Life cycle assessment of supercritical CO_2 extraction of caffeine from coffee beans

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The environmental impacts of caffeine extraction from coffee beans using supercritical carbon dioxide ($scCO_2$) were evaluated, through a Life Cycle Assessment (LCA) approach. Using this process, two products of interest were obtained: caffeine and decaffeinated coffee. All the emissions to air, water and soil were reported to 1 kg of decaf coffee constituted by a 60/40 Arabica/Robusta blend. The performed analysis showed that agricultural stages, transportation and caffeine extraction are the steps mostly affecting the environmental categories under study. Therefore, the process was optimised, considering the fertilisers' amount reduction and the substitution of a portion of electricity at grid with electricity produced by photovoltaic panels. Using this improved scenario, a reduction of the environmental impact equal to 176 % in terms of human health, 10.3 % in terms of ecosystem diversity and 16.1 % in terms of resource availability can be obtained.

Keywords: LCA; supercritical decaffeination; minimized emissions; process optimization; sustainability.

1. Introduction

Coffee is one of the most consumed beverages in the world and, after petroleum, is the second traded product worldwide [1]. In Western countries, a significant portion of the daily beverage is constituted by the different varieties of coffee [2]. Coffee grows mainly in Africa and South America and nowadays, among a large number of known species, only two varieties are successfully used in commercial cultivation: *Coffea arabica* var. Arabica and *Coffea canephora* var. Robusta. In particular, Arabica is mainly cultivated in Brazil, Colombia, Costa Rica, Guatemala and India, whereas Robusta is mainly cultivated in Vietnam, Ivory Coast, Guatemala and India.

Coffee is second only to water as the most widely consumed beverage in the US and Europe and it is the main source of caffeine in daily consumption in adults, even if caffeine is contained also in tea, chocolate, and soft drinks [3, 4]. The two coffee bean varieties of worldwide importance differ considerably in price, quality and consumers' acceptance. Indeed, Arabica is preferable for the aroma effect and Robusta for taste and body [5]; for these reasons, a good flavour is commonly obtained by blending the two varieties. Moreover, caffeine content of green coffee beans varies according to the species: Arabica beans contain about 1.0–1.2 %, whereas the caffeine content in Robusta beans is about 1.6–2.5 %.

Even if a moderate consumption of caffeine can have beneficial effects on adults' behaviour, numerous studies, in recent years, reported the effect of caffeine consumption on cardiovascular diseases [6] and on central nervous system [7], leading to an increasing consumption of decaffeinated coffee [8]. Moreover, caffeine recovery is important, because it can be used in cola-type drinks or in combination with other active principles in the pharmaceutical field (in the treatment of headache and neuralgia) [9], or as an ingredient in the cosmetic field (in the treatment of cellulitis and localised excess fat) [10].

Four main methods are used worldwide for the decaffeination: in the solvent based methods, organic solvents (mainly methylene chloride and ethyl acetate) are employed, whereas in the non-solvent based methods, water or supercritical carbon dioxide ($scCO_2$) are used for the caffeine extraction [11]. In all the cases, coffee is decaffeinated in its green state; i.e., before the roasting operation.

Until the mid-1970s, methylene chloride was considered the best solvent for extraction of caffeine with satisfactory results. However, subsequently, doubts arose about its risk to humans, due to the solvent high toxicity. Although the residual amount of methylene chloride in decaffeinated coffee was well below the limit of 10 ppm, established by the Food and Drug Administration, the suspected carcinogenicity of this solvent led to the choice of a less toxic solvent, such as ethyl acetate, a natural component detected in coffee aroma and found to occur naturally in different fruits. The use of ethyl acetate has two considerable drawbacks: it is highly flammable and has a fruity aroma. It has to be handled carefully, increasing production costs, and it tends to pass on its characteristic aroma to the coffee, slightly altering the flavour. The decaffeination using water was developed in Switzerland, and constitutes a green process with respect to the product. Unfortunately, water is not a particularly selective solvent and, therefore, not only caffeine but also various flavours were removed from coffee beans using this method. As a result, a less flavourful brew with respect to other methods was obtained. The most selective process for removing just caffeine and not the other flavour precursors from coffee is based on the use of $scCO_2$. This process was successfully developed on an industrial scale in the 1970s, based on two patents developed by Zosel: in the first one, the process was presented for the recovery of caffeine [12], whereas, in the second one, a detailed description aimed at obtaining decaffeinated coffee was proposed [13].

Supercritical fluids (SCFs) based techniques were proposed as an alternative to conventional processes, thanks to their specific characteristics, mainly, solvent power and liquid-like densities with gas-like transport properties that can be tuned by varying pressure and temperature. They were successfully applied in several fields, such as, for example, micronization [14], porous structures formation [15], adsorption [16]. Among the different $scCO_2$ based processes, one of the most studied one was supercritical fluids extraction (SFE), for the possibility of continuously modulating the solvent power/selectivity; this process was frequently used for the extraction of essential oils [17-19]. SFE was used also for the extraction of caffeine from natural sources, such as coffee husks [20], coffee beans [21] and tea leaves [22].

Since supercritical fluids' based technologies are considered as "eco-friendly", it is important to study the environmental emissions due to a specific production. One of the most common ways to determine, in a quantitative way, the environmental impact of a process or a product is the use of life cycle assessment (LCA) analysis.

Many papers based on LCA analyses were published in different research fields, such as energy [23], beverages [24-26], wines [27, 28], fruits [29, 30], pharmaceutical delivery systems [31, 32] and wastewater treatments [33]. In particular, food sector is among the most impactful ones for the environment, due to production, preservation and distribution steps [34], which consume a considerable amount of energy [35]. LCA studies regarding the food sector were addressed on agricultural stages [36], production steps [28] or packaging systems [37]. Some LCA studies regarding coffee were performed, considering agricultural stages [13], processing steps [38, 39] and packaging [40].

Concerning papers on LCA of decaffeination processes, a preliminary gate-to-gate study on the decaffeination of Arabica seeds, considering only the industrial stages of the process was attempted [41], but a complete LCA study on decaffeination of commercial decaf coffee (constituted by Arabica and Robusta blends) was not endeavoured until now.

Therefore, the aim of this work is to carry out a cradle-to-gate LCA analysis of the production of caffeine and of $scCO_2$ decaf coffee constituted by a 60/40 Arabica/Robusta blend. In the analysis, the considered steps are coffee cultivation (in Brazil for Arabica and in Vietnam for Robusta), its transportation to Italy, its processing to obtain decaf coffee and caffeine. Data regarding agricultural stages in Brazil and Vietnam were obtained from literature [36, 42], whereas data regarding the industrial stages were collected from an Italian processor.

2. Process description

In Table 1, the main activities and the details of the process under investigation are reported.

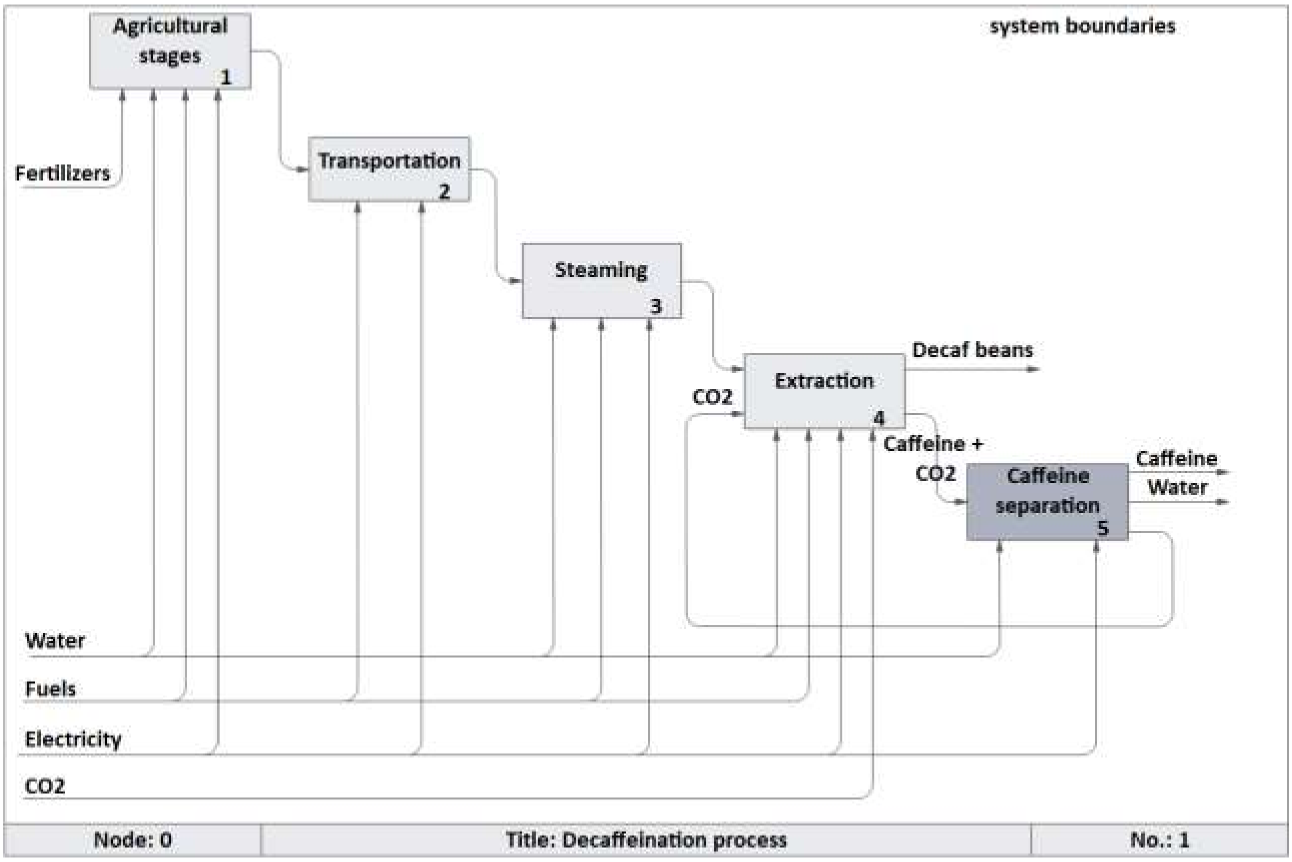
Table 1: Process details and assumptions

Process	Characteristics and details	
	Arabica	*Robusta*
Agricultural stages	Energy and water supply	Energy and water supply

	Nitrogen and fertilisers supply	Nitrogen and fertilisers supply
	Herbicides and pesticides supply	Herbicides and pesticides supply
	Diesel and fuel supply	Diesel and fuel supply
Energy supply for agricultural stages	Brazilian energy mix low voltage	Vietnamese energy mix low voltage
Coffee beans supply to facility	Transport by truck, 40 t from Genoa (distance = 650 km) + by large tanker from Brazil (distance = 9100 km)	Transport by truck, 40 t from Trieste (distance = 800 km) + by large tanker from Vietnam (distance = 13600 km)
Energy supply for processing stages	Italian energy mix medium voltage	Italian energy mix medium voltage
Coffee beans steaming	T = 90 °C; t = 5h; energy, water and fuel supply	T = 90 °C; t = 5h; energy, water and fuel supply
Pressurization	t=0.25 h; carbon dioxide, energy, water and fuel supply	t=0.25 h; carbon dioxide, energy, water and fuel supply
Operating conditions' stabilization	T=90 °C; P=25 MPa; t=0.25 h; carbon dioxide, energy, water and fuel supply	T=90 °C; P=25 MPa; t=0.25 h; carbon dioxide, energy, water and fuel supply
Caffeine extraction	T=90 °C; P=25 MPa; t=11.5 h; carbon dioxide, energy, water and fuel supply	T=90 °C; P=25 MPa; t=22 h; carbon dioxide, energy, water and fuel supply
Depressurization	T=25 °C; P=0.1 MPa; t=1 h	T=25 °C; P=0.1 MPa; t=1 h
Caffeine recovery	Water, energy and fuel supply	Water, energy and fuel supply

Coffee beans are cultivated in Brazil in the case of Arabica and in Vietnam in the case of Robusta. After harvesting, they are transported to the Italian processor by large tanker and by truck. Caffeine extraction from coffee beans using scCO_2 can be distinguished in three main steps: steaming, supercritical extraction and caffeine recovery, as represented in Figure 1a. After cultivation (stage 1) and transportation to the processor (stage 2), coffee beans are put in contact with superheated steam at elevated temperature (stage 3) until their moisture content reaches 30 % by weight; as a result, the beans swell considerably. Then, a 9 tons batch of water-moistened coffee beans is charged in a vessel with a volume equal to 22 m^3 (stage 4) and an extraction cycle begins. Indeed, the extraction vessel is pressurised by pumping CO_2 until the desired conditions of pressure and temperature are reached (25 MPa and 90 °C). The scCO_2 is passed through the beans' bed for approximately 11.5 hours in the case of Arabica coffee beans and 22 hours in the case of Robusta coffee beans, with the aim of extracting 97 % of the caffeine. The caffeine+CO_2 mixture leaves the extractor and accumulates in a holding tank, until the extraction is completed. Then, the extractor begins a down time, in order to be emptied from decaffeinated beans (which can be stored in silos) and charged with fresh beans. The last step is the caffeine recovery, shown in Figure 1b. The stream of caffeine rich CO_2 begins to flow at a steady state through a water wash packed column (stage 5.1), at conditions that are the same as those of the extractor to keep the carbon dioxide in its supercritical state. Here, the supercritical stream is counter-currently contacted with a stream of water, which removes 99.5 % of the caffeine from the CO_2, considering that caffeine has a higher affinity for water compared to $scCO_2$. The regenerated carbon dioxide leaves the water wash column and is pumped into its storage tank. The caffeine rich water stream exiting the water wash column is throttled to approximately atmospheric pressure, during a degassing step (stage 5.2). During this stage, a small amount of carbon dioxide dissolved in the mixture is vented as a gas. The caffeine + water mixture is sent to two evaporators in series (stage 5.3), where it is concentrated from 1 to 15 % in weight. In the last step (stage 5.4), the mixture is sent to a crystalliser where solid caffeine precipitates because of a sudden temperature decrease.

(a)



(b)

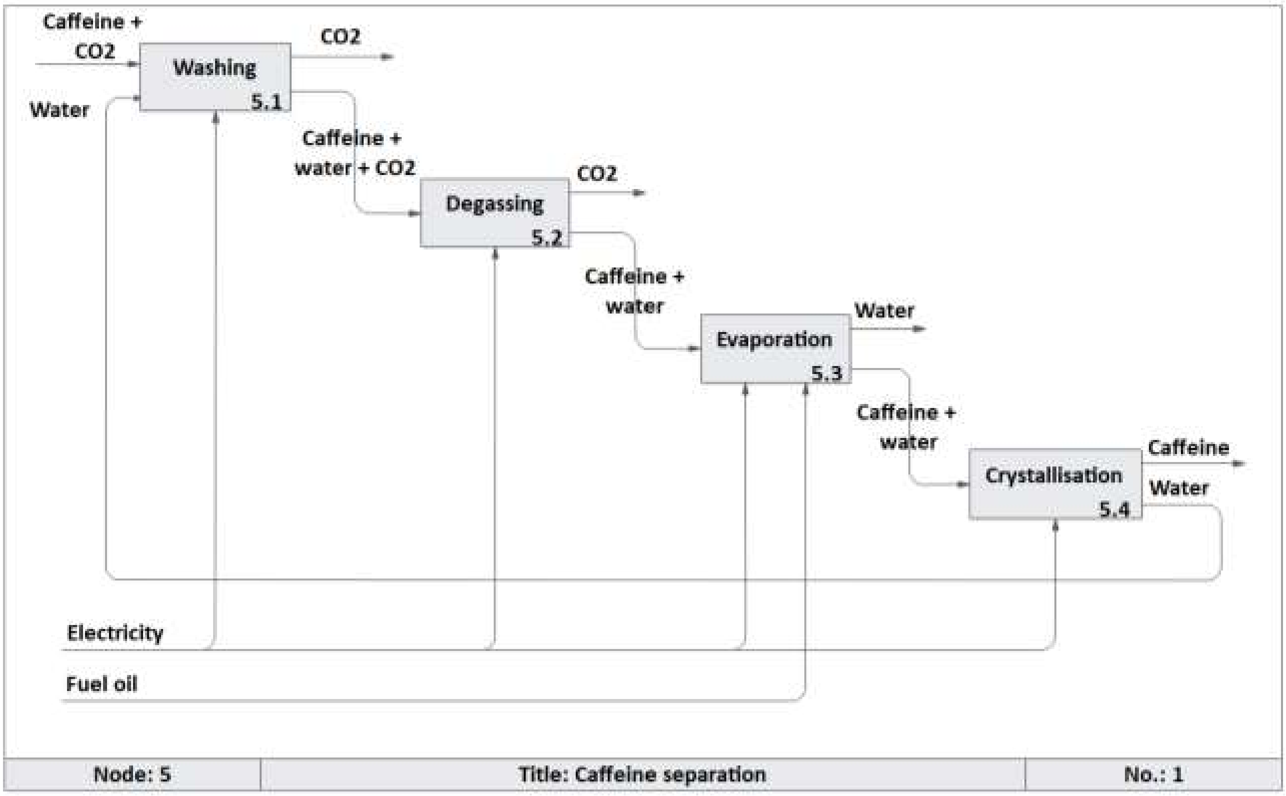


Figure 1: Main stages and system boundaries for the extraction of caffeine from coffee beans: (a) complete process scheme; (b) details of caffeine separation.

3. LCA methodology

LCA analysis allows to correlate a broad set of data regarding the life-cycle of a product or a process in order to identify the phases of the process that are critical from an environmental point of view. The main steps of an LCA analysis are presented in the following sub-sections.

3.1 Goal definition, functional unit and system boundaries

Goal definition is one of the most important phases of the LCA methodology, because the choices made at this stage influence the entire study. The goal of this study is the in-depth evaluation of the environmental impacts of coffee decaffeination using supercritical carbon dioxide ($scCO_2$). The functional unit (FU) is the reference to which all the inputs and outputs have to be related. Considering that:

1) the work has a dual objective, consisting in the LCA of both decaf coffee and caffeine products;

2) different data are obtained for Arabica and Robusta seeds processing,

the FU was defined as 1 kg of decaf blend coffee beans (constituted by 600 g of Arabica and 400 g of Robusta) corresponding to 11.4 g of dry caffeine recovered from the blend.

Through mass and energy balances of each operation, a cradle-to-gate analysis was performed; therefore, the system boundaries (reported in Figure 1a) are set from coffee cultivation to decaffeinated coffee and caffeine attainment.

3.2 Data collection and life cycle inventory

The life cycle inventory (LCI) is one of the most time consuming steps, because it consists of the activities related to the search, collection, and interpretation of the data necessary for the environmental assessment of the observed system. During this step, all inputs and outputs such as usage of resources and materials, consumption of electricity and fuels, and determination of transportation have to be quantified for the stages included in the system boundaries.

Data regarding the stages of Arabica beans cultivation in Brazil [36] and Robusta beans cultivation in Vietnam [42] were recovered from literature. Primary data regarding the industrial stages of caffeine extraction from the beans were collected from an Italian processor, which uses supercritical carbon dioxide to extract caffeine from coffee beans (the process details are listed in Table 1) through questionnaires and personal interviews. Background data regarding, for example, inputs and outputs associated with the production of 1 kWh of electricity were recovered from [43] for Brazilian and Italian energy mix. The Brazilian mix process available in Ecoinvent was also adapted to Vietnam, by replacing the proportions of energy sources for Brazil with the ones gathered for this country from [44]. Through mass and energy balances made on each of the single unit operations, data were organised in tables that constitute the inventory. The numerical results obtained after mass and energy balances are listed in Table 2.

Table 2. Life cycle inventory of the main inputs and outputs for decaf coffee production and caffeine extraction; data are referred to 1 kg of decaf coffee beans (constituted by 600 g of Arabica and 400 g of Robusta) and 11.4 g of caffeine

Phase	Input/Output	Unit	

Agricultural	Pesticides	kg	5.85E-03
	Nitrogen	kg	1.04E-01
	Phosphorous (P_2O_5)	kg	6.29E-02
	Potassium (K_2O)	kg	6.57E-02
	Herbicides	kg	6.36E-04
	Diesel	kg	1.06E-01
Transportation	Green coffee beans	kg	8.77E-01
	Transport by truck	tkm	6.24E-01
	Transport by large tanker	tkm	9.58E+00
Steaming	Coffee beans	kg	8.69E-01
	Water	kg	1.65E-01
	Methane	m^3	2.07E-03
Supercritical extraction	Coffee beans	kg	1.03E+00
	Carbon dioxide	kg	1.24E-01
	Methane	m^3	2.79E-01
	Electricity	MJ	5.24E+00
	Output		
	Decaffeinated beans	kg	1.00E+00
Washing	Caffeine	kg	1.28E-02
	Carbon dioxide	kg	7.43E-01
	Water	kg	1.12E+00
	Electricity	MJ	7.59E-05
	Output		
	Carbon dioxide	kg	6.86E-01
Degassing	Caffeine	kg	1.27E-02
	Carbon dioxide	kg	5.79E-02
	Water	kg	1.12E+00
	Electricity	MJ	8.07E-06
	Output		
	Carbon dioxide	kg	5.79E-02
Evaporation	Caffeine	kg	1.27E-02
	Water	kg	1.19E+00

	Fuel oil	kg	2.11E-02
	Output		
	Water	kg	1.12E+00
Crystallisation	Caffeine	kg	1.27E-02
	Water	kg	7.2E-02
	Electricity	MJ	1.18E-02
	Output		
	Caffeine	kg	1.14E-02

3.3 Impact assessment

The elaboration of the inventory data was performed through the LCA software SimaPro 8.0.5 (PRé Consultants, 2014) in agreement with the reference standard for LCA (i.e. ISO 14040-14044). ReCiPe method [45] was used to aggregate the inventory results first in terms of 18 midpoint categories and, then, in terms of damages to human health, ecosystem diversity and resource availability (endpoint). The list of the impact categories at midpoint and endpoint level assessed in the present study is shown in the first column of Table 3. The chosen time perspective, among the three proposed by the ReCiPe method, is the hierarchist (H), which is based on the most common policy principles concerning time-frame and is the most balanced one.

Table 3: Environmental impact categories with their respective acronyms and units and impact assessment at midpoint level

Impact category	Acronym	Unit	Impact assessment
Midpoint level			
Climate change	CC	kg CO_2 eq	3.29E+00
Ozone depletion	OD	kg CFC-11 eq[1]	6.82E-07
Terrestrial acidification	TA	kg SO_2 eq	1.82E-02
Freshwater eutrophication	FE	kg P eq	7.27E-04
Marine eutrophication	ME	kg N eq	7.68E-02
Human toxicity	HT	kg 1,4DCB eq[1]	8.69E-01
Photochemical oxidant formation	POF	kg NMVOC[1]	1.22E-02
Particulate matter formation	PMF	kg PM_{10} eq	5.95E-03
Terrestrial ecotoxicity	TET	kg 1,4DCB eq[1]	1.54E-03

Freshwater ecotoxicity	FET	kg 1,4DCB eq[1]	5.45E-02
Marine ecotoxicity	MET	kg 1,4DCB eq[1]	4.92E-02
Ionising radiation	IR	kBq U235 eq[1]	3.92E-01
Agricultural land occupation	ALO	m^2 x yr	2.33E+00
Urban land occupation	ULO	m^2 x yr	4.00E-02
Natural land transformation	NLT	m^2	6.47E-04
Water depletion	WD	m^3	3.67E-02
Mineral resource depletion	MRD	kg Fe eq	1.87E-01
Fossil fuel depletion	FD	kg oil eq	8.86E-01
Endpoint level			
Human health	HH	DALY[1]	
Ecosystem diversity	ED	species.yr	
Resource availability	RA	$	

[1]CFC-11: Chlorofluorocarbon; 1,4DCB: 1,4 dichlorobenzene; NMVOC: Non Methane Volatile Organic Carbon compound; U235: Uranium 235; DALY: disability-adjusted life years; species.yr: loss of species during a year; $: increased cost.

4. Results and discussion

4.1 Environmental analysis of coffee decaffeination

The environmental analysis of the production of decaffeinated coffee was performed in terms of ReCiPe midpoint categories. The analysis was performed considering the production of 1 kg of decaf coffee and 11.4 g of pure caffeine; the results of the impact assessment are reported in the last column of Table 3.

In order to identify the processing steps that generate the higher impact, an in-depth analysis was performed. The impact assessments at midpoint level related to each stage of the process are reported in Table 4.

Table 4: Impact assessment at midpoint level with respect to 1 kg of decaf coffee and 11.4 g of caffeine

Impact category	agricultural	transportation	steaming	extraction	washing	degassing	evaporation	crystallisation
CC	1.59E+00	2.54E-01	2.25E-03	1.43E+00	7.94E-04	1.41E-06	1.23E-02	2.07E-03
OD	2.94E-07	2.14E-07	2.26E-10	1.59E-07	3.25E-10	2.03E-13	1.46E-08	2.97E-10
TA	8.88E-03	3.20E-03	1.60E-05	6.01E-03	4.80E-06	5.61E-09	1.08E-04	8.23E-06

FE	3.67E-04	1.21E-05	1.22E-06	3.45E-04	2.64E-07	2.59E-10	1.28E-06	3.80E-07
ME	6.93E-02	1.76E-04	1.03E-05	7.32E-03	7.28E-07	9.18E-09	9.68E-06	1.35E-05
HT	4.66E-01	3.02E-02	1.27E-03	3.69E-01	3.72E-04	2.78E-07	1.90E-03	4.08E-04
POF	4.40E-03	3.56E-03	1.45E-05	4.16E-03	2.77E-06	3.30E-09	7.74E-05	4.85E-06
PMF	2.71E-03	1.11E-03	6.44E-06	2.09E-03	2.02E-06	1.78E-09	3.14E-05	2.61E-06
TET	9.91E-04	2.29E-05	3.38E-06	5.18E-04	6.78E-08	9.85E-11	1.31E-06	1.45E-07
FET	1.95E-02	4.75E-04	4.32E-05	3.43E-02	5.08E-05	4.35E-08	8.20E-05	6.38E-05
MET	1.82E-02	8.11E-04	3.87E-05	3.00E-02	4.45E-05	3.77E-08	6.80E-05	5.54E-05
IR	1.32E-01	3.44E-02	4.08E-04	2.18E-01	1.25E-04	2.46E-07	5.64E-03	3.60E-04
ALO	1.22E-01	1.19E-03	1.71E-02	2.19E+00	2.94E-05	5.77E-08	1.64E-04	8.46E-05
ULO	2.07E-02	5.93E-04	1.17E-04	1.84E-02	8.34E-06	4.97E-09	1.20E-04	7.30E-06
NLT	3.75E-04	3.74E-05	3.89E-07	2.05E-04	1.04E-07	2.28E-10	2.84E-05	3.35E-07
WD	2.31E-02	1.31E-03	1.93E-04	1.07E-02	1.12E-03	9.82E-09	2.05E-04	1.44E-05
MRD	1.22E-01	9.06E-03	8.44E-05	5.52E-02	7.67E-05	5.80E-08	3.73E-04	8.51E-05
FD	3.96E-01	8.57E-02	5.92E-04	3.76E-01	2.04E-04	4.36E-07	2.74E-02	6.40E-04

The relative contributions of the different stages of the complete process are reported in Figure 2.

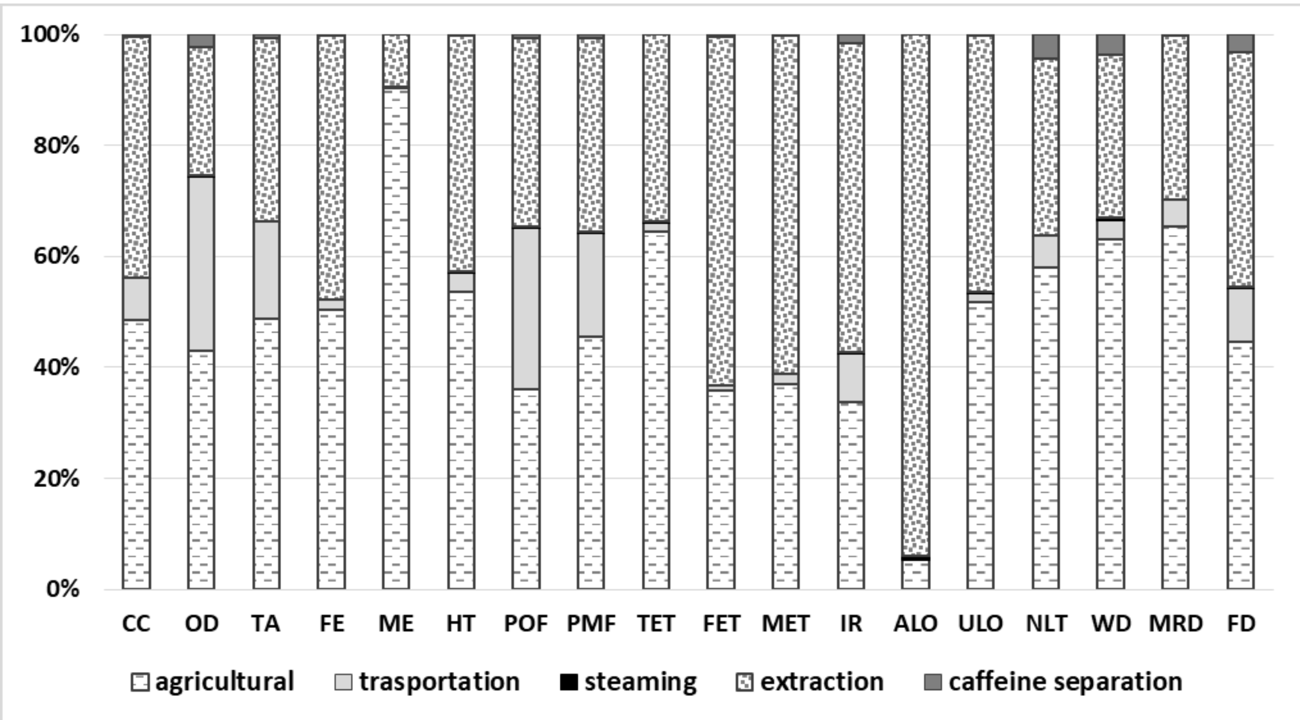


Figure 2. Relative contributions of the different stages with respect to the overall impact

It is clear that the steaming process contribution is negligible on all the midpoint categories. Indeed, its contribution is equal at most to 0.7 %, in the case of agricultural land occupation. The caffeine separation process is appreciable only in terms of ozone depletion (2.2 %), natural land transformation (4.5 %), water depletion (3.6 %) and fossil fuel depletion (3.2 %). The remaining steps; i.e., agricultural stages, transportation and caffeine extraction contribute to different extents on the midpoint categories.

Transportation contribution is higher than 15 % with respect to the overall impact in terms of ozone depletion, terrestrial acidification, photochemical oxidant formation and particulate matter formation.

The relative contribution of the agricultural step is higher than the contribution of supercritical extraction in terms of ozone depletion, terrestrial acidification, marine eutrophication, terrestrial ecotoxicity, natural land transformation, water depletion and mineral resource depletion. In particular:

- the emissions in terms of ozone depletion and natural land transformation are mainly due to diesel consumption for planting/harvesting operations and to the use of nitrogen fertiliser;
- the emissions in terms of terrestrial acidification, water depletion and mineral resource depletion are mainly due to the use of nitrogen fertiliser;
- eventually, the emissions in terms of marine eutrophication and terrestrial ecotoxicity are due to both nitrogen and potassium fertilisers.

On the contrary, the relative contribution of the extraction step is higher than the contribution of the agricultural step in terms of freshwater ecotoxicity, marine ecotoxicity, ionising radiation and agricultural land occupation. The emissions in terms of agricultural land occupation are mainly due to the production of the methane used in the hot utility, whereas the emissions in terms of the other categories are mainly due to the electrical energy generation.

Agricultural and extraction steps’ contributions are comparable in terms of the remaining impact categories.

4.2 Scenario analysis and improved solution

In order to estimate the possible reduction of the emissions due to the modification of some input variables, a scenario analysis is proposed. The performed analysis considers the possibility of reducing the amount of fertilisers used in the agricultural stage and modifying the electricity source. Indeed, in the last years, renewable energy sources were frequently used with the aim of improving processes' sustainability [46-48].

Therefore, the scenario analysis considers:

- different fertilisation strategies leading to a reduction of the amount of fertilisers (10 or 20 %) for the same coffee beans yield; indeed, the fertilisation can be carried out in different ways depending, for example, on the agricultural practice (conventional or biological), on the type of plantation (in shade or sun, monoculture or not), on the method of harvesting (manual or mechanised);
- for the electricity source, the installation and usage of photovoltaic panels and the substitution of a portion (20 or 40 %) of the electricity at grid referred to the Italian energy mix with electricity produced by the installed photovoltaic panels.

The results of the scenario analysis are shown in the radar charts in Figure 3.

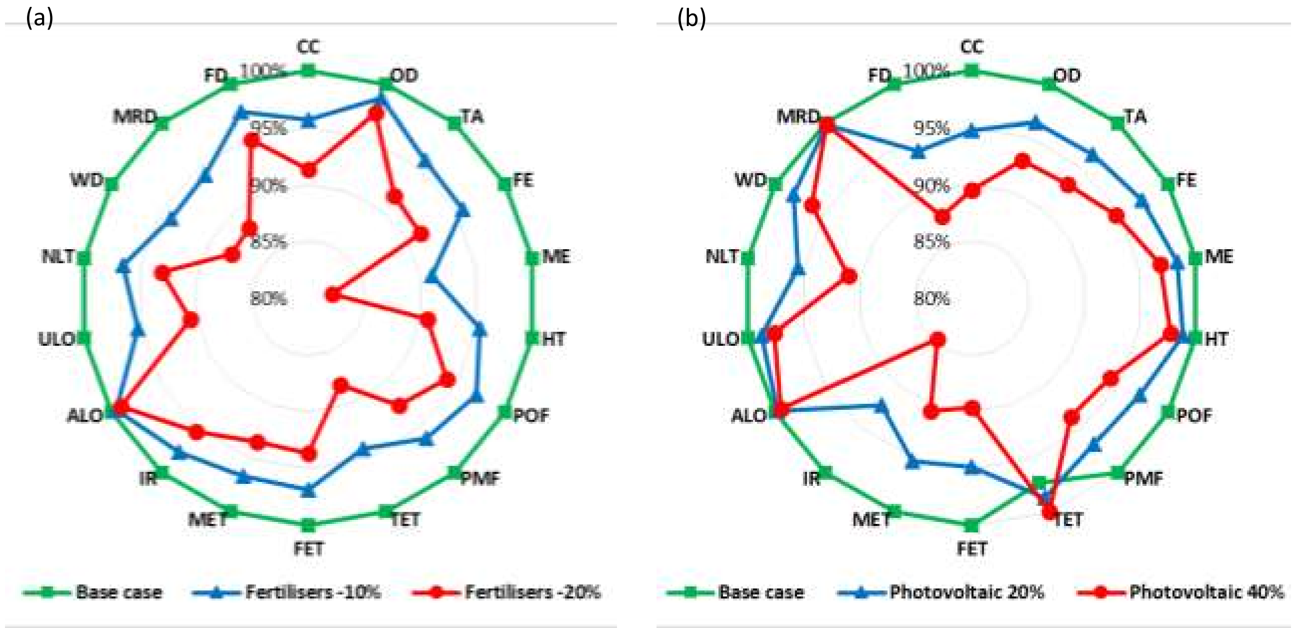


Figure 3: Scenario analysis at midpoint level: (a) different amount of fertilisers; (b) introduction of photovoltaic panels

It is possible to observe that:

1) the reduction of the amount of fertilisers used in the agricultural stages implies a lowering of the emissions in terms of all the midpoint categories;

2) the substitution of a portion of the electricity source using photovoltaic panels lowered the emissions in terms of all the ReCiPe midpoint categories, with an exception of TET. This result is in agreement with life cycle assessment studies performed on multicrystalline silicon photovoltaic panels, asserting that TET was the category most significantly affected by photovoltaic modules usage [49, 50].

On the basis of the performed analysis, an improved scenario is proposed, considering a reduction of the amount of fertilisers equal to 20 % and the substitution of the 40 % of the electricity grid with electricity produced by photovoltaic panels. In Table 5, the emissions at midpoint level of this improved scenario and its comparison with the base case are reported.

Table 5: Impact assessment at midpoint level of the improved scenario ant its comparison with the base case. Data are referred to the production of 1 kg of decaf coffee and 11.4 g of caffeine

Impact category	Base case (a)	Improved scenario (b)	Emissions' reduction with respect to the base case $\frac{(b-a)}{a} x100$
CC	3.29E+00	2.66E+00	-19.0%
OD	6.82E-07	6.19E-07	-9.3%
TA	1.82E-02	1.55E-02	-15.1%
FE	7.27E-04	6.25E-04	-14.1%
ME	7.68E-02	6.07E-02	-21.0%
HT	8.69E-01	7.67E-01	-11.8%
POF	1.22E-02	1.08E-02	-11.9%
PMF	5.95E-03	5.11E-03	-14.2%
TET	1.54E-03	1.39E-03	-9.5%
FET	5.45E-02	4.54E-02	-16.6%
MET	4.92E-02	4.13E-02	-16.0%
IR	3.92E-01	3.15E-01	-19.7%
ALO	2.33E+00	2.29E+00	-1.5%
ULO	4.00E-02	3.52E-02	-11.9%
NLT	6.47E-04	5.48E-04	-15.3%
WD	3.67E-02	3.11E-02	-15.3%
MRD	1.87E-01	1.65E-01	-12.2%

FD	8.86E-01	7.35E-01	-17.0%

It is clear that the improved scenario implies an appreciable reduction of the impacts on all the considered midpoint categories.

Finally, the environmental impacts were grouped and normalised, according to the ReCiPe method, considering the damage at the endpoint level; i.e., in terms of damage to human health (HH), to ecosystem diversity (ED) and to resource availability (RA). The comparison between the base case and the proposed improved scenario is reported in Figure 4.

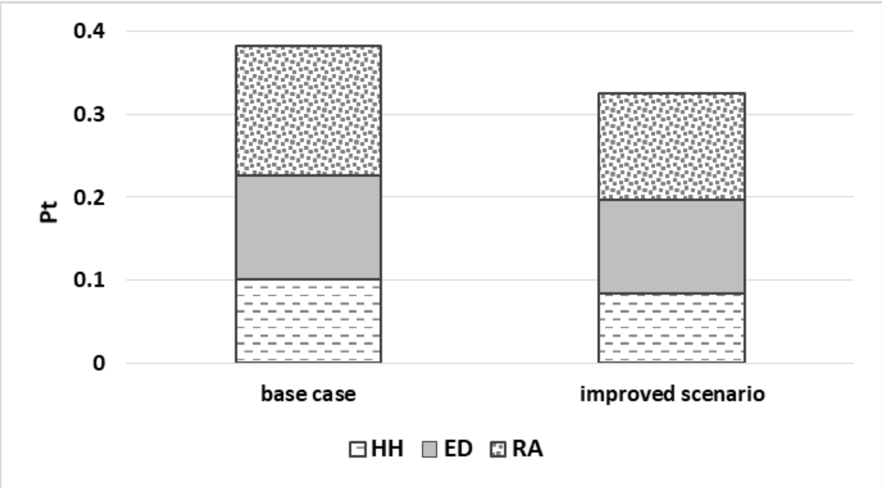


Figure 4: Environmental impact according to the normalised ReCiPe damage categories (point, Pt)

It is possible to observe that the improved solution generated a reduction of the environmental impact equal to 17.6 % in terms of human health, 10.3 % in terms of ecosystem diversity and 16.1 % in terms of resource availability with respect to the base case.

5. Conclusions and perspectives

The supercritical carbon dioxide caffeine extraction from coffee beans is a suitable process to obtain, in one single process, decaf coffee and pure caffeine. Besides, the cradle-to-gate LCA analysis provided quantitative information of the environmental performance of the process, showing that the major contributors to the environmental impact are agricultural stages, transportation and caffeine extraction steps. The scenario analysis demonstrated the importance of fertilisers' amount and electricity sources. An improved solution was proposed, obtaining a global reduction of the impact with respect to the base case equal to 14.6 %. A step forward of this work would be to analyse the correlation between the obtainable emissions' percentage reduction and the investment and management costs needed to obtain it.

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