Life Cycle Assessment of Ground Coffee and Comparison of Different Brewing Methods: A Case Study of Organic Arabica Coffee in Northern Thailand

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ABSTRACT

Billions of cups of coffee are consumed worldwide every year with little regard for the wide range of environmental impacts arising at different stages of its life cycle. This study aimed to assess the environmental impacts of a single cup of hot, black coffee brewed from ground organic Arabica beans produced and consumed locally in the northern region of Thailand. Environmental impacts throughout its life cycle were assessed and the influences of different brewing methods were compared. Life cycle assessment (LCA) was implemented to evaluate the environmental performance of the product system. The results found that coffee cultivation is a major contributor to ecosystem damage in all brewing scenarios, particularly on land-use related midpoint indicators. Preparing the coffee by moka pot is especially energy intensive and showed a high impact score on human health. It also demonstrated resource damage categories in the brewing stage that were directly related to fossil-based electricity consumption. For other brewing scenarios, the upstream processes such as cultivation and bean processing were major contributors to environmental harm. According to the farming scenario analysis, the application of chemical fertilizers during conventional farming can aggravate the impact from the cultivation process on human health and resources, as compared to organic farming. This study comprises an initial stage of a coffee LCA study in Thailand. Hopefully, it can add to the body of information pertaining to the life cycle environmental impacts of coffee, a popular beverage product, aid decision-making, and increase attention on the importance of sustainable products.

1. INTRODUCTION

Coffee is one of the most popular beverages in the world. On the supply side, it is a vital global commodity and contributes an important proportion of the export income of producing countries. Those are primarily developing nations in South America, Africa, and Asia. Major consuming countries are mainly located in Europe and North America. According to the International Coffee Organization (2016a), over 1.85 billion cups of coffee-equivalent to 25 million kilograms of beans-are globally consumed daily. In 2016, more than 20 million people from 55 producer countries in the tropical zone were employed to produce 8.83 million tons of coffee. That was still insufficient as consumption demand was 9.06 million tons in the same year (ICO, 2016b). There are two main commercial species of coffee, *Coffea arabica,* or Arabica, and *C. canephora,* or Robusta. Arabica coffee prefers higher altitudes and tends to be sensitive to disease and adverse climate conditions, while Robusta grows at relatively low elevations and can tolerate higher temperatures. However, Arabica is more popular than Robusta in the global market because of its sweeter, softer taste, and aroma. In Thailand in 2016, over 56,000 ha of arable land were occupied by coffee beans, of which Arabica coffee cultivated in mountainous areas in the northern region accounted for 45.2% (DOAE, 2016).

Apart from its economic importance, coffee also involves activities ranging from cultivation to roasting, packaging, transporting, brewing, and disposal, all of which entail potentially harmful environmental impacts. Different site-based studies have been conducted to monitor and survey the environmental impacts of coffee production, especially cultivation and production processes. Previous studies have found that coffee production is associated with impacts such as deforestation, leading to loss of biodiversity and habitat fragmentation (Ambinacudige and Choi, 2009), discharging of wastewater containing high levels of organic compounds, including solid and liquid residues from coffee processing, e.g., pulp, husk and parchment (Goncalves et al., 2013), and effects on microinvertebrates in aquatic ecosystems (Beyene et al., 2012). In addition to site monitoring, to achieve sustainable production and consumption, an environmental profile of coffee is needed to identify and quantify material and energy usage and associated environmental impacts. One of the effective environmental assessment tools for products is based on life cycle perspective. Called life cycle assessment (LCA), it is employed to assess environmental impacts of coffee throughout its life cycle, from raw material extraction to production processes, transportation, use, and disposal. One of the obvious benefits of LCA is that it is able to evaluate potential environmental impacts of products by compiling inventories of relevant inputs and outputs. The interpreted results can be used to aid decision-making for stakeholders to improve their environmental performance.

Previous LCA coffee studies include a cradle-to-gate analysis of coffee production, which concentrated on the life cycle inventory of coffee produced in Brazil. It found that large amounts of water, energy, and fertilizers were required for coffee production (Coltro et al., 2006). Humbert et al. (2009) pointed out that approximately half of the total environmental impacts arose from processes under control of coffee producers and suppliers (i.e., cultivation, treatment, processing, packaging, and distribution), while the other half resulted from the life cycle stage controlled by consumers (i.e., use and disposal). Cradle-to-grave studies also asserted that cultivation and consuming (brewing) were likely to be the key hotspots contributing to major midpoint environmental impacts. These were energy consumption-Cumulative Energy Demand, climate change, eutrophication, and acidification (Büsser and Jungbluth, 2009) and endpoint impacts like human health, ecosystem quality, and resources that depend on brewing methods and types of coffee (Chayer and Kicak, 2015). A comparative LCA of different brewing systems (drip filter, French press, and pod-style) was executed in the United States and revealed that pod-style coffee was the most environmentally friendly (Hick, 2017). With regard to greenhouse gas emissions, a study on the carbon footprint of coffee production based on the LCA method indicated that the application of fertilizers was the principal contributor to greenhouse gas emissions in coffee cultivation (Noponen et al., 2012). Hassard et al. (2014) likewise assessed carbon footprint and the energy consumption of different coffee products in Japan. Their work demonstrated that a majority of greenhouse gases is released from coffee farming and brewing while processing and brewing were associated with high energy consumption.

Although LCA has been extensively applied to different types of agricultural and agro-industrial products, among these studies, the application of LCA to evaluate the environmental impact of beverage crops-coffee, in this case-seems to be limited compared with other agro-industrial products, such as dairy products, canned food, and cash crops. Moreover, LCA of coffee in the context of Thailand is currently absent. Therefore, the objectives of this study were to assess the environmental impacts of a cup of hot, black coffee brewed from ground Arabica coffee produced via an organic farming system and consumed locally in the northern region of Thailand throughout its life cycle (cradle-to-grave), and to compare the influence of different brewing methods (i.e., by electric drip coffee maker, moka pot, and manual pour-over dripper) on its life cycle environmental impacts. The differences between organic and conventional farming results were also compared.

2. METHODOLOGY

2.1 Goal and scope definitions

The LCA was conducted in accordance with ISO14040:2006 and ISO14044:2006 standards. In this study, environmental hotspots of ground Arabica coffee throughout its life cycle were identified. Green beans were prepared by wet processing. The product system consisting of five main stages are displayed in Figure 1. In addition, since consumer behaviors are important parameters that can influence environmental impact results (Hick, 2017), three brewing method scenarios were established (Figure 1) in order to provide information for consumers to aid decision makers. The intended audience of this study, therefore, includes coffee farmers, producers, and consumers who can use the results to improve their activities and lower environmental impacts. The selected functional unit was to provide a cup of hot, black Arabica coffee, the equivalent of 13.5 g of ground coffee brewed in 150 mL of hot water.

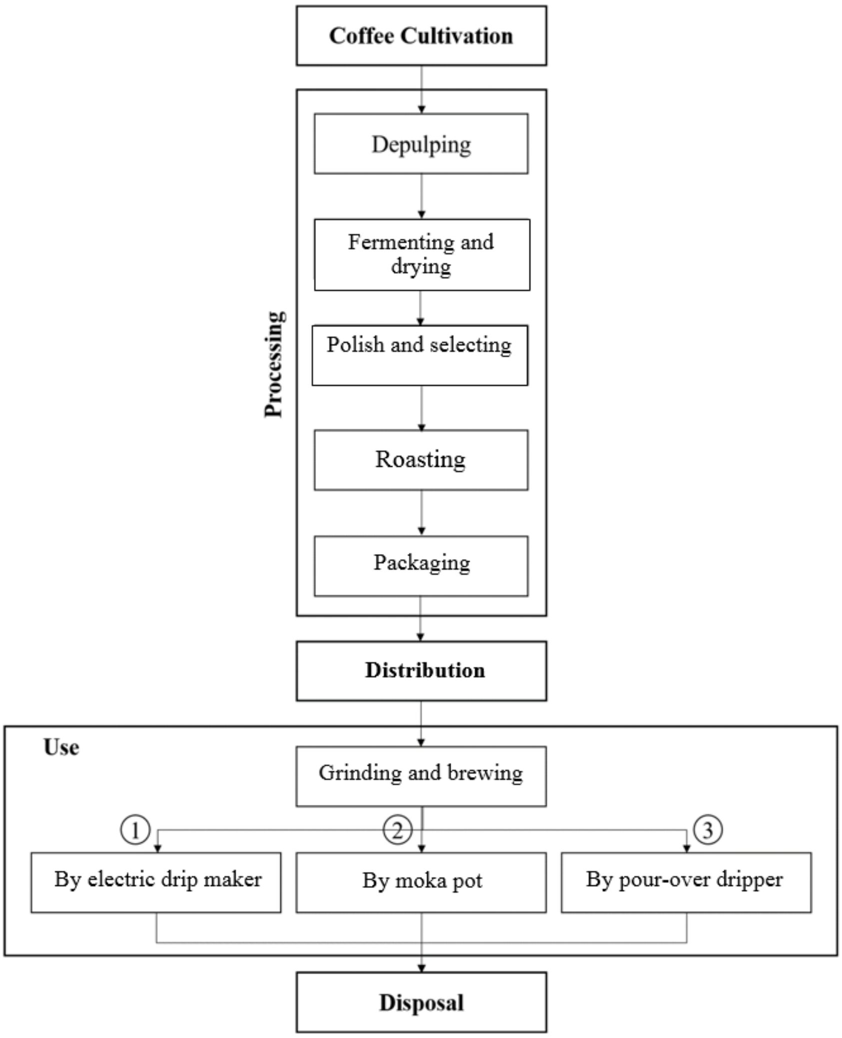

Figure 1. System boundary of coffee product system dividing into three brewing methods

The study was undertaken in the cultivation year of 2016 from July to November. The primary data related to the quantity of resource consumption, cultivation, transportation, and coffee bean processing. These were derived from a major coffee producer in Chiang Rai, a northern province of Thailand, the largest source of Arabica coffee production in the country (DOAE, 2016). Data on brewing were acquired from self-measurement. The secondary data of the background system was drawn from literature, along with the LCI database, Ecoinvent 3.1. The allocation applied in this study was based on the mass-based allocation method. The environmental impact method adopted in the analysis was ReCiPe (Goedkoop et al., 2009); the most recent indicator approach integrated the CML and Eco-Indicator '99 methods. The method classifies indicators at two levels: 17 midpoint indicators and three endpoint damage categories.

2.2 Life cycle inventory

The considered product system comprised five main phases, namely, coffee cultivation, bean processing, distribution, use, and disposal. Five sub-processes were included in the bean processing phase, i.e., depulping, fermenting and drying, polishing and selecting, and roasting and packaging. The use phase comprised grinding and brewing. All relevant parameters in each process are described in Table 1. Acquisition of data and assumptions used in the analysis for each life cycle stage are described as follows:

2.2.1 Coffee cultivation

The total arable land owned by the producer and used for Arabica cultivation covered 9.6 ha with an average coffee cherry yield of 5,000 kg/ha. The land was formerly a fruit orchard from 1995 to 2005, before being transformed into a coffee farm. Carbon dioxide emissions from land-use change were negligible in this study since site-specific data was highly uncertain. The owner claimed the farm was organic. Hence, chemical fertilizers and insecticides were not used in the cultivation model. Inputs in this stage included 3 kg organic fertilizers (compost and manure) per coffee tree, applied annually, with additional organic fertilizers from reused residues, and polypropylene (PP) woven sacks used for packing ripe coffee cherries for transport to the factory. The organic fertilizer production model was constructed based on the primary data; data pertaining to the production of PP woven sacks was derived from the KOAMI Company report. The principal source of water used on the farm was rain. Therefore, the amount of water use in this stage was excluded.

2.2.2 Manufacturing processes

After cultivating and harvesting, ripe coffee cherries were brought to a factory to be processed. The wet processing began with washing the coffee cherries with clean water. During this stage, some inferior fruit was separated by flotation. The ripe cherries were then conveyed to the de-pulping machine to separate the outer flesh, or pulp, from the bean. The beans were still covered with a mucilage layer and enclosed in an inner coating called parchment. In the next stage, during fermentation, the mucilage was removed by natural enzymes from yeast and bacteria. This could take as long as three or four days. In the washing stage, the fermented beans were thoroughly rinsed with clean water. After removal of the mucilage, the beans with parchment were sun-dried. At this stage, the dried beans lost 47% of their weight due to evaporation (Adam and Ghaly, 2006). The dried beans were then passed through a hulling process to separate the parchment from the bean, and then graded by sorting machine. The green beans were subsequently transported to a roasting and packing factory located 2 km away from the first one. The beans were roasted at a medium level (200 °C for 15 min) fueled by natural gas, with another 15% of the green bean weight lost (Jokanovic et al., 2012). Direct emissions of carbon dioxide arising from natural gas burning were noted. Roasted beans were packed in PET/Al/PE packages prior to distribution to retailers. An overview of inputs and outputs for each stage in the coffee's wet processing is summarized in Table 1.

Table 1. Inputs and outputs in different stages of the coffee life cycle used in the model.

Stage	Flow		Unit	Amount
Cultivation	Input	Compost	g	11.15
		Manure	g	11.15
		Residues	g	0.15
		PP granulate	g	33.71
		Electricity	J	26.27
	Output	Coffee cherries	g	74.34
Depulping	Input	Coffee cherries	g	74.34
		Electricity	J	1,997.90
	Output	Depulped beans	g	52.04
		Pulp	g	22.30
Fermentation and drying	Input	Depulped beans	g	52.04
		Water	g	78.06
	Output	Dried parchment coffee	g	19.86
		Mucilage	g	14.57
		Waste water	g	78.06
		Evaporated water	g	17.61
Polishing and selecting	Input	Dried parchment coffee	g	19.86
		Electricity	J	3,520.84
	Output	Green beans	g	15.89
		Parchment	g	3.97

Table 1. Inputs and outputs in different stages of the coffee life cycle used in the model (cont.)

Stage	Flow		Unit	Amount
Roasting	Input	Green beans	g	15.89
		Electricity	J	7,263.67
		Natural gas	g	1.57
	Output	Roasted beans	g	13.50
		Evaporated water	g	2.39
		direct CO_2 emission	g	4.76
Packaging	Input	Roasted beans	g	13.50
		Electricity (sealing)	J	172.84
		PET granulate	g	0.06
		Aluminum	g	0.07
		Polyethylene (high density)	g	0.36
		Electricity (PET/Al/PE production)	J	4,615.81
	Output	Packaged roasted beans	g	13.50
Distribution[1]				
Grinding	Input	Roasted beans	g	13.50
		Electricity	J	1944.00
	Output	Ground coffee	g	13.50
Brewing		Electricity (SC1)	MJ	0.11
		Electricity (SC2)	MJ	0.50
		Electricity (SC3)	MJ	0.09
		Paper filter (SC3)	g	1.7
		Production of brewing appliances[2]		
End-of-life		Waste collecting by truck and dumping at landfill		

[1]see Table 3

[2]see Section 2.2.4 and Table 2

Note:PET/Al/PE=polyethylene terephthalate/aluminum/polyethylene, g=gram, J=joule, MJ=megajoule, SC1=Scenario 1, SC2=Scenario 2, SC3=Scenario 3

2.2.3 Distribution

Packages of roasted beans were distributed by truck to a retailer in the city center. A 3.5-7.5t Euro 3 lorry (in an Ecoinvent 3.1) database was chosen to represent the vehicle in the transportation model. The distance between the factory and the shop was assumed to be 60 km.

2.2.4 Use

The roasted beans were ground by electric coffee grinding machines at the consumers' homes or offices. A cup of hot, black Arabica coffee was prepared by using 13.5 g of ground coffee in 150 mL of hot water, as referred to in Humbert et al. (2009). Brewing methods were varied according to the consumer's preference. In this study, three brewing scenarios by different appliances were investigated using appliances as described in Table 2.

To prepare a cup of coffee as defined in the functional unit, an electric coffee maker, hotplate for the moka pot and electric kettle for pour-over dripper required 0.11, 0.50, and 0.09 MJ of electricity on average, respectively. The amount of water used for brewing a cup of coffee (150 mL) was included in the analysis. The manufacturing of brewing appliances was taken into account. Usage frequency of filter machine (SC1) was assumed to be 1,095 cups of coffee per year (3 cups a day) over 5 years of its lifetime. Usage of the moka pot (SC2) and glass dripper cone (SC3) was assumed to be one cup a day or 365 cups per year over 5 years of their lifetimes. In addition, a piece of paper filter weighing 1.7 g was used for the pour-over dripper.

Table 2. Description of brewing scenarios and representative model of appliances.

Scenario	Method	Appliance (model)
SC1	Electric drip coffee maker with reusable stainless steel filter	- Severin™ (KA-4306)
SC2	Moka pot heated by a hotplate electric stove	- Bialetti™ moka pot (1-cup size) - HouseWorth™ hotplate (HP01-1500W)
SC3	Manual pour-over dripper using electric kettle to boil water and paper filter	- Boncafe™ filter paper (1 × 2 in) - Glass dripper cone - Phillips™ electric kettle (HD9306- 1800W)

2.2.5 Transport

In the cultivation stage, organic fertilizers were carried to the farm by a medium-sized truck (7.5-16t) over a distance of 30 km. The PP sack manufacturer was located 150 km away from the farm; the sacks were delivered to the farm by a medium-sized truck. Coffee cherries were transported to the first factory, located 12 km from the farm, by pickup truck. The green coffee was delivered to the second factory for roasting and packing in an adjacent area, 2 km away, by a pickup truck. Stand-up pouches (PET/Al/PE bags) that were used for final packaging were carried to the factory by the packaging company using a medium-size truck. The distance from Bangkok to the roasting factory was 800 km. Packaged products were distributed to the retailer by a small truck (3.5-7.5t). The transportation technology regarding fuel consumption and emissions models was based on European emission standards. A majority of freight vehicles operating in the country were EURO 3 (DLT, 2016). Table 3 shows data and the assumptions associated with transportation that were used in the analysis.

Table 3. Assumptions of transportation in the analysis

Carrying item	From	To	Distance (km)	Vehicle
Coffee cherries	Coffee farm	Factory 1	12	Pickup truck
Organic fertilizers	Agricultural store	Coffee farm	30	Medium truck
PP woven sacks	Sack factory	Coffee farm	150	Pickup truck
Dried parchment beans	Factory 1	Factory 2	2	Pickup truck
PET/Al/PE bags	Store	Factory 2	800	Medium truck
Packaged roasted beans	Factory 2	Retailer	60	Small truck
Waste after using	Consumer's home	Landfill site	20	Waste collecting truck

2.2.6 Electricity mix

The electricity consumed in the coffee life cycle was assumed to be from the Thailand grid mix, and modeled on the proportion of energy sources in 2016 (DEDE, 2016) illustrated in Table 4. The grid mix was modeled from a country-specific dataset (TH) from Ecoinvent 3.1. The national electricity grid mix is dominated by fuel-based sources, namely natural gas and coal (lignite).

2.2.7 End-of-life

After brewing, used coffee grounds and packaging (as well as paper filters, in the case of pour-over drippers in Scenario 3) were discarded as household waste. The waste was then transferred to a municipal solid waste landfill by a collecting truck. It was assumed that all waste collected from households was taken to the municipal landfill site located 20 km from the city center where the product had been used.

Table 4. Proportion of electricity in Thailand's grid mix by source in 2016

Source	Share (%)
Hydropower	1.78
Fuel oil	0.16
Coal	18.59
Natural gas	63.21
Diesel	0.09
Imported[1]	9.93
Renewable	6.24
Total	100

[1]Coal and hydropower from Lao PDR

Source: DEDE (2016)

3. RESULTS AND DISCUSSION

3.1 Life cycle impact assessment

LCIA results were assessed by ReCiPe Endpoint (Hierarchist; H) method normalized and weighted based on an average world environmental impact for the year 2000 (World ReCiPe H/H, 2000). The impact assessment was divided into two parts: results of characterization and damage assessment indicators, and results of the weight indicators. Impact assessment results of characterization indicators, as derived from comparing the three different brewing scenarios, were listed in Table 5. The contribution of the various processes to the midpoint indicators in the different brewing scenarios were illustrated in Figure 2-4 for SC1, SC2, and SC3, respectively.

Table 5. Impact assessment results of characterization indicators of the three brewing scenarios

Impact category	Unit	Damage category	SC1	SC2	SC3
Agricultural land occupation (ALO)	species.yr	Ecosystems	2.94E-09	2.95E-09	3.09E-09
Climate change (CC)	species.yr	Ecosystems	2.70E-10	8.46E-10	2.40E-10
Freshwater ecotoxicity (FET)	species.yr	Ecosystems	2.42E-13	6.50E-13	4.71E-13
Freshwater eutrophication (FE)	species.yr	Ecosystems	2.23E-13	8.13E-13	2.23E-13
Marine ecotoxicity (MET)	species.yr	Ecosystems	4.01E-14	1.02E-13	8.19E-14
Natural land transformation (NLT)	species.yr	Ecosystems	2.79E-11	4.61E-11	4.05E-11
Terrestrial acidification (TA)	species.yr	Ecosystems	6.64E-13	2.14E-12	6.30E-13
Terrestrial ecotoxicity (TET)	species.yr	Ecosystems	7.78E-13	1.29E-12	8.81E-13
Urban land occupation (ULO)	species.yr	Ecosystems	4.63E-12	1.13E-11	5.48E-12
Climate change (CC)	Daily	Human health	4.77E-08	3.86E-09	3.37E-09
Human toxicity (HT)	Daily	Human health	3.73E-09	1.49E-07	4.24E-08
Ionizing radiation (IR)	Daily	Human health	1.76E-11	1.25E-08	4.20E-09
Ozone depletion (OD)	Daily	Human health	5.55E-12	2.78E-11	2.18E-11
Particulate matter formation (PMF)	Daily	Human health	8.82E-09	9.49E-12	5.70E-12
Photochemical oxidant formation (POF)	Daily	Human health	2.59E-12	2.75E-08	8.86E-09
Fossil depletion (FD)	USD	Resources	1.85E-03	6.82E-12	2.60E-12
Metal depletion (MD)	USD	Resources	3.90E-05	1.89E-07	5.55E-08

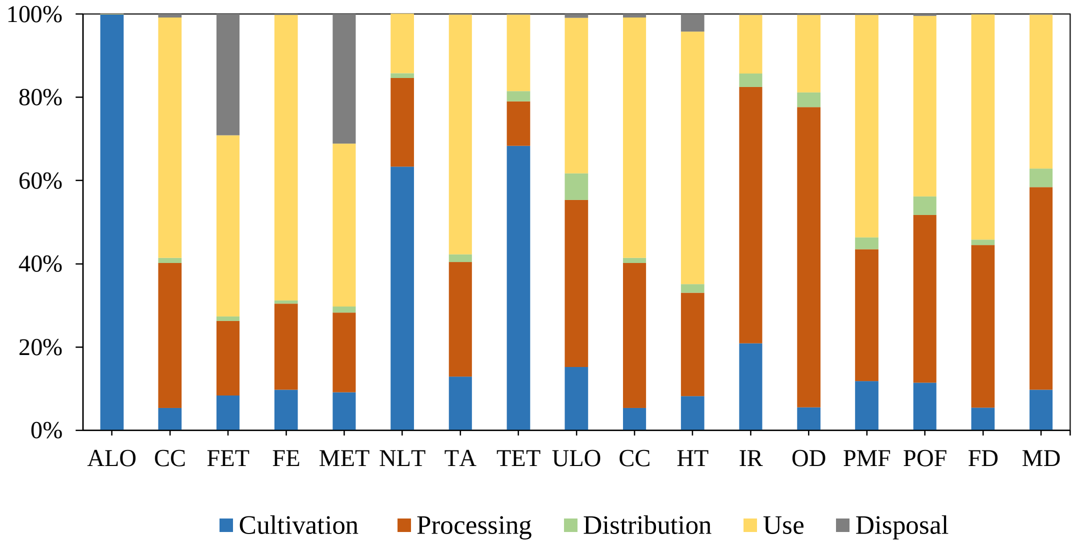

Figure 2. Impact assessment result of midpoint characterization indicators of SC1.

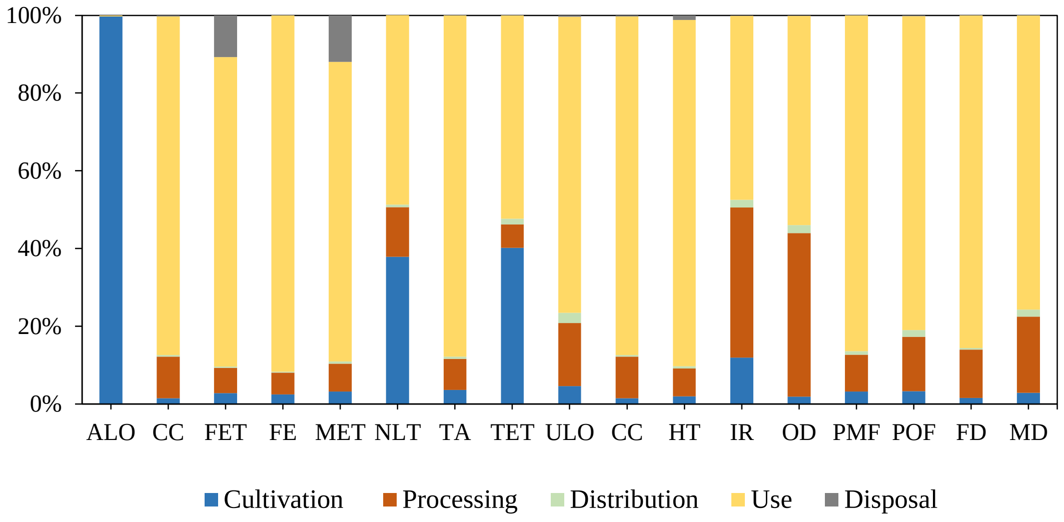

Figure 3. Impact assessment results of midpoint characterization indicators of SC2.

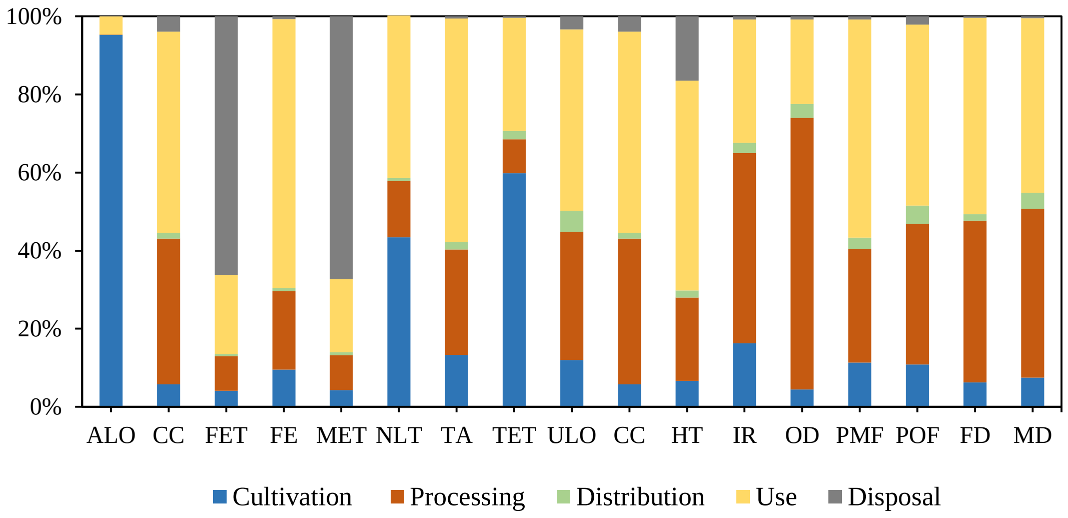

Figure 4. Impact assessment results of midpoint characterization indicators of SC3.

In comparing the various brewing scenarios, SC2 showed the highest impact of all midpoint indicators, with the exception of the ALO. On the contrary, SC1 demonstrated the least environmental impact in 15 out of 17 midpoint-impact categories. From a process perspective, the use stage, including coffee bean grinding and brewing, greatly contributed to most of the SC2 impacts. In SC1 and SC3, by contrast, the use stage tended to play an equal role to the processing stage in the same impact categories. Coffee cultivation causing the greatest impact on ALO, NLT and TET categories were directly related to ecosystems damage in all brewing scenarios. With SC3, in particular, the use of filter paper led to a higher impact at the disposal stage on FET and MET; and accounted for over 60% of the total impact.

In the endpoint assessment, the three main damage categories were ecosystems, human health, and resources. Figure 5 exhibits the contribution of different life cycle stages of coffee to damage assessment indicators. The comparison of results was displayed on a percentage share by setting the greatest result to 100%. The endpoints followed the same trend as midpoint assessment, that is, SC2 showed the highest total impact across three damage categories. The agriculture phase had the highest impact on ecosystems for all scenarios. In SC2, the use phase was the largest contributor to human health and resources. And finally, the processing and use stages showed equal contributions to human health and resources in SC1 and SC3. The weighted results of the damage categories were represented as a single score (Pt) shown in Table 6.

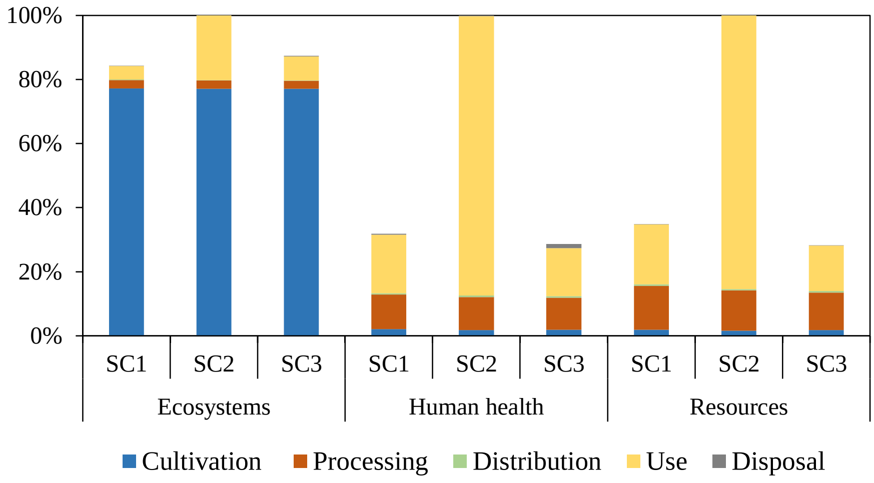

Figure 5. Impact assessment results of endpoint damage categories.

Table 6. Weighted results of the three damage categories (single score).

Damage category	Unit	SC1	SC2	SC3
Ecosystems	Pt	9.36E-13	2.73E-12	8.16E-13
Human health	Pt	2.65E-13	6.14E-13	2.76E-13
Resources	Pt	1.94E-13	3.15E-13	1.80E-13
Total	Pt	1.40E-12	3.66E-12	1.27E-12

3.2 Comparisons with coffee cultivated by conventional practice

Since the current study mainly focused on organic coffee cultivation, a conventional farming scenario using chemical fertilizers was assessed and compared. Data from Northern Thailand, documenting the use of chemical fertilizers for cultivation and bean yields (kg/ha) according to the amount of fertilizers applied, were obtained from a field experiment conducted by Methawarakul et al. (2017). The amount of fertilizer used was based on the recommendations of the Land Development Department. According to the study, 20 kg of 15-15-15 (N-P-K) fertilizer and 625 kg of 8-24-24 fertilizer were applied on one hectare of a coffee farm. Compared with organic farming practice using only compost and manure, chemical fertilizers produced 34.1% higher yields (Methawarakul et al., 2017). Therefore, in the product system model in the study, the area of land used for conventional coffee farming was proportionally reduced in order to produce the fixed amount of coffee beans in the reference flows. The analysis was executed based on the identical functional unit. Scenario analysis results were presented by brewing scenarios listed in Figures 6-8. Chemical fertilizers increased the cultivation phase damage categories to human health and resources in all brewing scenarios. By contrast, it reduced the impact on ecosystems due to the reduction of land use. As a result, the conventional farming practice showed relatively high impact score on human health and resources, whereas its impact score on ecosystems was reduced compared with the organic farming.

3.3 Sensitivity analysis

Sensitivity analysis was conducted to examine the robustness of results and their sensitivity in response to the variance of uncertainty factors. The range of distribution to consumers that appears to be uncertain since it can be varied from place to place was analyzed. To test the sensitivity of the single score (Pt) results, the distance of distribution was increased by 10% from their baseline values, as shown in Table 7. The increase in the distribution range slightly affected the results (less than 1% change).

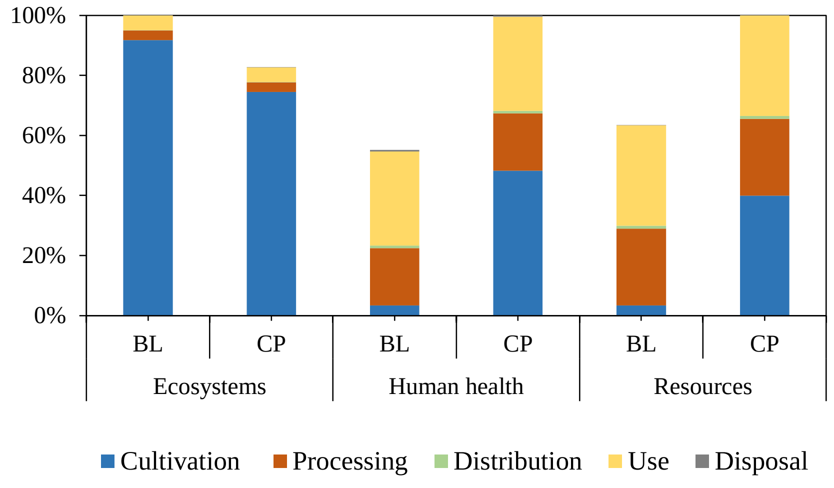

Figure 6. Comparison of results between baseline and conventional farming scenarios of SC1.

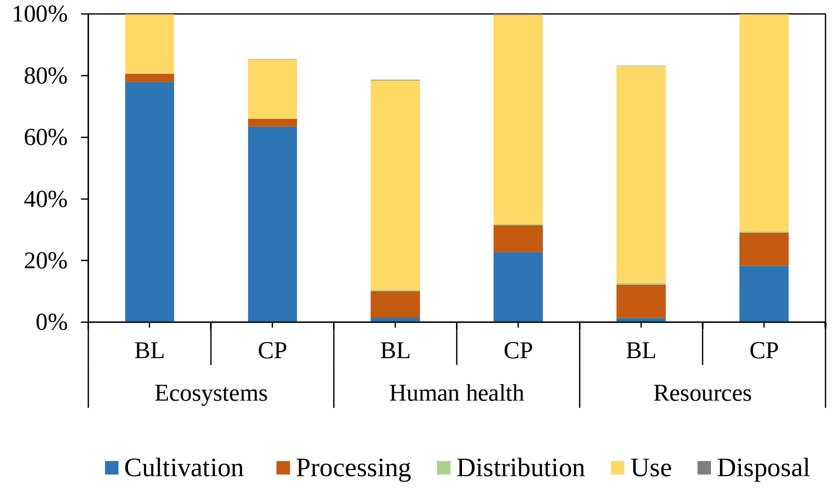

Figure 7. Comparison of results between baseline and conventional farming scenarios of SC2.

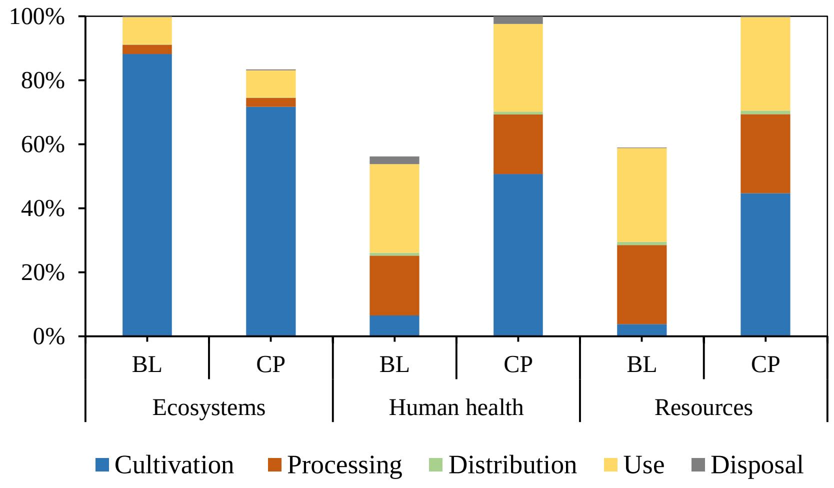

Figure 8. Comparison of results between baseline and conventional farming scenarios of SC3.

Electricity consumption in the brewing stage was indicated to be one of the major contributors to the environmental impact. To assess at which specific electricity consumption one scenario gets more beneficial than others, electricity consumption of SC1 and SC2 were reduced until the single score impact result equals the least impact scenario (SC3). The results showed that at least 18.20% and 82.20% of electricity in the brewing stage of SC1 and SC2, respectively, should be reduced in order to get an equal benefit to SC3. As there was the comparison between organic and conventional farming in the analysis, the amount of chemical fertilizer that is related to the area of land use (higher coffee bean yield - kg/ha) was examined. A full conventional farming applying chemical fertilizers based on the recommended amount (mentioned in Section 3.2) can lead to higher impact, over 40% in SC1 and SC3. However, there is a trade-off in the impact on ecosystem damage due to the reduction of land use (Figures 6-8). In addition, the decrease of chemical fertilizers applied in the conventional farming by 50% can potentially reduce the overall impact results by more than 50% in all scenarios, compared with the use of 100% chemical fertilizer, showing that the results are highly sensitive to the reduction of chemical fertilizers in the conventional farming. The final case shows the effect of the increase of yield by 10% from the baseline leading to a slight change (less than 2%) in the impact results. Ground coffee loss during the preparation by 10% can affect the overall results by at least 2.0% in SC2 to 6.2% in SC3.

Table 7. Sensitivity of single score impact results due to the variation of influencing parameters

Parameter	Variation	Change from baseline (%)		
		SC1	SC2	SC3
Distribution distance	-10.0%	-1.0	-0.3	-0.6
Electricity reduction SC1	-21.7%	-9.5	0.0	0.0
Electricity reduction SC2	-86.6%	0.0	-65.2	0.0
Conventional farming I	100% chemical fertilizer	44.2	17.0	49.2
Conventional farming II	50% chemical fertilizer	20.2	7.8	22.7
Yield increase	10.0%	-1.9	-0.7	-1.6
Ground coffee loss during preparation	10.0%	5.2	2.0	6.2

4. DISCUSSION

The contribution of this research is to reveal the full life cycle impacts of coffee cultivation in Thailand. The findings were consistent with previous studies (Büsser and Jungbluth, 2009; Chayer and Kicak, 2015; Salomone, 2003) in affirming that cultivation and brewing are significant environmental hotspots. Coffee cultivation is a major contributor to ecosystem damage, particularly from the standpoint of land-use related midpoint indicators. In addition, compared with organic farming, the application of chemical fertilizers in conventional farming can aggravate the impact of cultivation on human health and resources affirming that coffee cultivation and brewing are significant environmental hotspots. That is consistent with previous findings. A high quantity of fertilizers used to grow coffee, whether organic or chemical, can lead to higher environmental impacts (Salomone, 2003; Coltro et al., 2006; Hick, 2017).

The results of SC1 (brewing by electric coffee maker) and SC3 (brewing by manual, pour-over dripper) found that approximately half of the total environmental impacts arising from upstream processes (cultivation and coffee bean processing) under the control of coffee producers and suppliers, with the other half consequent to downstream processes under the control of the consumer, conforming with prior studies (Humbert et al., 2009; Chayer and Kicak, 2015). Nonetheless, the contribution of the use stage in SC2 (using a moka pot) was relatively high compared with upstream processes that could result from electricity source emissions. Coffee brewing was found to be an energy-intensive stage that consumes a large proportion of energy in the coffee life cycle and, subsequently, leads to energy-related environmental impacts (Chayer and Kicak, 2015). In some cases of coffee LCA, transport can contribute a more significant environmental score since coffee beans are typically imported from other countries (Hick, 2017; Tchibo, 2009).

According to the results, recommendations can be made for environmentally improving the product system of Thai coffee. Upstream, cultivation and roasting (use of energy) showed the biggest impacts compared with other processing stages. Environmental performance at this level can be enhanced by, for example, employing energy efficient roasters, regular maintenance of roasting equipment, and applying an appropriate amount of fertilizers. Organic cultivation can also reduce the impact on human health and resources. Consumers who are directly responsible for the use stage can play a key role in reducing environmental burdens of coffee life cycle by choosing the right brewing methods and using energy-efficient appliances.

Further studies are needed to fill the data gaps of this study. For example, this report investigated only one case study of a major organic coffee farm that could not be represented in all cases. Thus, we need data on bigger samples. A comprehensive meta-analysis of coffee LCA is also required to compare the results of previous studies in different contexts. A field study is also needed to investigate the effects of the amounts of fertilizer on coffee yields, in order to recommend the proper quantities and to better assess the impacts from their use. Direct field emissions from fertilizers are likely to make the case for the comparison of organic vs. chemical fertilizers that were not covered in this study. Different scenarios of waste management should be examined since only waste management by landfill was considered in this study. Moreover, studies of alternative brewing methods are recommended, especially given that only three brewing methods were investigated in the current work.

5. CONCLUSIONS

Environmental impacts of a cup of black coffee were assessed from a life cycle perspective. The results of this study uncovered environmental profiles for each stage of the coffee life cycle and indicated the environmental hotspots that can be beneficial for coffee producers, suppliers, consumers, and other stakeholders to improve their environmental performance. Environmental impact results can be varied according to different influencing factors such as brewing methods and farming practices, as investigated here. One of the key environmental hotspots originated from the use of fuel-based electricity in the brewing stage. That caused the highest impact on most of the impact categories, while agricultural land use and the use of fertilizers were the hotspots of ecosystems damage. Among the brewing methods, a cup of coffee prepared by electric coffee dripper seemed to be the more environmentally friendly option as it showed the lowest single-score environmental impact. By contrast, brewing by moka pot on a hotplate was considered to be the worst for the environment. It is necessary to adapt activities regarding both upstream and downstream processes to design their products in more environmentally friendly ways by resorting to the provided results to lower the impacts of consuming products on the environment. This study is an initial stage of coffee LCA study in Thailand and can be beneficial to fulfill the information of the life cycle environmental impacts of coffee, a popular beverage product, to aid decision-making and increase awareness of people on sustainable product consumption.

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