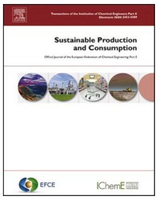
Sustainable Production and Consumption 47 (2024) 251–266

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc



Research Article

Unravelling life cycle impacts of coffee: Why do results differ so much among studies?

C. Chéron-Bessou [a,b,*], I. Acosta-Alba [c], J. Boissy [d], S. Payen [a], C. Rigal [a,e], A.A.R. Setiawan [f], M. Sevenster [g], T. Tran [h], A. Azapagic [i]

[a] CIRAD, UMR ABSys, Elsa Group, Av. Agropolis, F-34398 Montpellier, France
[b] James Cook University, PO Box 6811, Cairns, QLD 4870, Australia
[c] EvaLivo, Independent Consultant, F-02100 Saint Quentin, France
[d] Agro-transfert Ressources et Territoires, 80200 Estrées-Mons, France
[e] ICRAF, Vietnam office, Hanoi, Viet Nam
[f] Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency (BRIN), 15314 Tangerang, Selatan, Indonesia
[g] CSIRO, Black Mountain Science and Innovation Park, ACT 2601, Canberra, Australia
[h] CIRAD, UMR Qualisud, Elsa Group,73 rue JF Breton, F-34398 Montpellier, France
[i] Sustainable Industrial Systems, Department of Chemical Engineering, The University of Manchester, M139PL Manchester, UK

ARTICLE INFO

Editor: Prof. Shabbir Gheewala

Keywords:
Agriculture
Carbon footprint
Coffee
Environmental impacts
Life cycle assessment

ABSTRACT

Coffee beans are a major agricultural product and coffee is one of the most widely traded commodities and consumed beverages globally. Supply chains and cropping systems are very diverse, with contrasted potentials and performance, as well as environmental impacts. Life Cycle Assessment (LCA) studies are needed to inform on reduction in impacts, but there is a lack of comprehensive understanding of the variability of existing LCA results and impacts of the cropping systems and their trade-offs along the supply chains. In an attempt to address this knowledge gap, the paper presents a systematic literature review of coffee LCA, considering a total of 34 studies covering 234 coffee systems. Global warming potential (GWP) was the impact category most reported in the literature, but the results varied greatly at both the farm and drink levels. For the former, the GWP values ranged from 0.15 to 14.5 (median: 3.6) kg CO_2 eq./kg green coffee beans and for the latter the values ranged from 2 to 23 (median: 8.8) kg CO_2 eq./kg consumed coffee in drinks. Main contributors to the GWP of production of green coffee beans were land use change (LUC), fertilisers and wet processing. However, there were great inconsistencies across studies in terms of LUC accounting, field emissions and wet process modelling. Green coffee beans production was also the main contributor to the GWP of coffee consumed, followed by brewing and coffee cup washing. Some studies covered other impacts, in addition to GWP. At both the farm and drink levels, fertilisers and pesticides were the main contributors to eutrophication and acidification, and to ecotoxicity, respectively. Brewing was the second main contributor at the drink level, in some cases the top contributor for energy-related indicators. Assumptions on packaging, cup washing and waste disposal were highly variable across studies. Water impact indicators were hardly comparable due to the system variability and method inconsistencies. Given the large diversity of coffee cropping systems worldwide, but also the diversity of possible coffee drinks, we recommend that LCA studies be standardised with respect to the definition of the functional unit, including consistent quality aspects for both green coffee beans (moisture) and coffee drinks (organoleptic properties). They should also be more thorough in detailing processes at all stages. More attention should be paid to the farming system complexity and a mass balance should be ensured when assessing biomass flows concerning LUC, co-products and residue emissions. Finally, more primary data would be needed to decipher the cropping system diversity, as well as to characterise emissions from all inputs to the field and bean processing, notably for wet and semi-wet processing.

---

[*] Corresponding author at: CIRAD, UMR ABSys, Elsa Group, Av. Agropolis, F-34398 Montpellier, France.
E-mail address: cecile.bessou@cirad.fr (C. Chéron-Bessou).

https://doi.org/10.1016/j.spc.2024.04.005
Received 28 December 2023; Received in revised form 3 April 2024; Accepted 3 April 2024

1. Introduction

Coffee is one of the most widely consumed beverages and one of the most traded commodities in the world (FAO, 2023). It is a "typical example of a global commodity" (Viere et al., 2011). Over the past ten years, the global coffee production has continuously increased by 1.1–2.4 % annually (Statistica, 2023), catching up with the long-term average growth rate of coffee consumption worldwide of 2.3 % over the period 1990–2018 (ICO, 2023). To meet the growing global demand, coffee production is expected to double by 2050 (Conservation International, 2020), potentially driving land use change (LUC) and deforestation and impacting on biodiversity and climate change. In its recent policies against "imported" deforestation (EU, 2023), the European Commission targeted coffee, among other global commodities, that pose such risks. Although the environmental concerns have pushed a rapid development of sustainability initiatives among coffee sector stakeholders (Noponen et al., 2012), it is still not clear how these initiatives help to reduce the impacts of coffee in practice.

Coffee is grown in the tropics and consumed all around the world, and in particular in Europe (54 %), Asia and Pacific (46 %), and North America (31 %) (ICO, 2023). Western Europe concentrates the coffee roasting industry, which produces roasted coffee consumed locally or exported to other regions (Hejna, 2021). The great diversity of agricultural systems in the tropics and the various trade routes give rise to very diverse supply chains with contrasted potentials and performance. Coffee can notably be grown in agroforestry plots, whose potential triggers interests in the application of Climate Smart Agriculture strategies to coffee production (Djufry et al., 2022; Gabiri et al., 2022). On the other hand, several studies have shown the climate sensitivity of coffee and the variable impact of climate change on coffee suitability, yield and farmers' livelihoods (Alemu and Dufera, 2017; Grüter et al., 2022; Rahn et al., 2014). Both mitigation and adaptation strategies require quantifying the performance and improvement opportunities, while accounting for the diversity of the production systems.

In this context, Life Cycle Assessment (LCA) studies of coffee products are needed to provide information on impact contributions and improvement pathways. LCA is a widely used methodology for quantifying environmental impacts as its holistic approach covers the whole supply chain and a number of environmental impacts. However, given the variability in coffee production systems, as well as in the LCA studies, the results vary significantly. Consequently, there is still a lack of comprehensive understanding of the impacts of various management systems and their trade-offs along the supply chains. Therefore, there is a need for an in-depth review of existing LCA studies, disentangling methodological aspects from the inherent variability of coffee systems. This article presents a systematic review of coffee LCA literature, investigating first the diverse supply chains and system boundaries, then the main impact drivers for the various system boundaries. The goal of the study is two-fold: i) to dissect the intrinsic system variability and its influence on the results, as well as to understand better the need for more knowledge and data for coffee LCA; and ii) to provide insights on how to increase comparability between coffee LCA studies and harmonise LCA practices for coffee and perennial cropping systems at large.

2. Methods

2.1. Literature review

We conducted a systematic review of coffee LCA studies available in the literature. The search was carried out on August 14, 2023 using the search strings: "coffee (Topic)" AND lca OR "life cycle a*" (Topic) with no further restriction on language. The Web of Science and Scopus yielded 147 and 172 outputs, respectively. The search on Google Scholar yielded 285 outputs despite being more restricted to avoid too many false outputs, using the search strings: "coffee lca" OR "coffee life cycle assessment" OR "coffee life cycle analysis" OR "lca of coffee" OR "life cycle assessment of coffee" OR "life cycle of coffee" OR "life cycle analysis of coffee" OR "life cycle analyses of coffee" in English only and without including references. The least Google relevant pages, *i.e.* the second half of output pages (Jansen and Spink, 2006), were filtered manually.

We further added studies dedicated to carbon footprint analyses (*i.e.* 92 outputs from Google Scholar on August 14, 2023 using the search strings "coffee carbon footprint" OR "carbon footprint of coffee"). Although we originally aimed at reviewing LCA studies only, carbon footprint studies were also relevant since i) they mostly are LCA-based, *i.e.* partial LCA studies; ii) they are more numerous as many studies focus on climate change issues only; and iii) they could provide significant insights on how this impact was calculated, providing further clues on data or methodological bottlenecks. On the other hand, we did not specifically add partial studies on water footprint since, contrary to carbon footprint, there are too many diverging methodologies potentially involved behind the "water footprint" term, including mostly non-LCA-based approaches.

Checks on search errors and duplicates led to a consistent corpus of 227 papers and reports. Then, publications were first filtered according to their goal and scope, and studies eliciting no specific system boundaries or coffee LCA results were discarded (76 %). Most of those discarded studies i) did not present LCA coffee results but rather inventories, sustainability assessment indicators, LCA-based water footprints, and so on (21 %); ii) focused on technologies, processing or packaging only (18 %); iii) were out of scope, such as reviews on biomass or LCA recommendations (15 %); and iv) considered recycling processes for coffee waste that entered the system with no environmental burden, *i.e.* not accounting for coffee production and processing (15 %). Spent ground coffee, in particular, was the focus of many recent publications, occupying about a half of the coffee-related LCA studies published in 2022–2023. The rest of the studies were related to chemical analyses of coffee waste (3 %), socio-economic aspects including consumers' views on LCA results (3 %), or were inaccessible (1 %).

An in-depth review resulted in further 18 studies being discarded because they were either partially inconsistent or redundant. The most common source of error or uncertainty in the paper quality was the lack of explicit field emissions modelling. In case of any doubt, we wrote to the authors to seek clarification. When sufficient clarifications were given, studies were kept in the final corpus.

In the case of theses (PhD and MSc), whose parts were also published as articles or book chapters, we consolidated all needed information from the various sources and only kept a unique reference associated with a given dataset to avoid any redundancy. We did the same in the case of papers published in conference proceedings which were further published as journal articles, or articles from the same authors providing complementary information on unique LCA studies. As a result of the various filters and consolidated information, the final corpus consisted of 34 examined studies: 29 journal articles, three public reports that had undergone an external peer review, one non-peer reviewed report, and one PhD thesis (Table S1). Altogether, roughly 76 % of the studies were published in the last ten years.

2.2. Data collection and analysis

The data collection included metadata on the studied countries, coffee species, farming systems and processing types. Impact values were recorded per functional units and sub-systems. Where necessary, results on impacts and contributing stages were extracted from figures using a free online tool (https://apps.automeris.io/wpd/). In some cases, we also re-calculated some results to harmonise the functional units, *i.e.* to convert acre- into hectare-based results or coffee drink- into volume or coffee weight-based results (see further comments in Section 3).

The analysis was straightforward based on simple descriptive statistics. Data exploration was carried out with R v.4.2.1 on R studio v.2023.06.2. (RStudio Team, 2023). We first analysed the consistency and reliability of studies in methodological terms, notably, regarding the data representativeness and scopes of the studies. Then, we investigated further the impact values. How detailed the systems were, and whether results were disaggregated or not, varied widely across studies. Finally, combining reflection on the methods and results, we made some recommendations in order to make better use of coffee LCA studies, as well as to how to improve future studies.

3. Results and discussion

The following sections first provide an overview of the goal and scope considered across the studies, starting with coffee origins and cropping systems, followed by details on the system boundaries and impact assessments (Section 3.1). Then, impact results are presented and discussed in Section 3.2 for the global warming impact and in Section 3.3. for the other most reported impact categories encountered across the studies.

3.1. Goal and scope of the reviewed coffee LCA studies

3.1.1. Coffee origins and cropping systems

The great majority of reviewed studies (25, covering 76 % of the studied coffee systems) investigated *Coffea arabica* sp.; four studies looked at *Coffea canephora* sp. Robusta (7 % of the studied systems); the remaining studies (5) considered both or did not specify (17 % of the studied systems); and none investigated *Coffea liberica* sp. (Fig. 1a). Although the dominance of arabica was relevant in the past, robusta's global share is getting close to half nowadays, *i.e.* 44 % of total coffee production in 2023 (ICO, 2023). Hence, robusta and other species were underrepresented in the studies. Central and South America was the most represented region with 72 % of all studied systems (Fig. 1b), including 18 % and 16 % for Colombia and Brazil alone, respectively (Fig. S1). This is aligned with this region representing about 70 % of the global coffee production (Rega and Ferranti, 2019). Costa Rica and Vietnam were also considered in various studies. From the main current producing countries, only Ethiopia and Uganda were not represented in the studies reviewed here. In some cases, the indicated countries of origin were not actually investigated. In Humbert et al. (2009), for instance, the focus was to compare the impacts of various coffee preparations while mixing coffee from Brazil, Colombia and Vietnam as the main producers. The theoretical systems relied on secondary data for the farm stage, whereby Brazil was assumed as a proxy for all considered coffee producing countries. In fact, only transport routes were different depending on the origin, which may be misleading in terms of links between origins and country-specific cropping systems. Likewise, Hassard et al. (2014) used proxy data from Nicaragua to model their theoretical supply from Guatemala. Overall, a third of the studies did not use primary data for the farm stage and relied on existing published datasets; those were mostly the ones on Brazil by Coltro et al. (2006), with 43 % of studies relying on secondary data from this single reference. In these secondary data-based studies, the uncertainty of results was greater due to potential uncovered discrepancies between theoretical concatenated systems and actual practices in the field.

In terms of the cropping system complexity, four main categories were covered: complex agroforest (27 %); simple agroforest (22 %) - also called by some authors shaded monoculture; “full-sun” monoculture (27 %); and “full-sun” polyculture (1 %). The rest of the studied systems (23 %) were either mixes of various systems or did not provide enough details on the cropping system types; those studies mostly used secondary data for the farm stage. By definition, agroforestry is a broad concept whose baseline is the combination of crops, which can be both annuals or perennials, and trees. However, there are critical differences among various agroforestry systems. In a traditional coffee agroforestry system, also called “rustic” (Van Rikxoort et al., 2014), natural forest is only partially cleared in order to keep existing native trees within the plot. On the contrary, in commercial polyculture, new trees are usually planted together with coffee trees in order to provide specific benefits. Hence, both the density and the type of associated trees matter when analysing agroforest diversity, as both imply different practices and overall plot performance.

In this review, we categorised simple agroforestry systems as those encompassing coffee trees under a single shade tree species. The more complex systems, with several associated annual or tree species, were categorised as complex agroforestry systems. This category encompasses traditional polyculture, commercial polyculture with several shade tree species, and unspecified agroforestry coffee plantations. “Full-sun” polyculture differs from agroforestry systems due to coffee trees not being tall enough to create an actual vertical stratification as symptomatic for agroforestry systems. “Full-sun” polyculture may be associations of coffee with maize or banana, for instance, which may be rather common in some countries but were not much investigated in the reviewed corpus. Various typologies of coffee systems exist, which were not reviewed as that was beyond the scope of the LCA review. The simple typology discussed above and adopted here was aimed at helping with the result analysis and did not reflect further on other potential typologies.

In the reviewed studies, associated trees were mostly the focus of standing biomass estimation (see Section 3) and not much attention was paid to the interactions among crops and trees and how to account for associated ecosystem services and allocation issues within LCA, which is discussed further later on. Only a few studies explicitly accounted for allocation ratios among associated crops (*e.g.* Basavalingaiah et al., 2022; Enveritas, 2023) or investigated complex outputs from agroforestry systems (*e.g.* Acosta-Alba et al., 2020, 2019).

For the first processing stage, the great majority of studies (55 %)

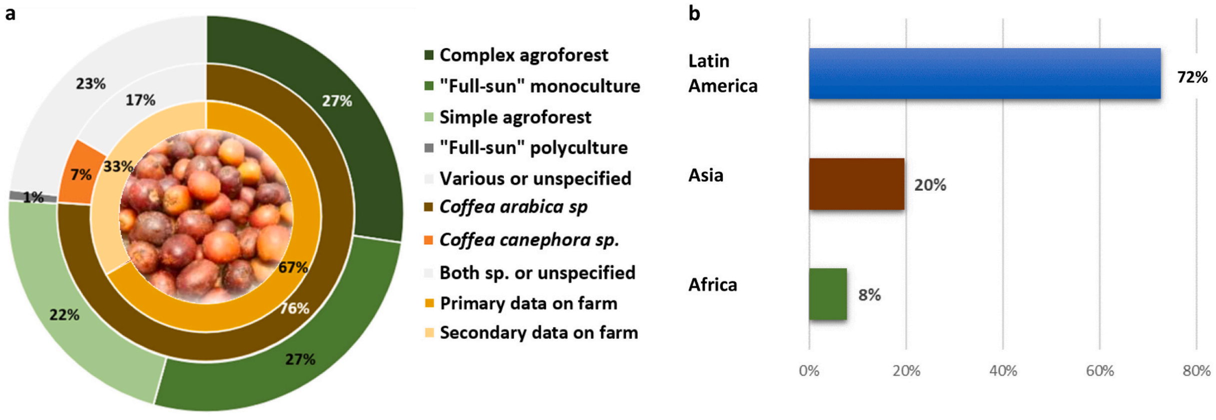


Fig. 1. Overview of the 234 studied coffee systems and origins (% of the total number of coffee system studied).

investigated wet processing only or together with dry processing (26 %); 19 % of the studies investigated dry processing only. Whether this processing was taking place on- or off-farm was not systematically specified but could be deduced from specific transportation details. Semi-wet processing was not explored in any reviewed study.

Very few studies considered the perennial cycle of coffee trees in the modelling of agricultural practices and related input-output fluxes. Most only gathered data for one year of productive coffee plantations. As shown in the literature, given the complex pluri-annual functioning of perennial plantations and delays in responses to environmental stresses or management practices, it is paramount to consider several consecutive years of production and also to integrate other development stages to average the performance and impacts (Bessou et al., 2016, 2013; Cerutti et al., 2013). Bias in results may be critical, particularly in studies relying on data collected in the field for a reduced number of plantations and over short periods of time (*e.g.* Quack et al., 2009), as well as in those comparing contrasted cropping systems (*e.g.* Brenes-Peralta et al., 2022). Such a bias would be less critical in studies covering several years (*e.g.* Noponen et al., 2012) or covering large samples, whereby regional disparities in practices and performance along the crop cycle may be geographically averaged (*e.g.* Enveritas, 2023).

There were a few exceptions, though, with some more systematic and holistic studies including the nursery stage, various productive years, or the full cycle (*e.g.* Acosta-Alba et al., 2020; Rahmah et al., 2023). Brenes-Peralta et al. (2022) included the nursery stage but then relied on data for just one harvest. In Trinh et al. (2020), data inventory was detailed by plantation stage. When focusing on yields, which directly influenced the impact values due to being the functional-unit common denominator, it was interesting to note that average yields of green coffee beans (t/ha) were 18–21 % higher when computed over the 21 years of full productivity compared to the average yields computed over the whole cycle of 30 years, with the latter including no or less productive years. Indeed, yields during the first six years of production initiation and the last three years of coffee aging were respectively 2.4 and 1.8 times lower on average than those during full productive years and the averaged cycle. Depending on the year for the data collection and the age of the plantation, those differences in yields over the whole crop cycle would have affected the LCA results if calculated without integrating the whole cycle. Moreover, those differences might vary across compared systems, leading to a consequent bias in the results. In the exemplified study, variability in yields along the whole cycle was smaller in the conventional intensive system compared to the two others, *i.e.* conventional moderate and organic intensive (Trinh et al., 2020).

Representativeness is a key data quality attribute in LCA because it defines how well-suited the data are to fulfil the study objectives. In agricultural systems, all dimensions of representativeness matter, including the geographical, temporal and technological ones, since management practices are highly dependent on the local contexts and can vary greatly. Table 1 lists some of the main agronomic parameters gathered from the reviewed studies. High standard deviations indicated a great variability in all parameters within the sample, in particular for nitrogen (N)-based fertilisers and green coffee bean yields. Seven studies considered irrigation in coffee plantations. More systems may have required some irrigation but the information was missing in many studies and irrigation practices were globally poorly detailed.

Table 1

Variations in key agronomic parameters across reviewed studies (both coffee species were considered together and results are displayed as they appeared in the studies, hence there is no linear relationship between outputs in the table).

Parameter	Mean	Median	Min	Max
Planting density (coffee trees/ha)	4,067 (±41 %)	4,500	150	10,000
Nitrogen fertilisers[a] (kg/ha)	215 (±72 %)	177	0	1152
Fresh coffee cherry yield (kg/ha)	5,288 (±51 %)	4,800	628	13,605
Coffee parchment yield (kg/ha)	1,094 (±56 %)	1,032	126	2,387
Green coffee beans yield (kg/ha)	1,419 (±79 %)	1,064	373	5,386
Irrigation water (m^3/ha)[b]	3,103 (±45 %)	3,458	1,124	4,940

[a] Not all studies displayed the detailed amount for each fertiliser types nor the N content of organic amendments applied. Total N fertiliser estimates are likely underestimated. Standard deviations to the means are given in brackets.

[b] Focusing on irrigated systems only (studied systems $n = 14$).

The least detailed practices at the farm level were related to crop residues and organic soil amendments. Crop residues on coffee farms may come from two main sources: the coffee itself and the associated crops or trees. Coffee residues consist of both leaf litter and pruning residues within the plantation and coffee residues from processing (coffee pulp, husks and parchment). Leaf litter and pruning residues may account for 5–12 t/ha depending on both coffee and shade trees densities (Van Rikxoort et al., 2013). Further crop residues may be brought from other plots or farms as organic amendments. Likewise, coffee plantation residues may be exported or recycled outside of the plot (such as pruning wood used for fences or fuel wood). However, those scenarios were not discussed in the coffee studies, apart from the two bioenergy-dedicated studies by the same authors (Aristizábal-Marulanda et al., 2021a, 2021b). The amounts and management types of crop residues and derived organic fertilisers may significantly influence coffee performance, both in terms of agronomic outputs and environmental impacts (Haggar et al., 2011; Van Rikxoort et al., 2013; Youkhana and Idol, 2016). Depending on the type of organic matter and how it may degrade, ferment or be stabilised (*e.g.* by composting), emission types and amounts will vary. According to the IPCC (2006) as implemented in the Cool Farm Tool, residues left in heaps or pits would emit 33 times more CO_2 eq. than when used as mulch in the field due to anaerobic conditions leading to emissions of potent greenhouse gases (GHG), such as N_2O and CH_4, while biogenic CO_2 from aerobic decomposition is considered as carbon-neutral. There are many possible emission intensities along this 33-fold span being determined by the various combination of co-products, residues and their managements. Nevertheless, very few studies recorded precise information on residues and none of them inventoried all potential residues and their fate. For instance, Enveritas (2023) inventoried coffee leaf litter and husks only, while Rahmah et al. (2023) compared scenarios with and without field application of coffee pulp. In the latter, however, the actual emissions of degrading coffee pulp were not explicitly accounted for.

3.1.2. *Coffee system boundaries*

LCA and carbon footprint studies aimed to assess either the impacts of coffee as an agricultural commodity, more or less processed, or the impacts of coffee drinks. All reviewed studies applied the attributional LCA approach. Details on the overarching methodologies applied are listed in Table S2. The supply chain from plantation up to the consumption of coffee as considered in the literature is summarised in Fig. 2, together with key information on details for the main stages and inputs. Across the reviewed studies, various plantations and processing routes were covered, except for semi-wet (also called honey) coffee, hence not displayed in the figure. As for the farming stage, about one third of the studies did not use primary data for the processing stages. The wet processing route was most represented across the studies (67 % investigating either wet processing only or both wet and dry processing), in accordance with arabica being the most studied species and the one mostly processed in this way. Primary processing is defined as the processing of cherries into green coffee beans; it includes several stages to separate the beans from the outer layers, then sort out the market-quality beans. Secondary processing involves a sequence of several processing stages further down the supply chain to convert green coffee beans into ground or instant coffee; it notably includes roasting and grinding but also packaging and, in some cases, further processing, such as instant coffee freeze or spray drying.

In terms of the system boundaries, about a third of the studied systems included consumption of coffee drinks, mostly comparing at least three types. Moreover, some studies presented results both at farm or processing-plant gate and post-consumption, which provided results for

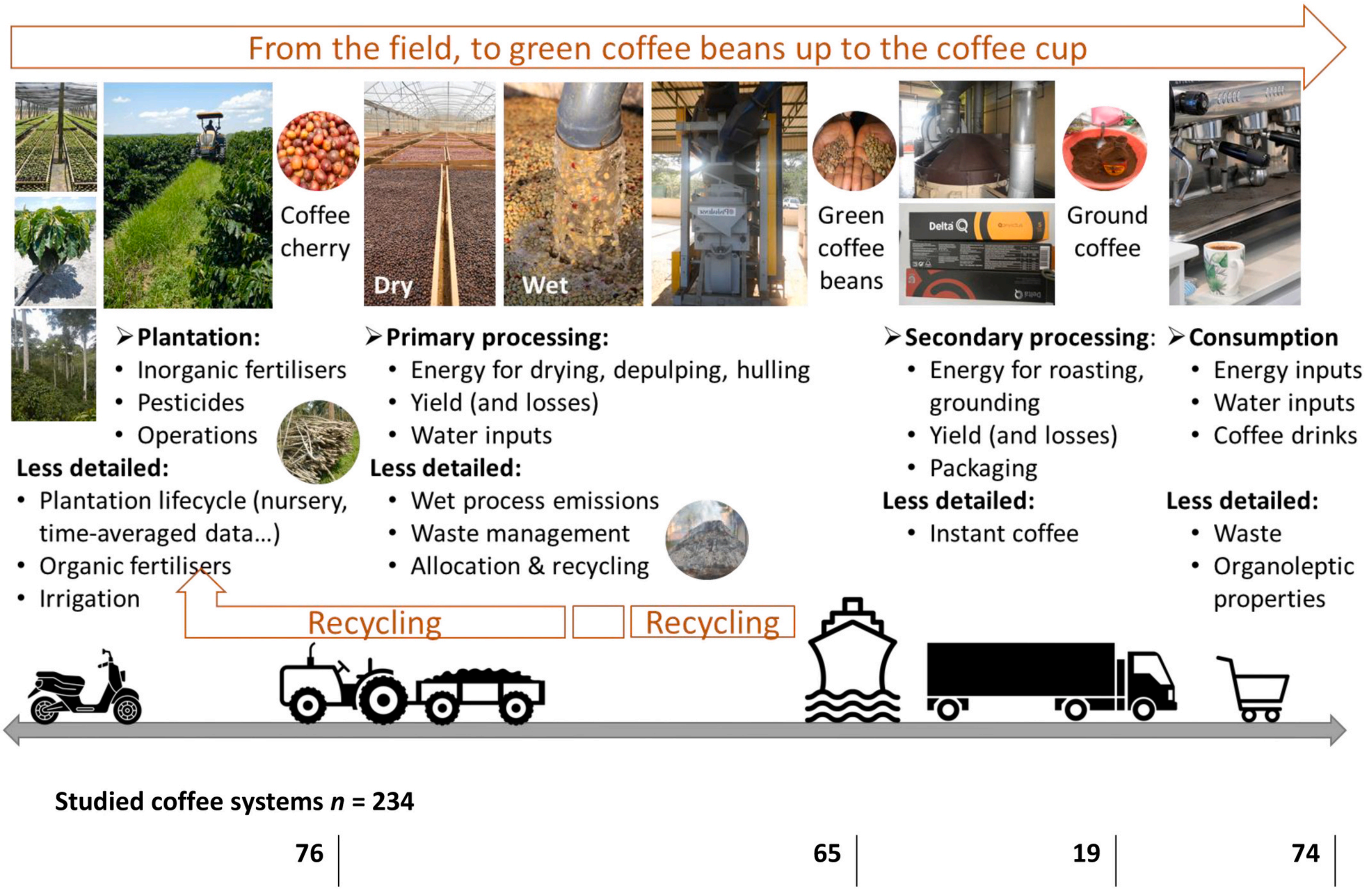


Fig. 2. Supply chain from plantation up to the consumption stage as explored in the reviewed literature, with corresponding numbers of studies according to the system boundaries.

Credits: Scooter by Draftphic; Tractor and trailer by Azam Ishaq; Ship by Jordan Ivey; Truck by Jonathan Li; Trolley by Saifurrijal – Noun Project CCBY3.0.

234 coffee systems in total. Surprisingly, three studies defined the functional unit as "1 kg of green coffee beans", although they included secondary processing and coffee consumption (Birkenberg and Birner, 2018; Killian et al., 2013; Nab and Maslin, 2020). These results could be misleading, especially if extracted from the studied contexts and compared on the same functional-unit basis but with different system boundaries. The use of the "green coffee beans per hectare" or "hectare" metrics when including primary processing of coffee cherries (*i.e.* at primary processing gate and not farm gate *per se*, even though "primary processing gate" maybe within the farm) may also be confusing as a hectare most commonly refers to outputs from the field without including any processing. Finally, none of the reviewed papers considered "the moisture in the coffee" functional unit. At the global level, the moisture of green coffee beans only varies between 10 and 14 % as this is standardised internationally. However, variations in this parameter could matter when comparing studies since cumulative losses in weight (through moisture) or actual quantities along the chain would affect linearly the impacts per unit output.

At the consumption level (cradle-to-grave), assumptions on coffee dilution and coffee waste varied across the type of the drink and serving and could lead to some confusion when comparing coffee drinks and their impacts. Some studies presented results for two functional units: "per serving" (with various volumes) and "per coffee volume", which made it possible to limit result differences strictly due to the dilution effect. To avoid confusion with the dilution effect, when analysing further the coffee drinks studies, we harmonised the results according to the actual coffee content. Note that coffee drinks including sugar or milk were not included in the review due to the added impacts from those components not related directly to the coffee itself.

Despite focusing on differences in the type of coffee drinks, none of the studies included organoleptic criteria within the functional unit. For instance, espresso or filtered coffee was mostly compared on a volume basis without any consideration of differences in strength or taste. As consumer taste preferences might be the main driver for the coffee preparation type, which in turn may influence the coffee impacts, it would be justified to consider some organoleptic properties. The only exception was the study by Gosalvitr et al. (2023), where the authors compared coffee drinks on the basis of a common amount of caffeine provided (100 mg). Future studies could further investigate organoleptic properties associated with both the type of coffee and its preparation, and adjust the LCA calculations to the actual expected function of coffee (*i.e.* more focused on the strength, taste or other coffee properties). Studies investigating coffee drinks composition depending on both coffee types (Mussatto et al., 2011; Vignoli et al., 2014) and drink preparation types (*e.g.* Gobbi et al., 2023) could help to define such a properties-based functional unit for coffee drinks. The details on the coffee drinks composition and how it may affect their taste and consumer choices could be useful to define a taste or properties-based functional unit for coffee drinks as it is done, for instance, when accounting for fat and protein content in milk with the fat- and protein-corrected functional unit in LCA of milk products.

Capital goods were generally excluded from the studies, which is in line with commonly used guidelines for agricultural or horticultural production such as PAS2050-1 (BSI, 2012), as justified by some authors. Capital goods were only included in two cradle-to-grave studies (Chayer and Kicak, 2015; Humbert et al., 2009), although they were excluded in background data for the farming stage. These studies highlighted some contributions of the manufacture of coffee brewer and the dishwasher, although more significantly for the water impact indicators. This suggests that it might be relevant to investigate further the discrepancies in impacts between coffee drinks prepared using different coffee machines.

A great majority of the studies did not consider or mention any co-product allocation. Among the remaining studies, there were i) three studies without primary data for the farming stage and relying on background data, including system expansion for waste management and energy recovery (Brommer et al., 2011; Gosalvitr, 2021; Hassard et al., 2014); ii) two studies (but by the same authors) focusing on downstream energy production from cut stems by applying mass allocation between coffee and stems, then substitution (Aristizábal-Marulanda et al., 2021a, 2021b); and iii) two studies applying economic allocation between coffee and associated crops in the same plot (Basavalingaiah et al., 2022; Enveritas, 2023). Given the diversity of systems, including within agroforestry types, as well as the diversity of coffee co-products, the lack of an in-depth investigation on co-products revealed potential gaps in accounting for the specificities and discrepancies across coffee supply chains.

3.1.3. Impact categories and assessment methods

About 60 % of the studies covered more than just GWP (a.k.a. climate change or carbon footprint). Half of those were full LCA mostly relying on various versions of the ReCiPe method (seven studies), with a small number using CML 2001 (two), and ILCD and TRACI (one each). The remaining studies looked at GWP and either water consumption or energy related impacts. In a few LCA studies, the focus on GWP plus one or a few more indicators did not align well with the ISO 14040 (2006) requirement to select a comprehensive set of impacts. Even when more indicators were selected, the choices were typically justified only partially compared to the ISO 14040 requirement. While it is recognised that studies are often limited in resources, better discussion of the limitations of the impact assessment method used would improve the interpretation of results.

Concerning the GWP, not all the studies relied on the same characterisation factors. Most single-impact or full LCA studies based on the ReCiPe 2008, CML 2001, TRACI 2008 and ILCD 2011 methods, as well as those using Cool Farm Tool v1., relied on the 100-year GWP values from the IPCC Fourth Assessment Report (IPCC, 2007). The other full LCA studies based on ReCiPe 2016 and Usva et al. (2020), estimated the 100-year GWP values based on the Fifth Assessment Report (IPCC, 2014). The discrepancies among the two versions would be mostly critical for biogenic methane emissions from wastewater treatment, since GWP varies from 25 to 34 kg CO_2 eq./kg CH_4 with feedback. No study used the IPCC Sixth Assessment Report from 2021, where discrepancies for the GWP of N_2O would have also mattered.

Besides the GWP, ILCD- and CML-based studies mostly focused on five to seven categories: eutrophication (including freshwater, marine or terrestrial eutrophication), acidification, ozone later depletion, non-renewable cumulative energy demand, human toxicity, abiotic depletion and water depletion. Contrary to the ILCD- and CML-based studies, those following the ReCiPe method focused more on the green coffee beans production and relied slightly more on primary data for the farm stage. Across these studies, not all ReCiPe indicators were considered or discussed in detail. One study applied the IMPACT 2002+ method (Humbert et al., 2009). Finally, one study reported eight other impact categories of TRACI to compare three brewing methods (Hicks, 2018).

Given differences in the applied impact assessment methods across all studies and impact categories, we could not carry out a quantitative analysis of all individual impacts. Instead, in the next section we focus on the GWP that was the most systematically investigated in the literature (Section 3.2). However, in a subsequent section we also provide some insights on the main other common midpoint indicators considered in the bulk of studies: terrestrial acidification, various eutrophication indicators, ecotoxicity and ozone depletion (Section 3.3.1). Finally, we discuss in more detail energy-, mineral resource- (Section 3.3.2) and water-related impacts (Section 3.3.3).

3.2. Global warming potential of coffee reported in LCA studies

3.2.1. A general overview

The results for the GWP varied greatly across studies depending on the system boundaries, but also for similar system boundaries. A summary of key results is given in Table 2. For different system boundaries, both originally published results and those adjusted in this study to enable comparisons are listed (see Table S3 for details). The adjusted results combined findings for the parchment and green coffee beans for the cradle-to-primary-processing gate system boundary, with or without LUC, and adjusted results per g of coffee for the cradle-to-grave boundary. For the latter, results expressed per “kg green coffee beans” were not included in the adjusted results range due to too many possibilities and uncertainties in the conversion ratios for final ground and consumed coffee.

3.2.2. Overview of cradle-to-grave results

For the cradle-to-grave system boundary, when adjusting the results to “per g of coffee”, the results for GWP varied by an order of magnitude, from 0.002 to 0.04 kg CO_2 eq. (Table 2). The adjusted range was 25 times lower than that of the published results, given the large differences across compared drink types and volumes, and even quantities in kg (80 times lower). Comparing on the same quantities of coffee stressed the variability due to actual differences in the supply chains (from coffee farming to brewing type and waste disposal), smoothing out the dilution effect. Comparing on a similar volume basis with different coffee dilution ratios would not be suitable as long as the quality of the drink is not investigated. One study investigating differences in coffee drinks impacts based on a common caffeine content highlighted that such a unit would further reduce the variability range (Gosalvitr et al., 2023).

Beyond the actual process differences across studied chains, the choice of the functional unit added further variability in the results. This variability was then linearly exacerbated by the varying assumptions on conversion ratios for the various processes along the supply chain; the cherry-to-green coffee ratio was particularly variable across studies (Table 2). Conversion ratios were not systematically reported in the studies, nor was the moisture content of the various coffee products (not even for the functional units), despite their potential influence on both the output flows and the final coffee quality.

The main impact contributors were the production of green coffee beans[1] (median 63 %), brewing, cup washing and waste management, each accounting for about 18 % (median), packaging (median 9–18 %) and roasting and grinding (median 8 %). The packaging contribution differed greatly in the case of single-pod or capsule use (18 %) compared to all the other systems (9 %). However, this contribution was associated with a great uncertainty as not all studies potentially using single-pods necessarily specified it. In particular, some studies investigating espresso, where the packaging contribution was significantly above the median, could be related to espresso single-pods.

Only one study (Hassard et al., 2014) provided the distinct contribution of instant-coffee processing, which was 14 % in the exemplified supply chain. In that study, instant coffee had much higher impact due to both the added process stage and the higher amount of green coffee beans needed per unit of instant coffee (Table 2), hence, enhancing the contribution of the farm stage. Three other studies compared instant coffee to other drinks (Büsser and Jungbluth, 2009; Gosalvitr, 2021; Humbert et al., 2009). In contrast to the above-mentioned study, the contribution of instant coffee processing was not detailed and the final impact of instant coffee was lower compared to the other coffee drinks. In Büsser and Jungbluth (2009), the amount of instant coffee used was

---

[1] Results from one study (Nab and Maslin, 2020), were left out of the average calculations due to a possible flaw in the theoretical modelling of supply chains based on secondary data on the green coffee modified from De Marco et al. (2018), so that the farm stage barely led to any emissions.

Table 2
Number of studied systems for which at least one impact result was provided in the reviewed studies and an overview of the results for global warming potential.

Total number of systems: 234	Cradle-to-farm gate without any processing	Cradle-to-primary-processing gate (on- or off-farm)	Cradle-to-secondary-processing gate	Cradle-to-grave (including coffee consumption)
Studied systems count (*n*)	76	65	19	74
Studied system count by functional unit	1 ha·yr: 42 1 acre·yr: 3 1 kg coffee cherry: 31	1 kg green coffee: 45 1 kg coffee parchment: 14 1000USD ha-outputs (although processed): 3 1 ha·yr (although processed): 3	1 kg ground coffee: 10 1 kg instant coffee: 4 1 kg decaf blend coffee: 1 1 MJ ethanol/ electricity: 4	Drip/filter coffee: 30 Espresso coffee: 8 Instant coffee: 6 Pressed coffee: 7 Single-pod coffee: 10 Ground coffee: 2 1 kg “green coffee” (although consumed as ground coffee): 6 Various: 5
Averaged coffee product ratios	Cherry kg/ha: 5288 (±51 %)	Cherry/parchment: 5 cherry/green: 5.7 (±19 %) parchment/green: 1.25	Green/ground: 1.20 (±6 %) green/instant: 2.5 (±4 %)	Various drinks with various coffee contents
Published GWP range: min-max (kg CO_2 eq.)	Per ha·yr (with and without LUC): −9960 to 102,330 per kg fresh cherry: 0.03 to 1.82	Per kg green coffee beans (with and without LUC): 0.15 to 10.52 per kg coffee parchment: 3.10 to 11.61 per 1000USD ha-outputs: 1500 to 3500 per ha·yr: 6400 to 8700	Per kg ground coffee: 0.53 to 8.50 per kg instant coffee: 15.2 to 17 per kg decaffeinated coffee blend: 3.29 per MJ ethanol/ electricity: −0.005 to 0.24	Drip/filter coffee (various functional units): 0.01 to 0.80 Espresso coffee (various functional units): 0.03 to 5.10 Instant coffee (various functional units): 0.035 to 0.20 Pressed coffee (various functional units): 0.01 to 0.06 Single pod coffee: 0.03 to 1.2 Ground coffee: 0.09 to 0.13 1 k g “green coffee” (although consumed as ground coffee): 3.02 to 16.04 Overall (various functional units covering a range from g to kg coffee): 0.01 to 16.04
Adjusted functional unit-GWP range (including differentiation between with or without LUC[a]): min-max (kg CO_2 eq.)	Per ha·yr (with LUC): −9960 to 102,330 per ha·yr (without LUC): 109 to 10,220 per kg fresh cherry (with LUC): none per kg fresh cherry (without LUC): 0.03 to 1.82	Per kg green coffee beans[b] (with LUC): 1.63 to 10.52 per kg green coffee beans[b] (without LUC): 0.15 to 14.51	Per kg ground coffee: 0.53 to 8.50 per kg instant coffee: 15.2 to 17 per kg decaf blend coffee: 3.29 per MJ ethanol/ electricity: −0.005 to 0.24	Drip/filter coffee (per g coffee consumed): 0.002 to 0.02 Espresso coffee (per g coffee consumed): 0.002 to 0.01 Instant coffee (per g coffee consumed): 0.007 to 0.04 Pressed coffee (per g coffee consumed): 0.002 to 0.01 Single pod coffee (per g coffee consumed): 0.003 to 0.02 Ground coffee and various (per g coffee consumed): 0.01 to 0.02 Overall per g coffee drunk: 0.002 to 0.04 Overall per 100 mg caffeine: 0.07 to 0.16

[a] LUC: land use change.

[b] Conversion of parchment into green coffee embodied uncertainty related to both the ratio and an underestimation of added potential impact from parchment hulling. Results expressed at the primary-processing gate per ha·yr and USD·ha were also available per kg green coffee and are therefore only provided in this latter functional unit to avoid redundancy.

3.5 times lower than that of ground coffee, compared to a 1–2.2 factor across all coffee drinks in Hassard et al. (2014). In Humbert et al. (2009), the amount of instant coffee used was 3.25–6.75 times lower than that of ground coffee, and the amount of green coffee beans needed to produce instant coffee was 1.8 times higher than to produce ground coffee.

Not all the studies distinguished all the various contributors to GWP. Brewing and cup washing were sometimes grouped together in a single contributor, with or without waste management, or all were grouped into a “use” contributor. Hence, the median profile for all contributors did not sum up to 100 % and only provided an approximation of the relative order of magnitude for the various contributions (Fig. 3). The contributions of brewing and washing stages were related to the amount of energy used and varied depending on assumptions related to coffee waste, including the energy for keeping the coffee warm. When looking at energy or water use indicators, the contributions of these stages were even greater (see Section 3.4). The variability in practices and studied details regarding the waste considered and their management increased the results variability and uncertainty. Standard deviations to the mean for all contributions were above 50 %, except for the green coffee production stage (32 %), which was consistently the main contributor. At the retail level, when consumption was not included, contributions of the other stages were proportionally higher. Median contribution of green coffee beans production reached 85 %. The key role of the farm stage up to green coffee production stressed the need to compare studies based on a similar coffee content.

About one third of the studies included coffee import, of which nine studies to European countries (mostly Germany, then Finland, UK and Italy), two to North America, one to Japan, and one to several of them. In the great majority of cases, coffee was imported from Latin America. Across these studies, the GWP of the import transport varied significantly from negligible in the case of ship transportation, up to >73 % in the case of airfreight. On average, when shipping was considered, the contribution of transport accounted for a few percentage points (up to 12 %, with the median of ~3 %) mostly correlated to the relative contribution of the green coffee production. None of the cradle-to-grave studies considered any LUC at the farm stage. Some investigated the

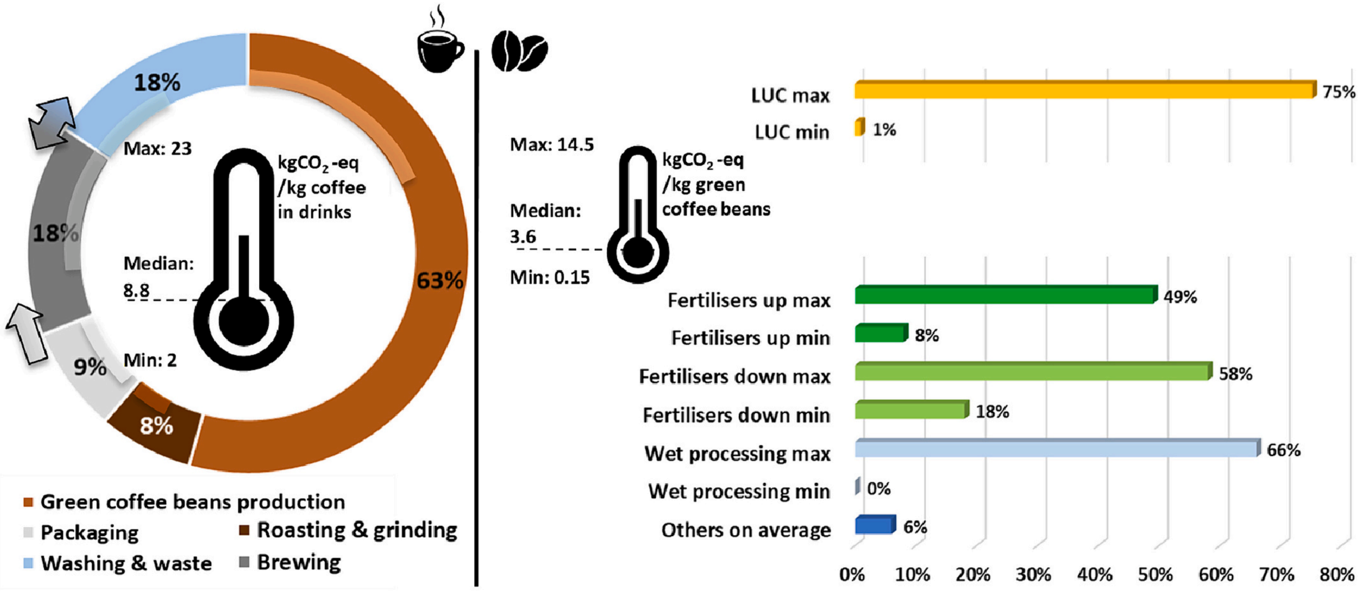


Fig. 3. Summary of global warming potential and main contributors; left: cradle to grave (studied systems $n = 141$) and right: cradle-to-primary-processing stage (studied systems $n = 68$). [Export and instant coffee are excluded from the cradle-to-grave contributors and values, and the contribution of packaging would be higher in the case of a single-serve pod. The value for green coffee beans is averaged for both dry and wet processing routes. Arrows indicate where overlapping and higher uncertainty in contributions would be most critical. These overlapping explain why the total contributions exceed 100%, since not all studies disaggregated packaging, brewing and washing & waste, some double-counting may be embedded in the displayed disaggregated contributions. Translucent overlapping lines indicate standard deviations to the sample means by contributor.]

Credits: Coffee icons by Dong Gyu Yang (cup) and Muhammad Nur Auliady Pamungkas (beans), Noun Project CCBY3.0.

potential influence of LUC but did not include it in the cradle-to-grave results.

3.2.3. Overview of cradle-to-primary processing gate results for green coffee beans

3.2.3.1. Global warming potential and contributors. Focusing on the green coffee beans production (with the system boundary from cradle-to-primary processing gate), the discrepancy across results could be critical, leading to either net positive or net negative GWP, depending on the considerations of biogenic carbon storage and LUC. Overall, four studies investigated direct LUC[2] (Enveritas, 2023; Noponen et al., 2013; Ruben et al., 2018; Usva et al., 2020) and four others considered some biogenic carbon storage in the coffee plantations without modelling any LUC (Basavalingaiah et al., 2022; Jaramillo et al., 2017; Maina et al., 2016; Van Rikxoort et al., 2013). Biogenic carbon stored within coffee or other trees at the plantations should not be included in the GWP unless considered within a proper long-term land use and LUC modelling, as specified by various guidelines (*e.g.* IPCC (2006) and PAS2050 (BSI, 2011)). Carbon storage in any stand may be accounted for only in relative quantities compared to previous stands and providing that a consistent time frame is aligned with a minimum time-averaged storage (at least over 20 years according to the IPCC (2006) recommendations). Across the reviewed studies, net negative GWP, such as in Noponen et al. (2013), might have resulted from distorted LUC modelling or inconsistent biogenic carbon accounting. Distortion might be due to varying choices across studies in terms of time parameters. Inconsistent biogenic carbon accounting might be due to flaws in the extrapolation of carbon stock changes or imbalanced accounting for carbon storage and release in LUC contexts. In Noponen et al. (2013), for instance, carbon stocks were estimated and amortised over nine years due to experimental constraints. The consensual time frame for carbon estimates is at least 20 years and short-term storage in waste should not be accounted for (IPCC, 2006). Therefore, the LUC modelling in Noponen et al. (2013) might be distorted and is not discussed further here.

According to the remaining studies, the GWP of green coffee beans following LUC to establish the plantations varied from 1.63 to 10.52 kg CO_2 eq./kg green coffee beans, based on the IPCC Tier 1 for LUC modelling (IPCC, 2006). The LUC contribution to the GWP ranged from 1 % to 75 % (Fig. 3), hence leading up to a four-fold increase in the impact. In the 1 % contribution case, LUC contribution was averaged over a whole region including thousands of farmers, among whom very few would mention any LUC. The authors specified that the modelled LUC was very likely underestimated and would require a more in-depth investigation (Enveritas, 2023). LUC contribution is usually quite critical in agriculture-related LCA, particularly in the tropics where rainforest may be converted into agricultural land (Gibbs et al., 2008). It can hence lead to significant differences between coffee systems given contrasted local development contexts and LUC history. Taking all the studies into account, with and without LUC, the total GWP of green coffee beans varied between 0.15 and 14.5 kg CO_2 eq./kg green coffee beans, with a median value at 3.6 kg CO_2 eq./kg green coffee beans (Fig. 3).

LUC apart (studied systems $n = 51$), the main contributors to the GWP of green coffee beans production were synthetic fertilisers with a total median contribution of 66 % for both fertilisers upstream (manufacture and transport) and downstream (field emissions; Fig. 3). In studies providing disaggregated information, GHG emissions from fertilisers upstream contributed 8–49 % to the impact (median value: 20 %) and those from downstream emissions 18–58 % (median value: 37 %).

The second main contributor was wet processing due to the energy used for processing and emissions from anaerobic treatment of wastewater. Fermentation emissions related to wet processing were not consistently modelled across studies, which raised a critical issue as they were quite significant contributors, from 27 % to 66 % of the total impact (*e.g.* Killian et al., 2013; Maina et al., 2016; Van Rikxoort et al., 2014). This contribution was highly variable and uncertain across

---

[2] None of the four studies included indirect LUC. These studies referred to IPCC (2006) to calculate LUC emissions but only one study mentioned the soil organic carbon and did not provide any further details.

studies. Some studies did not include emissions from wet processing due to a lack of data or provided no explanation (*e.g.* Brommer et al., 2011; Quack et al., 2009; Vera-Acevedo et al., 2016; Rahmah et al., 2023). In comparison, GHG emissions from dry processing and other post-harvest operations up to green coffee beans were negligible. Drying was mostly in the sun and hulling only contributed to 1–2 % when disaggregated from other post-harvest energy-related contributors.

The third main contributor was N_2O emissions from residues, albeit those emissions were not systematically considered and led to quite contrasted contributions. Overall, only nine studies considered some emissions from crop residue decomposition in the field and contribution varied from 4 % in Maina et al. (2016) up to 90 % in Jaramillo et al. (2017). In Noponen et al. (2012, 2013), emissions related to residue decomposition contributed 9–42 % to the GWP across systems. Crop residues in Maina et al. (2016) were not detailed. In the other eight studies, all except one study considered emissions from coffee leaf waste, but only five studies also considered those from coffee pruning and from litter and/or pruning from associated trees (Noponen et al., 2012; Van Rikxoort et al., 2014; Van Rikxoort et al., 2013; Acosta-Alba et al., 2020). The median contributions for those crop residues across these studies were 11 % and 14 % at the mill and farm gate (no processing), respectively. Finally, only one study also accounted for emissions related to coffee husk decomposition (Enveritas, 2023). Some other studies mentioned the application of coffee processing residues, such as waste from de-pulping but without making it clear whether and how related field emissions were accounted for. Only one study explicitly mentioned emissions related to coffee waste-based compost production and application (Acosta-Alba et al., 2019).

The contributions of other stages were less significant. This includes fuel for transport (median contribution of 3 % up to the primary processing stage) or field operations (median: 2 % up to the primary processing stage), pesticides upstream emissions (median: 5 % at the farm gate) and irrigation. Only 15 % of the studied systems (seven studies) included irrigation and only three provided some detail on its GWP contribution, which was highly variable (4–31 % up to the primary processing stage). The results on irrigation contributions are unlikely to be representative of contrasted types and intensities of irrigation across coffee farming systems and are not further discussed here.

3.2.3.2. Main uncertainties in the estimations of global warming potential of green coffee beans. At the plantation level, despite some mention of quite complex coffee systems, such as agroforestry plots, little attention was paid to this complexity and all potential flows. As indicated in Fig. S2 in Supplementary information, there was no clear difference in the GWP between different cropping system type, with large variabilities within each type. This may be partly due to the fact that the defined cropping farming types were not consistently discriminated against fertiliser inputs that were highly variable across all systems and the main contributor to the GWP. Some studies comparing extensive *versus* intensive cropping systems based on different fertiliser strategies showed a more contrasted impact across the systems (*e.g.* Basavalingaiah et al., 2022; Trinh et al., 2020; Noponen et al., 2012). However, part of the discrepancies in the impact among the systems may have also be missed due to incomplete descriptions and modelling of the diverse system structures and functioning. For instance, some studies estimated carbon stock in associated shade trees but did not investigate how competitions for resources may affect inputs and outputs among crops and trees and whether potential allocation issues would arise. Some other studies mentioned the potential importance of ecosystem services provided and how “shade system can also influence production (yield, quality and input efficiency), environmental indicators and production cost”, but that it was not accounted for (Brenes-Peralta et al., 2022). Apart from a few studies mentioned before, there was a lack of a clear systemic delineation between coffee and associated plants in the case of agroforestry plots.

Although fertilisers-related field emissions were explicitly modelled across the studies (mostly based on IPCC (2006) and derivatives), there was still a lack of transparency and details. Apart from a few studies (*e.g.* Maina et al., 2016; Noponen et al., 2012), most studies did not specify if indirect N_2O emissions or CO_2 field emissions related to urea and liming practices were accounted for. Moreover, not all studies provided a detailed inventory of inputs, notably of fertiliser types and amounts, nor did they differentiate systematically between synthetic and organic ones. The variability among studies with no details available spanned a range as large as that of the other studies (Fig. 4). Hence, the lack of transparency and details hampered a clear analysis of correlations. We tried to disentangle the main contributing factors, analysing GWP by considering different rates of nitrogen (N) application and splitting results based on primary processing type and inclusion or not of emissions from residues. The N-rate classes were defined in order to yield comparable sample sizes across classes. However, we could not identify any clear fertiliser-based tendency. Fig. 4 first shows a large variability across N-rate classes and no clear delineation in impacts between fertiliser management. Some low-input systems had large emissions and *vice versa*. Fertiliser management embeds many factors that could not be disentangled and fully discriminated against due to the lack of details available in the published studies. In particular, the difference between organic *versus* synthetic fertilisers played a key role in some comparisons of systems as upstream emissions from organic fertilisers were much lower than those of synthetic ones, while fertiliser upstream emissions were significant contributors (*e.g.* Acosta-Alba et al., 2019; Noponen et al., 2012). On the other hand, emissions from crop residues had a significant impact (Fig. 4a), so that more details on all residues or other organic inputs to the field and their emission profiles would be paramount to assess fully the impact of different fertiliser types. The lack of details on compost emissions, both up- and downstream, might be particularly critical where conventional and organic cropping systems were compared, with the latter mostly relying on compost instead of synthetic mineral fertilisers (*e.g.* Trinh et al., 2020). Finally, large discrepancies in emissions from wet processing may have also smoothed out part of the comparative results across the N-rate classes. For instance, in the “>334 N” class the wet-process coffee supply chains had a much lower impact than both the dry process coffee supply chains within the same N-rate class and the wet-process coffee supply chains within lower N-rate classes (Fig. 4b).

Most of the studies did not consider emissions from coffee cultivation residues and potentially other associated crops or trees, if the latter was considered within the system boundary. It was mostly implicit, but in some cases, authors specified that those emissions “were excluded because of insufficient data” (*e.g.* Trinh et al., 2020). As previously detailed, emissions from crop residues were identified as the third main contributor to GWP; hence, their inclusion or exclusion clearly affected the results (Figs. 4a and 5a). Also, depending on the processing chain, further residues might be brought to the field or wasted and lead to further emissions in both cases. More attention should be paid to quantifying on-farm or off-farm residue decomposition and emission profiles properly, so as to make sure that the quantification of emissions is complete, as well as to check whether synthetic fertilisers were or could be substituted. Studies focusing on coffee co-products or waste (*e.g.* Catalan et al., 2019; Cruz, 2014; Dadi et al., 2019) could have provided insights on quantities and properties of those residues to enable a more systematic accounting.

Finally, emissions from primary processing were also highly variable and questionable (Fig. 5b). The clear split between dry processing for arabica or robusta may relate to differences at the farm stage as dry processing would not be significantly different *per se* depending on the coffee species. The clear split between dry and wet processing for arabica is likely due to both large variabilities and uncertainties in the modelling of both coffee supply chains. It stresses the likely underestimation of emissions from the wet process, as not all studies included wet-processing emissions nor used the most updated characterisation

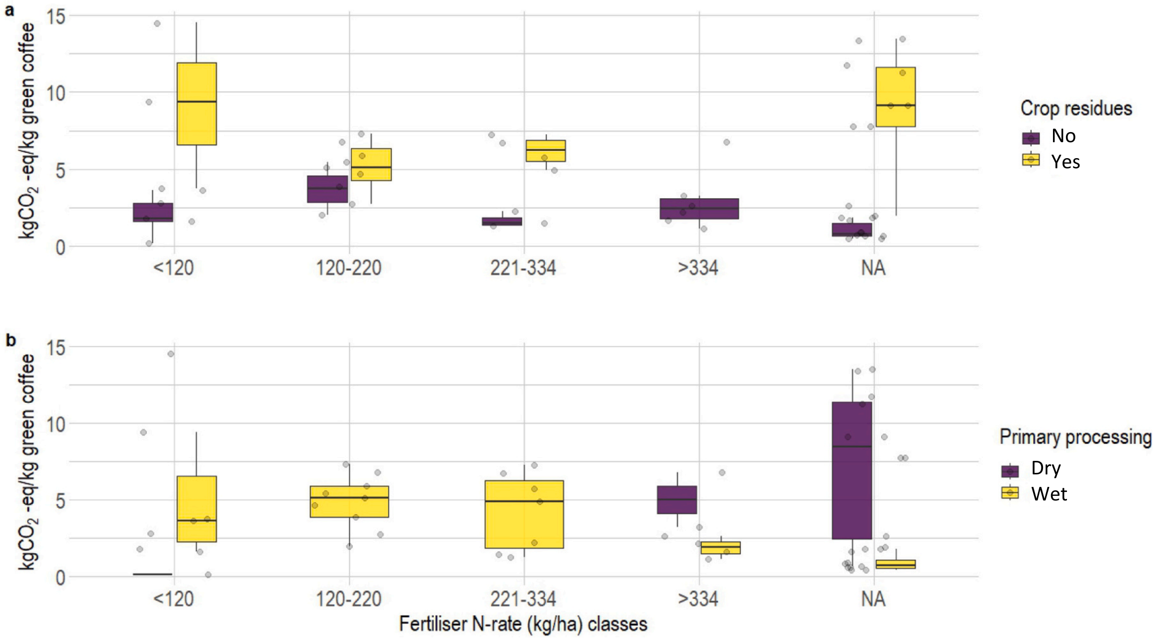


Fig. 4. Global warming potential of green coffee beans by applied N-rate classes and depending on the accounting for emissions from: (a) crop residues: no/yes; and (b) the type of primary processing: dry/wet [Cradle-to-primary-processing gate, no LUC considered, studied systems $n = 50$: one study is not displayed due to the first processing type not being discriminated. NA: details on applied N-rate not available].

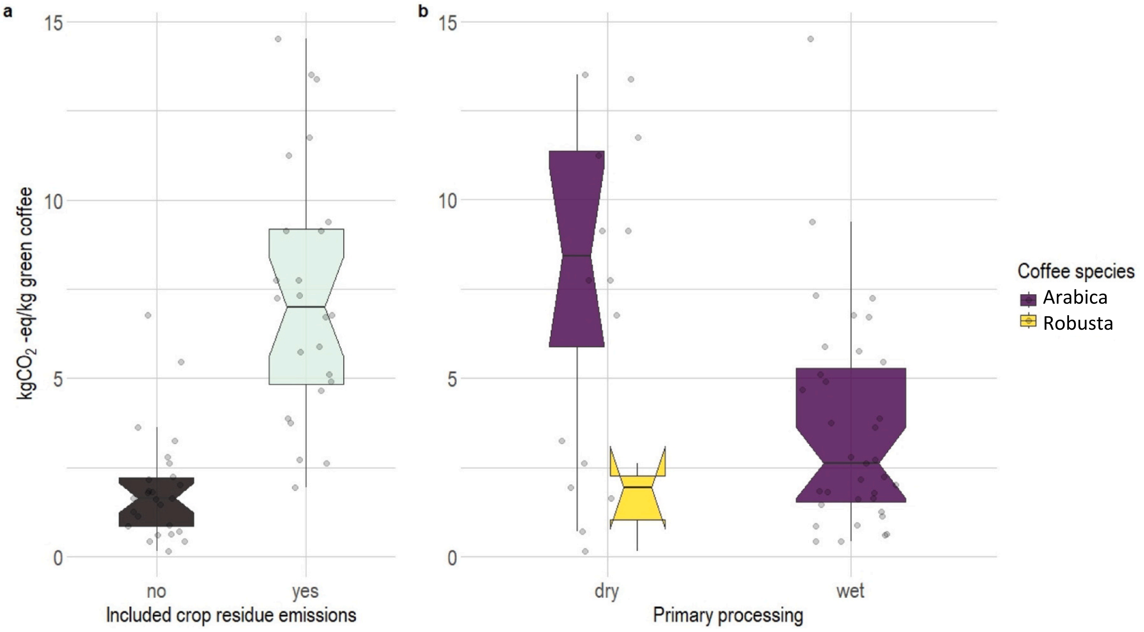


Fig. 5. Global warming potential of green coffee beans depending on the accounting for emissions from: (a) crop residues (studied systems $n = 50$: one study is not displayed due to the first processing type not being discriminated); and (b) type of primary processing: wet/dry (studied systems $n = 50$) [Cradle-to-primary-processing gate, no LUC considered].

factor for biogenic CH_4. Emissions from wet processing depend on many factors that can be highly variable, but mostly depend on the amount of water used for washing and fermenting. The origin of water may also affect the energy-related emissions for pumping. In the end, the amount of emitted CH_4 is related to the wastewater amount and treatment that differ widely among geographical contexts and applied processes. Traditional full washing processes use up to four times as much water compared to processes that reuse water (Van Rikxoort, 2011). CH_4 emissions, when included, were based on the IPCC (2006) (Chapter 5) coefficients for wastewater treatment. But there was still a lack of information on the overall process; *i.e.* detailing the origin of water (*e.g.* energy impact for pumping), the amount of water used (dilution effect), the duration of the whole process which influences fermentation outputs, and the type and duration of wastewater treatments. More data and knowledge would be needed to decipher the proper emission profiles of wet processes according to their specificities. Moreover, when wastewater is not treated, which reduces the CH_4 emissions linked to the treatment itself, other pollutants in the wastewater, such as reactive organic compounds, may also become an environmental threat (Beyene et al., 2012; Blinová et al., 2017; Chanakya and De Alwis, 2004).

However, downstream impact of wastewater discharged with or without pre-treatment was not investigated in the reviewed studies.

3.3. Other impact categories

3.3.1. Terrestrial acidification, eutrophication, ecotoxicity and ozone depletion

3.3.1.1. Overview of cradle-to-grave results. At the cradle-to-grave level, comparison across studies was hampered by both varying functional units and various impact assessment methods. In the two CML-based studies (Büsser and Jungbluth, 2009; de Figueiredo Tavares and Mourad, 2020), 12 coffee drinks were investigated with only two common ones, *i.e.* espresso and black coffee. Neither study used the same functional unit nor considered the same level of detail, in particular regarding the amount of consumed ground coffee. Common indicators among these studies were energy use (see Section 3.3.2), eutrophication and acidification. For the two last, the green coffee beans production was the main contributor (40–99 %) across the scenarios considered. The use of pesticides at the farm stage also contributed significantly to freshwater ecotoxicity and human toxicity, but as for the other indicators, no comparison or conclusion was possible since no discussion or details were provided in the papers. Overall, press-based and instant coffee drinks tend to have lower impacts compared to pod coffee due to waste management and relative to espresso due to the energy required by the coffee machine.

The other two studies (Gosalvitr, 2021; Humbert et al., 2009) also demonstrated the dominant contribution of the green coffee beans production across the various impact categories. In the ReCiPe-based study up to and including coffee consumption (Gosalvitr, 2021), green coffee beans production contributed 85–99 % to the impact categories across the drink types considered. The only exception was ionising radiation which was mainly due to the consumption stage, related to nuclear energy in the electricity mix. The importance of the green coffee stage was further emphasised when comparing roasting intensities and black coffee drinks[3], which affected the amount of coffee needed. Overall, coffee transportation had negligible impacts and packaging only mattered in the case of coffee pods and for other impact categories.

In the TRACI-based study (Hicks, 2018), the green coffee beans production was also the main contributor to eutrophication, ecotoxicity, and acidification. There were no significant differences in impact contributions across the three assessed drinks, *i.e.* drip filter, French press and coffee pods, except for the added impacts related to the plastic cup only used for the pod coffee. When focusing on eutrophication, the impacts increased with the amount of ground coffee, confirming the significant contribution of the farm stage. Brewing was the second main contributor across the impact categories and particularly to ozone depletion and smog.

Despite the great variability across the studies in both the goals and scopes and the applied impact assessment methods, the production of green coffee beans remained a major contributor to coffee drink impacts, notably eutrophication, acidification and ecotoxicity. Beyond variations related to the drink type and the amount of ground coffee used, main variations among studies concerned assumptions on waste, in terms of both consumption patterns (*e.g.* amount of water or coffee waste, the use of a cup) and disposal treatment (*e.g.* packaging). At the farm stage, as for GWP, fertilisers were the main contributors to these impacts, except for ecotoxicity which was mostly related to pesticide use, where applied. When including primary processing, emissions from wet milling and wastewater could add significantly to eutrophication and ecotoxicity, but there was an overall lack of details on this stage across the studies.

3.3.1.2. Overview of cradle-to-primary processing gate results. For the cradle-to-primary-processing gate system boundary, across the ILCD- and CML-based studies, the farm stage contributed in particular to eutrophication and acidification. In the only study with primary data for the farm stage (Acosta-Alba et al., 2020), the main impact sources were the use of fertilisers and their manufacturing. Post-harvest operations (wet mill located at the farm) had overall a lower contribution (median contribution across acidification, terrestrial, freshwater and marine eutrophication: 12 %), except for the less intensive system, for which orders of magnitude of post-harvest contributions were similar to those of upstream emissions from inputs. In-field emissions from inputs were the main contributors across impact indicators and cropping systems. Their median contribution was 55 % (min: 3 % to max: 99 %). In comparison, within on-farm impacts, weed management, compost use and pesticides had no significant impacts. The higher contribution of manufacturing inputs came from nitrogen mineral fertilisers (median contribution 17 %) for almost all categories and, in particular, terrestrial acidification (up to 25 %) and ecotoxicity (up to 43 %). Within post-harvest activities, the use of diesel for pulping machines contributed from 1 % up to 36 % for the ILCD indicators (median 12 %). Fig. 6 shows a qualitative synthesis of main contributors for this system boundary.

On-farm emissions and fertiliser manufacture also dominated the ReCiPe-based results for terrestrial acidification, freshwater eutrophication and fine particulate matter formation (Basavalingaiah et al., 2022), except for the organic farming system. The latter had very low

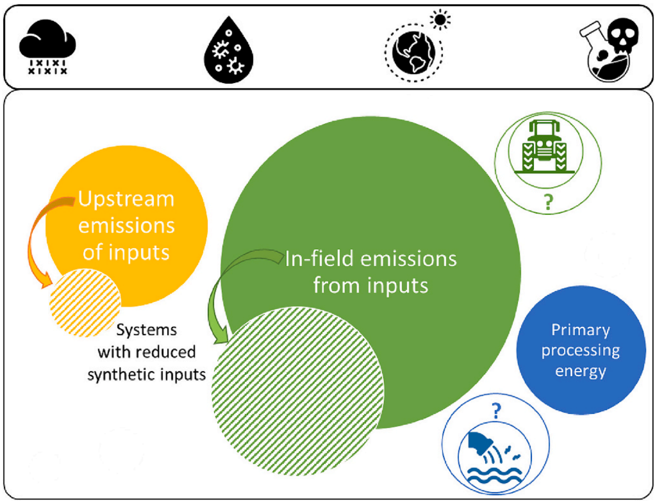


Fig. 6. Simplified overview of contributors to terrestrial acidification, eutrophication, ozone depletion, and ecotoxicity for the cradle-to-primary-processing gate system boundary.
[Surface areas reflect trends across systems and impact assessment methods regarding main contributors and median contributions but are not quantitatively proportional to exact values, given the heterogeneity in details across studies. Field operations (tractor icon) and wastewater pollution from processing (water discharge icon) were the most variable contributors across studies; therefore, their circle sizes are not proportional to the other filled or hatched circles and could be larger as indicated by the question mark in the outer circle. Field operations were significant for ozone depletion in one study (Hicks, 2018), whereas this impact was not investigated in Acosta-Alba et al. (2020), for instance. Wastewater pollution due to primary processing water discharge could matter, but was barely investigated and detailed across studies. Hatched circles show that the contributions from upstream emissions during production and transportation of inputs and in-field emissions decreased, and other contributors relatively increased, in the case of integrated or organic coffee systems, whose synthetic inputs were limited].
Credits: Acid rain icon by Bartama Graphic; Polluted water drop for eutrophication by Nawicon; Ozone depletion icon by Good Wife; Skull from the flak by zafdesign; Tractor by IronSV; Water discharge by Shashank Singh – Noun Project CCBY3.0.

---

[3] Drinks including milk were not considered here due to the added impacts from the milk.

impacts for these indicators (per ha), although eutrophication from on-farm emissions was higher than for the conventional and integrated systems. The ecotoxicity results were dominated by fertiliser manufacture, again with the exception of the organic system. Another study applying ReCiPe (Trinh et al., 2020) had overall larger impacts from conventional than from organic coffee cropping systems. Differences were due to the lack of synthetic mineral fertilisers and "manual pest control" in organic systems, leading to significantly lower eutrophication, acidification and terrestrial ecotoxicity impacts. However, more details on compost emissions and impact contributions would be needed in that study as compost proved to create some trade-offs across impact categories in Acosta-Alba et al. (2019). The dominant contribution of the farm stage to freshwater eutrophication, freshwater ecotoxicity and terrestrial acidification was also found in two other studies (Brenes-Peralta et al., 2022; Ruben et al., 2018). In Brenes-Peralta et al. (2022), contribution of the primary processing appeared not to be negligible, contributing 5 % to eutrophication and 8 % to ecotoxicity. Those contributions are likely due to the wastewater emissions from the wet mill processing; the authors provided inventory data on wastewater (*i.e.* biological oxygen demand and chemical oxygen demand) but did not actually discuss the impacts.

In the TRACI-based study (Hicks, 2018) considering the production of green coffee beans, fertilisers also played a major part in all the impact categories but two, in particular terrestrial acidification for N-fertilisers and eutrophication for P-fertilisers. Pesticide use in the coffee plantations almost entirely dominated the ecotoxicity impacts. Fuel use contributed to a few other impact categories, most significantly to ozone depletion (up to 88 %), although the study did not specify whether the split between diesel and gasoline was related to the farm stage and the primary processing. Overall, across all cradle-to-primary-processing studies, *i.e.* up to and including green coffee beans production, contribution of the primary processing to the impacts such as eutrophication was detailed and discussed. Impacts linked to the energy used for processing were sometimes detailed (*i.e.* Acosta-Alba et al., 2020), but further impacts due to wastewater discharge in the wet process, for instance, were not (Fig. 6).

3.3.2. *Energy, mineral and fossil resource use impact indicators*

Cumulative energy or primary energy demand were investigated in a few studies as part of a multi-criteria LCA or as a complementary indicator to global warming. Cumulative energy demand is widely used in LCA but there have been various conceptual approaches (Frischknecht et al., 2015). In some studies reviewed here, this energy indicator was a life cycle inventory flow rather than an impact indicator; it could sometimes be found in the life cycle inventory details of a study rather than as a midpoint impact (which is arguably a correct approach, although energy demand is widely reported as an "impact"). In other cases, the impact assessment methods weighted the energy inventory flows, depending on efficiency conversions or energy sources, such as renewables. Without any harmonised impact characterisation across studies, the energy indicators could hardly be compared. In an Indonesian study, in particular, human labour was included in the cumulative energy demand and was a main driver together with fertilisers (Rahmah et al., 2023). Human labour, as well as animal traction, are commonly excluded from LCA, which makes comparison with the other studies difficult. There were no further studies detailing energy consumption drivers at the farm level.

For the cradle-to-grave system boundary, results were extremely variable. First, approaches varied and were not systematically detailed. In one study, authors relied on CML 2001 but only provided life cycle inventory-based indicators (de Figueiredo Tavares and Mourad, 2020). Second, various drinks were studied and the system boundaries were not all harmonised. For instance, the farm stage was not systematically fully included; *e.g.* energy accounting started with cherry processing in Hassard et al. (2014). Hence, results varied from 0.02 to 0.12 MJ/g coffee in drinks (mean: 0.05 MJ/g) among three studies (de Figueiredo Tavares and Mourad, 2020; Domínguez-Patiño et al., 2014; Hassard et al., 2014) providing a life cycle inventory-based indicator and from 0.09 to 0.45 Non-renewable MJ eq./g coffee in drinks in the study based on CML 2001 (Büsser and Jungbluth, 2009) or 0.19 to 0.63 Non-renewable MJ eq./g coffee in drinks in the study based on IMPACT 2002+ (Humbert et al., 2009). Here too we only looked at black coffee and espresso in order not to add variability due to the impact of milk added to the drinks. Main contributors were quite variable across studies. In studies fully including the farm stage within the green coffee production, the median contribution of green coffee production was around 40 %, with a large variability (38 %–86 %) due to the system discrepancies and the lack of details on post-harvest processing on- or off-farm. Nevertheless, in all the studies green coffee production was among the three main contributors. Energy used to heat the water or brew the coffee was either the first or second contributor and its contribution varied drastically depending on the type of drinks (11–72 %), notably whether a coffee machine or a kettle was used and how much hot water was used. In one study, wet milling-based primary processing was the main contributor to energy demand before brewing (Hassard et al., 2014).

Coffee roasting and packaging were not systematically disaggregated. Overall, when disaggregated, packaging had a lower impact, except in cases of pod coffee (*e.g.* 41–74 % in de Figueiredo Tavares and Mourad (2020); 70 % in Büsser and Jungbluth (2009); 35 % in Humbert et al. (2009)) or canned coffee (55 % in Hassard et al. (2014)). As for GWP, the contribution of instant coffee processing to the overall energy demand varied with assumptions on the amount of both green and instant coffee compared to ground-coffee drinks (up to 35 % in Hassard et al. (2014), where the instant processing was disaggregated). There was not any further energy-demand impact assessment for the cradle-to-primary-processing gate system boundary.

Mineral and fossil resource depletion indicators were included in studies applying ReCiPe. These studies mostly ended with green coffee production without much detail on the contribution profiles (*e.g.* Trinh et al., 2020), except for De Marco et al. (2018) and Gosalvitr (2021). However, De Marco et al. focused on decaffeinated coffee so those results are not comparable to the other studies. Nevertheless, their study exemplified the relative contribution of the decaffeination process, whereby caffeine extraction and separation caused 30 % and 45 % of mineral and fossil resource depletion, respectively, per kg of decaffeinated coffee. In Gosalvitr (2021), who considered both mineral and fossil resource depletion and primary energy demand, green coffee was the main contributor, followed by consumption across all drinks; packaging was the second highest contributor to mineral resource depletion in the case of pod coffee. The study by Gosalvitr also provided a detailed analysis at the gate-to-gate level, investigating the disaggregated impacts from freeze-drying and various roasting intensities. Those details may be useful given the lack of details on these across the other studies. It showed a 1.6-fold difference in energy use from light to dark roasting; a 10-fold difference in energy used between roasting (higher) and grinding (lower); and 6 to 9-fold difference in energy use between roasting and freeze-drying.

For the three indicators considered in this section, the variability across the studies in both the goal and scope and the applied impact assessment methods had more influence on how dominant the green coffee production was. There were overall more details regarding energy and resource used beyond the farm stage. Like the contribution analysis for GWP, little information was provided on mechanised field operations, such as weed control or harvesting, that would notably contribute to fossil resource depletion. Manual harvesting is typical in many countries (Illy and Viani, 2005), but there has also been a move towards mechanisation (Adams and Ghaly, 2007). Besides differences in the functional unit across studies, impacts related to energy use were also dependent on varying background assumptions on electricity mixes, electricity consumption of coffee machines and washing up practices (Gosalvitr, 2021).

3.3.3. *Water impact indicators*

Water footprint was the most covered impact category after global warming. Twelve studies investigated water flows or impacts, but applying contrasted approaches. They covered various cropping systems from various origins. Five studies included the coffee drink assessment, *i.e.* for the cradle-to-grave system boundary. Although the ISO 14046 standard (ISO 14046, 2014) and its practical guide (ISO 14046, 2017) provide guidance and clear definitions of all aspects related to water footprint, a lot of studies did not use the correct terminology. In particular, authors mostly referred to water "use" without specifying if it was "consumption" or "withdrawal". This lack of clarity led to some misinterpretation: *e.g.* an amount of water withdrawn for coffee processing (Coltro et al., 2006) was interpreted as water consumption in some articles (*e.g.* De Marco et al., 2018; De Figueiredo Tavares and Mourad, 2020). However, this amount of process water was actually fully released as wastewater and was not consumed. This distinction is crucial because only water consumption (*i.e.* evaporated, incorporated in the product or transferred to another watershed) should be considered in the impact assessment. According to the ISO standard, the withdrawn water that is then released back in the same environment should not be part of any water-scarcity impact category. It may, however, contribute to water quality related impacts, such as eutrophication. Such a distinction affects agricultural LCA results, notably in the case of irrigated systems (Payen et al., 2018). In some cases (*e.g.* Ratchawat et al., 2020; Ruben et al., 2018), the distinction between water withdrawal and consumption was clearly made but the assumptions underlying the estimation of the actual water consumed were unclear or not provided. Overall, there was a great variability in primary data on water due to variabilities across both the covered systems and the water modelling assumptions. There was also a lack of clarity regarding the scope of the life cycle inventory for water flows: water consumption for background activities (*e.g.* farm input production) were likely not included in several studies.

When focusing on water consumption, irrigation was dominating at both cradle-to-primary processing gate and cradle-to-grave levels, despite the water consumed in the drinks (Fig. 7). Irrigation-water amounts were highly variable, ranging from 293 to 5825 m^3/t green coffee across the four studies, including irrigated plantations. The second contributor was wet processing and the actual amount of water consumed varied significantly depending on the process efficiency. Unless specified otherwise in the studies, we considered water consumption as the difference between total water use and water discharged. Wet-process water consumption ranged from 0 to 100 m^3/t green coffee (mean: 22.6) and wet-process water withdrawal ranged from 11.4 to 15.2 m^3/t green coffee (mean: 13.7). As observed in Coltro et al. (2006), primary data from various sites showed a large variability in the amount of wastewater from coffee washing during wet processing. Depending on the process, large amount of this water may be either discharged or recycled. Owing to the high volume of water potentially used during wet processing, a clear water inventory for coffee processing is crucial.

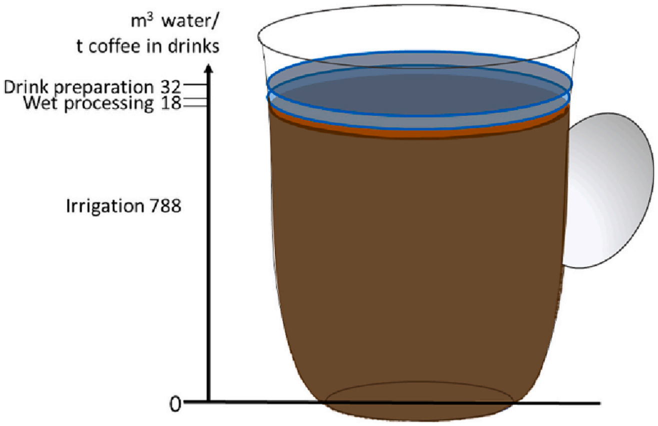


Fig. 7. Contributors to water consumption for coffee drinks (life cycle inventory indicators) based on ten studies assessing water impacts with full or partial data up to and including green coffee beans production (irrigation: studied systems $n = 4$; wet processing: studied systems $n = 7$) and four studies up to and including coffee drinks. [Water consumption flows are related to one tonne of ground coffee consumed as drinks, hence including the irrigation water, wet processing and water use at the consumption level. Based on the included studies, we considered a green-to-ground coffee ratio of 1.24:1. Displayed values are median values across the ten studies, including two systems with no irrigation compared to other systems within the same study. At the plantation level, water consumption in the nursery stage was not included. At the primary processing level, water withdrawal was not included (its amount was similar to the water consumption). For each stage, water flows were highly variable but only the median values were displayed due to graphical constraints].

The few cradle-to-grave studies with detailed information on water flows showed that, in between irrigation and wet processing, water use in the consumption stage might not be negligible but was too variable to be conclusive. However, even at the drink level, the main contributor was related to the green coffee production and depended on the amount of green coffee used per drink, which is directly related to the dilution effect. As discussed for the GWP, when comparing studies, the functional unit should account for organoleptic properties of coffee drinks or rely on an equivalent amount of coffee used. This is even more critical for water impact indicators, since irrigation (correlated with the amount of coffee used) is the key driver. Also, assumptions on water used to prepare drinks were quite contrasted across studies, varying from 39 to 8800 ml/functional unit or 1 to 37 ml/ml coffee (Chayer and Kicak, 2015; de Figueiredo Tavares and Mourad, 2020; Hassard et al., 2014; Humbert et al., 2009). Discrepancies in water use and wastewater in the coffee preparation stage, but also water used to wash coffee machines or even cups may influence the overall water use with contrasted distributions between water consumption and withdrawal.

Characterising impacts from water consumption requires going beyond a simple volumetric measure (*i.e.* an inventory flow) by including relevant geographical and temporal dimensions to reflect the pressure on water resources. Only three studies characterised impacts by accounting for local water scarcity: Humbert et al. (2009) and Acosta-Alba et al. (2020), using the EcoScarcity method (2006), and Usva et al. (2020) using the AWARE method (Boulay et al., 2018), the latter being notably recommended by the Global Guidance on Environmental Life Cycle Impact Assessment Indicators (UNEP and SETAC, 2019). Contribution analysis showed that irrigation dominated impacts, followed by coffee making and/or washing (Humbert et al., 2009; Usva et al., 2020). When there was no irrigation, background processes, such as fertiliser manufacture, were the main contributors (Acosta-Alba et al., 2020; Usva et al., 2020). Across these studies, wet processing water did not matter as it was considered only withdrawn and not consumed. Considering the water scarcity level may change the relative contribution of life cycle stages in comparison to the inventory data on water. For instance, the water consumed in the use phase for coffee making had an increased share of the overall impacts compared to the cultivation and processing stages in Humbert et al. (2009). This was due to the fact that the level of water stress was on average lower in the coffee producing countries compared to the consuming countries.

It is also worth mentioning that LCA databases use different interpretations of the water footprint indicator and that data are highly variable. Therefore, using different databases will also affect this impact significantly. This, together with the above discussion, reinforces the need for harmonisation of the water-related data and the estimation of water impact indicators.

3.4. *Further remarks*

For all coffee impacts, a considerable range of results was found in the literature, most notably for GWP, which varied by a factor of ten.

This is similar to the findings in Poore and Nemecek (2018) who found that impacts can vary by up to a factor of 50 for certain products. This is largely due to differences in production practices, but also due to the way LCA practitioners deal with more complex methodological issues, such as allocation, LUC accounting and emission modelling related to residues. The range for the other impacts was further influenced by the various impact assessment methods applied.

Overall, it was not possible to discriminate the quantified shares in the variability of results that are due either to the intrinsic system variability or to methodological discrepancies, given that both variability sources may have overlapped or could not be systematically disentangled across studies. Nevertheless, we can assume that both variability sources are of the same order of magnitude; for instance, when looking at Fig. 5. Both sources of variability may compound to split systems further apart (*e.g.* comparing first two systems with crop residues along the impact gradient due to methodological discrepancies, and then comparing a system without crop residues to a system with crop residues in the higher range of the impact in Fig. 5a) or compensate (*e.g.* within the span of impact ranges among the systems with and without crop residues in Fig. 5a). Also, looking at just one year of a perennial crop cycle instead of accounting for the whole perennial cycle would be a methodology-related variability, but final difference in results would also be influenced by the intrinsic variability within the system due to changes in practices or climate conditions over time.

From an ISO 14040/14044 perspective, we noted that the choice of the functional unit was not made sufficiently specific. For the cradle-to-grave boundary, functional units were problematic as they mostly did not account for organoleptic properties. Most studies compared very different coffee drinks in terms of coffee content and other ingredients, such as sugar and milk, but without considering their different tastes or potential effect as stimulant or other functions. The dilution effect, which was influential, was also not accounted for in the functional unit, except for a few studies looking at various functional units. For the cradle-to-farm-gate boundary, more than half of the studies used area (ha·yr), which is not a functional unit as intended by the ISO standards. Although a unit of area can "provide a reference to which the input and output data are normalised" (ISO 14040, 2006), it does not reflect the function of the system and it does not allow for discriminating land-use impacts in the impact assessment as they are correlated to the surface area used, which is not justifiable for "comprehensive" agriculture-related LCA. In the case of more or less complex agroforestry coffee systems in particular, the functional unit should be discussed in light of the structure and functioning of the complete ecosystems. Surface area-based functional units are often used in those cases to overcome allocation issues and the lack of harmonised framework to account for various functions at once, but it is a mere expedient. At least one study referred to coffee-equivalent yield for coffee-pepper co-production systems but results for that unit were not provided, nor were the economic values and the allocation fractions used to calculate it (Basavalingaiah et al., 2022). Another one used a fixed monetary output as the functional unit, which would be worth developing further based on contrasting economic and societal values of various ecosystem services (Acosta-Alba et al., 2020). Finally, the lack of precision in the functional unit sometimes hid critical assumptions, such as whether primary processing occurred on- or off-farm, the incremental processing and loss ratios, or the moisture content of the final product.

Also, in general, reporting of study assumptions, indicator choices and results was not fully transparent, with impact results sometimes only shown in a graphical form, or discussed partly in the text. It could be argued that this is another breach of ISO 14044 (2006) requirements that state "results […] shall be transparent and presented in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA". In this review, it prevented in some cases in-depth analyses of results and comparability across studies.

4. Conclusions

Overall, the variability across coffee LCA studies reflected the great diversity in coffee systems, the diverging assumptions, and data quality levels. In order to improve the robustness and accuracy of LCA of green coffee, we recommend:

i) to consistently apply the IPCC (2006) guidelines for land use and LUC accounting, *i.e.* clearly differentiating between long-term storage of biogenic carbon, over at least 20 years, and short-term biogenic carbon turnover, analysing transparently all carbon pools, including soil organic carbon;
ii) to model properly the perennial crop cycle, accounting for a weighted average of inputs and outputs along the cycle, depending on the various development stages;
iii) to quantify thoroughly all direct and indirect emissions in the field, including all amendments, mineral and organic, but also crop residues; and
iv) to check the mass balance along the supply chain, also beyond the plantation, in order to ensure that all co-products or wastes are considered and their emissions from treatment, recycling or disposal can be tracked.

At the coffee plantation level, more primary data would be needed in order to i) to account better for the cropping system complexity and interactions among crops within agroforestry systems; and ii) to characterise better the emission profiles from organic fertilisers, in particular those derived from coffee co-products, such as husk-based co-compost. At the primary processing level, more studies would be needed to investigate the various processing routes, especially to uncover the potential great diversity from small-scale artisanal up to industrial large-scale processing for all three (wet, semi-wet and dry) routes. In particular, there is a critical lack of information and data to characterise all potential impacts of wet processing, depending on the processing scale, the fermentation duration, the amount of wastewater and the duration and efficiency of the treatment before discharge. More site- and process-specific primary data would be needed to characterise better the GWP but also other impacts, notably water scarcity impacts.

Impacts of coffee drinks primarily depend on the impacts of green coffee. Hence the quality of the LCA of coffee drinks will mostly depend on the inventory data used to characterise the green coffee impacts (at least in the case of black coffee drinks without any added sugar or milk). Therefore, even at the coffee drink level, it is highly recommended to use primary inventory data for the cradle-to-primary-processing gate system boundary and to avoid using too many proxies for the green coffee suppliers based only on the country of origin and not considering the technical specificities of the coffee plantations. However, we recognise that such data are not widely available. Finally, the type of coffee drink will also influence the final impacts. Therefore, the consumers' choices may count notably in terms of relative impacts of the brewing method and packaging. This stresses the need to account for organoleptic properties within the functional unit, as those are the ones that ultimately drive consumer choices. Organoleptic properties could be related further to other aspects along the supply chains, from the coffee type and origin up to the quality of preservation related to the packaging.

Beyond coffee LCA, it might be worth reflecting on LCA practices in general. Despite the harmonised norms and detailed guidelines, there was overall a lack of transparency and details on the studied systems and assumptions made, which may be due, at least partly, to space constraints in scientific publications. We would recommend that all details, as required by the ISO standards, be provided in supplementary information, if not in the paper. We also believe that data quality and associated uncertainties should be assessed and discussed more systematically as LCA results are no more meaningful than identifying how improving knowledge and data quality might affect them. Scenario testing can help to explore sources of uncertainty and the robustness of results. However, it is paramount that scenarios be as realistic as possible. At the cradle-to-grave level in particular, given the length of the supply chain and the resulting large need for data, scenarios may combine primary and secondary data sets that are not consistent. Examples include a proxy for a farming system that is too different from the actual system, or a scenario that does not correlate changes in inputs and outputs at the plot level. Given that the agricultural stage often contributes significantly to many impacts, even at the cradle-to-grave level, we should bear in mind that agricultural systems are complex living ecosystems, whose configurations may be extremely numerous and proper characterisations lie in the detail.

CRediT authorship contribution statement

C. Chéron-Bessou: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **I. Acosta-Alba:** Data curation, Investigation, Writing – original draft. **J. Boissy:** Investigation. **S. Payen:** Data curation, Investigation, Writing – original draft. **C. Rigal:** Data curation, Investigation, Writing – original draft. **A.A.R. Setiawan:** Data curation, Investigation, Writing – original draft. **M. Sevenster:** Data curation, Investigation, Writing – original draft. **T. Tran:** Investigation. **A. Azapagic:** Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Cécile Chéron-Bessou reports financial support was provided by European Commission and the Institute for Scientific Information on Coffee. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is part of the project Soil quality Assessment in Agriculture For life cycle assessment-based Eco-design (SAAFE), funded by the European Commission under the Global Individual Marie Skłodowska-Curie Fellowship Grant Number: 843845. This work was co-funded by ISIC, the Institute for Scientific Information on Coffee.

The authors warmly thank the three reviewers and the editor for their very thorough and valuable comments on the manuscript. They greatly contributed to improve the quality of this article.

Finally, the authors would like to pay a tribute to their colleague and friend, Joachim Boissy, co-author of this work. Joachim was a beloved beautiful person, he will not be forgotten.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.04.005.

References

Acosta-Alba, I., Chia, E., Andrieu, N., 2019. The LCA4CSA framework: using life cycle assessment to strengthen environmental sustainability analysis of climate smart agriculture options at farm and crop system levels. Agr. Syst. https://doi.org/10.1016/j.agsy.2019.02.001.

Acosta-Alba, I., Boissy, J., Chia, E., Andrieu, N., 2020. Integrating diversity of smallholder coffee cropping systems in environmental analysis. International Journal of Life Cycle Assessment. https://doi.org/10.1007/s11367-019-01689-5.

Adams, M., Ghaly, A.E., 2007. Maximizing sustainability of the Costa Rican coffee industry. Journal of Cleaner Production, From Material Flow Analysis to Material Flow Management 15, 1716–1729. https://doi.org/10.1016/j.jclepro.2006.08.013.

Alemu, A., Dufera, E., 2017. Climate smart coffee (coffea arabica) production. American Journal of Data Mining and Knowledge Discovery 2 (2), 62–68.

Aristizábal-Marulanda, V., Garcia-Velasquez, C.A., Cardona Alzate, C.A., 2021a. Environmental assessment of energy-driven biorefineries: the case of the coffee cut-stems (CCS) in Colombia. International Journal of Life Cycle Assessment. https://doi.org/10.1007/s11367-020-01855-0.

Aristizábal-Marulanda, V., Solarte-Toro, J.C., Cardona Alzate, C.A., 2021b. Study of biorefineries based on experimental data: production of bioethanol, biogas, syngas, and electricity using coffee-cut stems as raw material. Environ. Sci. Pollut. Res. 28, 24590–24604. https://doi.org/10.1007/s11356-020-09804-y.

Basavalingaiah, K., Paramesh, V., Parajuli, R., Girisha, H.C., Shivaprasad, M., Vidyashree, G.V., Thoma, G., Hanumanthappa, M., Yogesh, G.S., Misra, S.D., Bhat, S., Irfan, M.M., Rajanna, G.A., 2022. Energy flow and life cycle impact assessment of coffee-pepper production systems: an evaluation of conventional, integrated and organic farms in India. Environ. Impact Assess. Rev. 92, 106687 https://doi.org/10.1016/j.eiar.2021.106687.

Bessou, C., Basset-Mens, C., Tran, T., Benoist, A., 2013. LCA applied to perennial cropping systems: a review focused on the farm stage. Int. J. Life Cycle Assess. 18, 340–361. https://doi.org/10.1007/s11367-012-0502-z.

Bessou, C., Basset-Mens, C., Latunussa, C., Vélu, A., Heitz, H., Vannière, H., Caliman, J.-P., 2016. Partial modelling of the perennial crop cycle misleads LCA results in two contrasted case studies. International Journal of Life Cycle Assessment 21, 297–310. https://doi.org/10.1007/s11367-016-1030-z.

Beyene, A., Kassahun, Y., Addis, T., Assefa, F., Amsalu, A., Legesse, W., Kloos, H., Triest, L., 2012. The impact of traditional coffee processing on river water quality in Ethiopia and the urgency of adopting sound environmental practices. Environ. Monit. Assess. 184, 7053–7063. https://doi.org/10.1007/s10661-011-2479-7.

Birkenberg, A., Birner, R., 2018. The world's first carbon neutral coffee: Lessons on certification and innovation from a pioneer case in Costa Rica. J. Clean. Prod. 189, 485–501. https://doi.org/10.1016/j.jclepro.2018.03.226.

Blinová, L., Sirotiak, M., Bartošová, A., Soldán, M., 2017. Review: utilization of waste from coffee production. Research Papers Faculty of Materials Science and Technology Slovak University of Technology 25, 91–101. https://doi.org/10.1515/rput-2017-0011.

Boulay, A.-M., Bare, J., Benini, L., Berger, M., Lathuillière, M.J., et al., 2018. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). Int. J. Life Cycle Assess. 23 (2), 368–378. https://doi.org/10.1007/s11367-017-1333-8.

Brenes-Peralta, L., De Menna, F., Vittuari, M., 2022. Interlinked driving factors for decision-making in sustainable coffee production. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-022-02821-6.

Brommer, E., Stratmann, B., Quack, D., 2011. Environmental impacts of different methods of coffee preparation. Int. J. Consum. Stud. 35, 212–220. https://doi.org/10.1111/j.1470-6431.2010.00971.x.

BSI, 2012. PAS 2050-1:2012 Assessment of life Cycle Greenhouse Gas Emissions From Horticultural Products, 46.

BSI (British Standards Institution), 2011. The Guide to PAS 2050:2011: How to Carbon Footprint Your Products, Identify Hotspots and Reduce Emissions in Your Supply Chain. London, UK, p. 79 (ISBN 978-0-580-77432-4).

Büsser, S., Jungbluth, N., 2009. The role of flexible packaging in the life cycle of coffee and butter. International Journal of Life Cycle Assessment 14, 80–91. https://doi.org/10.1007/s11367-008-0056-2.

Catalan, E., Komilis, D., Sanchez, A., 2019. Environmental impact of cellulase production from coffee husks by solid-state fermentation: a life-cycle assessment. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2019.06.100.

Cerutti, A.K., Beccaro, G.L., Bruun, S., Bosco, S., Donno, D., Notarnicola, B., Bounous, G., 2013. LCA application in the fruit sector: state of the art and recommendations for environmental declarations of fruit products. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2013.09.017.

Chanakya, H.N., De Alwis, A.A.P., 2004. Environmental issues and management in primary coffee processing. Process Saf. Environ. Prot. 82, 291–300. https://doi.org/10.1205/095758204323162319.

Chayer, J.-A., Kicak, K., 2015. Life Cycle Assessment of Coffee Consumption: Comparison of Single-Serve Coffee and Bulk Coffee Brewing. Quantis, Montreal, Canada.

Coltro, L., Mourad, A., Oliveira, P., Baddini, J., Kletecke, R., 2006. Environmental profile of Brazilian green coffee. Int. J. Life Cycle Assess. https://doi.org/10.1065/lca2006.01.230.

Conservation International, 2020. The Sustainable Coffee Challenge Sets Ambitious 2050 Climate Goal. retrieved from webpage: https://www.conservation.org/press-releases/2020/12/21/the-sustainable-coffee-challenge-sets-ambitious-2050-climate-goal.

Cruz, R., 2014. Coffee by-products: Sustainable Agro-Industrial Recovery and Impact on Vegetables Quality. Facultade de Farmacia, Master II, Universidade de Porto, Porto (117p).

Dadi, D., Daba, G., Beyene, A., Luis, P., Van der Bruggen, B., 2019. Composting and co-composting of coffee husk and pulp with source-separated municipal solid waste: a breakthrough in valorization of coffee waste. Int J Recycl Org Waste Agricult 8, 263–277. https://doi.org/10.1007/s40093-019-0256-8.

De Figueiredo Tavares, M.P., Mourad, A.L., 2020. Coffee beverage preparation by different methods from an environmental perspective. International Journal of Life Cycle Assessment 25, 1356–1367. https://doi.org/10.1007/s11367-019-01719-2.

De Marco, I., Riemma, S., Iannone, R., 2018. Life cycle assessment of supercritical CO2 extraction of caffeine from coffee beans. J. Supercrit. Fluids. https://doi.org/10.1016/j.supflu.2017.11.005.

Djufry, F., Wulandari, S., Villano, R., 2022. Climate smart agriculture implementation on coffee smallholders in Indonesia and strategy to accelerate. Land 11, 1112. https://doi.org/10.3390/land11071112.

Domínguez-Patiño, J., Martínez, A.R., Romero, R.J., Orozco, I.H., 2014. Life cycle assessment on real time in a coffee machine. J. Chem. Eng. https://doi.org/10.17265/1934-7375/2014.12.007.

Enveritas, 2023. Establishing carbon footprint baselines for Robusta coffee production in two origins in Southeast Asia: Central Highlands in Vietnam and Southern Sumatra in Indonesia. In: Lead Implementing Partner. Enveritas.

EU, 2023. Position of the European Parliament adopted at first reading on 19 April 2023 with a view to the adoption of Regulation (EU) 2023/1115 of the European Parliament and of the Council on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation and repealing Regulation (EU) No 995/2010.

FAO, 2023. Markets and Trade, Commodities, Coffee. webpage. https://www.fao.org/markets-and-trade/commodities/coffee/en/.

Frischknecht, R., Wyss, F., Büsser Knöpfel, S., Lützkendorf, T., Balouktsi, M., 2015. Cumulative energy demand in LCA: the energy harvested approach. International Journal of Life Cycle Assessment 20, 957–969. https://doi.org/10.1007/s11367-015-0897-4.

Gabiri, G., Luswata, K.C., Sebuliba, E., Nampijja, J., 2022. Climate Smart Agriculture in Uganda (Report). Accelerating Impacts of CGIAR Climate Research for Africa.

Gibbs, H.K., Johnston, M., Foley, J.A., Holloway, T., Monfreda, C., Ramankutty, N., Zaks, D., 2008. Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology. Environ. Res. Lett. 3, 034001 https://doi.org/10.1088/1748-9326/3/3/034001.

Gobbi, L., Maddaloni, L., Prencipe, S., Vinci, G., 2023. Bioactive compounds in different coffee beverages for quality and sustainability assessment. Beverages 9. https://doi.org/10.3390/beverages9010003.

Gosalvitr, P., 2021. Life Cycle Environmental and Economic Sustainability of Energy and Resource Recovery Options in the Food and Drink Sector in the UK. PhD thesis, University of Manchester, Manchester, p. 430.

Gosalvitr, P., Cuellar-Franca, R., Smith, R., Azapagic, A., 2023. An environmental and economic sustainability assessment of coffee production in the UK. Chem. Eng. J. 465 https://doi.org/10.1016/j.cej.2023.142793.

Grüter, R., Trachsel, T., Laube, P., Jaisli, I., 2022. Expected global suitability of coffee, cashew and avocado due to climate change. PloS One 17, e0261976. https://doi.org/10.1371/journal.pone.0261976.

Haggar, J., Barrios, M., Bolaños, M., Merlo, M., Moraga, P., Munguia, R., Ponce, A., Romero, S., Soto, G., Staver, C., de M. F. Virginio, E., 2011. Coffee agroecosystem performance under full sun, shade, conventional and organic management regimes in Central America. Agroforestry Systems 82, 285–301. https://doi.org/10.1007/s10457-011-9392-5.

Hassard, H.A., Couch, M.H., Techa-erawan, T., McLellan, B.C., 2014. Product carbon footprint and energy analysis of alternative coffee products in Japan. Journal of Cleaner Production 73, 310–321. https://doi.org/10.1016/j.jclepro.2014.02.006. Towards eco-efficient agriculture and food systems: Selected papers from the Life Cycle Assessment (LCA) Food Conference, 2012, in Saint Malo, France.

Hejna, A., 2021. Potential applications of by-products from the coffee industry in polymer technology – current state and perspectives. Waste Manag. 121, 296–330. https://doi.org/10.1016/j.wasman.2020.12.018.

Hicks, A.L., 2018. Environmental implications of consumer convenience: coffee as a case study. J. Ind. Ecol. 22, 79–91. https://doi.org/10.1111/jiec.12487.

Humbert, S., Loerincik, Y., Rossi, V., Margni, M., Jolliet, O., 2009. Life cycle assessment of spray dried soluble coffee and comparison with alternatives (drip filter and capsule espresso). J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2009.04.011.

ICO, 2023. Coffee Report and Outlook. International Coffee Organization. December 2023. (43p.).

Illy, A., Viani, R., 2005. Espresso Coffee: The Science of Quality. Academic Press.

IPCC, 2006. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan. Published.

IPCC, 2007. In: Core Writing Team, Pachauri, R.K., Reisinger, A. (Eds.), Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland (104 pp.).

IPCC, 2014. In: Core Writing Team, Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland (151 pp.).

ISO 14040, 2006. Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization, Geneva.

ISO 14044, 2006. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organisation for Standardisation, Geneva.

ISO 14046, 2014. Environmental Management—Water Footprint—Principles, Requirements and Guidelines. ISO, Geneva, Switzerland.

ISO 14046, 2017. Environmental Management—Water Footprint—A Practical Guide for SMEs. ISO, Geneva, Switzerland.

Jansen, B.J., Spink, A., 2006. How are we searching the World Wide Web? A comparison of nine search engine transaction logs. Inf. Process. Manag. 42, 248–263.

Jaramillo, S., Saraz, J.A.O., Correa, G., 2017. Emission and fixation of greenhouse gases in potential specialty coffee production zones in Antioquia -Colombia. Revista Facultad Nacional de Agronomía Medellín 70, 8341–8349. https://doi.org/10.15446/rfna.v70n3.62639.

Killian, B., Rivera, L., Soto, M., Navichoc, D., 2013. Carbon Footprint across the Coffee Supply Chain: The Case of Costa Rican Coffee.

Maina, J.J., Mutwiwa, U.N., Engineering, G.M.K., M.G. 1Department of A. and B.E.S. of B. systems and E., Technology, J.K.U. of A. and, Works, P.O.B. 62000-00200 N. 2Wildlife, Voi, P.O.B. 310-80300, 2016. Evaluation of Greenhouse Gas Emissions along the Small-Holder Coffee Supply Chain in Kenya.

Mussatto, S.I., Machado, E.M.S., Martins, S., Teixeira, J.A., 2011. Production, composition, and application of coffee and its industrial residues. Food Bioprocess Technology 4, 661–672. https://doi.org/10.1007/s11947-011-0565-z.

Nab, C., Maslin, M., 2020. Life cycle assessment synthesis of the carbon footprint of Arabica coffee: case study of Brazil and Vietnam conventional and sustainable coffee production and export to the United Kingdom. Geo: Geography and Environment 7, e00096. https://doi.org/10.1002/geo2.96.

Noponen, M.R.A., Edwards-Jones, G., Haggar, J.P., Soto, G., Attarzadeh, N., Healey, J.R., 2012. Greenhouse gas emissions in coffee grown with differing input levels under conventional and organic management. Agr. Ecosyst. Environ. 151, 6–15. https://doi.org/10.1016/j.agee.2012.01.019.

Noponen, M.R.A., Haggar, J.P., Edwards-Jones, G., Healey, J.R., 2013. Intensification of coffee systems can increase the effectiveness of REDD mechanisms. Agr. Syst. 119, 1–9. https://doi.org/10.1016/j.agsy.2013.03.006.

Payen, S., Falconer, S., Ledgard, S.F., 2018. Water scarcity footprint of dairy milk production in New Zealand – a comparison of methods and spatio-temporal resolution. Sci. Total Environ. 639, 504–515. https://doi.org/10.1016/j.scitotenv.2018.05.125.

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992. https://doi.org/10.1126/science.aaq0216.

Quack, D., Eberle, U., Liu, R., Stratmann, B., 2009. Case Study Tchibo Privat Kaffee Rarity Machare by Tchibo Gmbh. PCF Pilot Project Germany, Berlin.

Rahmah, D., Mardawati, E., Kastaman, R., Pujianto, T., Pramulya, R., 2023. Coffee pulp biomass utilization on coffee production and its impact on energy saving, CO2 emission reduction, and economic value added to promote green lean practice in agriculture production. Agronomy-Basel 13. https://doi.org/10.3390/agronomy13030904.

Rahn, E., Läderach, P., Baca, M., Cressy, C., Schroth, G., Malin, D., Van Rikxoort, H., Shriver, J., 2014. Climate change adaptation, mitigation and livelihood benefits in coffee production: where are the synergies? Mitig Adapt Strateg Glob Change 19, 1119–1137. https://doi.org/10.1007/s11027-013-9467-x.

Ratchawat, T., Panyatona, S., Nopchinwong, P., Chidthaisong, A., Chiarakorn, S., 2020. Carbon and water footprint of Robusta coffee through its production chains in Thailand. Environ. Dev. Sustain. 22, 2415–2429. https://doi.org/10.1007/s10668-018-0299-4.

Rega, F.V., Ferranti, P., 2019. Life cycle assessment of coffee production in time of global change. Encyclopedia of Food Security and Sustainability. 497–502.

RStudio Team, 2023. Developer: Posit, Joseph J. Allaire, License: GNU Affero General Public License v3. https://posit.co/products/open-source/rstudio/.

Ruben, R., Allen, C., Boureima, F., Mhando, D.G., Dijkxhoorn, Y., 2018. Coffee value chain analysis in the southern highlands of Tanzania. In: Report for the European Commission, DG-DEVCO. Value Chain Analysis for Development Project (VCA4D CTR 2016/375-804), p. 135. + annexes.

Statistica, 2023. Coffee production worldwide from 2003/04 to 2021/22 (in million 60 kilogram bags). In: Data for Coffee Production by All Exporting Countries Retrieved From the Webpage. https://www.statista.com/statistics/263311/worldwide-production-of-coffee/ (viewed on 2023.12.12).

Trinh, L.T.K., Hu, A.H., Lan, Y.C., Chen, Z.H., 2020. Comparative life cycle assessment for conventional and organic coffee cultivation in Vietnam. Int. J. Environ. Sci. Technol. https://doi.org/10.1007/s13762-019-02539-5.

UNEP and SETAC, 2019. In: Frischknecht, R., Jolliet, O. (Eds.), Global Guidance on Environmental Life Cycle Impact Assessment Indicators, 2, p. 202.

Usva, K., Sinkko, T., Silvenius, F., Riipi, I., Heusala, H., 2020. Carbon and water footprint of coffee consumed in Finland-life cycle assessment. International Journal of Life Cycle Assessment. https://doi.org/10.1007/s11367-020-01799-5.

Van Rikxoort, H., 2011. The Potential of Mesoamerican Coffee Production Systems to Mitigate Climate Change. In: Climate Change Management. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-31110-9_43.

Van Rikxoort, H., Läderach, P., Van Hal, J., 2013. The potential of Latin American coffee production systems to mitigate climate change. In: Leal Filho, W. (Ed.), Climate Change and Disaster Risk Management, Climate Change Management. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 655–679. https://doi.org/10.1007/978-3-642-31110-9_43.

Van Rikxoort, H., Schroth, G., Läderach, P., Rodríguez-Sánchez, B., 2014. Carbon footprints and carbon stocks reveal climate-friendly coffee production. Agronomy and Sustainable Development. 34, 887–897. https://doi.org/10.1007/s13593-014-0223-8.

Vera-Acevedo, L.D., Vélez-Henao, J.A., Marulanda-Grisales, N., 2016. Assessment of the environmental impact of three types of fertilizers on the cultivation of coffee at the Las Delicias indigenous reservation (Cauca) starting from the life cycle assessment. Revista Facultad de Ingeniería Universidad de Antioquia 93–101. https://doi.org/10.17533/udea.redin.n81a09.

Viere, T., von Enden, J., Schaltegger, S., 2011. Life cycle and supply chain information in environmental management accounting: a coffee case study. Environmental Management Accounting and Supply Chain Management, Eco-Efficiency in Industry and Science. https://doi.org/10.1007/978-94-007-1390-1_2.

Vignoli, J.A., Viegas, M.C., Bassoli, D.G., Benassi, M.D.T., 2014. Roasting process affects differently the bioactive compounds and the antioxidant activity of arabica and robusta coffees. Food Res. Int. 61, 279–285. https://doi.org/10.1016/j.foodres.2013.06.006.

Youkhana, A.H., Idol, T.W., 2016. Leucaena-KX2 mulch additions increase growth, yield and soil C and N in a managed full-sun coffee system in Hawaii. Agrofor. Syst. 90, 325–337. https://doi.org/10.1007/s10457-015-9857-z.