

Coffee Supplier Emission Toolkit

Methodology Report



**DAMN
GOOD
COFFEE
COMPANY**

Coffee Supplier Emission Toolkit

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Summary

Fueled by Damn Good Coffee Company's commitment to understanding and reducing greenhouse gas emissions in its coffee supply chain, SuFu developed a Coffee Supplier Emission Toolkit. This toolkit aims to estimate the carbon footprint of green coffee beans. Building upon previous work done in 2021, where SuFu developed two frameworks to provide a climate impact score for different coffee suppliers, the current focus was to expand on those efforts by enabling emissions estimation even when data on coffee farming and processing is limited.

The toolkit consists of two interconnected parts:

1. The Coffee Supplier Emission Survey, which collects data on the farming and milling stages through an online form.
2. The Coffee Supplier Emission Calculator, an Excel-based model that provides estimations and comparisons of GHG emissions based on the data collected from the survey.

To ensure accurate estimations even in the absence of specific data on fertilizer, fuel, electricity use, and other farming-level factors, the calculator was developed through an extensive review of current coffee literature. A total of 50 scientific papers were analyzed, and relevant data on farming and milling emissions were extracted from 30 articles published in scientific journals.

Compared to the previous Coffee Climate Impact Framework, the new toolkit offers several advantages:

- It provides a clear value of GHG emissions expressed in kg CO₂e / kg green coffee for each supplier who completes the related survey.
- Emissions are accurately calculated when data on fertilizer, fuel, and electricity use is provided.
- Emissions are estimated even when the required information is missing.
- The model includes reference scenarios extracted from literature data, allowing DGCC coffee suppliers to compare their emissions with other coffee production systems.

Consistent with the current coffee literature, the model demonstrates that organic coffee systems can lead to an average of 63% reduction in agricultural emissions compared to conventional systems. When compared to monoculture systems, agroforestry has shown an average of 48% emission reduction at the agricultural level.

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List of Acronyms

AF	Agroforestry
DGCC	Damn Good Coffee Company
CF	Carbon Footprint
CO₂e	Carbon dioxide equivalent
EF	Emission Factor
GHG	Greenhouse Gas
LCA	Life cycle assessment
LPG	Liquefied petroleum gas
N	Nitrogen
N₂O	Nitrous oxide
S1	Scope 1 emissions
S2	Scope 2 emissions
S3	Scope 3 emissions
t	Metric tonnes

Note: English numerical notation has been used for the decimal numbers (.), not Danish notation.



Introduction

This report provides an overview of the Coffee Supplier Emission Toolkit, outlining its main sections and underlying assumptions. The toolkit consists of two primary components: a Survey and a Calculator.

The Survey, built using Google Form, encompasses questions pertaining to the agricultural and milling stages. Suppliers responding to the questionnaire can provide specific data on fertilization, fuel, and electricity usage, or alternatively, qualitative information regarding farming practices and types of fertilization employed. The Survey was designed to be adaptable and accommodate various data inputs.

The Calculator was developed to analyze the data collected through the Survey. It employs predefined conditions to calculate or estimate coffee emissions based on data availability. The model presented in this study builds upon previous work by SuFu (2021a) but includes significant improvements that enable the estimation of GHG emissions specifically for green coffee production. While SuFu's previous work may have laid the groundwork, this model introduces new methodologies and data collection techniques to address the specific challenges and complexities associated with estimating emissions in the coffee industry.

The improvements in the model include a more comprehensive data collection process, with a carefully curated literature review to gather relevant emission factors and data from various sources. The model also incorporates decision flows to handle missing data, enabling estimations to be made even when specific information is not available.

Additionally, this model offers a user-friendly interface through the Coffee Supplier Emission Toolkit, allowing coffee growers and stakeholders to input data and obtain emission estimates easily. The inclusion of regional and national average emission values as reference baselines further enhances the model's versatility and applicability across different coffee-producing regions.

The emissions data for each coffee supplier can be compared to values found in relevant literature. The results are visualized through bar charts that offer comparisons to country or regional averages of green coffee emissions.

Overall, the Coffee Supplier Emission Toolkit provides a comprehensive framework for assessing and comparing emissions in the coffee supply chain, utilizing both quantitative and qualitative data inputs.



Methodology

Literature review

For the construction of the model, a literature review was conducted. The main objectives of the literature review were to:

- Understand the main phases involved in the production of green coffee beans
- Gather data on GHG emissions for the different stages and substages of the green coffee production
- Collect data on compounds, energy, water, and fuel use at different stages
- Select the main influencing factors that enable estimating GHG emissions

Data on green coffee production was obtained from peer-reviewed studies or other publications issued by relevant institutions working in the coffee sector. A total of 50 scientific papers were retrieved, and relevant data were extracted from 30 articles after the review process. Studies were mainly based on Life cycle assessments (LCA), emission calculators (e.g. CoolFarm) or commonly used emission databases (e.g. Ecoinvent). Thus, they were considered to be in line with the guidelines provided by the GHG Protocol (WRI & WBCSD, 2011). The complete list of the literature used to estimate green coffee emissions can be found in the section *Data sources included in the Calculator*.

The collected data was categorized into two main categories:

1. *Influencing Factors*: variables that have an impact on greenhouse gas emissions in the agricultural context. These factors may include farming practices, management techniques, land use, and other variables that influence emissions. These factors can be considered as independent variables in the study.
2. *Emission Categories*: different types of emissions relevant to the study. This may include emissions from fertilizers, energy use, transportation, waste management, and other sources of greenhouse gas emissions. These factors can be considered as dependent variables in the study.

Influencing factors and emission categories will be highlighted for each production stage in the later sections.

A total of 90 data entries were included in the model, with each data entry representing a unique value of GHG emissions associated with the main influencing factors reported in a given study. This means that comparative studies contributed with two or more data entries. Data completeness was calculated by dividing the number of data entries including information on a specific emissions category by the



total number of data entries (90). Throughout this document, data completeness figures will be provided as a reference for the statistical analysis of each category.

During the literature review, all data was converted to a common functional unit of 1 kg of green coffee (see next section). In cases where data was partially missing from some sources, GHG emissions for different substages were estimated by averaging across the dataset.

The accuracy of the data was double-checked, and outliers were excluded from the dataset. Notably, data retrieved from Van Rikxoort et al. (2014) was discarded due to significantly higher emissions compared to the average values for conventional and organic management in agriculture, as well as the dry and wet milling processes.

In the Coffee Supplier Emission Calculator section, the main assumptions and statistical operations performed for each coffee production stage will be described.

Functional Unit and Conversions

Researchers have the flexibility to select coffee cherries, green coffee beans, or roasted ground coffee as a functional unit in their studies, depending on their research goals and variables of interest. Each of these choices offers unique insights into various aspects of coffee production and its environmental impact.

In this study, the functional unit (FU) chosen was 1 kg of green coffee beans. This decision aimed to provide better information to DGCC regarding the carbon footprint of a specific coffee supplier upon reaching Denmark. To ensure consistency across different studies, precise unit conversions were performed to standardize the data obtained from the literature. The average conversion factors used can be found in Table 1, while a comprehensive list of references is available in the "Conversion to Green Coffee" tab of the calculator sheet.

Table 1. Conversion values for different functional units across studies.

Original unit	Green coffee bean equivalent [kg]
1 kg of coffee cherries	0.220
1 kg parchment coffee	0.792
1 kg of roasted ground coffee	1.227



Statistical analysis

First, the data collected from the literature review was meticulously categorized based on the country of origin, as well as the main influencing factors and emission categories specific to each stage of coffee production. Next, a statistical analysis was conducted to derive reference average emission values. Finally, emission figures were calculated as the average across regional areas, namely Latin America, Asia, and Africa.

The calculator is designed to utilize both regional and national average emission values as reference baselines, providing a useful tool for comparison purposes. Assumptions made at each stage and emission category will be elaborated upon in the later sections, offering a comprehensive understanding of the methodology and approach used in the Coffee Supplier Emission Toolkit.

Decision flows

As mentioned earlier, the Coffee Supplier Emission Toolkit is specifically designed to generate emission figures for a coffee farm, even when detailed data on resource use is limited. The calculator utilizes decisional flows tailored to each emission category.

Farm characteristics

The first section of the Coffee Supplier Emission Survey gathers information about basic farm characteristics. These include: *country of origin*, *farm size* (in ha), *coffee yields* (in kg per year), *coffee type* (cherry or green beans). Additionally, farming style can be selected between *unshaded monoculture*, *shaded monoculture*, and *shaded polyculture*.

To handle missing data, some simplifications are made by the model:

- When information is lacking on the use of shade trees, farms are assumed to use conventional monoculture practices.
- Agroforestry farms are considered as those including shade trees, regardless if they are polycultures or simply shaded monocultures.
- Farm size is set to 1 ha whenever farm size is unknown.
- When coffee yields are unknown, an average value is present according to fertilization type (Table 2).



Table 2. Average coffee yields for different fertilization types. Data was converted from Noponen et al. (2012) according to conversion values reported in Table 1.

Fertilization type	Green coffee yields [kg/ha]
Conventional	1622.5
Organic	1237.5
Integrated	1430

Agricultural emissions

The model employed in this study is designed to estimate emissions for each category in cases where data is not directly available from survey responses. Decision flows are incorporated into the model to evaluate the availability of data at each step. For instance, Figure 1 illustrates how fertilizer emissions are calculated or estimated by the model. This user-friendly and practical approach ensures that emission figures can be obtained even when specific data is missing.

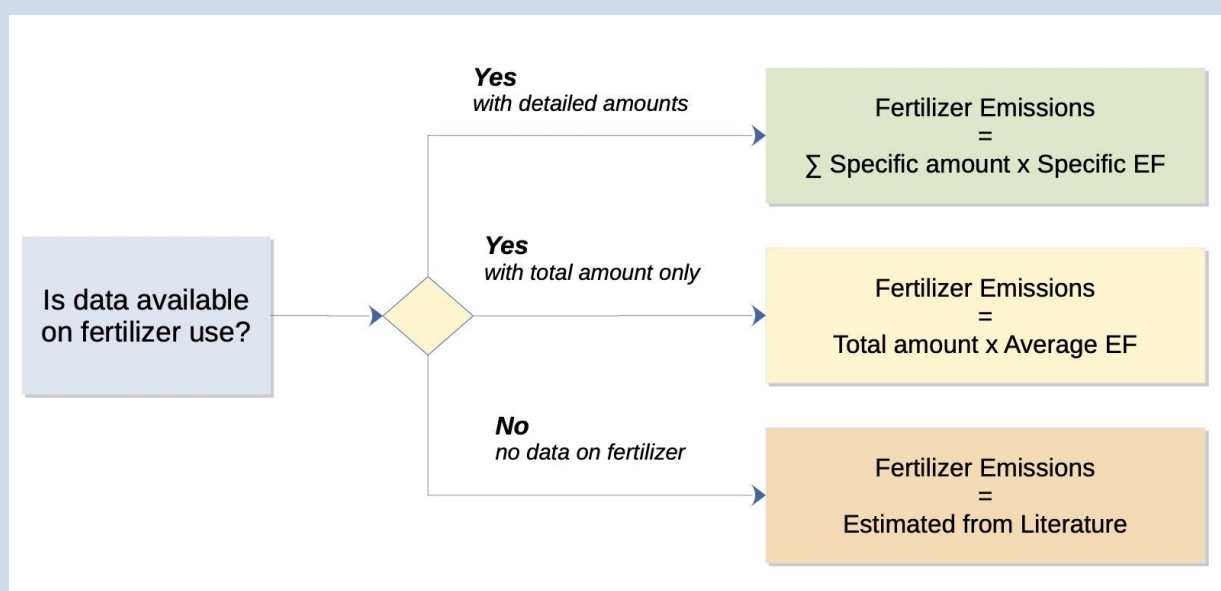


Figure 1. Decisional flow for fertilizer emissions calculated or estimated by the Coffee Supplier Emission Calculator.

Similar estimation processes are applied to other emission categories, as outlined in Figure 1. In the subsequent sections, more detailed information will be provided on the assumptions made and the reference emission factors used for each category. This comprehensive approach will offer a thorough understanding of the emission calculation process and the sources that contributed to deriving the emission factors. By combining available data and estimation techniques, the model delivers a robust and informative tool for estimating GHG emissions from coffee farms, contributing to better understanding and management of the carbon footprint in the coffee industry.

Coffee Supplier Emission Calculator

The main stages of green coffee production included in this model are Agriculture, Intermediate, Milling, and Export. The following sections will explain the main influencing factors and emissions categories associated with each production stage.

Agriculture

Significant differences were found in the reporting of agricultural emissions across the literature, with some studies being more detailed and explicit while others providing less clear data. After reviewing the selected studies on coffee GHG emissions, data was organized according to most relevant *influencing factors* and *emission categories* found across studies (Table 3).

The chosen influential factors for the study were the farming style (monoculture or agroforestry) and the type of fertilization (conventional, organic, or integrated). Some papers also provided information on farm management, specifically related to fertilization input, which was further categorized as low-input, moderate, or intensive (Flysjö, 2006; Noponen et al., 2012; Hassard et al., 2014; Vera-Acevedo et al., 2016; Ortiz-Gonzalo, 2018; Trinh et al., 2020). However, farm management was ultimately excluded from the model for two reasons. First, only a limited number of studies provided sufficient data on resource use intensity to categorize it accurately. Second, due to time constraints, it was not feasible to harmonize and categorize farm management data into consistent ranges of low-input, moderate, or intensive. Although farm management can have significant implications for fertilizer-related emissions, the lack of comprehensive data and time constraints prevented its inclusion in the model. The focus of the study remained on the primary influential factors of farming style and fertilization type.

The study identified several emissions categories, including Synthetic and Organic fertilizers, Water, Fossil fuels, Electricity, Lime, and Pesticides. However, only one paper provided comprehensive data on GHG emissions from Materials and Transport within the farm (Noponen et al., 2012). Unfortunately, the significance of this category across the dataset was poor, leading to its exclusion from the model.

In the following sections, each emission category will be described in detail, including the factors considered and the methods used to gather and harmonize the main figures.



Table 3. Main influencing factors and emissions categories for agriculture GHG emissions of the coffee supply chain.

Influencing factors	Options	Emission categories
Farming style	Monoculture Agroforestry	• Synthetic fertilizers • Organic fertilizers • Water • Fossil fuels • Electricity • Lime • Pesticides
Fertilization type	Conventional Organic Integrated	

The data input from the Google Form was categorized based on the influencing factors and emissions categories outlined in Table 2. This categorization served two main purposes: first, it allowed for the estimation of greenhouse gas emissions from green coffee production even when partial or incomplete data were available. By utilizing the provided influencing factors and emissions categories, a reasonable estimation of emissions could be derived for coffee suppliers. Second, the categorized data enabled a comparison of coffee supplier emissions with regional or national values obtained from the literature. This comparison provided valuable insights into the emissions performance of coffee suppliers in relation to broader regional or national benchmarks. Overall, the categorization of data based on Table 2 facilitated the estimation of emissions and facilitated meaningful comparisons with existing literature on coffee supplier emissions.

Assumptions made during data categorization

- If no data on fertilization and farming style was provided, reported agricultural emissions were considered to be of conventional monoculture systems.
- Organic systems were considered as the ones with no use of synthetic fertilizers and pesticides.

Estimating emissions from agriculture

Emissions from the agricultural stage result from the sum of the emissions categories highlighted in table 2. A detailed explanation of how each category is calculated is provided in the following sections.

Reference average values for agricultural emissions obtained from the literature review are reported in Table 4. These were used for two main purposes:

- Creating a national or regional reference value to use as a comparison for coffee supplier emissions
- Estimate GHG emissions from the agricultural stage in all cases where accurate data is not available

Table 4. Average GHG emissions in coffee agriculture for different countries of origin. Values are reported in kg CO₂e / kg green coffee for different farming styles (agroforestry or monoculture) and fertilization types (organic, integrated, conventional).

Origin	Agroforestry			Monoculture		
	Organic	Integrated	Conventional	Organic	Integrated	Conventional
Brazil	0.050	0.983	1.632	1.479	3.368	3.521
Vietnam	0.090	0.876	1.265	0.641	0.726	2.292
Costa Rica	0.878	0.935	1.552	1.002	2.281	2.385
Nicaragua	0.970	0.740	1.228	1.343	1.628	1.702
Mexico	0.567	0.667	1.107	1.410	2.013	2.104
Kenya	2.544	2.713	6.441	3.335	3.230	9.888
Colombia	0.372	0.326	0.541	1.877	4.274	4.468
Honduras	0.567	0.667	1.107	1.564	3.563	3.724
Tanzania	1.492	1.591	3.776	1.955	4.453	5.797
India	0.727	2.271	3.360	1.477	2.703	6.088
Indonesia	0.306	0.826	1.165	0.363	0.983	2.110
Thailand	0.155	1.883	2.719	0.315	1.928	4.927
El Salvador	0.209	0.258	0.428	0.388	0.884	0.924
Guatemala	0.202	0.616	1.023	0.375	2.112	2.208
AVERAGE						
Latin America	0.477	0.649	1.077	1.180	2.515	2.630
Asia	0.319	1.464	2.127	0.699	1.585	3.854
Africa	2.018	2.152	5.108	2.645	3.842	7.842
Total Average	0.652	1.096	1.953	1.252	2.439	3.724
Legend	Description					
	Estimated from ratios to conventional farming within agroforestry or monoculture category.					
	Estimated from ratios between agroforestry and monoculture for a corresponding fertilization type.					

The cell colors in Table 4 indicate that some assumptions had to be made to calculate a given value. A complete explanation of statistical assumptions made to obtain the final figures is included in the calculator tab “Adjusted Agriculture”. Table 4 can be interpreted as follows:

- **No color:** Represents the average value of data entries available from the literature review, providing a general estimate of emissions for the specified country and fertilization type combination.
- **Yellow:** Indicates that emissions for a specific country and fertilization type combination were inferred from average ratios calculated within the farming style category. This means that the emissions were estimated based on the average emissions ratio observed within the same farming style category, such as organic agroforestry versus conventional agroforestry.
- **Green:** Represents emissions for a particular country and fertilization type combination calculated based on the difference observed with the same combination in the opposite farming style category. For example, emissions for organic agroforestry are compared to emissions for organic monoculture to determine the emissions difference.

Average emissions values for the macro regions of Latin America, Asia, and Africa were calculated based on the inferred values from the specific countries within each region.

Fertilizer emissions

GHG emissions generated along the supply chain of fertilizers are mainly due to production, storage, transportation and application (Walling & Vaneckhaute, 2020). For the purpose of this study only emission from the released during the production and the post-application of fertilizer were considered.

Fertilizer emissions at the production phase are mainly due to the energy-intensive manufacturing processes involved in producing synthetic fertilizers . These processes typically rely on fossil fuel combustion, which releases greenhouse gasses into the atmosphere. Additionally, the production of nitrogen-based fertilizers can result in the release of nitrous oxide (N₂O), a potent greenhouse gas, during chemical reactions and manufacturing (Walling & Vaneckhaute, 2020).

Emissions generated after fertilizer application are primarily due to the subsequent interactions between the fertilizer and the soil. Nitrogen-based fertilizers, in particular, can undergo processes such as nitrification and denitrification in the soil, leading to the production and release of nitrous oxide (N₂O). In both conventional and organic agriculture, post-application emissions can be the largest contributor to GHG emissions from farms (Walling & Vaneckhaute, 2020).

Synthetic fertilizers

In this study, emissions from synthetic fertilizer included emission from production and application. Reference values used in the Calculator are shown in Table 5.

Table 5 Emission from synthetic fertilizer production and application. Average values for production were calculated from Hoxha & Christensen (2019). Average values for application were calculated from Quiñones-Huatangari et al. (2022).

Synthetic Fertilizer	GHG emissions [kg CO ₂ e / kg product]		
	Production	Application	Total
Urea	1.837	2.436	4.273
Ammonium nitrate	2.316	0.996	3.312
Calcium nitrate	1.933	0.357	2.29
Polymer coated urea	1.837 ^a	0.489	2.326
Urea Ammonium Nitrate	1.639	1.716 ^b	3.355
Average	1.912	1.199	3.111

^a Production assumed equal to urea
^b Application as an average of urea and ammonium nitrate

The total carbon footprint of synthetic fertilizer production (in kg CO₂e / kg product) was obtained as an average of regional values reported by Hoxha & Christensen (2019).

Emissions from fertilizer application were instead calculated from the N₂O emissions provided by Quiñones-Huatangari et al. (2022). Emissions N₂O in kg N per kg N applied were calculated as the ratio between yearly emission per ha and fertilization rate. To convert these to kg of N₂O, the following formula was utilized:

$$1 \text{ kg N}_{2\text{O}}_N = \frac{44}{28} \cdot 1 \text{ kg N}_{2\text{O}} = 1.57 \text{ kg N}_{2\text{O}} \quad (1)$$

Application emissions per kilogram of product were then calculated based on the nitrogen content of each synthetic fertilizer¹. Lastly, N₂O emissions were converted to CO₂e using the global warming potential of N₂O, which is 273 times that of carbon dioxide.

¹N content: Urea - 0.46, Ammonium nitrate - 0.335, Calcium nitrate - 0.27, Polymer coated urea - 0.46



Organic fertilizers

For the purpose of this study, emissions from organic fertilizers were only considered to be derived from the application of the compounds. The production emissions of organic fertilizers were not included in the analysis. It is worth noting that emissions from compost production are often considered to be biogenic and therefore do not contribute significantly to global warming (Walling & Vaneeckhaute, 2020). This is also true for the production of animal manures. The challenges of allocating GHG emissions from manure production have been previously described and addressed by some authors (Dalgaard & Halberg, 2007). In this study, emissions from manure production were not considered as they were assumed to be allocated to animal production only.

Emission factors for application of manures and slurries were retrieved from Walling & Vaneeckhaute (2020). Average values were obtained by regrouping each manure type according to the categories listed in Table 6. Emission figures expressed in kg CO₂e / kg N were converted to kg CO₂e / kg product by multiplying them by the average nitrogen content of each organic fertilizer type. Nitrogen content data was sourced from Warrick (2023) for animal manure, Timsina (2018) for green manure, and Sullivan et al. (2018) for compost.

Table 6. Application emissions factors and nitrogen content for different organic fertilizers. Emissions per kg of fertilizer used are obtained as the product of the average EF expressed in kg CO₂e / kg N by the specific nitrogen content. "Other organic" is an average of all organic types.

Organic fertilizer	Average EF [kg CO ₂ e / kg N]	Nitrogen Content [%]	EF [kg CO ₂ e / kg product]
Cattle manure	2.932	0.015	0.044
Pig manure	5.904	0.006	0.035
Poultry manure	4.54	0.021	0.095
Green manure	3.8	0.018	0.069
Mixed manure	3.715	0.014	0.052
Compost	0.88	0.015	0.013
Other organic	3.629	0.015	0.051

Due to the monogastric nature of pigs, the manure they produce generally contains a greater proportion of biodegradable carbon compared to ruminant manure, such as cattle manure (Dennehy et al., 2007). Consequently, pig and poultry manure application emissions were found to be higher compared to cattle manure. Total emissions from cattle manure may be higher than non-dairy manure if production emissions are allocated to manure use (Walling & Vaneeckhaute, 2020).



Estimating fertilizer emissions

When no data on fertilizer use is provided by the user, total fertilizer emissions are estimated from average shares obtained from the literature review. Differences between regions, farming style and fertilization type are shown in Table 7.

Table 7. Fertilizer share of coffee agricultural emission for agroforestry and monoculture systems, under organic, integrated and conventional management.

	Agroforestry			Monoculture		
Region	Organic	Integrated	Conventional	Organic	Integrated	Conventional
Latin America	66.66%	87.31%	90.43%	69.00%	83.10%	89.33%
Asia	48.71%	88.15%	92.22%	69.17%	83.10%	92.87%
Africa	58.97%	85.63%	90.31%	69.10%	83.10%	89.67%
Total Average	58.97%	87.31%	90.91%	69.10%	83.10%	90.01%

Thus, final emissions from synthetic fertilizers (E_{syn}) and organic fertilizers (E_{org}) are obtained as:

$$E_{syn} = E_{agr} \cdot s_{fer} \cdot q_{syn} \quad (2)$$

$$E_{org} = E_{agr} \cdot s_{fer} \cdot q_{org} \quad (3)$$

where E_{agr} is total estimated emission from agriculture (Table 4), s_{fer} is the fertilizer share of agricultural emissions (table x) and q_{syn} and q_{org} are the usage quotas for synthetic and organic fertilizer. No use of synthetic fertilizer was assumed in organic farms ($q_{org} = 1$), while an average value of 41.49% was used for integrated systems. For conventional farming, all fertilizer emission are allocated to synthetic fertilizers ($q_{org} = 0$ or $q_{syn} = 1$).

Fuel and electricity

When respondents provide information on fuel consumption in the survey, emissions from fuel are calculated by multiplying the reported amount for each fuel by the corresponding emission factor. The emission factors for diesel, petrol, biodiesel, and LPG were obtained from Defra (2022). In cases where fuel consumption is not reported, average emission values for fuel emissions per kilogram of green coffee were obtained from the literature review. Approximately 31.11% of the data points included specific emission figures for fuels, with average values of 0.065 and 0.082 kg CO₂e/kg green coffee for organic and conventional farms, respectively.



Emissions from electricity were estimated by multiplying the electricity consumed at the farm by the national emission intensity of electricity. In cases where data on electricity consumption was missing or unknown, an average value of 328.89 kWh/ha was used based on the study by Coltro et al. (2006). The carbon intensity of electricity was obtained from Our World in Data (2023) and filtered for the year 2022 in coffee producing countries.

Lime and pesticides

In coffee agriculture, emissions in relation to pesticides come from their application and production processes. Pesticide application involves emissions from handling and application, while pesticide production contributes to emissions through energy-intensive synthesis and the use of fossil fuels. These emissions have implications not only for greenhouse gasses but also for ecological toxicity and biodiversity. Similarly, lime usage in coffee agriculture, primarily as a soil amendment, leads to emissions during its production. Lime is produced by heating calcium carbonate in a kiln, releasing carbon dioxide from the combustion of fossil fuels. The amount of emissions from lime can vary depending on production methods, energy sources, and transportation. Coffee producers should consider the environmental impact of pesticide and lime usage, exploring sustainable alternatives to minimize emissions while maintaining soil health and productivity.

Table 8. Emission factor used for pesticides, expressed per kg of green coffee.

Farming style	kg CO2e / kg green	Notes
Conventional	0.061	Average from literature review
Organic	0.014	Average from literature review
Integrated	0.037	Average of conventional and organic

Pesticide emissions were reported in 16.67% of the data collected, and reference values used by the model as shown in Table 8. Lime emissions were reported in 6.67% of the data, and the average value found was 0.259 kg CO2e per kg of green coffee.



Out of boundaries

The calculations do not account for the following factors:

- Emissions from crop residues or prunings management: Some studies reviewed did not provide comprehensive data on greenhouse gas (GHG) emissions associated with crop residues or prunings. Therefore, emissions released from these sources were not considered in order to maintain comparability across the dataset (Nojonen et al., 2012; Van Rikxoort et al., 2014).
- Emissions from land use change: Although previous findings have indicated that emissions from land use change can be significant in certain cases (SuFu, 2021b), they were not included in the calculations due to variations in their reporting across studies.
- CO₂ sequestration: The estimation of CO₂ sequestration was not included in the calculations due to insufficient data available in the literature review. A separate review may be conducted in the future to assess the feasibility of integrating CO₂ sequestration analysis within shaded and unshaded coffee systems.

Intermediate emissions

Intermediate emissions were considered in the study to cover GHG emissions arising from:

- Sorting of coffee before or after the milling process.
- Transportation of coffee cherries from the farm to coffee mill facilities.

As only one paper (Adiwinata et al., 2021) provided specific data on sorting emissions, sorting emissions were disregarded. Thus, this stage primarily accounts for emissions resulting from transportation from farm to mill. On average, the intermediate emissions were found to be 0.034 kg CO₂e per kg of green coffee. This value was applied to all farms that reported transporting their coffee cherries to off-farm milling facilities.



Milling

Milling is the process of separating coffee cherries from green coffee beans. It involves removing the outer layers of the cherry, such as the skin, pulp, and parchment, to reveal the green coffee beans. The post-harvest steps typically involved in this conversion are depulping, fermentation and washing, drying, and hulling. At this stage, the coffee cherries have undergone processing and transformed into green coffee beans, which are the raw, unroasted form of coffee beans.

Emissions factor for the milling stage are reported in Table 9. In this study three main types of milling were considered:

- *Wet Milling Process*: coffee cherries are first pulped and then fermented in water to break down the remaining pulp. After fermentation, the beans are washed to remove any residual pulp and are then dried to the desired moisture content. Wet milling is commonly used in regions with access to ample water resources.
- *Dry Milling Process*: coffee cherries are dried in the sun or using mechanical dryers until they reach the desired moisture content. Once dried, the outer skin and parchment layer surrounding the coffee bean are removed through hulling. Dry milling is often used in areas with limited water availability or where natural sun drying conditions are favorable.
- *Semi-Wet Milling Process*: coffee cherries are pulped like in wet milling, but instead of undergoing full fermentation, they are partially dried immediately after pulping. This intermediate drying stage reduces the water content before completing the drying process. Semi-wet milling is practiced in regions where both wet and dry milling methods are used, offering a balance between water usage and processing efficiency.

Apart from the influence on coffee flavor and quality, various milling processes can result in distinct greenhouse gas (GHG) emissions. Wet milling tends to generate higher emissions compared to dry milling, while the semi-wet process falls between the two. This discrepancy can be attributed to factors such as methane emissions resulting from inadequate wastewater treatment (Killian et al., 2013), as well as greater consumption of gasoline and electricity (Rahmah et al., 2023). Fuel is primarily utilized during pulping and hulling, while electricity powers the water supply for washing activities.

Table 9. Emission factors for dry, wet and semi-wet milling processes.

Milling Process	kg CO2e / kg green coffee	Notes
Dry	0.140	Average from literature review
Wet	0.629	Average from literature review
Semi-wet	0.178	Average from the above



Limitations

Milling data accounted for 64 data points, representing approximately 71% of all entries in the model. Among these, information on dry, wet, and semi-wet milling was found in 12.50%, 70.31%, and 17.19% of the milling data points, respectively. While several studies have provided data on wet milling emissions, literature data appeared limited for dry and semi-wet milling. Therefore, future reviews of additional literature may enhance the model's validity.

The model currently offers a straightforward CO₂ emission estimation for the milling process by solely knowing the type of milling process. However, this simplicity may come with a trade-off in accuracy, as milling emissions can also depend on the energy consumed at the milling facility in terms of fuel and electricity. To improve the model, future enhancements could include additional questions about energy consumption at the milling facility. This would allow for accounting for grid emission intensity during the milling process, providing more refined estimates for coffee produced in different countries.

It is essential to note the high variability in milling practices, with some growers using minimal electricity to power coffee mills (Fauzi et al., 2019). Even considering the maximum values found in the literature, emissions from electricity consumption during milling would range from 0.003 to 0.182 kg CO₂e / kg green coffee, with an average of 0.084 kg CO₂e / kg green coffee. Similarly, for fuel consumption, assuming all fuel used is diesel, GHG emissions from fuel use vary from 0.013 to 0.160 kg CO₂e / kg green coffee, with an average of 0.095 kg CO₂e / kg green coffee. Indeed, while variations in energy consumption during the milling process can influence emissions, the overall impact may be relatively contained compared to more significant emission categories, such as fertilizer use.



Export

Export emissions were calculated for each coffee-producing country by considering the following factors:

1. Land transportation from the farm to the main national port.
2. Shipping to Europe.
3. Land transportation to Denmark.

It was assumed that:

- The starting point for land transportation within the country of production is the country's center point. This approximation was made to simplify data handling from the Google Form questionnaire.
- Shipping routes are calculated from the main national port of the coffee-producing country to the port of Rotterdam, Netherlands. This is due to the high significance of the port as a major entry hub for imported products into Europe.
- Land transportation from Rotterdam to Denmark is conducted by truck.

Limitations

The approach employed to estimate emissions from coffee exportation is susceptible to inaccuracies stemming from the assumptions made. In the model, there is a possibility of overestimation or underestimation when selecting the starting point location, port of departure, or port of arrival for a specific farm. However, we deemed the resulting error to be acceptable since, on average, export emissions represented approximately 12.39% of the total emissions from green coffee.

Future versions of the model have the potential to incorporate more precise location functions, such as the integration of map API services.



Model Limitations

The presented model offers several advantages for DGCC's work in the coffee industry. Firstly, the Coffee Supplier Emission Survey provides a user-friendly data collection form that respondents can easily complete with minimal time and cognitive effort. Secondly, the Coffee Supplier Emission Calculator enables estimations of GHG emissions for coffee farms, even in cases where detailed data on fertilizer use and other relevant resources may be scarce or unavailable.

However, it is important to acknowledge that the simplicity and adaptability of the Toolkit may result in reduced accuracy, particularly in situations where data is lacking. This can be especially true for smallholder coffee growers, as highlighted by Ortiz-Gonzalo et al. (2018). GHG emissions in smallholder farms may be significantly lower than what is estimated by GHG calculators, and commonly used emissions factors may not be suitable for tropical countries and small farm contexts (Ortiz-Gonzalo et al., 2018). Furthermore, when compared to field measurements, GHG calculators may overestimate certain emission sources (Ortiz-Gonzalo et al., 2017).

Additionally, it is important to note that the current model does not incorporate the intensity of farm management practices, primarily due to limited data availability and time constraints for accurately categorizing farm management intensity. According to Quiñones-Huatangari et al. (2022), N₂O emissions in coffee plantations seem to be directly proportional to the fertilization rate. However, this limitation can be mitigated if precise data on resource use, particularly fertilization intensity, is provided by the coffee growers. Future improvements to the model could include an additional component that accounts for fertilization intensity at the farm level, thereby enabling a more comprehensive assessment of GHG emissions from green coffee.

Despite these limitations, based on the extent of the research conducted, we maintain that the Coffee Supplier Emission Toolkit can provide a valuable preliminary assessment of GHG emissions in green coffee production, aligning with the current scientific literature.

Therefore, we endorse the utilization of the toolkit and propose transparent communication of the study's findings and underlying assumptions. It is crucial to openly share the results, as well as the limitations and uncertainties associated with the toolkit, to promote a robust understanding of the GHG emissions in green coffee production. Transparent reporting enhances the credibility and allows for informed decision-making by stakeholders in the coffee industry.

Recommendations

Fertilizer Use and Management

Fertilizer use in coffee production plays a significant role in achieving high yields, but it can also contribute to greenhouse gas emissions, particularly through the release of nitrous oxide (N₂O) and carbon dioxide (CO₂). Implementing sustainable practices and optimizing fertilizer use can help reduce emissions and mitigate environmental impact.

Organic Fertilizers

One effective strategy to reduce carbon emissions associated with fertilizer use is to promote the use of organic fertilizers. Organic fertilizers, such as compost, animal manure, and coffee pulp, can provide essential nutrients to coffee plants while minimizing the release of greenhouse gasses. Consider the following suggestions:

- Encourage farmers to adopt composting practices and establish composting facilities on coffee farms.
- Promote the use of coffee pulp as a nutrient-rich organic fertilizer. The complementation of fertilizer application with coffee pulp has been shown to provide significant reduction in carbon emissions and energy demand at the farming stage (Rahmah et al., 2023).
- Provide training and education to farmers on proper application rates and timing of organic fertilizers.

Precision Fertilizer Management

Precision fertilizer management focuses on optimizing nutrient application by considering the specific needs of each coffee farm. This approach minimizes fertilizer waste and reduces greenhouse gas emissions. Key recommendations include:

- Conduct soil testing to determine the nutrient status of the soil and adjust fertilizer application accordingly.
- Implement site-specific nutrient management plans that consider soil characteristics, plant requirements, and environmental conditions.
- Use technologies such as remote sensing and geographic information systems (GIS) to monitor nutrient levels and apply fertilizers precisely where needed.



Milling and Processing

Coffee milling and processing involve various energy-intensive steps, including pulping, fermentation, drying, and hulling. Implementing energy-efficient practices and utilizing renewable energy sources can significantly reduce carbon emissions in the milling and processing stages.

Energy Efficiency Measures

Improving energy efficiency in coffee milling and processing can help minimize the carbon footprint of these operations. Consider the following strategies:

- Install energy-efficient machinery and equipment.
- Optimize the sequencing and timing of milling processes to minimize energy consumption.
- Implement heat recovery systems to capture and reuse waste heat.

Renewable Energy Integration

Shifting to renewable energy sources can further reduce carbon emissions in coffee processing. Some suggestions for utilizing renewable energy include:

- Install solar panels on milling facilities to generate electricity.
- Utilize biomass energy from coffee waste or other sustainable biomass sources.
- Explore opportunities for collaborating with local renewable energy providers.

Fuel Consumption and Transport

Fuel consumption and transportation in coffee production contribute to carbon emissions. Implementing efficient fuel use and adopting sustainable transport practices can help reduce the industry's environmental impact.

Equipment and Machinery

Optimizing fuel use in coffee production machinery and equipment is crucial for carbon reduction. Here are some recommendations:

- Upgrade old and inefficient machinery with newer, more fuel-efficient models.
- Regularly maintain and tune equipment to ensure optimal fuel efficiency.
- Explore alternative fuels, such as biodiesel, for machinery operation.



Sustainable Transport

Efficient transport logistics and alternative transportation methods can contribute to lowering carbon emissions in coffee production. Consider the following strategies:

- Optimize route planning to minimize transportation distances.
- Promote collective transport or shared logistics to reduce the number of individual vehicles.
- Encourage the use of low-emission vehicles or electric vehicles for transporting coffee beans.

Irrigation Management

Effective irrigation management is crucial for optimizing water use and reducing carbon emissions associated with coffee production. Implementing efficient irrigation systems and practices can help conserve water and minimize energy requirements.

Water-efficient Irrigation Systems

Investing in water-efficient irrigation systems can significantly reduce the amount of water and energy needed for coffee production. Consider the following strategies:

- Implement drip irrigation systems that deliver water directly to the plant roots, minimizing water loss through evaporation.
- Utilize sensor-based irrigation technologies to monitor soil moisture levels and provide precise irrigation scheduling.
- Promote the use of rainwater harvesting systems to supplement irrigation water requirements.

Soil Moisture Monitoring and Water Conservation

Monitoring soil moisture levels and adopting water conservation practices can further enhance irrigation efficiency and reduce carbon emissions. Some suggestions include:

- Install soil moisture sensors in coffee fields to monitor moisture levels and avoid overwatering.
- Encourage farmers to practice mulching, which helps retain soil moisture and reduce evaporation.
- Provide training on proper irrigation scheduling and techniques to ensure optimal water use.



Lime Use Management

Emission reduction strategies for lime use and management in coffee agriculture focus on minimizing greenhouse gas (GHG) emissions associated with lime production and application. Lime is commonly used to improve soil pH and nutrient availability, but its production process can be energy-intensive and result in significant carbon emissions. This section provides some key strategies to reduce emissions related to lime use.

Lime Production Methods

- Promote the use of energy-efficient technologies and practices during lime production. This can include adopting cleaner energy sources, optimizing kiln design and operation, and implementing energy-saving measures to minimize emissions during the manufacturing process.
- Explore alternative sources of lime that have lower carbon footprints. For example, using locally sourced limestone or byproducts from other industries can reduce transportation emissions and lower the overall environmental impact of lime use.

Lime Application Methods

- Implement precise and efficient lime application methods to minimize wastage and ensure optimal use. This can include site-specific application based on soil testing, using equipment that provides uniform coverage, and avoiding excessive application.
- Combining lime application with organic amendments, such as compost or biochar, can enhance soil health and nutrient retention. Organic amendments can reduce the need for lime application and synthetic fertilizers, leading to lower GHG emissions.

Pesticide Use and Management

Pesticides play a vital role in protecting coffee crops from pests and diseases, but their use can contribute to environmental pollution and carbon emissions. Adopting integrated pest management (IPM) practices and reducing pesticide use can help mitigate these impacts.



Integrated Pest Management

Integrated pest management combines various pest control methods to minimize pesticide use while effectively managing pests. Key strategies to reduce pesticide use include:

- Implement biological control methods, such as the introduction of beneficial insects or the use of microbial agents.
- Encourage biodiversity on coffee farms to enhance natural pest control.
- Train farmers on pest identification, monitoring, and the use of non-chemical pest control measures.

Organic and Low-toxicity Pesticides

Promoting the use of organic and low-toxicity pesticides can minimize the environmental impact associated with chemical pesticides. Consider the following suggestions:

- Provide information and training on the availability and benefits of organic and low-toxicity pesticide alternatives.
- Support the development and dissemination of locally adapted pest management solutions.
- Encourage certification programs that promote sustainable and environmentally friendly pest control practices.

Coffee yields

The carbon footprint (CF) of coffee can exhibit interannual fluctuations, despite the consistent application of inputs per hectare by farmers. This variation is primarily attributed to the fluctuating yields experienced within a specific farm over different years. Consequently, enhancing resource use efficiency and agricultural productivity becomes crucial for reducing the carbon footprint of agricultural products (Birkenberg & Birner, 2018).

To obtain more precise emission figures, it is advisable to collect data and conduct repeated analyses over multiple consecutive years. This approach allows for a more comprehensive understanding of the temporal dynamics and trends associated with the carbon footprint of coffee production. By considering data from various years, it becomes possible to capture the variability and identify patterns that can inform targeted strategies for emission reduction and sustainability improvements.



Agroforestry

Although some authors have assessed the potential for carbon sequestration in agroforestry systems (Andrade et al. 2014; Zaro et al. 2020; Lugo-Pérez et al. 2023), very few studies report both emissions sequestered by trees on-farm while at the same time considering the emissions due to nitrogen release from crop residues or prunings. This may be also related to the lack of precise guidelines when considering carbon stock and sequestration rate from farming activities which are different from land use changes (PAS 2050, 2011).

Nonetheless, the literature review conducted by SuFu showed that a significant difference in GHG emissions was found across coffee production systems which included trees in their fields.

Report communication statement

If questioned about the results this report, we recommend the following statement about the method used and the results:

'We, Damn Good Coffee Company commissioned SuFu ApS, an external consulting agency, to develop the Coffee Supplier Emission Calculator in accordance with the GHG Protocol. The main sources of emissions included in this model are related to agriculture, milling, transport and intermediate.. We have been transparent with our data throughout the process, and SuFu has provided us with an accurate account of coffee production emissions from an extensive literature review comprising more than 30 papers. The Coffee Supplier Emission Calculator was produced in accordance with the principles and guidelines of the WRI GHG Protocol. We are now working to reduce and offset our emissions throughout our supply chain.'

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