, technical reports, FAOSTAT, Tea Board of India publications, and governmental bulletins. The scope encompasses both black and green tea systems, with a particular focus on Northeast India, especially Assam. Emission sources were categorized across all major lifecycle stages: cultivation (land preparation, fertilizer application, pest control, pruning, plucking), processing (withering, rolling, fermentation, drying, sorting, packaging), transportation, and consumption. Standardized metrics such as kg CO₂-equivalent per hectare or per 1000 kg of made tea were used for uniformity and comparison. Methodological emphasis was placed on estimating emissions based on energy inputs (fuel, electricity, coal) and calculating sequestration from tea bushes and associated shade tree systems. Furthermore, emission factors and thermal/electrical energy consumption values were derived from credible regional and national data. Comparative analysis was conducted with other studies on emissions from agricultural systems to contextualize findings and identify high-emission hotspots along the tea value chain. This framework allowed a comprehensive carbon accounting to be developed and supports recommendations for emission mitigation strategies.

**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**

The findings indicate that plucking and transportation are the most significant contributors to emissions during the cultivation stage, accounting for 47% of total field-level emissions. These are primarily driven by labor-intensive operations and extensive use of diesel-powered vehicles. In the processing stage, drying alone emits approximately 2762.28 kg CO₂-equivalent per 1000 kg of made tea, constituting over 80% of total factory-related emissions. This aligns with studies by Sharma et al. (2019) and Aditya et al. (2023), which emphasize the energy-intensity of the drying phase in tea processing. When comparing black and green tea systems, black tea has a notably higher carbon footprint due to additional oxidation steps and longer drying durations. However, green tea, though less energy-intensive in processing, may still carry environmental burdens depending on fertilizer application and shade tree management. Recent research from other agricultural sectors, such as rice and oilseed production (Pathak & Wassmann, 2007; Ozbek et al., 2021), underscores the impact of mechanized field operations and nitrogenous fertilizers on GHG emissions. When juxtaposed with such crops, tea plantations demonstrate both emission challenges and sequestration advantages. For instance, organic tea cultivation practices were shown to improve above- and below-ground biomass carbon accumulation (Subramanian et al., 2013), highlighting their potential role in emission mitigation strategies.   
Moreover, lifecycle comparison suggests the most viable intervention points include transitioning to biodiesel or electric vehicles for inter-factory transport, solar-assisted drying, and reconfiguration of pruning/plucking cycles for reduced fuel use. These practices are consistent with mitigation strategies applied in other sectors and should be supported through policy frameworks and carbon auditing tools. Collaborative industry efforts and data-driven interventions are essential for aligning tea production with sustainability targets.

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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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