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the case study of Indian Robusta coffee

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Full Length Article

Carbon footprint of coffee production: the case study of Indian Robusta coffee

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ABSTRACT

Coffee processing encompasses the conversion of coffee cherries into marketable products, including the removal of outer layers to produce green coffee and, in extended chains, their roasting into roasted coffee, and grinding into ground coffee. Calculating the carbon footprint (CF) in coffee processing is crucial for identifying and mitigating key sources of greenhouse gas (GHG) emissions. Utilizing the Life Cycle Assessment (LCA) methodology, the current study quantifies the CF associated with Robusta dry coffee processing by collecting primary data through interviews with coffee producers and visits to coffee processing units, roasting, and grinding facilities in Wayanad, India. The study identifies GHG emission hotspots across two scenarios. Scenario A includes transportation of dried coffee beans from farm to coffee processing unit, green coffee production, packaging, roasting, and grinding at a local unit, while Scenario B covers local transportation of green coffee beans from India to The Netherlands, green coffee production, packaging, and its transportation from India to The Netherlands. Cultivation and harvesting of coffee cherries, consumer-level preparation and use, and disposal of coffee products are outside the scope of this study. The functional unit is defined as 1 kg of green coffee for both scenarios. Findings show that the CF equals 0.62 and 0.38 kg CO_{2eq} per kg of green coffee for scenarios A and B, respectively. Roasting (78 % of CF), and sea transportation (66 % of CF) emerged as the main hotspots of GHG emissions for scenario A, and scenario B, respectively.

1. Introduction

Approximately 54 Gt CO_{2eq} are released into the atmosphere annually on a global scale [1]. The food sector contributes around 25–33 % of global emissions [1], and the coffee supply chain contributes about 1 % of the global food system emissions [2]. Given that the coffee industry sustains over 25 million families across >80 countries [3], measuring greenhouse gas (GHG) emissions at coffee processing is crucial for its sustainability.

To effectively reduce emissions, it is essential to quantify their sources within the coffee supply chain. A systematic approach to assessing these emissions is the life cycle assessment (LCA), a standardized methodology (ISO 14,040:2006, 14,044:2006) for evaluating the environmental impacts of a product, or process or service across its entire life cycle [4,5]. The Carbon footprint (CF) measures the environmental impact of GHG emissions, expressed as CO_2 equivalents

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(CO_{2eq}), which are released directly or indirectly due to a particular activity [6]. The potential emission sources involve categorizing emissions based on the organization's control level. GHG emissions are generally divided into direct emissions, stemming from activities under the organization's control, and indirect emissions, which arise from the consumption of purchased electricity, heat, steam, cooling, and other related activities, such as downstream emissions from the use and disposal of products [7,8].

Previous studies have applied LCA to evaluate the carbon footprint of coffee along the supply chain, distinguishing between agricultural production and post-harvest processing, to identify environmental hotspots across diverse regions and coffee varieties. Researchers in Costa Rica assessed the CF of the entire coffee supply chain, including farming, milling, land and sea transportation, roasting, packaging, distribution, grinding, consumption, and disposal, finding a total CF of 4.82 kg CO_{2eq} per kg of green coffee [9]. They identified that processing in Costa Rica contributes 1.77 kg CO_{2e}q per kg of green coffee, while roasting within Europe contributed to 3.05 kg CO_{2eq} per kg. The study identified hot spots in fertilizer use, wastewater from coffee processing, and electricity consumption during coffee preparation. To mitigate these impacts, they proposed using anaerobic digesters to convert wastewater into biogas for fueling coffee dryers.

Similarly, researchers from Thailand calculated the CF of Robusta coffee through cultivation, transportation, processing using wet processing, roasting, and grinding [10]. They found that the coffee production impacts are 0.40 kg CO_{2eq} per kg of cherry coffee, 0.55 kg CO_{2eq} per kg of roasted coffee, and 0.56 kg CO_{2eq} per kg of ground coffee. Around 70 % of emissions were attributed to chemical fertilizer use, followed by LPG in roasting and electricity in grinding [11]. To reduce CF, they suggested optimizing fertilizer application, reducing chemical fertilizer use, and improving energy efficiency during roasting [11].

A comparative LCA of conventional and sustainable coffee production in Brazil and Vietnam, exported to the UK, revealed an average carbon footprint of 15.33 kg CO_{2eq} per kg of green coffee for conventional Arabica coffee and 3.51 kg CO_{2eq} per kg of green coffee for sustainable coffee production [12]. The study concluded that the 77 % reduction for sustainable coffee is attributed to lower agrochemical use and the preference for sea freight over air freight. The authors concluded that the CF of coffee transportation is significantly influenced by the geographic separation between production and consumption regions. Coffee is primarily consumed in non-producing regions, which accounted for approximately 116–123 million 60-kg bags annually from 2018 to 2023, more than twice the volume consumed in producing countries [13]. International transport is responsible for approximately 15 % of coffee's lifecycle GHG emissions [14,15]. While shipping remains the most efficient method for large-scale coffee exports, it relies on heavy fuel oil, which releases considerable emissions (6–11 % of total coffee's total GHG emissions) [12]. Air freight, though used less frequently, significantly increases the carbon footprint, contributing approximately 72–73 % of coffee's total emissions when employed [12].

In 2024, India's coffee market is projected to generate 0.5 billion USD in revenue, with a 9 % annual growth rate between 2024 and 2028 [16]. Robusta accounted for 70 % of the total production, with 250,000 tonnes in 2022 [17], and Wayanad alone contributing 60,000 tonnes annually, underscoring the significant economic role of coffee in the region. Moreover, Wayanad Robusta coffee gained international recognition at the World of Coffee 2024 in Copenhagen, highlighting its potential for global export [18], and quality of Robusta variety [19]. As the demand for coffee rises, it is critical to assess the processes that support this growing industry, particularly given the reliance on small farmers and producers. This situation presents significant challenges for the coffee industry due to its heavy dependence on agriculture and the livelihoods of small farmers reliant on coffee [20–22].

Chéron-Bessou et al. [23] conducted a systematic review of 34 coffee LCA studies analyzing 234 systems. The majority (76 %) focused on Arabica, while only 7 % studied Robusta, leaving it underrepresented and a gap. Central and South America dominated the studies, accounting for 72 %, with Colombia and Brazil alone contributing 18 % and 16 %, respectively. India, Ethiopia, and Uganda were not represented. The review also revealed that one-third of the studies relied on secondary data, increasing uncertainty due to discrepancies between theoretical models and real-world practices. The lower number of studies focusing on Robusta coffee is also verified by a literature search in Scopus [24], focusing on the carbon footprint using LCA of Arabica and Robusta coffee production from 2014 to 2024, showing a clear disparity 33 studies on Robusta compared to 64 on Arabica.

While extensive research exists on the carbon footprint of coffee, the focus has primarily been on the Arabica variety, reflecting its market dominance. Notably, no study has specifically evaluated the carbon footprint of Indian Robusta coffee. Due to the significant impact of data quality, regional conditions, and methodological assumptions, carbon footprint results are not transferable across different coffee varieties and processing systems. This study fills this knowledge gap by presenting the first region-specific LCA assessment of Wayanad Robusta coffee, employing primary data collection to enhance accuracy and providing representative GHG hotspot findings for India's coffee processing sector.

Therefore, there is a need for LCA studies focusing on Indian Robusta coffee processing. While existing studies have evaluated the carbon footprint of coffee, they primarily focus on Arabica, which limits their applicability to Robusta due to differences in processing methods, regional conditions, and data quality. This study employs LCA methodology and primary data gathered through interviews at coffee processing units in Wayanad to examine two scenarios: (A) green coffee production, transportation, packaging, and roasting and grinding at a Wayanad roasting facility to ground coffee production, and (B) green coffee production, packaging, local transportation to Cochin Port, and sea shipping to The Netherlands. The analysis identifies key carbon-intensive stages in both scenarios and establishes a systematic framework for carbon footprint assessments applicable to other regions. By integrating region-specific primary data, this study enhances the methodological rigor of coffee LCAs, providing actionable insights for targeted emission reduction strategies within India's coffee sector for future research.

2. Materials and methods

2.1. Site description

India's coffee production is primarily observed in the hilly tracts of South Indian states, with Karnataka contributing nearly 70 %, followed by Kerala at 28 % of the total national production [17]. The study was conducted in Wayanad, a district in the northeast of Kerala, South India. Wayanad features various significant plantation crops, but its primary cultivation is Robusta coffee. Wayanad accounts for 85 % of Kerala's total coffee production [17]. The main coffee regions, including Wayanad, are illustrated in Fig. 1.

In 2022–2023, coffee plantations in Wayanad employed an average of 31,556 individuals daily [25]. The Robusta variety, a cornerstone of regional production, is cultivated by over 60,000 farmers [25], predominantly on smallholdings. Of these, 59,821 coffee holdings are <10 hectares, while only 151 exceed this size [25]. Production is largely driven by small and marginal farmers [26] employing traditional or semi-mechanized practices [27]. These methods, while integral to sustaining livelihoods, contribute to elevated energy use and greenhouse gas emissions, intensifying climate change impacts and threatening the resilience of local agricultural systems [28].

2.2. Value chain description

The journey of a cup of coffee, from producer to consumer, includes cultivation, local transport, processing, packaging, export, roasting, grinding, distribution, consumption, and disposal of ground coffee. In

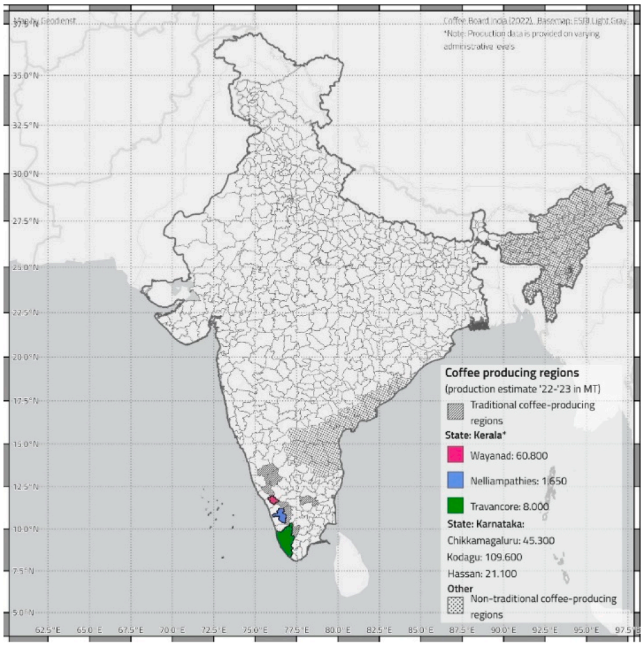

Fig. 1. Coffee-producing regions in India. Source: Geodienst, RUG, 2024.

Wayanad, farmers cultivate and harvest the coffee cherries and then send them for processing. During processing, coffee beans are processed through dry processing to produce green coffee. Traders export this green coffee to consumer countries, where roasters handle roasting, grinding, and packaging. This study examines the Wayanad coffee supply chain, focusing on processing, local transportation, packaging, roasting, and grinding stages at the local level, as well as the international exportation of green coffee, as shown in Fig. 2. Cultivation and harvesting of coffee cherries, consumer-level preparation and use, as well as end-of-life disposal of coffee products, are excluded from the system boundaries of this study.

The production of green coffee occurs at coffee processing units, facilities that use dried coffee to produce green coffee. In Wayanad, there are approximately 20 coffee processing units, with 10 classified as small-scale and the remainder as large-scale. Coffee producers in this region, classify small-scale units that produce <4 tonnes per hour, while those exceeding this threshold are classified as large-scale.

Then, these green coffees are processed at roasting factories to produce ground coffee, a value-added product with a higher market price in international markets. According to coffee producers in the region, approximately 80 % of the coffee produced in Wayanad is exported as green coffee, and the price of green coffee ranges from 4 to 6 USD per kg [29]. Value-added products such as roasted and ground coffee powder can yield better returns, with a minimum 40 % rate of return, with ground coffee sold in the market, especially in Europe, which ranges from 10 to 15 USD per kg [30].

Apart from the economic dimensions, which lie outside of the scope of the current study, and which are related to the production costs and the potential financial benefits on a local level, a holistic sustainability approach would also include raising the environmental responsibility in Wayanad. LCA could be an appropriate analytical tool to identify and quantify the stages in the coffee supply chain that contribute most significantly to environmental burdens. Through a comprehensive evaluation of resource inputs, emissions, and waste outputs, LCA enables the identification of critical areas for improvement, such as reducing energy consumption in processing and minimizing waste generation. Identifying and optimizing these main sources of carbon footprint emissions is crucial for improving processing and elevating the region's competitiveness. This approach seems to be important as many coffee consumers prefer to support companies that demonstrate a commitment to environmental sustainability, preceded by labels that highlight social issues [31,32].

2.2.1. Dry coffee processing description: green coffee production (phase 1)

In India, green coffee is produced through two main methods: wet and dry [33]. Generally, dry coffee processing is a method of processing coffee beans where the entire coffee cherry is dried in the sun before undergoing de-pulping, [34]. Approximately 80 % of Robusta is processed using the dry method [33]. The following description of dry coffee processing presents firsthand numerical data obtained through interviews and visits with coffee producers in Wayanad.

In the conventional dry method, coffee cherries are laid out on large concrete or brick patios, and exposed to sunlight for approximately four weeks, achieving a moisture reduction of 10–13 % [35]. After this drying phase, coffee farmers transport the dried beans to primary coffee processing units for the production of green coffee [36].

In Wayanad, dried coffee beans are typically transported from farms to coffee processing units using auto rickshaws that utilize diesel as fuel. This mode of transport is chosen primarily due to its cost-effectiveness and adaptability to the region's terrain. Auto rickshaws can navigate narrow and uneven rural roads more efficiently than larger vehicles, making them ideal for reaching remote coffee farms. Additionally, they are economically viable for small-scale farmers, who often operate on limited budgets [21].

The block flow diagram of conventional dry Robusta coffee processing in Wayanad is shown in Fig. 3. The processing begins with the pre-cleaning and cleaning section. Dried coffee beans are subjected to sorting and cleaning to segregate overripe beans and eliminate dirt, earth, branches, and leaves. This is typically achieved mechanically using the aspirator system for a vibro cleaner. Following this, the dried coffee beans are likely separated from stones, constituting a range from 0.4 to 0.6 wt. %.

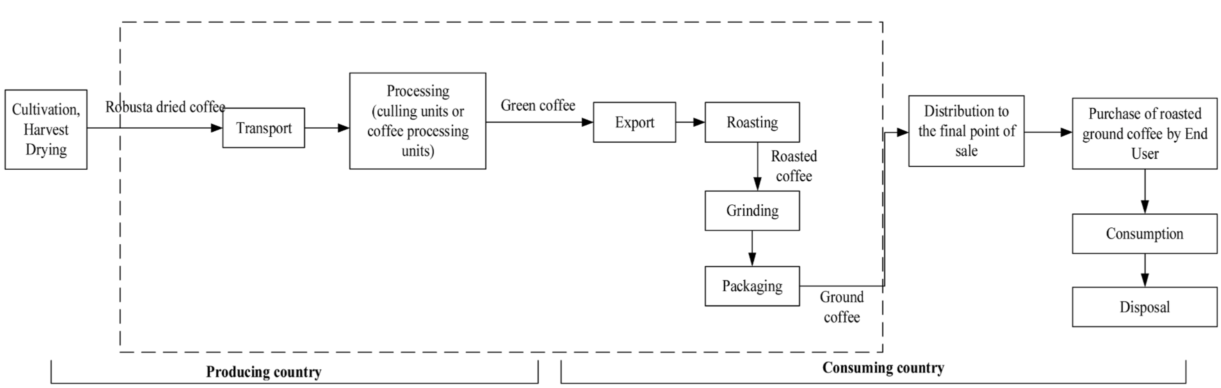

Fig. 2. Overview of the Wayanad coffee value chain stages assessed for their carbon footprint impact study.

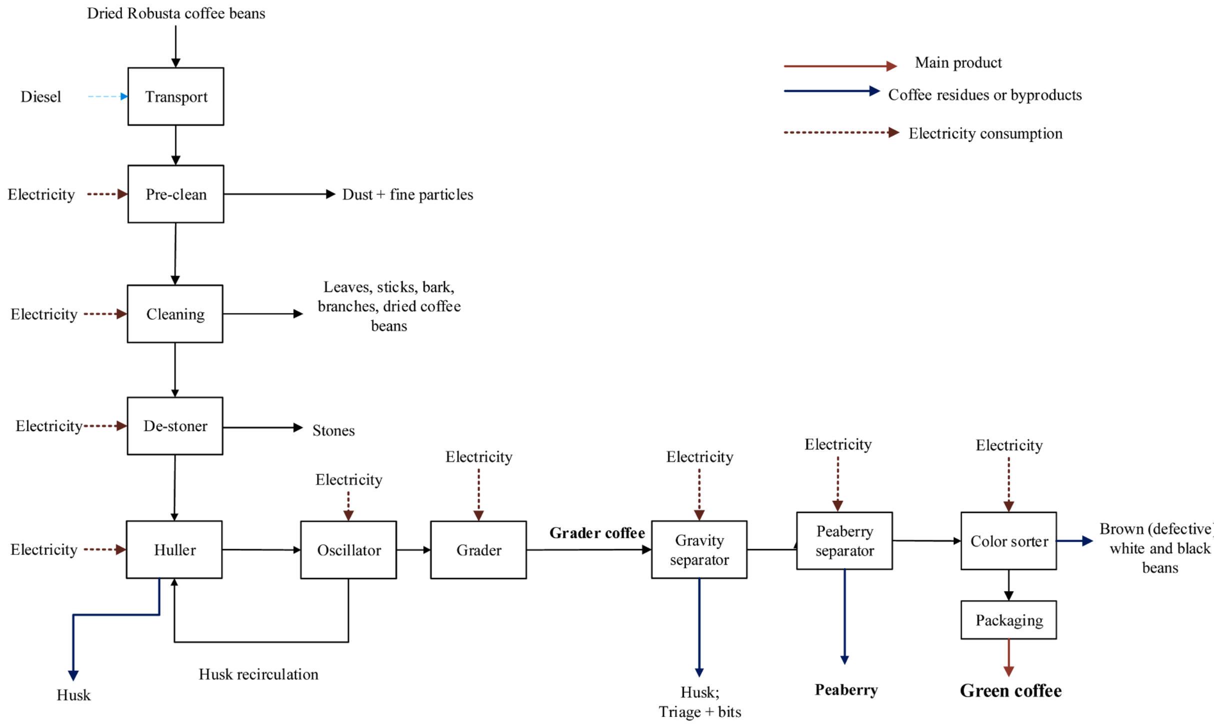

Fig. 3. A block flow diagram of conventional dry coffee processing to produce green coffee, case study: Wayanad.

The next step involves husk removal from the dried coffee beans using a huller machine. The huller removes approximately 40–45 % of the husk from the dried coffee beans [36]. Subsequently, unhulled coffee beans pass through an oscillator to recirculate unhulled coffee beans back into the huller (5–7 wt. %). The product obtained at this stage is termed green coffee.

After hulling, the green coffee is subjected to classification to assess its suitability for export or domestic consumption. The main aim of this process is to create consistent commercial batches that meet specific quality standards and a consistent outcome during the roasting process.

Subsequently, the remaining husk, bits, and triage are eliminated through a process involving a catador or gravity separator, accounting for approximately 1 % of the total output. Thereafter, black, white, and brown coffee beans are segregated (12–14 %) by color sorting. Finally, the cleaned and sorted green coffee are then measured and packed into jute bags which typically hold around 60 kg of green coffee [37].

2.2.2. Ground coffee production at the local roasting unit (scenario A)

Following the production of green coffee using the dry method (Section 2.2.1), the next step involves converting the green coffee into ground coffee through roasting and grinding processes. This scenario specifically investigates roasted and ground coffee production at a typical local roasting unit in Wayanad, using green coffee as the input, as shown in Fig. 4.

Using green coffee as described in the Section 2.2.1, the next step involves domestic commercialization, initiated by the transportation of green coffee from processing units to a roasting unit for ground coffee production, covering approximately 10 km. Autorickshaws, primarily fueled by diesel, serve as the main mode of transport for green coffee.

The study investigated the roasting process at two Wayanad roasting units, using data gathered on-site. A typical local roasting unit in Wayanad operates with a capacity to roast approximately 500 to 800 kg of green coffee per day. In the roasting phase, temperatures are progressively elevated within the range of approximately 180 to 200 °C. The overall duration of the roasting process spans between 10 and 20 min, contingent on the desired roast type. Both liquefied petroleum gas (LPG) and electricity power the process, with LPG heating the roasting machine for the first 10 min, consuming 18 kg of LPG per 200 kg of roasted coffee, and electricity completing the remainder of the roasting process until green coffee reach their desired color and development level, such as light, medium, or dark roast.

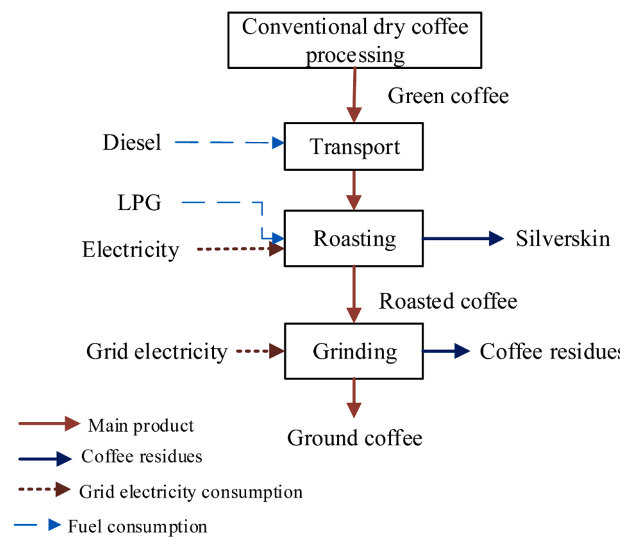

Fig. 4. Local roasting unit to ground coffee production.

Finally, an electric grinding machine transforms the roasted coffee into ground coffee, ensuring uniform particle size for optimal flavor extraction. After grinding, the coffee is immediately packaged in airtight containers to preserve freshness, aroma, and flavor. The packaged ground coffee is labeled and prepared for distribution to various markets, though this step is not included in this study.

2.2.3. Production and exportation of green coffee from India to The Netherlands (scenario B)

High-quality Wayanad Robusta green coffee reaches foreign markets, while lower grades cater to the local coffee sector. From 2016 to 2020, Indian Robusta exports to Europe declined by an average of −3.2 % [17], influenced by increased demand for specialty coffee [38], which refers to high-quality beverages made from the finest coffee beans, Arabica coffee is typically used for specialty coffee. Hence, this scenario examines the export of green coffee as a representative case from Wayanad to The Netherlands, focusing on GHG emissions in terms of CF. It includes the production and packaging of green coffee, road transport from Wayanad to Cochin Port (280 km), and maritime shipping over 12,000 km to Rotterdam, primarily using Heavy Fuel Oil (HFO) for the maritime segment.

2.3. Carbon footprint using life cycle assessment (LCA)

The method to assess CF is based on ISO standards for LCA 14,040:2006 [5], and ISO 14,044:2006 [4]. These standards establish four main steps to be followed: i) Definition of the goal and scope, ii) Life cycle inventory (LCI) analysis, iii) Life cycle impact assessment (LCIA), and iv) Life cycle interpretation.

2.3.1. Goal and scope definition

The goal of the present study is to evaluate the environmental impact, in terms of carbon footprint, of coffee production across two scenarios: scenario A, which includes transportation of dried coffee from the farm to the coffee processing unit, green coffee production, packaging, transportation, roasting and grinding at a local unit. Scenario B, transportation of dried coffee beans to the coffee processing unit, green coffee production, packaging, local transportation, and sea shipping for exportation of the green coffee from India to The Netherlands. The aim is to identify the primary carbon footprint hotspots and assess opportunities for future improvements within the Robusta coffee processing supply chain in Wayanad. Cultivation, harvesting, consumption, and disposal of ground coffee are excluded from this research study.

The analysis for both scenarios include green coffee production using the dry coffee processing, defined as phase 1, and is shown in Fig. 5.

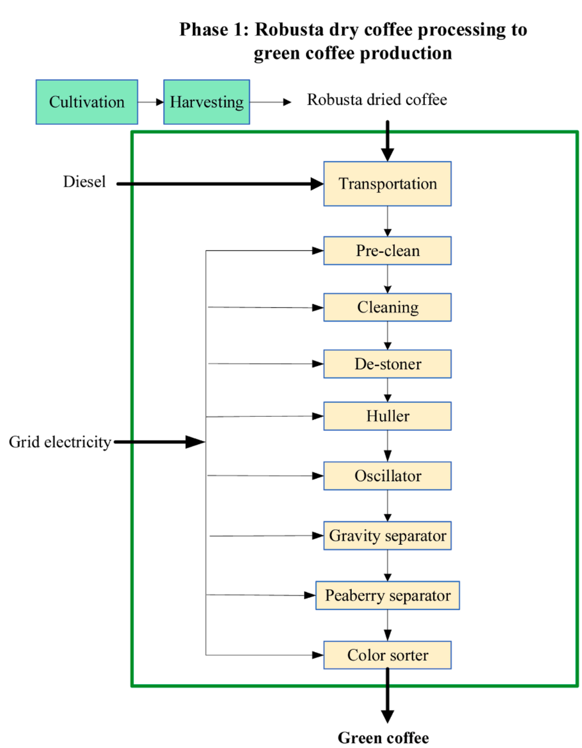

Fig. 5. Process block diagram and system boundaries considered in phase 1, Robusta dry coffee processing from dried coffee beans to green coffee production. Cultivation and harvesting are outside the system boundaries.

Green coffee production refers to the dry processing of coffee cherries to obtain green coffee. This term does not include agricultural practices. Phase 1 encompasses the transportation of dried coffee from the farm to the processing unit, and dry coffee processing to green coffee production.

Fig. 6 outlines the process block diagram and system boundaries of scenarios A, and B evaluated in this LCA study. The system boundaries for scenario A include the green coffee production, transportation of green coffee from the processing unit to the roasting facility via auto rickshaw, packaging of green coffee in jute bags and its subsequent conversion into ground coffee at a local roasting facility. Jute bags, known for their durability, are used to maintain appropriate moisture levels, thereby preventing mildew or mold that could impair the quality of green coffee. The processes of roasting and grinding are included, while the packaging of the ground coffee and consumption are excluded from the scope of this study.

Coffee roasting is an energy-intensive process due to the thermal transformation of organic material. During roasting, the decomposition of organic compounds results in the release of carbon dioxide, which constitutes approximately 87 % of the emitted gases [39]. These emissions, however, derive from biogenic carbon—carbon that was recently absorbed from the atmosphere by the coffee plant—thus forming part of the natural carbon cycle. Unlike fossil fuels, which introduce additional carbon into the system, biogenic emissions do not increase net atmospheric CO_2 levels. Forest fires, by contrast, involve both biogenic and non-biogenic emissions and lead to ecological degradation; however, they are unrelated to the controlled and contained process of coffee roasting. Therefore, such emissions fall outside the scope of this study. Instead, life cycle assessments of coffee roasting should focus on improving energy efficiency and optimizing fuel sources to reduce overall climate impact.

Conversely, in scenario B, LCA includes green coffee production, packaging in jute/PP bags, land transportation by truck to Cochin Port, and overseas transportation by cargo ship to Rotterdam Port.

The functional unit (FU) of 1 kg of green coffee is selected for both scenarios (A and B), to ensure consistency and comparability in the LCA. In scenario A, green coffee serves as the primary input for roasting and grinding, resulting in ground coffee for local consumption. Scenario B, in contrast, involves exporting of green coffee to the international market. This common FU facilitates a direct comparison between the two pathways despite their distinct processing and distribution stages. For example, in scenario A, carbon emissions are linked to the roasting, grinding, and local transportation of processed coffee. In contrast, scenario B is characterized by emissions related to the logistics of exporting unprocessed beans, including transport and storage. Using green coffee as the FU ensures both scenarios are benchmarked from the same production stage, enabling a comparison of their respective carbon footprints while accounting for variations in processing and transportation.

2.3.2. Life cycle inventory (LCI) analysis

LCI was conducted through a collection of firsthand data, identifying the main inputs in the two scenarios of the supply chain of Robusta coffee. The fieldwork was realized through visits to the coffee processing units in Wayanad, in the period from July to August 2023. Fig. 7 presents an overview of the coffee processing facilities visited for data collection for this study.

To gather comprehensive data across the coffee processing chain, we initially visited seven processing units and two roasting factories. For the LCI, we selected the unit providing the most detailed and complete data at all stages. The remaining units showed minimal variation in process methodology and data values. Thus, the most comprehensive unit served as the representative source. For roasting and grinding, where generalized data was available, average values were calculated across units to account for slight operational differences. Appendix C presents data on electricity consumption and mass and energy balances for dry coffee processing and roasting selected for this study.

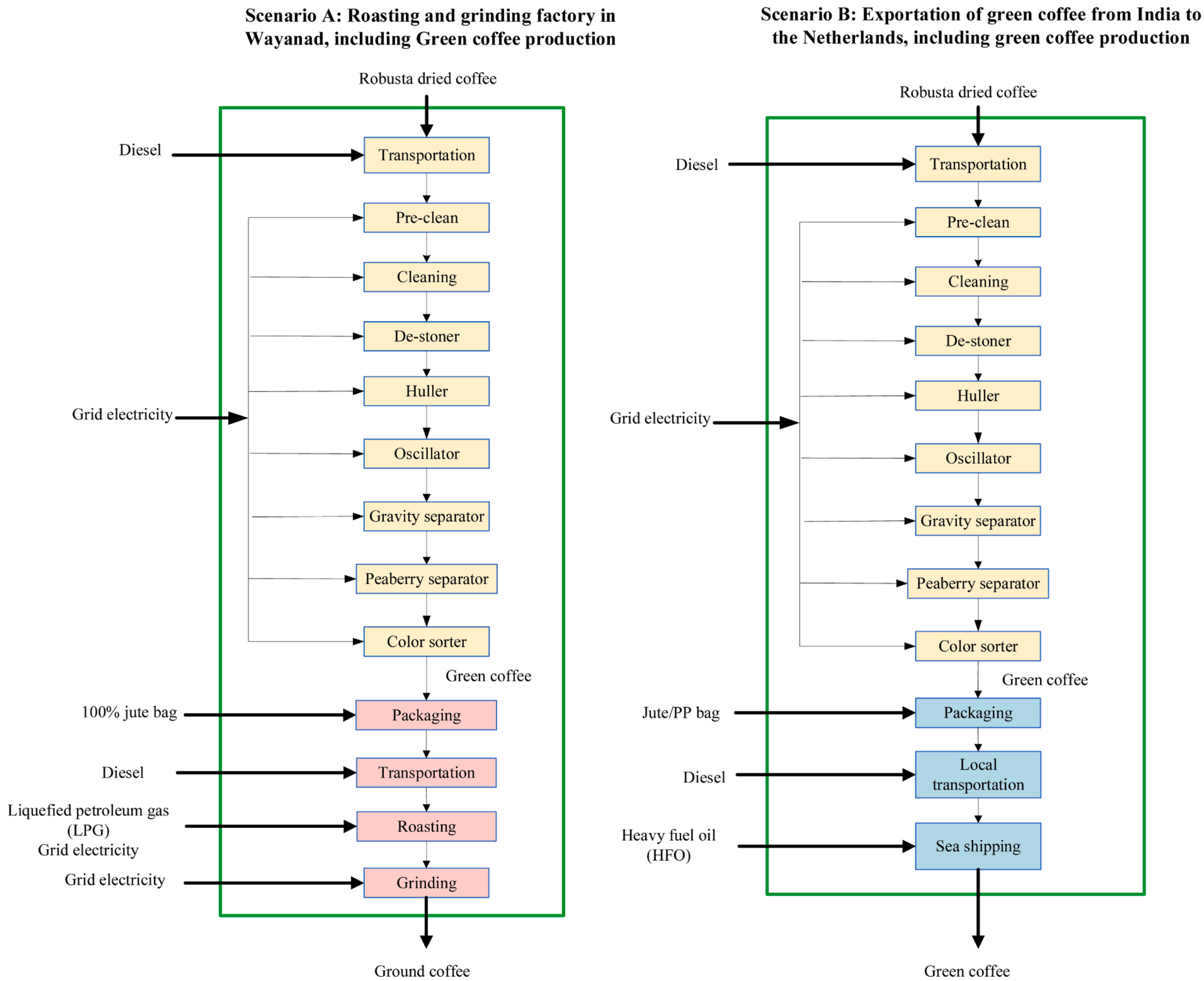

Fig. 6. Process block diagram and system boundaries of scenarios evaluated in this LCA study. Scenario A: transportation of dried coffee beans from farm to coffee processing unit, green coffee production, packaging, transportation, roasting, and grinding. Scenario B: transportation of dried coffee beans from farm to coffee processing unit, green coffee production, packaging, local transportation, and sea shipping from India to The Netherlands by cargo ship. Cultivation and harvesting are outside the system boundaries.

Data collection involved structured questionnaires and site visits (Appendix A). Detailed data from five coffee processing units were used for phase 1 and Scenario B, while the remaining units provided general information on dry coffee processing. Two roasting factories contributed data for Scenario A.

Information on green coffee production and export was collected from five processing units, including details on feedstock types (e.g., cherry coffee, dried coffee), yields, waste generation, product types (green, roasted, ground coffee), energy consumption (fuel and electricity), packaging materials, transportation logistics, and green coffee prices. Two facilities provided basic data on dry processing, including methods, yields, product types, energy sources, and market prices, but lacked specific energy consumption data.

Scenario A data related to packaging materials, transportation modes, roaster types (e.g., drum or hot air), fuel sources (LPG or electricity), roasting time, temperature, and energy consumption was collected from the two roasting factories, ensuring a thorough analysis of energy use and process details.

Table 1 presents the life cycle inventory of the main inputs and outputs, along with parameters for dry coffee processing in scenarios A and B. The data refer to 1 kg of green coffee as FU. For dry coffee processing, the LCI includes dried coffee beans, electricity, and diesel for transportation. Transportation of dried beans from farms to processing facilities was carried out by auto rickshaws, with diesel consumption data sourced from coffee producers and corroborated by literature [40]. Electricity is the primary energy input for the dry coffee processing stages. Packaging for green coffee involves 100 % jute bags, used for domestic and international distribution. The distance from farms to the processing units was estimated by Geodienst Center at the University of Groningen (Appendix B).

In scenario A, the LCI includes electricity, LPG, diesel, and packaging inputs. Transportation from the processing facility to the roasting unit is conducted by auto rickshaw, with distances estimated using Google Maps (2024). Roasting consumes both electricity and LPG, while only electricity is required for grinding.

In scenario B, the LCI included packaging, diesel fuel for truck transportation, and heavy fuel oil (HFO) for cargo ships. The green coffee is packaged in Jute/PP bags as per local coffee producers' practices. These packaged beans are transported by truck from the processing unit to Cochin Port, consuming diesel fuel. Subsequently, the beans are shipped from Cochin Port to Rotterdam Port in The Netherlands, utilizing cargo ships powered by HFO. The transport distances from the coffee processing unit to Cochin Port and from Cochin Port to The Netherlands have been estimated using Google Maps and sea-distance.org [41], respectively.

2.3.3. Life cycle impact assessment (LCIA)

The impact category considered in this research is the carbon

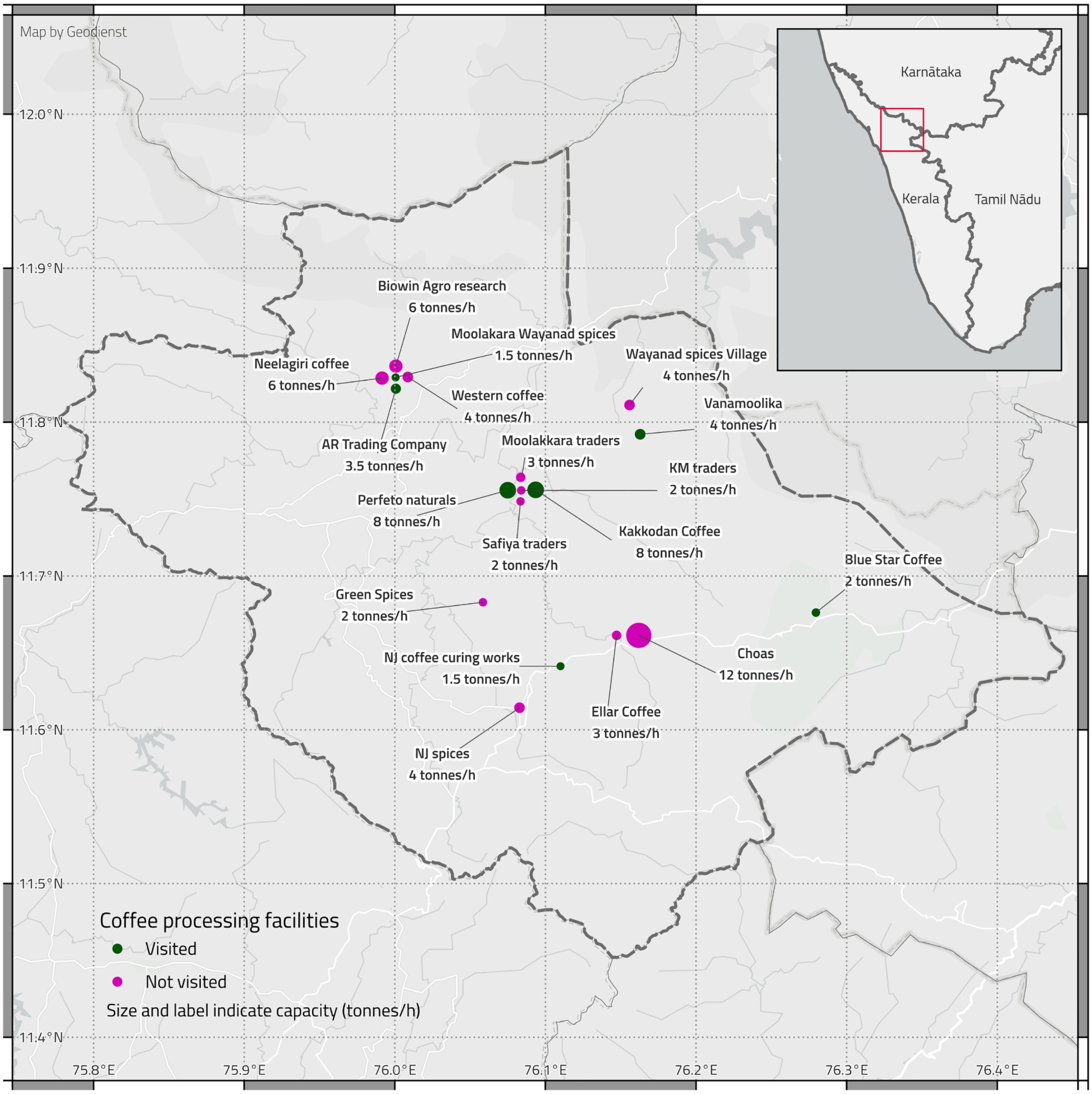

Fig. 7. Coffee processing facilities (green coffee production) visited in Wayanad. Source: Geodienst, RUG, 2024.

footprint. A carbon footprint represents the total greenhouse gas emissions generated both directly and indirectly by an individual, organization, process, or product. It is determined by adding up the emissions produced at each stage of a product or service's life cycle [46]. Direct GHG emissions originate from sources that are owned or controlled by the reporting entity. Indirect GHG emissions, on the other hand, are a result of the reporting entity's activities but occur at sources owned or controlled by another entity [47].

An emission factor (EF) quantifies the average emissions produced per unit of activity or output. It is utilized to estimate the environmental impact of various processes by linking specific emissions to particular activities, such as fuel combustion [48]. EFs are categorized into direct and indirect types. Direct EFs quantify emissions directly released into the atmosphere from the activity being measured, such as combustion. Indirect EFs estimate emissions resulting from intermediate activities caused by the original activity that supplies with materials or energy the system boundaries of the studied system. For example, an electrical grid emission factor (EF) is an indirect measure that proportionally averages emissions from different power producers and fuel types used to generate electricity for utility customers.

The calculation of the carbon footprint involved identifying the primary sources of emissions, collecting relevant data, and converting this data into values using an EF. An EF is a coefficient that facilitates the conversion of activity data into greenhouse gas emissions. For this work, the carbon footprint was calculated using indirect EFs for grid electricity and packaging (jute and jute/PP bags). For LPG, diesel, and HFO, both direct and indirect EFs were applied. Indirect EF was provided by the Ecoinvent V3.8. The EFs utilized in this study are detailed in Table 2.

The CF impacts of each activity data presented in the LCI, Table 1, are calculated by multiplying them by their specific EF, Table 2. The impacts at each stage of coffee production along the value chain are aggregated and expressed in kg of CO_2eq. These impacts are then divided by the total amount of coffee processed at each stage, resulting in the CF of each stage expressed in kg CO_2eq per kg of green coffee.

The total CF of each system studied in this work is calculated using the following equations:

Table 1
Life cycle inventory of the main inputs and outputs, and parameters for dry coffee processing, scenarios A and B. Data refer to 1 kg of green coffee.

Stage	Parameters and activity data	Value	Unit	Reference
Phase 1: Dry coffee processing				
Input: dried coffee beans	Feedstock	2.32	kg	Visits to nine coffee processing units
Output: green coffee	FU	1.00	kg	Mass balance, Appendix C
Transportation: Distribution from farm to coffee processing unit by auto rickshaw	Distance travelled	42	km	Appendix B
	Fuel efficiency	20	km/L	Interviews, [40]
	Load capacity autorickshaw	1500	kg	Interviews, [40]
	Diesel consumed	0.001	L	(Distance traveled/fuel efficiencyxload capacity)
Pre-clean	Electricity	0.001	kWh	Visits to nine coffee processing units (Appendix C)
Cleaning		0.002		
De-stoner		0.003		
Huller		0.02		
Oscillator		0.001		
Grader		0.002		
Gravity separator		0.01		
Peaberry		0.003		
Color sorter		0.01		
Total	Electricity	0.05	kWh	
Scenario A: Roasting&Grinding				
Input	Green coffee	1	kg	Appendix C
Output	Ground coffee	0.95	kg	Appendix C
Green coffee	FU	1	kg	
Transportation: Distribution from phase1 to roasting & grounding unit by auto rickshaw	Distance travelled	10.00	km	Google Maps (2024)
	Diesel consumed	0.0003	L	(Distance traveled/fuel efficiencyxload capacity)
Packaging	Weight of jute bag (100 % jute) carries 1 kg of coffee	0.01[1]	kg	100 % jute bag is 0.58 kg holding 60 kg of green coffee. For 1 kg of green coffee, the mass of the jute bag is: 0.58 kg jute bagx1 kg of coffee/60 kg of coffee [42]
Roasting	Electricity	0.16	kWh	Appendix C
	LPG calorific value	45.20	MJ/kg	[43]
	Ground coffee	0.95	kg	Appendix C_mass balance
	LPG consumed per kg roasted coffee	0.09	kg LPG/kg roasted coffee	Visits to two roasting facilities (Appendix C)
	LPG consumed	3.86	MJ	(LPG consumed per kg of roasted coffee x kg of roasted coffee x LPG calorific value)
Grinding	Electricity	0.07	kWh	Visits to two roasting facilities (Appendix C)
Total	Electricity	0.23	kWh	
Total	LPG	3.85	MJ	
Scenario B: Exportation				
Green coffee	FU	1.00	kg	
Packaging	Weight of jute bag carries 1 kg of green coffee	0.01	kg	1 bag of jute/PP is 0.36 kg holding 60 kg of green coffee. For 1 kg of green coffee, the mass of the jute/PP bag is: 0.36 kg jute/PP bagx1 kg of coffee/60 kg of coffee., [42]
	Weight of jute / PP union bag	0.006[1]	kg	[42]
Local transportation: Distribution from roasting unit to Cochin port by truck (medium duty vehicles)	Distance traveled	280	km	Google Maps (2024)
	Fuel efficiency	5.00	km/L	[40]
	Load Capacity	7000	kg	[40]
	Diesel consumed	0.008	L	(Distance traveled/fuel efficiencyxload capacity)
Sea transportation by cargo ship from Cochin Port to Rotterdam Port	Average fuel efficiency	31	kg/km	[44,45]
	Cargo ship capacity	5E+06	kg	[43–45]
	Distance travelled	12,000	km	Google Maps (2024)
	Weight of heavy fuel oil (HFO) consumed	0.07	kg	(Fuel efficiency x distance traveled/cargo capacity)

[1] This value represents the amount of one bag, equivalent to the quantity of 1 FU.

$$CF_{S1} = CF_{\text{transport dried coffee}} + CF_{\text{electricity}} \tag{1}$$

$$CF_{S2} = CF_{\text{transport green coffee}} + CF_{\text{packaging}} + CF_{\text{LPG}} + CF_{\text{electricity}} \tag{2}$$

$$CF_{S3} = CF_{\text{packaging}} + CF_{\text{Land transport}} + CF_{\text{sea transport}} \tag{3}$$

The CF of each scenario studied in this work is calculated as follows:

$$CF_{\text{scenario A}} = CF_{S1} + CF_{S2} \tag{4}$$

$$CF_{\text{scenario B}} = CF_{S1} + CF_{S3} \tag{5}$$

The carbon footprint caused by electricity or fuel was calculated using the following equations 6 and 7, based on the guidelines for estimating greenhouse gas emissions of Asian Development Bank projects [52].

When fuel is burned/used:

$$CF = \left(\sum A * EF_i\right) \Big/ \text{Output} \tag{6}$$

Where:
CF = the sum of the GHG emission (in kg CO_2eq/kg of green coffee)
A: = activity data (consumption of fuel in kg)
EF = emission factor of fuel burned/used (in kg CO_{2eq}/kg of fuel)
Output=mass of green coffee (in kg)
When electricity is used:

$$CF = \left(\sum (A * EF \big/ 1 - \%L)\right) \Big/ \text{output} \tag{7}$$

Where:
CF = the sum of the GHG emission (in kg CO_{2eq}/kg of green coffee)
A: = activity data (for electricity consumption in kWh).
EF = emission factor for grid electricity (in kg CO_{2eq}/kWh)

Table 2
The GHG emission factors for dry coffee processing, scenarios A and B.

Activity data	Classification EF	GHG emission factor (kg CO_2 eq per unit)	Definition	Unit	Reference
Grid electricity	Indirect	0.71	All generation sources except so-called low-cost or hydro, nuclear, and other renewable stations	kWh	[49]
Liquied petroleum gas	Direct	3.14	Combustion	kg	[50]
	Indirect	0.70	Emissions from extraction, processing, and distribution		Liquefied petroleum gas {IN}| market for liquefied petroleum gas | APOS, U Ecoinvent V3.8 [51]
Diesel	Direct	2.64	Combustion	L	[40]
	Indirect	0.50	Emissions from extraction, processing, and distribution		Diesel {IN}| diesel production, petroleum refinery operation | APOS, U Ecoinvent V3.8 [51]
HFO	Direct	3.11	Combustion	kg	[44]
	Indirect	0.50	Emissions from extraction, processing, and distribution		Heavy fuel oil {IN}| market for heavy fuel oil | APOS, U Ecoinvent V3.8 [51]
Packaging (100 % jute bag)	Indirect	2.76	Extraction, processing, transportation, usage, and disposal	kg	[42]
Packaging (Jute/PP union bag)	Indirect	5.28	Extraction, processing, transportation, usage, and disposal	kg	[42]

%L = energy losses due to transmission and distribution of electricity between the sources of supply and points of distribution (for this work, 0.20 fraction of losses is assumed [52]).

Output=mass of green coffee (in kg)

The Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories outline two methods for computing CO_2 emissions in transportation: the 'top-down approach' and the 'bottom-up approach. In this work, GHG emissions for the transport of green coffee were calculated using the bottom-up approach. This methodology entails determining emissions based on the fuel consumption corresponding to the distance traveled [53,54]. The contributions to the emissions depend on an emission factor, the distance traveled, and fuel efficiency. The GHG emissions in terms of kg CO_{2eq} for transportation were calculated using Eq. (8): [55]

$$CF = EF * D * FF/W \tag{8}$$

Where:

CF = CF (in kg CO_2eq/kg of green coffee)

EF= emission factor of the type of fuel when combusted or produced (in kg CO_{2eq}/L)

D = distance traveled (in km)

FF= fuel efficiency average (in L/km)

W= weight of green coffee (in kg)

CF caused by packaging was estimated as follows, Eq. (9):

$$CF = EF * M/W \tag{9}$$

Where:

CF = CF (in kg CO_{2eq}/kg of green coffee)

EF= emission factor of the type of bag (plastic or jute, converting raw materials to shaped packaging), (in kg CO_{2eq}/kg of bag)

M = weight of type of bag (in kg)

W= weight of green coffee (in kg)

3. Results

The results section presents the carbon footprint breakdown calculations for phase 1, Scenario A, and Scenario B. Direct emissions, arising from the combustion of diesel, LPG, and HFO, and indirect emissions, originating from grid electricity, packaging, production of diesel, LPG, and HFO are calculated for each stage, as outlined in Table 2. Stages such as transportation (local distribution, with diesel as an energy source), roasting (using LPG), and sea transportation (using HFO) contribute to both direct and indirect GHG emissions. Packaging, roasting with grid electricity as the energy source, and grinding are classified exclusively as sources of indirect emissions. The numerical details corresponding to each segment of the figures are provided in Appendix D. This appendix contains the data for each part of the bar charts presented in Figs 8, 9, and 10.

3.1. Phase 1: dry coffee processing: green coffee production

Fig. 8 presents the carbon footprint for dry coffee processing, amounting to 0.044 kg of CO_{2eq} per kilogram of green coffee. The contributions from various stages are as follows: direct emissions for distribution account for 7 %, indirect emissions for distribution for 2 %, pre-cleaning for 2 %, and cleaning for 5 %. The de-stoner process contributes 7 %, while hulling is the predominant stage, contributing 36 % to the total emissions. The oscillating process accounts for 2 %, gravity for 16 %, peaberry for 7 %, and grading for 5 %. Finally, color sorting contributes 11 %.

3.2. Scenario A: ground coffee production at the local roasting unit (scenario A)

The CF for Scenario A is 0.62 kg CO_{2eq} per kg of green coffee, as depicted in Fig. 9. The roasting phase, utilizing LPG (both direct and indirect) and grid electricity, was identified as the predominant source of emissions, accounting for 78 % of the total CF. Specifically, direct LPG emissions contributed 45 %, indirect LPG emissions 10 %, and electricity 23 %. Grinding and packaging accounted for 10 % and 5 % of the CF, respectively, while dry processing contributed 7 %.

3.3. Scenario B: production and exportation of green coffee from India to The Netherlands

Fig. 10 presents the CF of scenario B. The production and exportation of one kilogram of green coffee from India to The Netherlands (Scenario B) resulted in a carbon footprint of 0.38 kg CO_{2eq} per kilogram of green coffee. Sea transportation's stage, primarily reliant on HFO, was the principal contributor, accounting for 66 % of the total CF, with direct emissions comprising 57 % and indirect emissions 9 %. Distribution processes contributed 7 % to the total CF, 6 % direct and 1 % indirect emissions, using diesel. Packaging and initial dry processing stages were responsible for 16 % and 12 % of the CF, respectively.

3.4. Comparison to other LCI coffee studies

Several authors have reported the carbon footprint of coffee processing using the life cycle assessment. Table 3 compiled CF of green coffee production, roasting & grinding, and supply chain of coffee (Robusta and Arabica) based on conventional processing.

The electricity requirements in green coffee production may vary

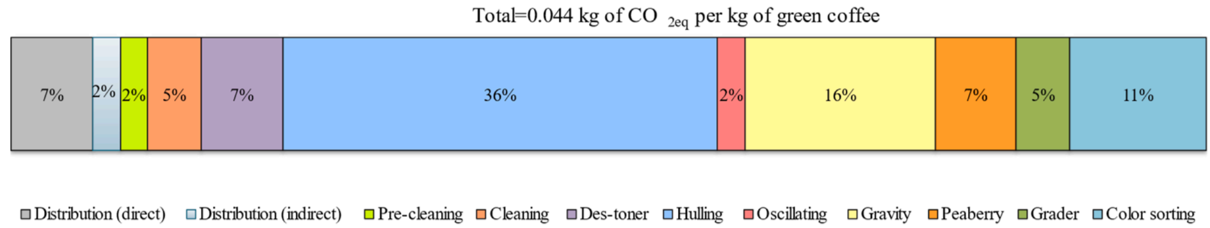

Fig. 8. Carbon footprint of Robusta dry coffee processing (green coffee production), phase 1.

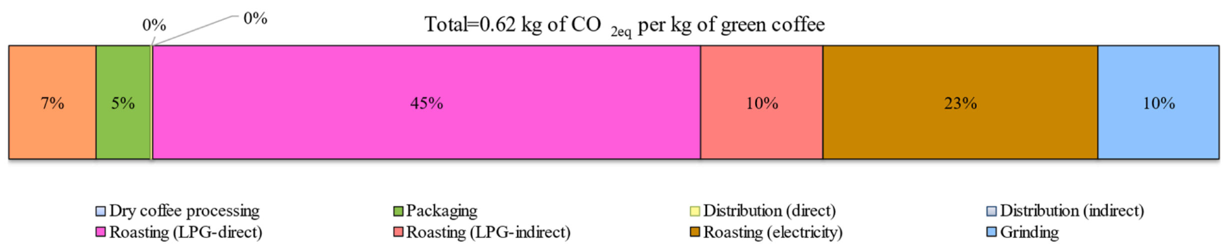

Fig. 9. Carbon footprint of green and ground coffee production at the local roasting unit, scenario A.

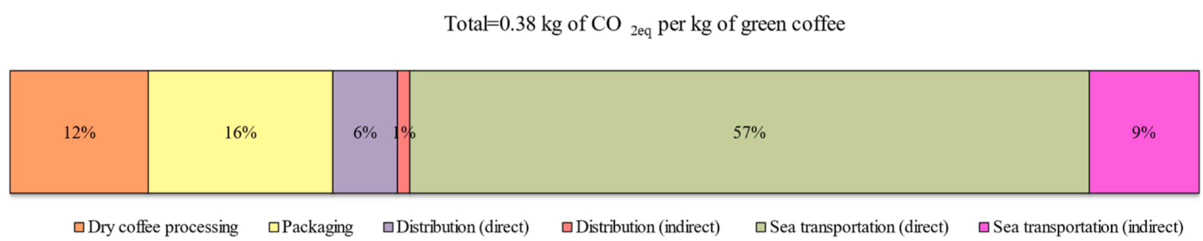

Fig. 10. Carbon footprint of exportation of green coffee in The Netherlands, scenario B.

Table 3
Comparison of carbon footprint emissions in green coffee production[1], roasting &grounding, and the coffee processing supply chain.

Processing	Variety	Method	Country	Grid electricity (MJ/kg)	Fossil fuel (MJ/kg)	Total energy consumption (MJ/kg of coffee)	CF (kg CO_2eq/ kg of green coffee)	Reference
Green coffee production	Robusta	Dry	India	0.18		0.18	0.04	This work
	Robusta	Washed	Indonesia		0.10	0.10	0.03	[56]
	Arabica	Washed	Indonesia		0.10	0.10	0.02	[56]
	Robusta	Washed	Thailand	0.04		0.04		[10]
	Arabica	Washed	Brazil	0.94		0.94	0.10	[57]
	Arabica	Washed	Vietnam	0.94		0.94	0.18	[57]
Green coffee production+ Roasting and grinding	Robusta	Dry	India	0.83	3.86	4.69	0.62	This work
	Arabica	Washed	Mexico				2.90	[58]
	Robusta	Washed	Thailand	0.69	3.17	3.86	0.56[2]	[10]
Exportation, scenario B	Robusta	Dry	India	CF = 0.38 (See Fig. 9)				This work
Supply chain	Robusta	Dry	India to The Netherlands/ Case study: CF=S1 + scenario *A* + scenario B	CF = 0.96 Dry coffee processing (4 %), distribution (2 %), roasting (52 %), grinding (7 %), packaging (9 %), sea transportation (27 %).				This work (Appendix D)
	Arabica	Washed	From Costa Rica to Europe	CF = 4.98 Farm level (21 %), coffee processing (10 %), exportation (5 %), roasting (4 %), packaging (3 %), distribution (3 %), grinding and purchasing (6 %), consumption (45 %), disposal (3 %).				[9]
	Arabica	Washed	Tanzania coffee (from Dar es Salaam Port) to Germany (Hamburg Port)	CF = 3.05 Roasting (6 %), packaging (4 %), distribution (5 %), grinding + purchasing (9 %), consumption (71 %), disposal (5 %).				[15]

[1] Green coffee production specifically refers to the post-harvest processing stages required to convert coffee cherries into green coffee, which are subsequently prepared for roasting and grinding.
[2] Per kg of ground coffee.

across studies due to differences in energy efficiency, processing technologies, LCA inventory quality and system boundaries. For example, the study of Ratchawat et al. (2020) for Thailand's washed Robusta [10] processing is based on primary data from 180 coffee farms in Thailand. The study reports energy requirements equal to 0.04 MJ/kg of green coffee attributed to electricity use for pulping 0.03 MJ/kg and polishing 0.03 MJ/kg of ground coffee (with an efficiency of 1.4 kg of green coffee needed for 1 kg of roasted coffee) and drying via solar radiation. In contrast, the study referring to Brazil and Vietnam [12] uses inventory data taken from Chavez's (2009) study [59] and presents higher energy demands (0.94 MJ/kg for Arabica washing) compared to the other values in Table 3. Chavez et al. (2009) [59] refers to a conventional technology consuming 0.94 MJ/kg of electricity to produce 1 kg of green coffee, with drying representing nearly eighty percent of the total electricity consumptions, while in the study of Ratchawat et al. (2020) for Thailand this amount of energy need is provided by solar radiation in the drying stage. However, according to Chavez et al. (2009) the electricity consumption can be reduced from 0.94 to 0.16 MJ/kg which is of the same order of magnitude of the current study, when new technologies are applied (e.g. use of biomass for drying). These variations are compatible with the study of Chéron-Bessou et al. [60] that summarizes the factors for differences among studies based on the collection of primary data (detail each processing stage, energy source, and technology etc.), system boundaries definition, and methodological choices.

Carbon footprint values for Arabica and Robusta vary considerably by region, processing method and methodological choices, such as system boundaries, assumptions, and data quality in LCA [60]. Arabica, accounting for approximately 70 % of global coffee production [61], is typically processed using the wet method, which involves pulping, fermentation, and drying. This process requires substantial water usage and generates organic effluents that contribute to GHG emissions [62]. In contrast, Robusta is predominantly processed using the dry method, which relies on sun or artificial drying and generally has lower water and energy requirements. While Robusta coffee tends to exhibit a lower carbon footprint due to its resilience and reduced energy consumption [62], the overall impact either Robusta or Arabica depends on regional factors, agricultural practices, and processing efficiencies. Consequently, LCA studies should account for specific system boundaries, assumptions, and geographical contexts to provide accurate comparisons, rather than generalizing differences based solely on coffee variety.

For example, in the green coffee production scenario, the GHG emissions for Arabica-washed coffee are 0.10 kg CO_{2eq} per kg of green coffee in Brazil, and 0.18 kg CO_{2eq} per kg of green coffee in Vietnam, which is different to the value of 0.02 kg CO_{2eq} per kg of green coffee for the case of Indonesia presenting the same type of processing method and coffee variety. The current study shows lower GHG emissions but in the same order of magnitude with the other two studies, in terms of carbon footprint, for the Robusta dry process in India at 0.04 kg CO_{2eq} per kg of green coffee, underscoring regional differences in energy source mixes and differences in the efficiencies of the processing as it is shown from the values of the electricity consumption among these three cases.

In ground coffee production, comparing Arabica-washed from Mexico (2.90 kg CO_{2eq} per kg of green coffee) and Robusta-washed from Thailand to our work (0.62 kg CO_{2eq} per kg of green coffee) reveals Thailand's CF at 0.56 kg CO_{2eq} per kg of green coffee is marginally lower that the outcome of the current study, contradicting typical expectations that washed methods generate, in general, higher GHG emissions than dry methods. This can be attributed to the energy consumption values as shown in Table 3. The authors of the Thailand study attribute emissions primarily to electricity and LPG use, suggesting that replacing conventional stoves with high-efficiency models could cut LPG consumption by 60 %, reducing further, the total GHG emissions by 0.10 kg CO_2 during roasting [10,11].

In the case we consider the export of ground coffee instead of green coffee to The Netherlands, (as the scenario B), the total carbon footprint rises to 0.96 kg CO_{2eq} per kilogram of green coffee (Appendix D). According to PAS 2050, emissions above 5 kg CO_{2eq} per kg are classified as "very high intensity" [48] while those between 0.1 and 1.0 kg CO_{2eq} per kg fall under the "medium intensity" category [63,64]. Consequently, the carbon footprint of the currently study, excluding cultivation and harvesting, is classified as "medium intensity" and is comparatively lower than that of coffee sourced from Costa Rica and Germany, which are categorized as "high intensity." This variation of this study with Costa Rica and German cases can be attributed to the use of fertilizers during cultivation and the energy-intensive nature of processing methods, particularly in the pulping stage.

Our findings indicate that roasting is the predominant contributor to carbon footprint, accounting for 52 % of total emissions when considering processing, distribution, roasting, grinding, packaging, and sea transportation. In Wayanad, conventional roasting methods primarily utilize LPG and electricity. To mitigate GHG emissions, a transition to more sustainable roasting technologies is necessary. This study recommends that Indian coffee roasters explore advanced roasting machines that enhance energy efficiency and lower carbon emissions.

Various strategies can effectively reduce emissions during roasting [58]. Traditional roasters typically employ separate burners for roasting and emissions incineration, leading to higher GHG emissions due to excessive gas consumption and elevated temperatures required for incineration. In contrast, innovative roasting technologies can utilize a single burner for both functions, thereby reducing gas usage and emissions [65].

Indian roasters may also consider investing in energy-efficient equipment or transitioning to renewable energy sources. For example, the installation of solar panels can provide a sustainable energy source for equipment, lighting, and operational activities. In other simple measures, such as minimizing unnecessary lighting and optimizing water heating systems, can significantly reduce energy consumption. One example is Joh Johannson Kaffe AS in Norway [66], which utilizes energy wells and solar cells extensively. The facility incorporates heat recovery and biogas, achieving energy self-sufficiency for heating purposes. Biogas is employed in the roasting process, where air is heated to 400 °C. An integrated energy center enables efficient use of excess heat generated during coffee roasting.

In conclusion, while the roasting process is just one segment of the coffee supply chain, enhancing energy efficiency within roasting facilities offers numerous benefits, including reduced emissions, economic savings, and alignment with sustainable practices [67]. Therefore, ongoing efforts to reduce fuel consumption, transition to alternative fuels, and repurpose energy within roasting facilities will be explored in future research.

4. Discussion

Currently, there is a lack of studies on the environmental impact of Indian coffee processing. Therefore, this work contributes to identifying high-emission stages and enabling targeted mitigation strategies in future research. By pinpointing which processes contribute most to the carbon footprint, such as roasting and sea transportation, stakeholders can focus their efforts on reducing emissions in these specific areas.

The hotspot of GHG emissions from scenario A is roasting, accounting for 78 % of the total CF. Roasting and grinding operations contribute substantially to the carbon footprint, primarily driven by liquefied petroleum gas consumption, which constitutes about 56 % of the total emissions in scenario A. This suggests that energy efficiency improvements in the roasting process could yield significant reductions in overall emissions. The roasting and grinding coffee processing in scenario A are energy-intensive, significantly contributing to the carbon footprint, primarily due to LPG consumption in the roasting section. When comparing with S1 and scenario B, the CF of scenario A tends to exceed theirs. This is mainly due to the high energy inputs required to maintain elevated temperatures during roasting and the mechanical action involved in grinding. Traditional roasting methods in India often rely on fossil fuel sources to achieve and sustain the necessary high temperatures, approximately 200 °C.

Exploring the use of coffee by-products, such as coffee husks, for renewable energy generation could further reduce the carbon footprint. For example, converting coffee husks into syngas could provide a sustainable energy source for heating and electricity within SOFC system, this point is already being addressed in a subsequent paper, aligning with the United Nations Sustainable Development Goals (SDGs) [68].

By-products such as husks can be anaerobically digested to produce biogas, the energy contained in biogas can be used to generate heat and electricity [69,70]. This process captures methane emissions that would otherwise be released into the atmosphere, thus reducing the overall carbon footprint. Biogas can be used for heating and electricity generation within the processing plant, decreasing reliance on fossil fuels. This intervention supports SDG 7 (Affordable and Clean Energy) by providing a sustainable energy source and SDG 13 (Climate Action) by reducing greenhouse gas emissions.

Additionally, residues like husk, silverskin, and coffee grounds (see Fig. 4) can be gasified to produce syngas, a mixture of hydrogen and carbon monoxide [71]. Syngas can be used as fuel for combined heat and power (CHP) systems, further lowering the carbon footprint of the coffee processing facility [71]. This aligns with SDG 9 (Industry, Innovation, and Infrastructure) by promoting sustainable industrial processes and SDG 12 (Responsible Consumption and Production) by ensuring efficient use of resources. Optimizing energy and resource use in the processing plant also contributes to SDG 11 (Sustainable Cities and Communities) by fostering sustainable industrial development.

The possibility to implement these interventions enables coffee processing plants to reduce their carbon footprint, contribute to sustainable development, and support global efforts to combat climate change. The pioneer case of the Costa Rican coffee cooperative Coopedota, which is the first organization worldwide that achieve certification for carbon neutrality [72], after making investments to increase its production quality through an efficient production system that reduces its environmental impact [73]. These measures demonstrate a commitment to environmental stewardship and align with the broader objectives of the United Nations Sustainable Development Goals. However, the first step is to measure the amount of GHG emission generated by the coffee production identifying the hotspot of GHG emissions.

Transport optimization is essential for reducing the carbon footprint of coffee exports, particularly in long-distance shipments where sea transportation accounts for a significant share of emissions. In Scenario B, HFO reliance contributed to 66 % of total emissions. Key strategies include selecting fuel-efficient vessels equipped with hybrid or LNG-powered technology, optimizing shipping routes using advanced software to minimize fuel consumption, and consolidating shipments to maximize container space and reduce trips [74]. Decarbonization efforts require the adoption of alternative fuels such as jet fuels [75], hydrogen, and compressed natural gas, with promising options like butanol and hydrogenated farnesene under investigation, though their large-scale application remains challenging [76]. The adaptation of internal combustion engine vehicles to biofuels is essential for emission reductions, as highlighted by [76]. Additionally, optimizing local transportation through the use of fuel-efficient vehicles and improved logistics can further mitigate emissions. Strengthening regional supply chains and sourcing coffee from local producers where feasible can also contribute to reducing transportation-related carbon emissions.

The Life Cycle Inventory methodology used in this study might be replicated in other cases within the dry Robusta coffee industry due to its systematic and standardized approach. LCA involves comprehensively collecting and quantifying inputs and outputs for each stage of the green coffee production process, as shown in the questionnaires provided in Appendix A. This structured framework for collecting information ensures accurate capture of all relevant data, enabling replication of the study across different regions and production methods.

While this study is limited to the processing stages of coffee and does not include agricultural activities within its system boundaries, we acknowledge the significant mitigation potential of sustainable agricultural practices. Substituting synthetic fertilizers with organic manure [77], employing solar energy for bean drying [35], and adopting organic farming systems [78–80] are effective strategies to reduce greenhouse gas emissions at the cultivation stage. Also, implementing organic agroforestry systems, which integrate shade trees into coffee plantations, has been shown to enable farms to operate at carbon-neutral or even carbon-negative levels, as demonstrated in [81]. These practices offer promising avenues for reducing the carbon footprint associated with coffee cultivation.

5. Conclusion

This study highlights the significant factors contributing to the carbon footprint of Robusta coffee processing, focusing on the differences between ground coffee production and the export of green coffee to The Netherlands. The findings indicate that local ground coffee production in Wayanad is particularly energy-intensive, primarily due to high LPG consumption, emerging as the largest contributor to GHG emissions (0.62 kg $CO_{2e}q$/kg of green coffee), 78 % of the total carbon footprint for ground production is generated by LPG consumption. In an exportation scenario, transporting 1 kg of green coffee from India to The Netherlands results in 0.38 kg CO_{2eq} /kg of green coffee. Sea transportation, primarily using heavy fuel oil, contributes 66 % of total GHG emissions, making it the main emission hotspot.

GHG emissions, as measured by CF, exhibit variation across each stage of the coffee supply chain, necessitating life cycle assessment (LCA) studies to identify hotspots for conceptualizing future strategic mitigation alternatives. As environmental challenges persist, the first step starts with a clear and effective calculation and communication of CF results, which serves as a vital tool for driving positive change in the coffee sector. Therefore, LCA studies might account for specific system boundaries, assumptions, and geographical contexts to ensure accurate comparisons, rather than generalizing differences based solely on coffee variety.

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CRediT authorship contribution statement

Sandra P. Iglesias: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paraskevi Karka:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **John A. Posada:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Ralph E.F. Lindeboom:** Supervision, Conceptualization. **Machteld van den Broek:** Conceptualization. **Girigan Gopi:** Resources. **Manju Mathew:** Resources. **TD John:** Resources. **Vipin Champatan:** Conceptualization. **P.V. Aravind:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nexus.2025.100456.

Data availability

data is available on Appendices

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