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Carbon Footprint across the Coffee Supply Chain: The Case of Costa Rican Coffee

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Abstract: The issue of carbon emissions has been on the corporate sustainability agenda for some years. For those working in agricultural supply chains, the challenges remain significant, given the diverse direct and indirect emissions occurring throughout the value chain. This study determines the carbon footprint of the supply chain of Costa Rican coffee exported to Europe, using best practice methodology to calculate greenhouse gas emissions. Overall, it was found that the total carbon footprint across the entire supply chain is 4.82 kg CO_{2e} kg^{-1} green coffee. The carbon footprint of the processes in Costa Rica to produce 1 km of green coffee is 1.77 kg CO_{2e}. The processes within Europe generate 3.05 kg CO_{2e} kg^{-1} green coffee. This carbon footprint is considered as "very high intensity". This paper also identifies the sources of the most intense emission and discusses mitigation possibilities on which efforts must be focused.

Key words: Climate change, carbon footprint, coffee supply chain, Costa Rica.

1. Introduction

Climate change is a known and largely accepted reality, and the world's climate will continue to change as long as greenhouse gas levels keep rising [1]. The effects of climate change are clearly perceivable, and impacts are being felt worldwide. This is especially so for communities dependent on climate for their livelihoods, namely farmers. Human activity in industry and agriculture has much responsibility in this regard; agriculture directly contributes to approximately 10%-12% of global greenhouse gas (GHG) emissions, according to the latest IPCC report [2].

The growing public concern about climate change has given rise to responses from government and industry. The corporate world has responded by starting to evaluate the global warming potential of their products. For those working in agricultural supply chains, the challenges remain significant, given the diverse direct and indirect emissions occurring throughout the value chain.

In terms of GHG emissions, agriculture is a complex process that results in many direct non-carbon dioxide emissions in addition to direct carbon dioxide and indirect GHG emissions [3]. This complexity is particularly significant in coffee supply chains, since coffee beans change hands dozens of times on the journey from producers to consumers [4].

Over the last 20 years, with growing demand, there has been a move to greater intensification of coffee growing and heavy use of agrochemicals [5], which led to an increase in environmental impacts at farm level. In the next stage of the coffee supply chain, a common practice for processing coffee is the wet milling process. Coffee produced through this method is regarded as being of better quality [5], but inherent in this method lays the significant challenge of properly managing the resulting effluent.

"Carbon footprint" has become a widely used term

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and concept to define responsibility and abatement action against the threat of global climate change [6]. A carbon footprint is obtained by quantifying GHG emissions produced during a defined period of time, which is then expressed in carbon dioxide equivalent.

To date, there is little information in scientific literature about carbon emissions in the coffee sector. Given this lack of information, this study is an attempt to understand coffee's carbon footprint and to identify a response that helps to reduce impacts over time.

The main purpose of this study has been to determine the carbon footprint of a Costa Rican coffee supply chain using best practice methodology to calculate greenhouse gas emissions. Its purpose was also to develop a tool to calculate GHG emissions in the coffee supply chain, to enable replication in other coffee supply chains as necessary. Additionally, the study sought to identify "hot spots" of GHG emissions in the coffee supply chain, in order to determine where mitigation efforts should be focused, and to evaluate alternatives of mitigation efforts and their impact on the carbon footprint.

To meet these objectives, the study focused on different stages of the coffee supply chain: at farm level, in the central mill, and during the process of exportation. In order to assess the carbon footprint of the entire coffee supply chain, results of processes undertaken outside Costa Rica and within Europe were drawn from an existing study that evaluates the carbon footprint of coffee exported to Germany [7].

Finally, it is worth noting that sustainability measures and carbon reductions are still largely optional practices within supply chains. However, as consumers, NGOs and governments increasingly demand more of it, companies and stakeholders involved in the coffee business will have to meet these expectations through greater efforts on sustainability practices and through lower carbon emissions. The adaptability of the results of the present study and the calculation tool developed will be extremely valuable in evaluating carbon footprint in other regions.

2. Literature Review

The current section synthesizes published information related to carbon footprints. It summarizes public knowledge on greenhouse gas emissions, the impact of coffee in terms of carbon emissions, the definition of carbon footprint and carbon footprint methodologies as well as the theoretical base and understanding of the topic.

2.1 Greenhouse Gas Emissions

The effects of climate change are clearly perceivable and accelerating. Whereas all of these changes cannot be attributed to human activities only, it has to be acknowledged that the accelerated concentration of carbon dioxide (CO_2) particles in the atmosphere which reached 389 ppm in September 2011 [8] and the implications of altering natural lifecycles, have not occurred randomly.

The United Nations Framework Convention on Climate Change (UNFCCC) acknowledges in its definition of climate change that the change of climate is attributed directly and indirectly to human activity, which alters the composition of the global atmosphere [9]. Levels of all key greenhouse gases are rising as a direct result of human activities [1].

Of the greenhouse gases, CO_2 is of greatest concern because it contributes the most to enhanced greenhouse effect and climate change [10]. Currently, carbon dioxide is responsible for over 60% of the enhanced greenhouse effect, mostly from the burning of fossil fuels [1]. Deforestation is the second largest source of carbon dioxide, when forests are cleared for agriculture or development. The production of lime to make cement accounts for 3% of CO_2 emission from industrial sources [11].

Methane is the second most abundant GHG after carbon dioxide [12]. Domesticated animals (cattle) emit methane, which is produced by enteric fermentation of food by bacteria and other microbes in the animals' digestive tracts. The decomposition of manure also releases methane. Other sources of

methane include wetland rice farming by the decomposition of organic matter in the flooded soil, disposal and treatment of garbage and human wastes by anaerobic decomposition [1].

Nitrous oxide is an important anthropogenic GHG and agriculture represents its largest source [13]. Part of that nitrous oxide is produced by the use of fertilizers and manures. The nitrogen contained in those products enhances the natural process of nitrification and denitrification. Bacteria and other microbes in the soil carry out this process to convert part of the nitrogen into nitrous oxide [14].

Chlorofluorocarbons (CFCS), hydro chlorofluorocarbons (HCFCs), hydro fluorocarbons (HFCs), per fluorocarbons (PFCs) and sulfur hexafluoride (SF_6) are long-lived and potent greenhouse gases; very small emissions of these gases relative to CO_2 can have a large climate impact [15].

Agriculture directly contributes to approximately 10%-12% of global greenhouse gas emissions, according to the latest IPCC report [2]. Agricultural practices generate the greenhouses gases from carbon dioxide (CO_2) linked to land conversion, soil management and energy use, nitrous oxide (N_2O) connected to the use of fertilizers, and methane (CH_4) which is mainly related to waste management of the product [16]. Globally, agricultural methane (CH_4) and nitrous oxide (N_2O) emissions increased by nearly 17% from 1990 to 2005 [2].

According to the Carbon Dioxide Information Analysis Center (CDIAC), Costa Rica emitted about 2,000 thousand metric tones of carbon during 2010 and an average of 0.5 metric tones of carbon per capita [17]. Greenhouse gas emissions from agriculture represent approximately 39% of the Costa Rican emissions, according to the national inventory of GHG emissions carried out in 2005 [18].

2.2 Impact of Coffee in terms of Carbon Emissions

Coffee is the world's most widely traded tropical agricultural commodity [19]. In the world economy, the coffee trade was worth approximately US$16.5 billion by 2010 [20]. It is a major source of revenue for more than 40 tropical countries, and it generates more than 120 million jobs [21]. Around 125 million people worldwide depend on coffee for their livelihoods [4], and people are involved in the sector from farm level through to processing and sale [5].

According to CIRAD, coffee is grown on more than 10 million hectares worldwide [21]. The world production for 2011/2012 was estimated at 131.4 million bags [22], and the USDA has forecasted a record 148 millions bags of coffee worldwide for the 2012/2013 harvest [23].

Coffee is particularly important to the Costa Rican export portfolio. In 2010 dry green coffee[1] exports were ranked 9th in terms of importance and represented 12.1% of the total value of agricultural exports and 2.8% of the total exportation of the country [24]. During the coffee harvest season 2010/2011, Costa Rica was the 14th largest coffee producing country, producing 1.19% of the worldwide coffee production, according to the International Coffee Organization [25].

As a result of production on such a large scale, the coffee supply chain is an important contributor to global GHG emissions [26].

A study carried out in Costa Rica and Nicaragua during 2011 at farm level (which evaluated greenhouse gas emissions in coffee grown with differing input levels under conventional and organic management) found that the carbon footprint for 1 kg of fresh coffee cherries were between 0.26 and 0.67 kg CO_{2e} for conventional and 0.12 and 0.52 kg CO_{2e} for organic management systems. According to this study, it can be deduced that main contributors to GHG emissions were the inputs of organic and inorganic nitrogen [26].

In terms of footprint throughout the whole coffee value chain from bean to cup, the full carbon footprint including these various different processes reaches 59.12 g CO_{2e} per cup of coffee [7].

[1]Green coffee is the coffee in the naked bean before roasting.

2.3 Defining Carbon Footprint

The growing public concern about climate change has aroused the interest of industries to evaluate the global warming impact of their products across their supply chain. Carbon accounting in today's globalised world is becoming complex and difficult, because value chains are growing longer and even more complex [27]. In agricultural commodities like coffee (the unit of analysis for this study) the value chain starts from cultivation and end at the disposal after consumption [28].

The carbon footprint is recognized as a valuable indicator of GHG emissions [29]. The United States Environmental Protection Agency points out that a carbon footprint represents the total amount of greenhouse gases that are emitted into the atmosphere each year by a person, family or company [30]. Department for Environment Food and Rural Affairs (DEFRA) suggested that the carbon footprint should be used as a tool to identify main sources of emissions for all types of goods and services [3].

Wiedmann et al. [6] proposed a definition of carbon footprint exclusively related to the total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or product. Wright et al. [31] suggested that as data collection for CO_2 and CH_4 emissions is relatively straightforward, these two carbon-based gases should be used in the determination of carbon footprint. They propose the term "climate footprint" for the inclusion of other GHG (non carbon-based gases) for full life cycle assessments [31].

For the purpose of this study, the concept of carbon footprint includes the emissions of GHG involved in the assessed activity. Taking into account that no greenhouse gas affects the atmosphere to the same extent, that each GHG has different global warming potential, and each GHG is normalized against CO_2 using a global warming factor, the carbon footprint is therefore expressed as CO_2 equivalent (CO_{2e}) [32].

2.4 Carbon Footprint Methodologies

In recent years, voluntary initiatives to mitigate climate change and overall sustainability have increased. Worldwide standards and methodological frameworks have been developed in the context of carbon footprint. These standards aim to identify, measure, reduce, mitigate and even neutralize the emissions of products, events, companies or territories. Both private stakeholders and public-private partnerships have been implemented and are working on these initiatives [33].

The European Union is leading this field. More specifically, the United Kingdom and France are the world leaders in the development of strategies and tools for the determination and assessment of the carbon footprint [34].

The British government, through its DEFRA and the Carbon Trust, teamed up with the British Standard Institute (BSI) to create a methodology for calculating GHG emissions embedded in goods and services by developing a Publicly Available Standard 2050 (PAS 2050), it was one of first public product carbon methodologies to be published [35].

The French Agency for Environment and Energy Management (ADEME) created Bilan Carbone, a GHG emission assessment tool. It is widely used in France and has influence in neighboring countries. The main aim of Bilan Carbone is to audit and set the GHG emissions according to weight, within a given scope of study, so that practical conclusions and areas of improvement can be put forward [36].

In 2008, Germany created the Project Carbon Footprint of Products (PCF Projekt), a practical tool for the estimation of the climate impact of individual products and processes [37].

International standards of carbon accounting include the Greenhouse Gas Protocol, which is an accounting tool to understand, quantify, and manage greenhouse gas emissions [38]. Finally, ISO 14067, a carbon footprint standard for products, is currently under development by the International Organization

for Standardization [39]; it is considered a fully international-based standard for the quantification and communication of GHG emissions of products and services [33].

3. Materials and Methods

Coffee goes through several stages on its journey from the grower to consumer; multiple sites and multiple companies are involved in this supply chain, which makes it complex. Traceability is difficult; data in the different process is in many cases not available, especially at farm level. This study extends its analysis to the whole coffee supply chain, emphasizing the collection of high quality data of its life cycle, and backtracking to their origin.

The methodology is structured in three sections: scope of the study, carbon footprint calculation tool and the process of data collection (farm level, central mill, exportation, and processes within Europe).

3.1 Scope of the Study

This study was conducted in Costa Rica and evaluates the different processes involved in the supply chain of coffee exported to Europe. The information used is drawn from the 2009/2010 coffee production period.

The study covers three different stages of the coffee supply chain in Costa Rica: farm level, milling and the process of exportation (Fig. 1).

In order to take a broader view of carbon emissions across the coffee value chain, other stages such as final processing (roasting), distribution and preparation related to the final country destination were integrated but not directly counted; information at these stages was taken from a previous coffee carbon footprint study (Fig. 2).

The scope for this study was defined using PAS 2050:2011 a carbon standard development by the British Department for DEFRA and the British Standards Institution (BSI) [3].

The main scopes defined for the stages directly evaluated are presented in Fig. 3.

Defining the functional unit

According to PAS 2050, the functional unit defines the function of the product that is being assessed and the quantity of product to which all of the data collected will relate, so the carbon footprint must be defined in terms of a functional unit [3].

The functional unit defined for this study was 1 kg of green coffee. Therefore, the results of the carbon footprint are presented as kilograms of carbon dioxide (CO_{2e}) per 1 kg of green coffee (kg CO_{2e} kg^{-1} green coffee).

Exclusion of process from the analyzed system

In order to simplify the process PAS 2050 allows the exclusion of some elements of the carbon footprint.

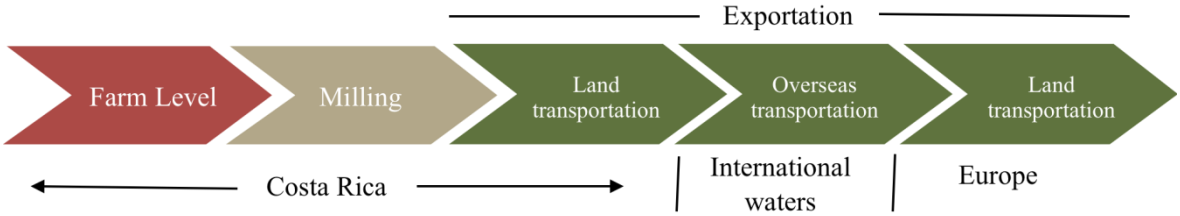

Fig. 1 Stages of the coffee supply chain evaluated.

Fig. 2 Stages of the coffee supply chain within Europe.

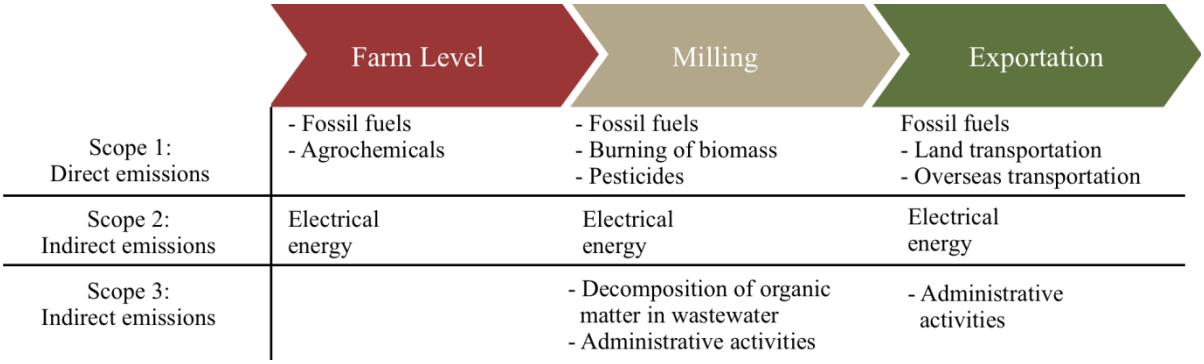

Fig. 3 Scopes defined for the stages of the coffee supply chain carried out in Costa Rica.

At least 95% of the total emissions have to be assessed, but materials that contribute less than 1% of the footprint can be excluded.

When land use change occurred more than 20 years prior to assessment, no land use change emissions should be included [3]. The land under coffee production in Costa Rica during 1990 to 2002 has been maintained at a constant level, registering reduction of the production area by 2008 [40]. Because the land destined to produce coffee has been in agricultural production for more than 20 years, no emissions from land-use change have been included. Carbon storage from shade trees and perennial crop are also excluded from the PAS 2050 method.

Other things not included are: human energy inputs to process and preprocess, transport of employees to and from their normal place of work.

3.2 The Carbon Footprint Calculation Tool

Before collecting primary data from the field, a methodology was developed to quantify the GHG emissions. As guidance, PAS 2050:2011 [3] were used, as well as the IPCC guidelines for National Greenhouse Gas Inventories [41].

Conversion factors provided by the IPCC and DEFRA were used to determine the footprint of each emission factor. Because of variation in factors caused by the sources of inputs (e.g., electricity) from country to country, specific Costa Rican conversion factors on electricity and fossil fuels were used from the National Climate Change Strategy (NCCS) [42].

To measure the carbon footprint, an Excel calculation tool was created, into which all data and emission factors were inputted. The model is structured in three different steps, as is explained in the following section (Fig. 4).

Step 1: Coffee production

First, the amount of coffee produced or processed at every stage was determined, in order to have a reference for which the emissions of each stage can be divided to obtain the carbon footprint of a specific source of emission. The information on coffee is presented as green coffee;

Step 2: Calculating carbon emissions

To calculate the emissions of each source, every activity data (e.g. amount of fossil fuels) is multiplied by its specific emission factor, as explained in Eq. 1 [3];

$$(\text{Eq. 1}) \quad CO_2 \text{ emissions} = \text{source of emission or activity data} \times \text{emission factor}$$

Eq. 1 was used mostly to calculate the emissions caused by the consumption of fossil fuels, electricity, aerial transportation for marketing purposes, oversea transportation and administrative activities.

Different conversion sources were used to calculate the emissions as follows: Fossil fuel emissions and the electricity were calculated using the national average fossil fuels and energy emission factors for Costa Rica, provided by ENCC [42, 43]. The emission factors from the use of goods and services by the administrative department in Costa Rica, aerial transportation, the overseas transportation, and the land transport in Europe from port to warehouse were obtained from DEFRA.

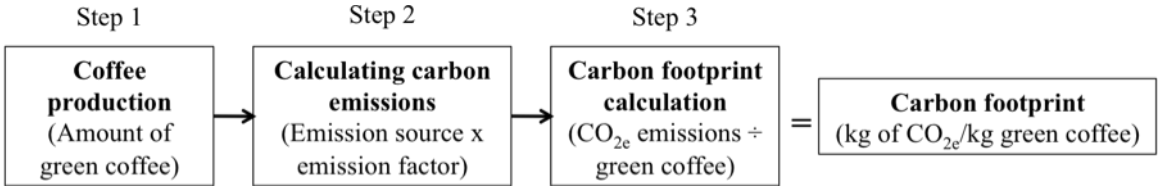

Fig. 4 Steps followed to calculate coffee carbon footprint.

Carbon emissions from the use of fertilizers, the decomposition of organic matter in wastewater and from burning biomass were calculated with the following specific equations.

Emissions from fertilizers

Agrochemicals encompass the production of chemicals, transportation, and direct and indirect N_2O emissions from soil for the application of fertilizers. The emission factors for producing fertilizers and pesticides were obtained from DEFRA [44]. The N_2O emissions were estimated using equations introduced by IPCC guidelines [45].

Eq. 2 was used to calculate the direct emissions by the application of nitrogen from synthetic fertilizers.

(Eq. 2) $CO_{2e} = (F_{SN} \times FE_1) \times (44/28) \times (GWP\ N_2O/1000)$

CO_{2e} = equivalent CO_2 emissions;

F_{SN} = annual amount of synthetic fertilizer N applied to soils, kg N yr^{-1};

FE_1 = emission factor for N_2O emissions from N inputs, kg N_2O–N (kg N input)$^{-1}$;

F_{SN}*FE_1 = annual direct N_2O–N emissions from N inputs to managed soils, kg N_2O–N yr^{-1};

44/28 = conversion of N_2O–N emissions to N_2O emissions;

GWP N_2O = Global Warming Potential of N_2O, t CO_{2e};

The indirect emissions, by the application of nitrogen from synthetic fertilizers, were calculated using Eq. 3 to calculate volatilization of N_2O, and Eq. 4 to calculate the leaching of N_2O.

(Eq. 3) Volatilization $CO_{2e} = ((F_{SN} \times Frac_{GASF}) \times EF_4) \times (44/28) \times (GWP\ N_2O/1000)$

CO_{2e} = equivalent CO_2 emissions;

F_{SN} = annual amount of synthetic fertilizer N applied to soils, kg N yr^{-1};

$Frac_{GASF}$ = fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x, kg N volatilized (kg of $N_{applied}$)$^{-1}$;

FE_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N_2O (kg NH_3 – N + NO_x–N volatilized)$^{-1}$];

($F_{SN} \times Frac_{GASF}$) × EF_4 = annual amount of N_2O–N produced from atmospheric deposition of N volatilized from managed soils, kg N_2O–N yr-1;

44/28 = conversion of N_2O–N emissions to N_2O emissions;

GWP N_2O = Global Warming Potential of N_2O, t CO_{2e}.

(Eq. 4) Leaching $CO_{2e} = ((F_{SN} \times Frac_{LEACH\text{-}(H)}) \times EF_5) \times (44/28) \times (GWP\ N_2O/1{,}000)$

CO_{2e} = equivalent CO_2 emissions;

F_{SN} = annual amount of synthetic fertilizer N applied to soils in regions where leaching/runoff occurs, kg N yr^{-1};

$Frac_{LEACH}$ = fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)$^{-1}$;

FE_5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N (kg N leached and runoff)$^{-1}$;

($F_{SN} \times Frac_{LEACH\text{-}(H)}$) × EF_5) = annual amount of N_2O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg N_2O-N yr^{-1};

44/28 = conversion of N_2O–N emissions to N_2O emissions

GWP N_2O = Global Warming Potential of N_2O, t CO_{2e}.

Emissions from decomposition of organic matter in wastewater

The emissions of methane (CH_4) produced by the decomposition of organic matter in wastewater were estimated using equations obtained from the waste section of the IPCC guidelines [46].

The emissions by the decomposition of organic matter in wastewater were calculated as follows: to obtain the amount of organic degradable material the Eq. 5 and Eq. 6 were used to determine the emission factor for treatment systems, and net methane emissions were calculated with Eq. 7. Finally, CO_{2e} released by burning CH_4 in the dryers was calculated using Eq. 8.

(Eq. 5)	Total organic degradable material in wastewater for each industry sector	=	Total industry product × Wastewater generated × Chemical Oxygen Demand
(Eq. 6)	Emission factor	=	Maximum Methane Producing Capacity × Methane Correction Factor for the Treatment

(Eq. 7)	Net methane emissions	=	((Total organic degradable material in wastewater – Sludge removed) × (Emission factor for treatment system)) – Recovered CH_4
(Eq. 8)	CO_{2e}	=	(Net methane emissions)*(44/16)

44 = Molecular weight of CO_2; 16 = Molecular weight of CH_4.

Emissions from burning biomass

The emissions caused by burning biomass, for drying coffee, were calculated with equations obtained from the energy section of the IPCC guidelines [47].

The biomass consumed was calculated with Eq. 9. From the burning of biomass different GHG are emitted, such as CO_2, CH_4 and N_2O, the emissions of these gases are calculated with Eq. 10.

To convert the emissions of CH_4 and N_2O to CO_{2e}, the emissions of each gas were multiplied by its specific global warming potential, and the results were totaled to obtain the emissions expressed in CO_{2e} by burning biomass (Eq. 11).

(Eq. 9)	Consumption (TJ)	=	Consumption (mass, volume or energy unit) * Conversion factor (TJ/unit)
(Eq. 10)	Emission of CO_2	=	Consumption (TJ) * Emission factor (kg CO_2/ TJ) * Efficiency factor (0.98)
	Emission of CH_4	=	Consumption (TJ) * Emission factor (kg CH_4/ TJ) * Efficiency factor (0.98)
	Emission of N_2O	=	Consumption (TJ) * Emission factor (kg N_2O/ TJ) * Efficiency factor (0.98)
(Eq. 11)	CO_{2e}	=	Emission of CO_2 × 1(GWP) + Emission of CH_4 × 25(GWP) + Emission of N_2O × 298(GWP)

Step 3: Carbon footprint calculation

The emissions of each stage are totaled and standardized in kg of CO_{2e}. These emissions are divided into the total amount of coffee produced or processed in each stage. The result of this division is the carbon footprint of each stage; it is expressed in kg CO_{2e} kg^{-1} green coffee (Eq. 12).

(Eq. 12)	Carbon footprint = emissions/green coffee
	kg CO_2 kg^{-1} green coffee = kg CO_2 emitted/kg green coffee produced or processed

3.3 Data Collection

With established scopes for the study and the tools with which to calculate the emissions, the primary data was obtained at each stage of the coffee supply chain evaluated, as described below.

Farm level

Costa Rican coffee production is largely concentrated in smallholder systems, about 92% of them produce less than 26 ton of cherry coffee per year, and their production represents 41% of national production [48].

In order to assess the CO_{2e} emissions for the farm level, a range of farms in the Costa Rican Central Valley coffee cluster were selected for the study.

The farms were visited to collect data from the producers using a questionnaire; records of the farms were also reviewed to understand the usage of fossil fuels in different farm activities, agrochemicals and fertilizer, and electricity consumed during this period.

The principal sources of emissions identified at farm level are presented in Fig. 5.

It is important to note that the farms evaluated produce coffee under shade in a poly-culture system. Coffee plants and shade trees are CO_2-fixing; plants absorb CO_2 from the atmosphere though photosynthesis and use light energy to run enzyme-catalyzed reactions; in this process, plants produce sugars and other organic compounds for growth and metabolism [49]. The absorbed carbon goes to form above-ground biomass, as well as roots.

Wasmman et al. [50] indicated that there is an equilibrium point when no more carbon is stored. That is when new carbon fixation is cancelled out by attrition of trees. This carbon will eventually return to the atmosphere if and when the trees are liquidated. According to Hester et al. [51] carbon accumulated in leaves comes back to the atmosphere after a relatively short period of time, when the fallen leaves decompose. Carbon in wood is stored for years; the time depends on the tree species, growing condition, and on various uncertain occurrences such as fire or diseases. According to this information, fixation and emissions of carbon through the decomposition of organic matter in an established coffee-producing system are in a constant balance; leaves and wood

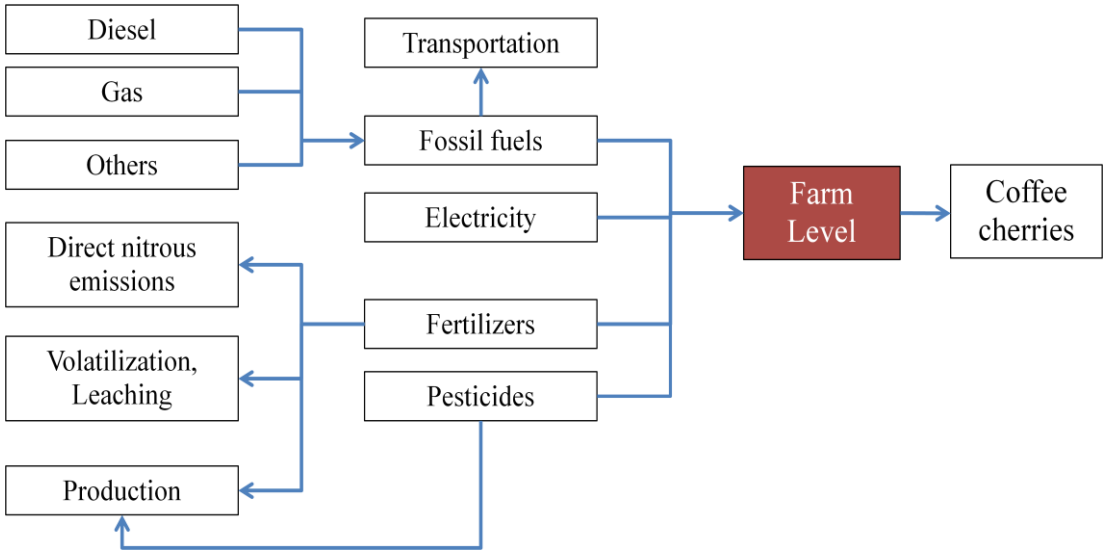

Fig. 5 Overview of the sources of emissions identified at farm level.

from pruning practices eventually decompose and carbon stored is released into the atmosphere. In Costa Rica, the pruning system on coffee varies depending on the technical criteria; the total pruning is done above 40 cm to 50 cm, and renovation of coffee plantation varies between 15 and 20 years [52].

Since PAS 2050 excludes carbon stored in living organisms, such as trees or perennial crops [26], the carbon stored in the coffee stem and shade trees were not considered in this study for the carbon inventory.

Central mill

After the harvest, the producers bring their coffee from the farm to the central mill, where the coffee cherries are concentrated and processed as parchment, and then it is converted into green coffee. This study evaluates two different milling facilities with these characteristics. The mills are located in the Central Valley of Costa Rica.

The milling process used in Costa Rica is the wet process, a common practice in Central America. The wet milling process is the practice used to convert the cherry coffee into green coffee at the central mill [53]. This process consists in selection, washing, natural fermentation, de-pulping and drying. From washing to de-pulping, a considerable amount of water is used. After wet processing, the water contains coffee mucilage[2]; this wastewater was sampled and a lab carried out COD[3] analyses; these results were used in the calculations (specifically in Eq. 7) to obtain the emissions of methane through the decomposition of organic matter in wastewater.

In addition, the records and information of fossil fuels, electricity, administrative activities, and the amount of biomass burned to dry coffee were collected for both mills. The sources of emissions identified for the milling process are presented in Fig. 6.

Exportation

According to ICAFE, 18% of coffee production of Costa Rica is sold in the local market and 82% is exported [48]. The United States is the principal market destination, representing 56% of the total exportation, and 39% is exported to Europe: Belgium, Luxemburg, Germany, Italy, the Netherlands and Portugal are the main buyers in Europe [24].

This study evaluated coffee exported to Europe. In this stage, a number of actors are involved in the transporting process from the central mill to its final destination in a warehouse in Europe, as explained below.

[2]The mucilage contains 50% sugars, 33% protein and pectin, and 17% dashes [54].
[3]Chemical Oxygen Demand.

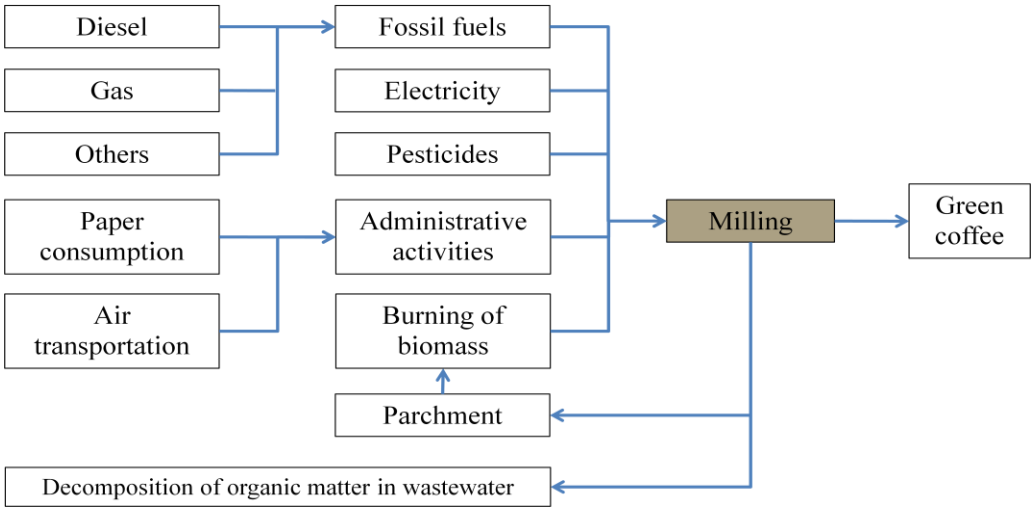

Fig. 6 Overview of the source of emissions identified for the milling process.

The information collected at this point is related toland transportation from the mill to port in Costa Rica: records of fossil fuels consumed were obtained. With regard to overseas transportation, information was obtained on both the amount of containers, the weight in tons of coffee exported, as well the distance in kilometers (7,869 km) from Costa Rica to Europe. In the absence of data from a particular carrier of the land transport in Europe from port to warehouse, an average of 600 km was used as the distance from port to the final destination. The sources of emissions identified for the process of exportation are detailed in Fig. 7.

The processes in Europe

In order to assess the remaining carbon footprint of the coffee value chain, findings of an existing study were used. This information was obtained from a case study that evaluates the carbon footprint of coffee processed in Germany [7]. Originally, this information was given in g CO_{2e} per cup, but for standardizing the functional unit defined in this study, it was converted into kg of CO_{2e} per kg of green coffee. PAS 2050 permit the use of secondary data from a published study or other source to calculate the impact of downstream life cycle stages [3].

The information of processes within Europe included the following stages: roasting, packaging, distribution, grinding and purchasing, consumption and disposal. The modeling of these stages is detailed in Fig. 8.

Electric energy is relevant in the roasting process; the general German electricity network provides this service. Besides electric energy, natural gas is also used in the roasting phase, and nitrogen gas is applied injected into the package to preserve the beans. The direct emissions of CO_2 from roasting coffee beans are excluded, since PAS 2050 exclude biogenic carbon sources from the assessment.

The roasted coffee is then packaged and distributed to retailers. Packaging includes primary and secondary packaging for the handling and delivery of the coffee as well as consumer packaging. The packaging used by end consumers includes a bag and a clip per 500 g of ground coffee. Electricity used at this stage is also significant in terms of emissions.

During the distribution stage, the roasted coffee is transported from the roasting plant to the coffee shop stores. From the roasting plant in Hamburg, the roasted coffee beans are delivered to the centre (Gallin) by lorries. From here, the coffee is distributed to three different distribution points: Bremen, Gerhnsheim and Neumarkt. From these distribution centers, the coffee is transported to affiliated shops.

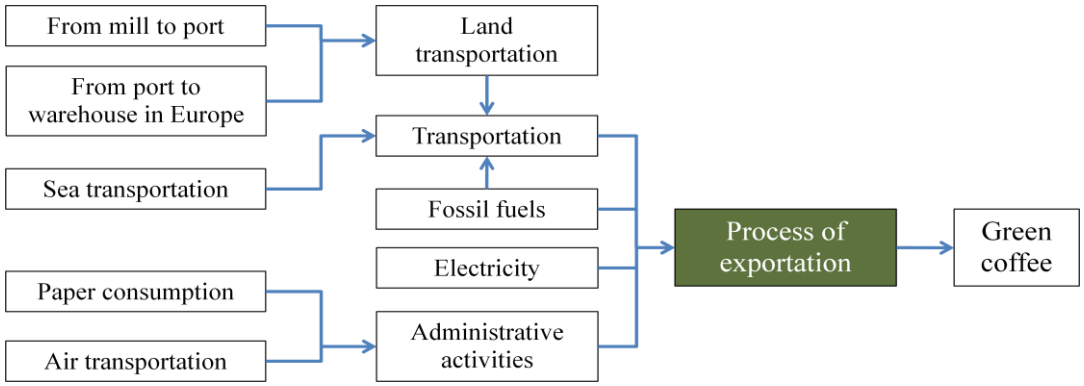

Fig. 7 Overview of the source of emissions identified for the process of exportation.

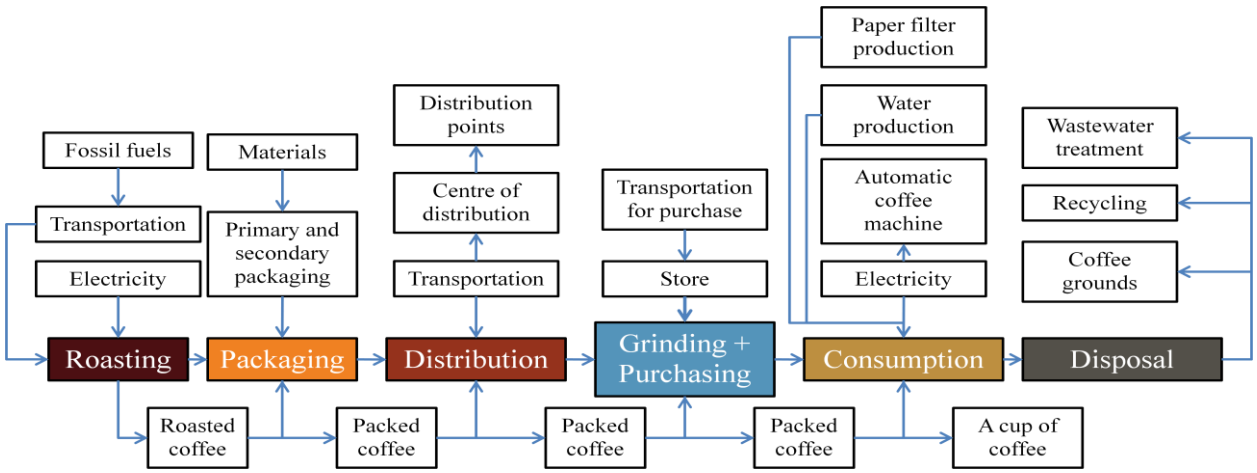

Fig. 8 Overview of the source of emissions identified for the process in Europe.

At the point of purchase, it has been assumed that not only one package of 500 g of coffee is purchased but also a whole basket of commodities with an overall weight of 20 kg. It is also assumed that the products come with a shopping bag made from low-density polyethylene, as secondary packaging. The purchase is done by car in an average distance of 5 km.

Consumers use different methods to prepare coffee: French press, filter drip, and automatic coffee machine. To prepare a cup of coffee using a French press, 125 g of water is needed, together with 0.0141 kw h of electricity. For filter drip coffee, 0.0125 kw h, and for an automatic coffee machine 0.085 kw h. Data drawn from the combination of these preparation methods is used.

The end of life phase took into account the disposal of primary and secondary packaging and coffee grounds. The coffee skin from the roasting plant is used to generate thermal energy and as a substitute for wood pallets and natural gas.

4. Results and Discussion

The following section addresses the potential carbon footprint of Costa Rican coffee. Additionally is presented a case study of the contribution of mitigation measures implemented at the stage of the milling process.

4.1 The Processes in Costa Rica

The carbon footprint calculated for the Costa Rican coffee, from farm level to a European warehouse is 1.77 kg of CO_{2e} per kilogram of green coffee (Fig. 9).

The emissions at farm level are the greatest (58%), followed by the central mill (27%), and finally the process of exportation to Europe (15%). PAS 2050 classifies as “high intensity” emissions in a range of

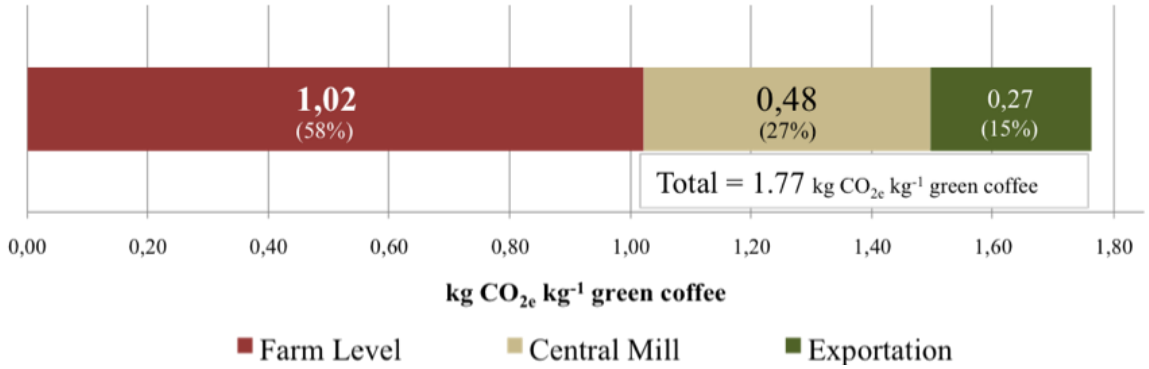

Fig. 9 Carbon footprint of three stages of the coffee supply chain.

1-3 kg CO_2 per kg. Products in this category include: greenhouse crops, rice and dairy [3]. According to this Classification, this coffee carbon footprint is technically considered a high intensity source of emissions.

The following section describes in detail the contribution of the respective processes in the value chain.

Farm level

This stage represents the most carbon intensive of the processes in Costa Rica. The farm level is responsible for 58% (Fig. 9) of total carbon footprint calculated for the processes in Costa Rica, or 1.02 kg CO_{2e} kg^{-1} green coffee (Table 1).

Fertilizers represent the highest inputs on the farm, both from the production of chemical fertilizers and due to N-fertilization: N_2O emissions of leaching and volatilization. 94% of the emissions at this stage come from fertilizers (Table 1). In contrast, the emissions from pesticides represent just 1%. Emissions from fossil fuels total 3%, mostly for the transportation of coffee cherries to the gathering centers. Electricity represents 2% of the emissions at the farm level.

Central mill

The central mill contributes 27% (Fig. 9) of emissions in Costa Rica, which represent 0.48 kg CO_{2e} kg^{-1} green coffee (Table 2).

The process of wet milling requires substantial amounts of water. After the wet processing, the remaining wastewater retains large amounts of solids and decomposing sugars. When this wastewater is not treated, it represents a source of pollution mainly if it is dumped directly into local water bodies. Additionally, the process releases gases such as methane (CH_4), which has a much higher global warming potential than CO_2. The emissions from untreated wastewater account for 79% of the total emissions at this stage (Table 2).

Table 1 Carbon footprint at farm level.

Emission source	CO_{2e} emission (kg CO_{2e} kg^{-1}) green coffee	(%)
Fertilizers	0.96	94
Fossil fuels: diesel, gas, others	0.03	3
Electricity	0.02	2
Pesticides	0.01	1
Total	1.02	100

Table 2 Carbon footprint at central mill.

Emission source	CO_{2e} emission (kg CO_{2e} kg^{-1}) green coffee	(%)
Decomposition of organic matter in wastewater	0.374	79
Fossil fuels: diesel, gas, others	0.076	16
Administrative activities	0.024	5
Biomass burning	0.001	0.3
Total	0.48	100

Exportation stage

Exporting 1 kg of green coffee from Costa Rica to Europe produces 0.27 kg CO_{2e} kg^{-1} green coffee (Table 3) and represents 15% of the emissions in Costa Rica (Fig. 9).

The overseas transportation is the main factor in terms of CO_{2e} emissions at this stage (70%). The distance from Costa Rica to Europe explains the large percentage of emissions for this phase.

Table 3 Carbon footprint of the exportation stage.

Emission source	CO_{2e} emission (kg CO_{2e} kg^{-1}) green coffee	%
Sea transportation	0.185	70
Transportation by land from port to storage destination	0.041	15
Transportation by land from mill to port	0.033	12
Administrative activities	0.006	2
Total	0.27	100

In order to obtain the carbon footprint of the processes within Europe (from roasting processes to disposal of the waste generated), results from existing literature were used. These results are presented in the following section.

4.2 Processes in Europe at Destination

The carbon footprint related to the processes in Europe is 3.05 kg CO_{2e} kg^{-1} green coffee (Table 4), which represents 63% of total emissions (Fig. 10).

Table 4 indicates that emissions are released in the roasting process (6%), packaging (4%), distribution (5%), grinding and purchasing (9%); the emission by consumption are the greatest (71%), and from the end of phase (disposal) (5%).

In the roasting stage, emissions are mainly driven by both electricity supply and provision of thermal energy. According to PAS 2050, the direct CO_{2e} emissions of the roasting process are not included as they originate from biogenic source [7].

The consumption stage is the most intensive source of emission and has a big impact on the overall carbon footprint; emissions at this stage come from the high demand of energy required for the preparation of coffee with an automatic coffee machine. The carbon footprint at this point is 2.15 kg CO_{2e} kg^{-1} green coffee, higher than the sum of the emissions from all other stages in Europe.

In the following section, the results of the carbon footprint in Costa Rica were combined with the results of the processes within Europe in order to obtain the total carbon footprint of the Costa Rican coffee supply chain.

Table 4 Carbon footprint of the processes in Europe.

Stage	CO_{2e} Emission kg CO_{2e} kg^{-1} green coffee	%
Roasting	0.19	6
Packaging	0.13	4
Distribution	0.15	5
Grinding + purchasing	0.29	9
Consumption	2.15	71
Disposal	0.14	5
Total	3.05	100

PCF Pilotprojekt Deutschland [7].

4.3 Overall Results

The total carbon footprint calculated for Costa Rican coffee across its full supply chain is 4.82 kg of CO_{2e} per kilogram of green coffee. The carbon footprint covered all processes conducted in Costa Rica and Europe. Farm level to a European warehouse produced 1.77 kg CO_{2e} kg^{-1} green coffee, and processes in Europe produced a carbon footprint equal to 3.05 kg CO_{2e} kg^{-1} green coffee (Fig. 10).

The main carbon emissions in the coffee supply chain are released at farm level (21%), the central mill (10%), and the process of consumption (45%); the carbon footprint related to consumption is 2.15 kg CO_{2e} kg^{-1} green coffee, higher than the total emissions released by the process carried out in Costa Rica (1.77 kg CO_{2e} kg^{-1} green coffee) (Fig. 10).

PAS 2050 classifies as "very high intensity" emissions in a range of > 5 kg CO_2 per kg. Products in this category include some concentrated foodstuffs [3]. According to this classification, the carbon footprint of Costa Rican coffee is technically considered a very high intensity source of emissions.

However, comparing the results of this study with other carbon studies on coffee, the level of emissions produced by Costa Rican coffee is lower (4.82 kg CO_{2e} kg^{-1} green coffee) than the total carbon footprint of a study of coffee exported to Germany, which showed emissions equivalent to 7.15 kg CO_{2e} kg^{-1} green coffe[4] [7]. Differences are mainly concentrated at farm level by the use of fertilizers.

[4]Information originally given in g CO_{2e} per cup, and converted into kg of CO_{2e} per kg of green coffee.

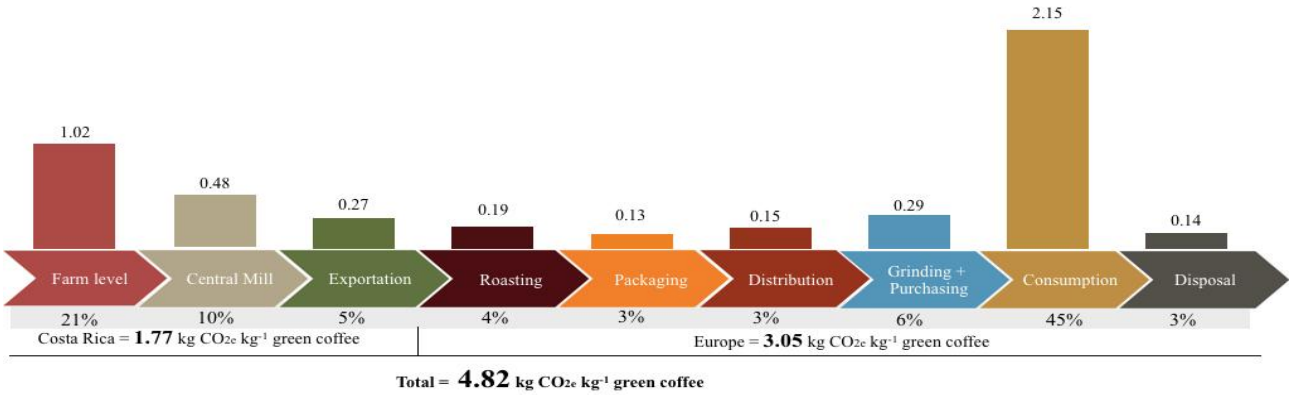

Fig. 10 Carbon footprint of Costa Rican coffee supply chain.

The following section describes in detail, the contribution of the respective processes in the supply chain to the resulting carbon footprint.

4.4 Hot Spots

The hot spots identified by this study are: fertilizers applied at farm, wastewater as a result of the wet milling process, and the electricity used for the preparation of coffee consumption using an automatic coffee machine. These emissions are collectively responsible for 73% of total emissions in the supply chain evaluated.

Fig. 11 shows in detail the contribution of each emission source in the potential carbon footprint of the Costa Rican coffee.

These results show the prominence of specific emissions variables for each component in the coffee supply chain. This can help to guide and establish mitigation strategies that can form the basis for action and reduce the impact of these activities on the environment.

The following section presents a specific mitigation strategy implemented at the milling stage; it includes the resulting implications of this strategy on the reduction of emissions.

Mitigation Possibility at Milling Stage

This section reveals the results of mitigation practices implemented in the central mill evaluated by this study. This mitigation effort is specifically focused on treating the wastewater generated after the milling process. The data for potential emissions is linked to the information presented in section 4.3 (overall results). The result of mitigation practices at this stage makes a substantial difference to resulting emissions (Fig. 12).

In terms of carbon footprint, the mitigation efforts carried out in the central mill represent a reduction of 7% or 0.34 kg CO_{2e} per kilogram of green coffee. This means that producing 1 kg of green coffee under these conditions reduces the potential emissions equal from 4.82 kg CO_{2e} to 4.48 kg CO_{2e} (Fig. 12).

Mitigation was achieved in the following way: one bio-digester or anaerobic reactor in each mill reprocesses the remaining wastewater. The decomposition of sugars and solids (contained in the coffee mucilage) in an anaerobic environment break down this organic matter into biogas (methane CH_4). The biogas obtained is burned in the coffee dryers. (The equivalent in CO_2 from burning this gas is much less than if the gas were emitted as methane[5] or if the wastewater were not treated).

Based on the assumption that most countries have regulations to restrict dumping of untreated wastewater, it can be inferred that most mills in the region have some type of wastewater treatment system in order to operate legally. These measures could be considered as part of a mitigation effort, though the treatment systems would need to be assessed in order

[5]The Global-warming potential of methane is 25 times more than carbon dioxide [55].

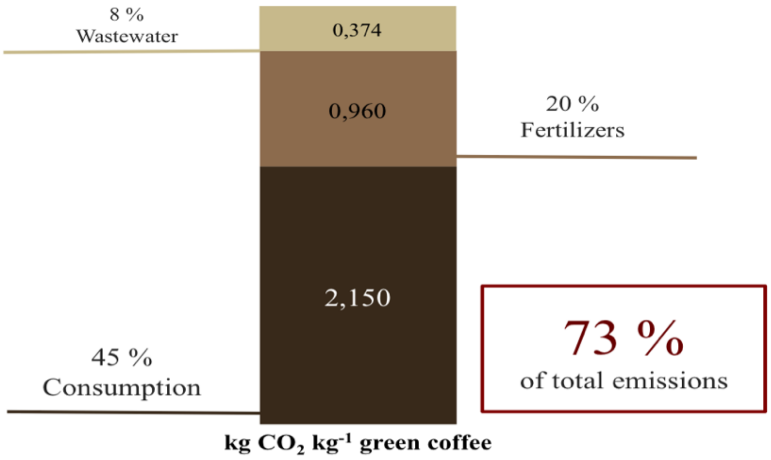

Fig. 11 Hot spots identified.

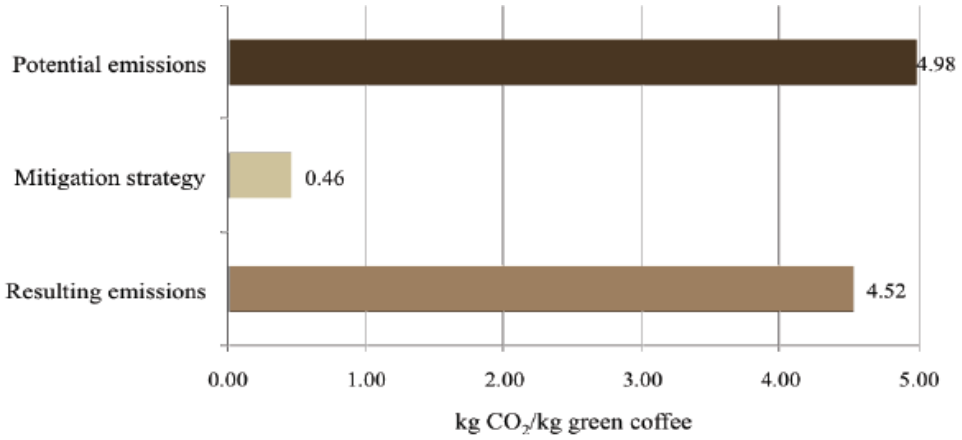

Fig. 12 Results of mitigation strategy implemented in the central mill.

to establish their real impacts on emissions and the potential financial cost of implementation and that they could represent.

4.5 Implications

In order to reduce the carbon footprint of coffee during its life cycle, the multiple actors implicated in the supply chain need to establish concrete actions or strategies to address the principal sources of emissions. Emissions vary across each stage of the chain, hence, it is reasonable to focus first on managing the key hot spots identified.

Large companies such as roasters and retailers could engage their suppliers in order to manage their GHG emissions in a more integrated and collaborative way, with a common plan and focused efforts to optimize efficiency.

It is also important to consider the promotion of technical upgrades at producer level, for example, improving their management practices through training programs in order that they optimize the use of inputs on the farm, specifically the use of fertilizers. These actions can reduce the carbon footprint at farm level.

Efforts should also be focused on the milling process, specifically proper management of wastewater. This study has given an example of how biogas can be produced from wastewater and the use of that gas used for the drying process of coffee. This effort reduced the carbon footprint significantly. Nevertheless, a cost benefit analysis of the implementation and operation of the anaerobic reactors would be needed in order to understand its

financial viability.

With regards to overseas transportation, companies involved at exportation stage could proactively seek to work with shipping companies that are actively working on reducing their own footprints.

Stakeholders involved in the coffee value chain have to take into account that consumers are now more aware about environmental issues including their own consumption. Increasingly, they are asking companies to provide information on emissions of products and services that they purchase and seeking to reduce their own footprints.

Aside from the potential cost savings to be made in reduction of carbon in the supply chain (e.g., through energy, fertilizers or transport costs), the proper management of emissions is also an opportunity for companies to develop competitive advantages in the marketing of their products or services. Some are already actively doing so. Despite the fact that sustainable practices and reduction of carbon emissions are still largely voluntary in most countries, there is a growing move towards regulation and carbon credit schemes that seek to incentivize and reward business for adopting carbon reduction strategies. For this reason it is increasingly important to invest in reduce or even neutralizing the carbon footprint in the supply chain. Australia, by way of example, is facing an emerging new business landscape in this respect; the transition to a low-carbon economy has begun [56, 57], and with the Clean Energy Act 2011 that came into effect in 2012, government has introduced a price on carbon to entities with greater emissions such as energy; even though agricultural emissions are not yet covered, it will face indirect effects through the increase of costs of electricity, amongst other utilities.

Compared with other agricultural products such as banana or pineapple that can be consumed as fresh products, the consumption of coffee requires a considerable amount of CO_{2e}, as was evidenced in this study, largely due to the highly energy demand from automatic coffee machines. Consumers also therefore play a critical role in the life cycle of coffee; as the most significant contributor to the overall footprint, they are directly part of the problem and should take the responsibility to minimize their own impact. Interesting work could also be done in improving the energy efficiency of coffee machines in this regard. Some companies (that manufacture products such as shampoo, with a similar consumer-heavy footprint) have embarked on consumer-focused campaigns to raise awareness and reduce water and energy usage at point of use.

The effecting of a range of policies and tools can reduce net carbon emissions from the supply chain too. According to the World Bank the carbon market has demonstrated that it is an effective tool in reducing GHG emissions [58]. Based on the principle that polluters pay, Bowen [59] suggested that a uniform global carbon price delivered by carbon taxes or carbon trading would be an ideal tool to reduce GHG emissions in a cost-effective way. In Europe for example, the carbon price in the market varies between US$18.8 ton^{-1} (€13.5 ton^{-1}) and US$ 12.9 ton^{-1} (€9.2 ton^{-1}) [60], which can be translated to US$0.019 and US$0.013 per kilogram of CO_{2e} emitted. Therefore, if the externality cost associated to the carbon footprint calculated were applied on coffee, it would vary between US$0.09 and US$0.06 per kilogram of coffee. This cost should be shared out amongst the key actors involved and thereby it would be reflected in the "social cost"[6] of coffee.

5. Conclusions

Coffee has considerable impact on the environment; the carbon footprint of the coffee supply chain calculated in this study is classified as a product with very high intensity emissions. Most emissions come from a few sources, which account for most of the impact generated per unit produced. In this sense

[6]The social cost includes the private costs plus the externalities costs [61].

focused mitigation efforts should be easier to implement. The hot spots identified produce about 72% of total emissions across the coffee supply chain evaluated, these are: fertilizers applied at farm level, wastewater as a result of the wet milling process, and the preparation of coffee using an automatic coffee machine due to the consumption of coffee in Europe.

A greater understanding of the topic and lessons learned by other business can be beneficial in helping to manage the carbon footprint generated. For instance, this study presented a mitigation strategy implemented in the milling process for managing wastewater, the result of which significantly reduced the carbon emissions.

Complementary studies are necessary to determine the real impact of the poly-culture system in the fixing and storing of carbon in order to establish the potential compensation of GHG emissions, mostly in the early growing stages of the plants.

For those involved in the coffee supply chain; this carbon footprint study reveals a useful perspective on carbon emissions through the life cycle of the product. The concern over GHG emissions and climate change is growing, so an effective management of carbon generated can only imply long-term benefits to both business and the environment.

Finally, as consumers are also directly and significantly part of the story on the coffee carbon footprint, they must be involved in the task of reducing its impact and be part of the solution.

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