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RESEARCH ARTICLE

Insights of carbon footprint of tea through life cycle approach

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Abstract

Stabilizing GHG emissions in the agri-food sector is crucial for climate change mitigation. Tea is one of the most consumed drinks worldwide and such high levels of consumption necessitate for the carbon footprint (CF) assessment of its entire life cycle encompassing all six stages such as cultivation, processing, packaging, transportation, consumption and disposal to understand the environmental impact of tea industry at large. In this context, this study is a maiden attempt to quantify and compare CF for the entire life cycle of all three types of tea such as black, green and white tea in a single research paper by employing the life cycle assessment (LCA) method in significant tea growing areas of Tamil Nadu, India. The findings revealed that the consumption stage contributed the highest CO_2 emissions, accounting for 45%-56% to overall CF. Black tea consumption contributed 45% (5.8 kg CO_2-eq/kg of made tea) of the total CF, while green tea and white tea had higher CF (8.3 kg CO_2-eq/kg of made tea), contributing 56% to the total CF. The processing stage was the second largest source, contributing 12-19% to overall CF, followed by packaging (15-17%) and cultivation (10-11%) stages. Overall, the total CF (cradle to grave) for black tea and white tea had a similar value of 12.9 kg CO_2-eq/kg of made tea, whereas green tea registered a higher value of 14.79 kg CO_2-eq/kg of made tea. Furthermore, this assessment identified hotspots of GHG emissions. It enabled the recommendation of CF reduction measures to promote carbon neutrality in tea sector while being a part of global climate change mitigation efforts.

Keywords

carbon footprint; greenhouse gas; life cycle assessment; tea

Introduction

Tea (*Camellia sinensis*), the most popular non-alcoholic beverage globally, plays a crucial role in India's cultural and economic landscape. India is a leading tea producer, contributing 20-25% of the worlds' total tea production and a significant consumer, with domestic consumption reaching approximately 1.1 billion kilograms annually (1). The tea industry is vital to the livelihoods of millions of smallholder farmers and the inter-generational pride of big growers. Despite its economic importance, the environmental sustainability of tea industry, particularly the carbon footprint (CF) needs to be assessed in the backdrop of growing concerns due to excessive production of GHG and its associated climate change impacts. According to ISO 14067, the CF determines GHG emissions produced during each stage of a product's life cycle. As global awareness of climate change intensifies, the agricultural sector, including the tea industry, is increasingly scrutinized for contributing to GHG emissions (2,3). The production processes, from cultivation to processing, followed by packaging, transportation and consumption, significantly contribute to GHG emissions. Literature review suggests that GHG emissions from the tea industry are majorly due to the extensive use of synthetic fertilizers in tea cultivation, energy-intensive processing methods and transportation (4,5). Despite the availability of such a dataset, the novelty of this study lies in its comprehensive evaluation of the CF across all stages of tea from the cultivation stage to the disposal stage, specifically comparing different tea types (black tea, green tea and white tea). Thus, this study is a maiden attempt to quantify the CF of tea production in Tamil Nadu, India, for all three tea types in a single research work by employing Life Cycle Assessment (LCA) method. Furthermore, this analysis also documented the differences in CF between big and small tea growers, thus incorporating region-specific data. Overall, this investigation led to identifying hotspots of GHG emissions throughout the entire life of the tea industry and eventually recommended emission reduction strategies to lower the CF and promote the tea industry to adopt sustainable practices for marching towards carbon neutrality.

Materials and Methods

This study was undertaken in Tamil Nadu, India, with representation from significant tea-producing regions such as Region I (Ooty, Kothagiri, Coonoor in Nilgiris district) and Region II (Valparai in Coimbatore district) (Fig.1). Extensive survey was conducted to collect primary data from a diverse group of respondents, including small tea growers (<25 acres), big tea growers (>25 acres), tea processing industries (including CTC [Crush, Tear and Curl] and Orthodox methods for black tea besides green tea and white tea factories) and tea shops by adopting convenience random sampling method (6). Information for other stages and relevant emission data were obtained by reviewing existing literature and thematic studies. Globally, two methods, Life Cycle Assessment (LCA) and Input-Output, are employed for undertaking CF. The literature review suggests that LCA is the most suitable and appropriate method for CF assessment of the tea life cycle (4, 5).

Life cycle assessment

Life Cycle Assessment (LCA) is a "bottom-up" process of analysis that considers the whole process from raw material extraction, production and processing, storage and transportation, use and waste disposal. In this research paper, the International Organization for Standardization (ISO) established standardized procedures (ISO series 14040, 42, 44, 64, 67) was followed for conducting Life Cycle Assessment (LCA) and CF (7). The LCA methodology consists of four primary phases: a) goal and scope definition, b) life cycle inventory (LCI), c) life cycle impact assessment (LCIA) and d) interpretation and the key details are furnished below.

System boundary

This study established the system boundaries and functional units in accordance with ISO 14067:2018 and PAS 2050:2011 guidelines outlined by the British Standards Institution (BSI) (8). Accordingly, the system boundary for this investigation included all six stages: cultivation, processing, packaging and transport, consumption and disposal (described as "cradle to grave") (Fig. 2).

Functional unit

The functional unit used to quantify farm CF was kilograms of CO_2-equivalent emissions per hectare (kg CO_2-eq/ha) and the unit used to measure product CF was kilograms of CO_2-equivalent (kg CO_2-eq) emissions per functional unit of the product (E.g. kg CO_2-eq/kg of made tea).

Inventory analysis

***Tea cultivation stage*:** This study accounted for GHGs associated with fertilizer production and the aftermath of its application in the field. Since pesticide use does not directly produce emissions, we calculated the emissions generated by the production of pesticides. Tea picking is performed in 15-30 day intervals (based on the weather conditions), with half of the farmers using machines for the picking process. Heavy pruning

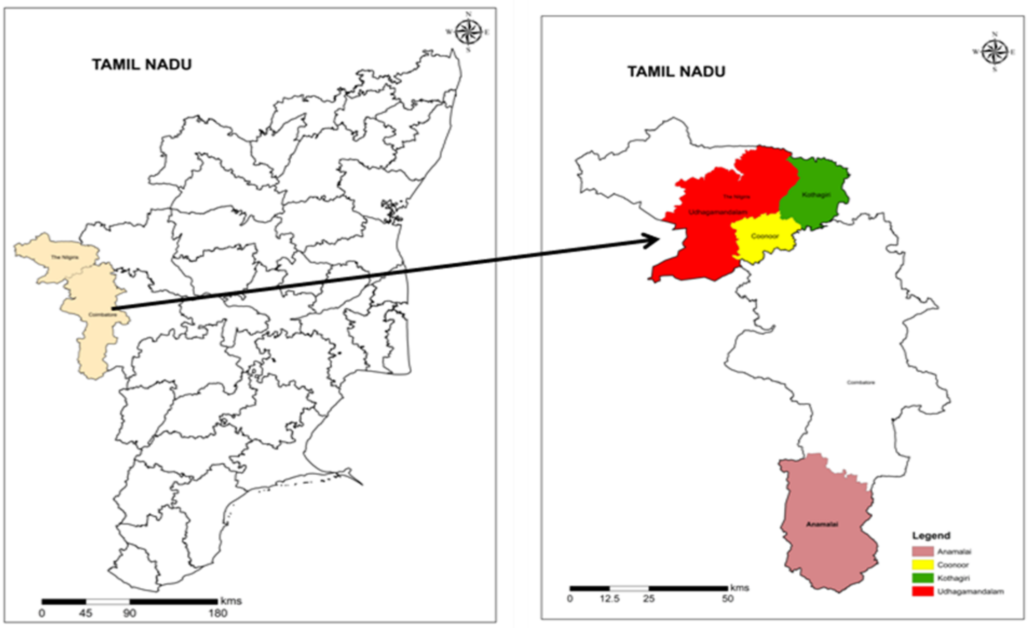

Fig. 1. Study area.

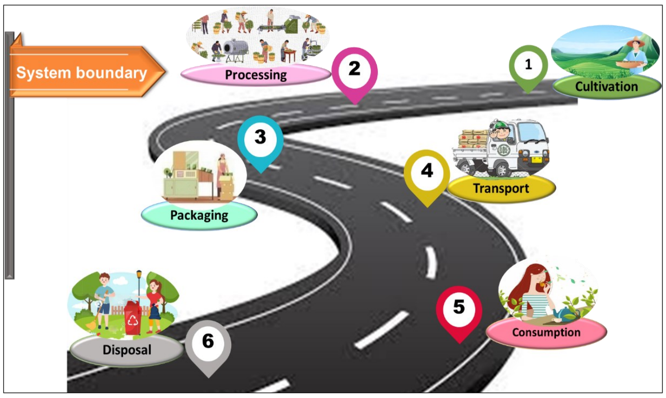

Fig. 2. System boundary of the study.

is conducted every four years following the harvest using trimmers. The carbon emissions from tea cultivation were quantified as kg CO_2-eq /kg of made tea, standardized using yield data for different tea types. The average yield was 8000 kg/ha for black tea, 6000 kg/ha for green tea and 60 kg/ha for white tea. Consequently, we considered mechanical equipment a source of carbon emissions during pruning and harvesting. Data on emission factors at the cultivation stage are presented in Table 1.

***Tea processing stage*:** The survey was conducted in four different types of tea processing: CTC, Orthodox, Green tea and white tea.

i. ***CTC Tea (Crush, Tear, Curl)*:** The CTC processing technique is a highly mechanized approach for generating black tea that uses a CTC cutter to transform tea into tiny granules. This process yields vigorous and brisk tea, a product designed for quick infusion and suitable for blending. It involves the following methods: withering, rotorvane, CTC, fermentation, drying, grading and conveyor.

ii. ***Orthodox Tea*:** This process relies on a machine-formed rolled tea bag method to preserve the whole leaf structure. It yields a flavour profile that is more subtle and complex than CTC. The steps involved in this process are withering, rolling, rotorvane, fermentation, drying and grading.

iii. ***Green Tea*:** Green tea does not include an oxidation phase. In the processing of green tea, the green colour and fresh grass taste are meant to be preserved. After the harvest, the tea leaves are steamed, rolled and pan-fired to stop oxidation. Green teas are thin delicate and contain many antioxidant properties that black teas do not have. It involves steaming, rolling and drying.

iv. ***White Tea*:** White tea undergoes the least processing among all tea types, with young buds and leaves withered and dried, often in sunlight. This minimal handling preserves its light, subtle flavour, pale infusion and delicate aroma with the lowest oxidation level.

Processing steps for each of these methods are shown in Fig. 3. On average, 4 kg of fresh leaves produce 1 kg of tea. During the survey, the energy consumption and the amount of fresh leaf processed for each equipment were collected from the respective factories. Information on the energy input of each procedure and emission factors of different energies are also presented in Table 1.

***Tea packaging and transportation stage*:** The packaging stage is divided into primary, transportation and product packaging. Primary packaging refers to the plastic mesh bags used in tea plantations to process industries. Secondary packaging includes the paper-plastic bags used to transport tea to sales locations. Product packaging pertains to the final packaging for tea sales, such as boxes, bags and cans. This study considered the average emission factors of each type of product packaging (Table 1).

The distance of transport primarily influences CO_2 emissions during the entire transportation stage. The transport distance is divided into three parts: from the tea plant to the factory, from the factory to the sale location and from the sale location to the consumer. We calculated both the emissions and the data acquired based on the survey. With 1 litre of diesel fuel, the transport vehicle can travel up to 7 km in hilly areas. The details are provided in Table 1.

***Tea consumption and disposal stage*:** This study accounted for specific energy consumption patterns in tea preparation. Based on the survey, 2.5 g of tea leaves were boiled with 100 ml of water for black tea, whereas for green and white tea, 1.75 g of tea leaves were used with the same water quantity. Notably, the combustion of LPG, primarily composed of propane and butane, results in CO_2 emissions. Emission factors obtained from the US EPA were employed to quantify the carbon footprint, explicitly considering the energy required for water heating. In the final stage, tea waste disposed of, particularly in landfill was accounted. Tea residue is anaerobically decomposed in a landfill, producing CH_4, a very potent greenhouse gas. Emissions were quantified by adopting relevant emission factors from existing studies and databases (Table 1).

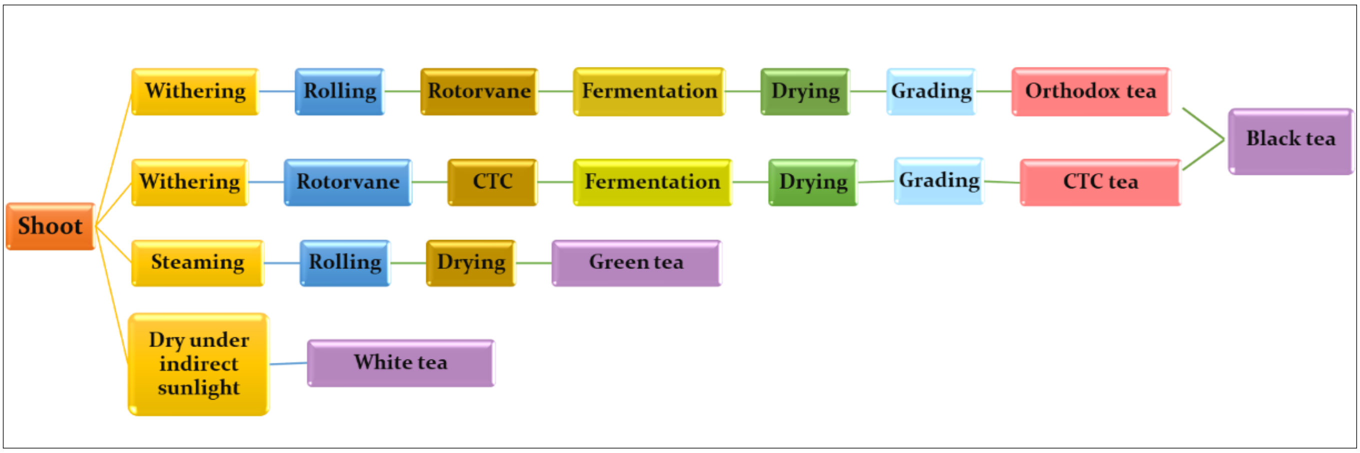

Fig. 3. Processing steps for different kinds of tea.

Carbon footprint calculation method

CO_2 and N_2O are significant GHGs emitted in tea production, and standard protocols were adopted for CF calculation.

CO_2 emissions: The emissions resulting from the use of materials and their production during the cultivation, processing, packaging, transportation and consumption of tea, along with CO_2 emissions from the combustion of electricity or fossil fuels, were calculated using the following formula (Eqn. 1):

$$CF_A = \sum (A_i * EF_i) \qquad \text{Eqn. 1}$$

Where CF_A represents the total GHG emissions attributable to the i^{th} activity/input, expressed kg CO_2-eq, A_i denotes the activity data or the quantity of the i^{th} agricultural input (kg/ha for fertilizers and pesticides, L/ha for diesel fuel and kwh/hr for electricity) and EF_i is the emission factor associated with the i^{th} process (kg CO_2-eq)

Electricity consumption for tea processing was calculated using the following equations (Eqn. 2 & Eqn. 3.)

$$\text{Electricity consumption (kWh/kg)} = \frac{E_c\text{(kWh)}}{\text{Total amount of leaves processed (kg)}} \qquad \text{Eqn. 2}$$

Where *Ec* is the electricity consumption of an industry

$$Ec \text{ (in kWh)} = Hp * n * d * Fc \qquad \text{Eqn. 3}$$

Where *Hp* = energy rating of the machinery (in horsepower), *n* is the no. of units per machine, *d* is the approximate duration of machine operation for processing one kg of leaves and *Fc* is the conversion factor (0.746) of horsepower into kilowatt-hour (kWh). Hp, n, d data was based on a survey.

N_2O emissions: Field N_2O emissions were computed using the 2006 IPCC Guidelines for National Greenhouse Gas Inventories as a guide, while energy use emissions were calculated using the Central Electrical Authority of India (CEA) Guidelines (12, 13).

Nitrogen fertilizer application during the cultivation stage generates N_2O emissions, categorized into direct and indirect pathways. Direct emissions result from directly adding or removing nitrogen in the soil. Indirect emissions occur through two primary pathways: (i) volatilization and atmospheric deposition of ammonia (NH_3) and nitrogen oxides (NO_x) and (ii) leaching and runoff of nitrogen, primarily as nitrate (NO_3) (10). GHG emissions from both direct and indirect N_2O emissions were calculated using the Tier 2 methodology, employing the following equations (Eqn. 4 -8).

$$N_2O_{total} = N_2O_{direct} + N_2O_{indirect} \qquad \text{Eqn. 4}$$

$$N_2O_{direct} = (F_{SN} + F_{ON} + F_{CR}) * EF_1 * \gamma_{N2O} \qquad \text{Eqn. 5}$$

$$N_2O_{indirect} = N_2O_{(ATD)} + N_2O_{(L)} \qquad \text{Eqn. 6}$$

$$N_2O_{(ATD)} = (F_{SN} * EF_4 * Frac_{GASF} + F_{ON} * EF_4 * Frac_{GASM}) * \gamma_{N2O} \qquad \text{Eqn. 7}$$

$$N_2O_{(L)} = (F_{SN} + F_{ON} + F_{CR}) * EF_5 * Frac_{LEACHING} * \gamma_{N2O} \qquad \text{Eqn. 8}$$

In this methodology, F_{SN}, F_{ON} and F_{CR} represent the amounts of nitrogen (N) from synthetic fertilizers, animal manure and crop residues (both above-ground and below-ground) added to soils, measured in kilograms per crop season. $N_2O_{(ATD)}$ and $N_2O_{(L)}$ indicate N_2O emissions resulting from atmospheric deposition and leaching and nitrogen additions' runoff in managed soils, respectively. EF_1 is the emission factor for N_2O emissions from nitrogen inputs (expressed in kg N/ input). EF_4 and EF_5 are the emission factors for N_2O emissions

Table 1. Emissions factors (EF) for assessing CF of tea

Inputs	EF	Calculation of CF (EF x Quantity)	References
		Fertilizer production	
Urea	7.41	kg CO_2-eq/kg N	(9)
Ammonium sulphate	5.2	kg CO_2-eq/kg N	
MOP	1.91	kg CO_2-eq/kg K_2O	
		Fertilizer application	
Urea	0.2	kg CO_2-eq/kg	(10)
Dolomite	0.13	kg CO_2-eq/kg	
		Pesticide	
Fungicide	10.2	kg CO_2-eq/kg of ai	(11)
Insecticide	15.2	kg CO_2-eq/kg of ai	
Herbicide	9.95	kg CO_2-eq/kg of ai	
		Factors for N_2O emission	
EF_1	0.01	kg N_2O-eq/kg N	(10)
EF_4	0.01		
EF_5	0.0075		
$Frac_{GASF}$	0.1		
$Frac_{GASM}$	0.20		
$Frac_{LEACH-(H)}$	0.30		
Firewood	1.0	kg CO-$_2$-eq/kg	(12)
Electricity	0.82	kg CO_2-eq/kWh	(13)
Diesel	2.68	kg CO_2-eq/l	(14)
LPG	3.0	kg CO_2-eq/kg	
Inputs		**CF**	**References**
Primary packaging		0.637kg CO_2-eq/bag	(15)
Secondary packaging		0.536kg CO_2-eq/bag	
Product packaging		2.30 kg CO-$_2$-eq/ bag	(4)
Landfill		0.674kg CO_2eq/kg	(5)

$Frac_{GASF}$- fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x (kg of N applied)$^{-1}$, $Frac_{GASM}$-= fraction of applied organic N fertilizer materials and of urine and dung N deposited by grazing animals that volatilizes as NH_3 and NO_x (kg of N applied or deposited)$^{-1}$, $Frac_{LEACH-(H)}$- fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff (kg of N additions)$^{-1}$

due to the volatilization and leaching of nitrogen from fertilizers and manure.

$Frac_{GASF}$, $Fracs_{GASM}$ and $Frac_{LEACHING}$ refer to the fraction factors for atmospheric deposition of volatilized N from mineral fertilizers, organic materials and leaching from managed soils. The factor ɣN_2O (44/28) is the mass conversion factor for converting nitrogen (N_2) to nitrous oxide (N_2O) (10).

Results

Carbon footprint of tea cultivation stage

The total carbon emissions for tea plantations of big growers in region I were 3077.56 kg CO_2-eq/ha, while tea plantations of small growers emitted 2981.56 kg CO_2-eq/ha. In Region II, tea plantations of big growers recorded the highest emissions of 3157.25 kg CO_2-eq/ha and tea plantations of small growers emitted 2920.16 kg CO_2-eq/ha.

The average CF across both regions was calculated (Table 2), with region I recording 3029.56 kg CO_2-eq/ha and Region II slightly higher at 3038.70 kg CO_2-eq/ha. Finally, the average total CF value across all growers in both regions was 3034.13 kg CO_2-eq/ha, reflecting the combined impact of various cultivation practices. Overall, the carbon footprint for the tea cultivation stage is quantified as 1.5 kg CO_2-eq/kg of made tea. In this analysis, CF of the cultivation stage for black tea (3 leaves & 1 bud) shared 100% of total CF, green tea (2 leaves & 1 bud) shared 75% and white tea (bud only) shared 1%. Carbon emissions emitted during fertilizer production contributed the highest share of CF across all categories of tea cultivation stages. Secondly, our observations indicated that applying fertilizers to tea plantations was the second largest contributor of CF in the cultivation stage.

Carbon footprint of tea processing stage

The CF of tea processing stage varied significantly across different types. Black tea derived from the Orthodox method (2.637 kg CO_2-eq /kg) had the highest emissions, followed by the CTC method (2.375 kg CO_2-eq /kg), whereas green tea accounted for 1.867 kg CO_2-eq /kg and white tea recorded negligible emissions. In CTC and Orthodox methods, the drying process is the most carbon-intensive step, contributing approximately 50% and 64% of total emissions, respectively. Fig 4A-4D shows that the drying stage of Orthodox and CTC tea processing recorded the highest CF of 1.395 kg CO_2-eq/kg of made tea and 1.512 kg CO_2-eq/kg of made tea, respectively, in the region I. However, region II reflected slightly lower CF at the stage of drying with 1.323 kg CO_2-eq/kg of made tea for Orthodox and 1.535 kg CO_2-eq/kg of made tea for the CTC processing method. Followed by the second highest CF in the CTC method was registered in the CTC stage, whereas in the Orthodox method, rolling and rotorvane steps had the second highest CF. Green tea's lower emissions (1.88 kg CO_2-eq/kg of made tea) resulted from its more straightforward processing as the fermentation stage is skipped (Table 3). Being minimally processed using only indirect sunlight, white tea registered the least CF.

Carbon footprint from packaging and transportation

In the packaging stage, the tertiary packaging that used laminated plastic bags, contributed the highest carbon emissions at 2.3 kg CO_2-eq/kg, accounting the significant share of CF. In contrast, the packaging of primary (plastic mesh bags) and secondary (paper plastic bags) contributed only 0.02 kg CO_2-eq/kg each. Transportation contributed 0.096 kg CO_2-eq/kg and the emission level depends on transport distances, fuel type and the efficiency of the vehicles used to transport goods.

Carbon footprint of consumption and disposal

The comparison of the CF values for the consumption of black, green and white tea is based on the amount of tea used per 100 ml of water. 2.5 g was used for black tea, resulting in a CF of 5.8 kg CO_2-eq/kg of made tea. In contrast, green and white tea required a smaller quantity of 1.75 g per 100 ml of water; accordingly, their CF was higher (8.3 kg CO_2-eq/kg of made tea). This difference is due to the smaller quantity of tea products used for green and white tea in each serving, thus contributing to higher CF compared to black tea when calculated for one kg of made tea. However, consumer preference, which altered the quantity of tea and water for preparation, significantly affected carbon emissions. The GHG emissions associated with the disposal of tea residue after consumption were substantial, contributing 8.03 kg CO_2-eq/kg and 0.674 kg CO_2-eq/kg, respectively.

Carbon footprint of tea for entire life cycle

The total CF of green tea from the cradle to the grave was quantified as 14.79 kg CO_2-eq/kg of made green tea, followed by black and white tea amounting to each with 12.9 kg CO_2-eq/kg of made tea. For green and white tea, the consumption stage accounted for the largest CF, generating 8.3 kg CO_2-eq/kg of made tea, while black tea consumption contributed slightly less CF (5.8 kg CO_2-eq/kg of made tea). The processing stage

Table 2. Carbon Footprint of tea cultivation (kg CO_2-eq/ha)

Farm practices	Region I (Nilgiris)		Region II (Valparai)	
	Big Growers	Small Growers	Big Growers	Small Growers
Fertilizer application	1171.39	973.46	1241.84	954.82
Associated fertilizer production	1880.9	1977.54	1886.45	1943.46
Pesticide	20.69	25.2	22.8	19.2
Machinery	4.8	5.36	6.16	2.68
Total	**3077.78**	**2981.56**	**3157.25**	**2920.16**

Table 3. Carbon Footprint of green tea for the processing stage

Processing steps	HP of the equipment	Kwh (HP*0.746)	Capacity of the machine (kg)	Duration of operation (hr)	CF (kg CO_2-eq/kg of made tea)
Steaming	32	23.87	400	0.03	0.010
Hand Rolling	-	-	-	-	-
Drying*	15	11.19	200	1	1.867
Total					**1.877**

*For every 1 kg of made tea, 1.25 kg of firewood is used in the drying process

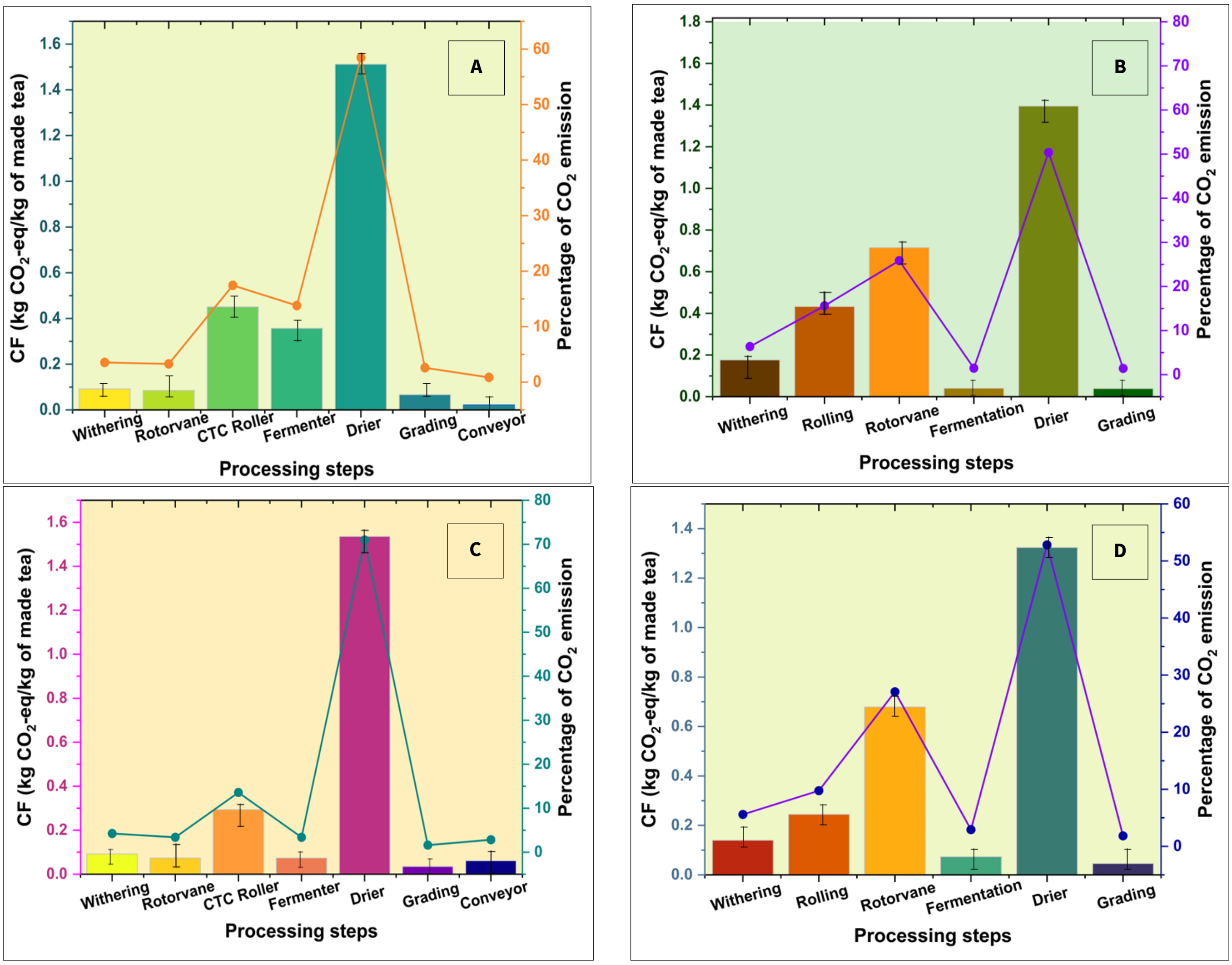

Fig. 4. Carbon Footprint of A: CTC method of black tea processing in Region I, B: Orthodox method of black tea processing in Region I, C: CTC method of black tea processing in Region II, D: Orthodox method of black tea processing in Region II.

ranked second in carbon emissions (2.51 kg CO_2-eq/kg of made tea) for black tea, while the packaging stage was the second highest contributor for green and white tea. However, packaging emissions contribute equally across tea types (black, green and white tea) at 2.34 kg CO_2-eq/kg of made tea, marking it as a significant source in the tea life cycle. Transportation, with a much lower CF, produced 0.096 kg CO_2-eq/kg of made tea for all tea types, while disposal contributed similarly low emissions at 0.674 kg CO_2-eq/kg of made tea. Cultivation emissions, identical for all tea types, stand at 1.5 kg CO_2-eq/kg of made tea. Overall, the LCA indicated that CF is highest for green tea to the tune of 14.79 kg CO_2-eq/kg of made tea, followed by black and white tea, each with a total of 12.9 kg CO_2-eq/kg of made tea (Table 4).

Discussion

The tea industry has been identified as a considerable source of GHG emissions (16,17). Estimating GHG emissions from tea production vary significantly, reflecting regional differences in production practices and efficiencies and the diverse modelling approaches employed (18-22). Hence, it was necessitated to undertake this comprehensive study to quantify CF in the entire life cycle of different tea types to identify hotspots of GHG emissions in the current scenario and find the solutions to reduce the CF. There are six stages in the life cycle of tea and each stages' contribution in the CF is presented in Fig. 2.

Among the six stages, the highest contribution of CF was the tea consumption stage, followed by the processing stage. Our assessment found that the consumption stage contributed the highest carbon footprint (CF) share in the tea life cycle. Black tea consumption accounted for 45% (5.8 kg CO_2 -eq/kg of tea) of the total CF, a contrast to the researcher, who

Table 4. Total Carbon Footprint of tea for the entire life cycle

Life cycle stages	Black tea (kg CO_2-eq/kg of made tea)	Green tea (kg CO_2-eq/kg of made tea)	White tea (kg CO_2-eq/kg of made tea)
Cultivation	1.5	1.5	1.5
Processing	2.506	1.88	-
Packaging	2.34	2.34	2.34
Transportation	0.096	0.096	0.096
Consumption	5.8	8.3	8.3
Disposal	0.674	0.674	0.674
Total	12.9	14.79	12.9

reported 84% CF for tea consumption in Kenya, driven by emissions from the electricity needed to boil water in a kettle (9.2 kg CO_2-eq/kg dry tea) (23). Similarly, a 60% CF for tea consumption in China, is based on 2 g of dry tea and 250 ml of boiling water per cup (6). In India, 51% of total CF to consumption is influenced by boiling 1 litre of water in a kettle, with higher emissions in scenarios using excess bottled water with an electric stove (17). A 75% CF contribution from boiling water at home with 48 g of tea per cup (16). In our study, the CF of the consumption stage for green tea accounted for 8.3 kg CO_2-eq/kg of tea, or 56.1% of the total CF. Such quantification varies from region to region due to differences in tea preferences, leaf quantities and boiling water volumes. For instance, 45.3% of Chinas' CF for green tea cited significant water requirements (200 litres for 1 kg of green tea brewed with 800 ml of hot water per 4 g) (5). The 45.5% CF in Taiwan is mainly due to electricity used in an electric kettle (0.06 kWh) (25). These reports demonstrated that consumption consistently contributes the highest CF in tea life cycles, with water usage and energy sources significantly impacting emissions, underscoring the need for optimized brewing methods to lower CF.

Secondly, the processing stage is another primary emission source during tea production. This stage involves significant machinery and equipment input, reflecting a high level of mechanization and energy consumption. The CF of tea showed that during the processing stage, the values were in the range of 6.3-9.7 kg CO_2-eq/kg, respectively, which were higher when compared to the CF values (2.506 kg CO_2-eq/kg) recorded in this study (4, 5, 26). Other studies in India documented that the tea processing stage contributed 12% to 15% to the total carbon emissions (16,17). In other tea-producing countries, the processing stage for black tea was also reported as the second highest contributor of carbon emissions in the tea life cycle, with 7% in Kenya and 13.1%-16.13% in China (4,23). For green tea, our study identified processing as the third largest contributor to emissions, following the packaging stage. This aligns with findings where the processing stage contributed 18.7% in Taiwanese Dongshan tea and 12.76% in Iranian tea, respectively (21, 25). The difference in CF depends on electricity -driven energy structure, which significantly lower emissions than coal-based processes. Energy consumption during processing activities such as drying and withering substantially contributes to the overall CF (5, 19). When compared to our CF values observed for processing stages, several data on CF of tea processing stages had higher values. This is mainly due to an inadequate energy structure, with a continued reliance on firewood closely tied to processing equipment. Among the various stages in tea processing stages, the drying stage recorded the highest carbon emissions and most factories use firewood to generate heat for this purpose.

In the current analysis, the packaging stage emerged as the third largest contributor to the carbon footprint (CF) in the black tea life cycle and the second largest for green tea. Tertiary packaging was the primary contributor within this stage, accounting for 98.29% of emissions. The lower CF (10%) for packaging in China is likely due to different materials or practices, whereas a higher CF (39.44%) in China, driven by aluminium foil (84.14%) and cardboard (15.74%) emissions (19, 24). It was found that packaging contributes about 7.2% (2.30 kg CO_2-eq/kg) to the life cycle CF of green tea, mainly when non -recyclable materials are used. The significant emissions from high-impact materials like tin and plastic in vacuum-sealed packaging for Taiwanese Oolong tea (27). This comparison underscores the impact of material choices like aluminium on packaging emissions, highlighting the potential for alternative materials to reduce CF.

Our study showed that the CF for the tea cultivation stage is 10-11% of the total CF, while a 14.9% CF for this stage is in China and 8% is in Sri Lanka (23, 24). In India, case studies on Darjeeling tea recorded that CF of cultivation contributed 7% and 31%, with variations mainly due to differing fertilizer usage across regions (16,17). Globally, tea plantations emit N_2O at an average of 17.1 kg N/ha/yr, equivalent to 8008 kg CO_2-eq ha^{-1}, significantly higher than emissions in cereal croplands (662-3757 kg CO_2-eq/ha) (28). Although tea plantations occupy just 0.3% of global cropland, the higher nitrous oxide emissions emphasize this sectors' need for mitigation strategies. Nitrogen fertilizers, used extensively, are a primary driver, with application rates exceeding 800 kg N/ha/yr globally and reaching 2000 kg N/ha/yr in Japan (29, 30). In China, the average N input is 553 kg N/ha/yr (31, 32), while in Kenya, an N application rate of 200-800 kg N/ha/yr is standard, influenced by quality-linked compensation from tea companies (33, 34). By contrast, our survey in Tamil Nadu, India, found an average N application of 250 kg N/ha/yr.

Carbon Footprint reduction strategies in hotspot areas

To reduce carbon footprint across the tea production lifecycle, strategies are needed to address GHG emission reduction from fertilizer use, energy in processing, packaging, transportation and consumption. Replacing chemical fertilizers with organic alternatives besides utilizing nitrification inhibitors can lower GHG emissions significantly, as seen in reductions from 9.6 kg CO_2-eq ha^{-1} to 3.3 kg CO_2-eq ha^{-1} in Darjeeling tea cultivation and improve nitrogen utilization (17, 35). Transitioning to renewable energy sources and upgrading to energy-efficient equipment in processing, such as combined heat and power (CHP) systems and biomass energy, can lower emissions by up to 58% (2). Sustainable packaging materials, like bioplastics, can reduce environmental impacts while adopting biofuels and electric vehicles in transportation can reduce CO_2 emissions by up to 50% (36, 37). Finally, promoting efficient boiling methods, such as electric kettles and switching from LPG to electric heating can decrease emissions by 36% in tea preparation (38).

Future thrust

This study provided an in-depth analysis of the CF of tea in general and highlighted CF variations among three different tea types: black tea, green tea and white tea. Our dataset revealed that tea cultivation stage is one of the significant GHG hotspots. Hence, future research should focus on applying nitrogenous fertilizers in combination with nitrification inhibitors to generate a dataset to understand its potential to reduce N_2O emissions and lower CF. Secondly, the drying stage during tea processing contributed to the highest carbon emissions; therefore, energy-efficient measures need to be explored by utilizing renewable energies which has a great scope to reduce CF. More importantly, our data clearly showed that CF of packaging is almost close to entire processing stage which opens the scope to explore possibilities for developing advanced yet eco-friendly packaging technologies to reduce CF. Besides such scope for future research and development in the tea industry, there is also a need to generate datasets in diverse landscapes to fine-tune emission factors to quantify CF more realistically.

Conclusion

This comprehensive carbon footprint (CF) assessment across the tea life cycle identified the consumption stage as the highest emissions contributor, accounting for 45-51% of total CF. The processing stage, especially the drying process, ranked second, with the CTC method showing a lower CF than the Orthodox method. Green tea processing had lower CF than black tea, while white tea processing had negligible emissions. In the packaging stage, the tertiary level contributed the most CF. Finally, tea cultivation contributed 10-11% of total CF. These findings highlighted CF hotspots and suggested suitable recommendations for CF reduction through energy optimization, improved fertilizer efficiency, renewable energy adoption in processing and energy-efficient boiling during consumption to promote carbon neutrality in the tea industry.

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Authors' contributions

SKR conceptualized the research work, finalized the methodology, interpreted the results and edited the manuscript. RS supervised the research work, analyzed the data and co-ordinated the study. VP carried out the research work and drafted the manuscript, which included graphs and images. RM and DR designed the survey questionnaire. SPT and RR facilitated in the field survey for data collection and carried out the data analysis. PSM verified the data and supported in writing discussion section. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this work, the author(s) used ChatGPT to improve the language quality and communication clarity. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publications' content.

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