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Life cycle assessment of spray dried soluble coffee and comparison with alternatives (drip filter and capsule espresso)

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ABSTRACT

This paper aims to evaluate the environmental burdens associated with spray dried soluble coffee over its entire life cycle and compare it with drip filter coffee and capsule espresso coffee. It particularly aims to identify critical environmental issues and responsibilities along the whole life cycle chain of spray dried coffee. This life cycle assessment (LCA) specifically uses foreground data obtained directly from coffee manufacturers and suppliers. Aside from energy consumption and greenhouse gases emissions, water footprint is also studied in detail, including regionalization of water impacts based on the ecological scarcity method 2006. Other impact categories are screened using the IMPACT 2002+ impact assessment method.

The overall LCA results for a 1 dl cup of spray dried soluble coffee amounts approximately to 1 MJ of primary non-renewable energy consumption, to emissions of 0.07 kg of $CO_{2\text{-eq}}$, and between 3 and 10 l of non-turbined water use, depending on whether or not the coffee cultivation is irrigated and wet treated. When considering turbined water, use can be up to 400 l of water per cup. Pouch – and to a lesser extent metal can packaging alternatives – show lower environmental burdens than glass or sticks.

On average, about one half of the environmental footprint occurs at a life cycle stage under the control of the coffee producer or its suppliers (i.e., during cultivation, treatment, processing, packaging up to distribution, along with advertising) and the other half at a stage controlled by the user (shopping, appliances manufacturing, use and waste disposal). Key environmental parameters of spray dried soluble coffee are the amount of extra water boiled and the efficiency of cup cleaning during use phase, whether the coffee is irrigated or not, as well as the type and amount of fertilizer used in the coffee field. The packaging contributes to 10% of the overall life cycle impacts.

Compared to other coffee alternatives, spray dried soluble coffee uses less energy and has a lower environmental footprint than capsule espresso coffee or drip filter coffee, the latter having the highest environmental impacts on a per cup basis. This study shows that a broad LCA approach is needed to help industry to minimize the environmental burdens directly related to their products. Including all processes of the entire system is necessary i) to get a comprehensive environmental footprint of the product system with respect to sustainable production and consumption, ii) to share stakeholders responsibility along the entire product life cycle, and iii) to avoid problem shifting between different life cycle stages.

1. Introduction and objectives

This paper aims to identify critical environmental issues and responsibilities along the whole life cycle chain of spray dried coffee and compare it with drip filter coffee and capsule espresso coffee.

Several life cycle assessment (LCA) studies have been published on coffee. However, few studies have performed a detailed analysis covering the full life cycle of a product system with the function of providing a cup of coffee, and even less have proposed a comparison between different alternatives of serving a coffee. Table 1 presents a summary and a short evaluation of the literature review on LCA of coffee production and consumption. There is also a need to go beyond energy consumption and greenhouse gases emissions and to study the water footprint of coffee in more details.

The general objective of this study is to assess the life cycle environmental impacts associated with spray dried soluble coffee (also called 'instant' coffee) applying the LCA methodology and compare it with drip filter coffee (also called 'traditional' coffee)

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Table 1
Summary of the literature review on LCA of coffee.

Stages	References and short evaluation
Growing and treatment	Coltro et al. [1] – Environmental profile of Brazilian green coffee. Strong paper. Covers energy, chemicals, land and water use for the growing and pulp and mucilage removal stages. Hergoualch [2] – Soil greenhouse gases emissions and carbon storage in coffee plantations.
Beans removal	Chanakya and De Alwis [3] – Environmental issues and management in primary coffee processing. Good description of processing including pulping, washing, and roasting. Includes a description of the social and economic conditions. Concentrates on water use and runoff and potential solutions to these problems.
Roasting	De Monte et al. [4] – Waste heat recovery at roasting plant. Concentrates on the roasting process and some of its costs. Menezes et al. [5] – Drying performance of vibrating tray. Very specific article. Gives an overview of the drying process. Comparison of energy costs for different methods.
Transport	De Monte et al. [6] – Alternative coffee packaging: an analysis from a life cycle point of view. Very specific thorough part of the whole seed-to-cup process with focus on packaging.
Consumption	Lopez Aizcorbe et al. [7] – LCA coffee maker. Specific and thorough. Student project: quality is not perfect but wide range of data is included.
Complete cycle	Büsser and Jungbluth [8]. Complete LCA, with focus on packaging issues and influence of consumer behavior. International Coffee Organization Study [9]. Study of the environmental issues relating to the coffee chain within a context of trade liberalization, through a life cycle approach. Outlines all the areas that need to be covered, including carbon balance, water pollution, biodiversity, and global warming. Salomone [10] – LCA coffee production. LCA applied to coffee production: investigating environmental impacts to aid decision making for improvements at company level. Traditional LCA. Covers energy use, waste management, raw material consumption from cradle to grave. Hanssen et al. [11,12]. Complete life cycle. Diers et al. [13]. Complete life cycle.
Social and economic effects	Cuadra [14] – Emergy evaluation on the production, processing and export of coffee in Nicaragua. Pelupessy [15] – Int. chain of coffee and the environment. Perfecto [16] – Biodiversity, yield, and shade coffee certification. Van der Vossen [17] – Agronomic and economic sustainability of organic coffee production

and capsule espresso coffee. This paper presents the main results of a study authored by Humbert and colleagues [18], with a focus on energy consumption, greenhouse gases emissions and water footprint, complemented by a screening of other impact categories. This study applied the international standards ISO 14040 [19] and ISO 14044 [20], but was not critically reviewed by an external review panel.

2. Methodology

2.1. Goal and scope

The goal of this LCA is primarily to identify the environmental hotspots of spray dried soluble coffee product system and its drip filter and capsule espresso coffee alternatives. It intends to be sufficiently robust and reliable to inform consumers about the comparative impacts of these three alternatives.

More specifically this study aims to: 1) assess the life cycle environmental impacts associated with spray dried soluble coffee (SDC); 2) compare the environmental impacts of spay dried coffee with those of drip filter coffee (DFC) using roasted and ground (R&G) coffee, and capsule espresso coffee (CEC); and 3) identify the key parameters and opportunities for optimization.

The functional unit used as a basis for comparison between the three systems is to ‘provide a 1 dl cup of coffee ready to be drunk, at the consumer's home’. The product system covers the full life cycle needed to provide a cup of coffee. It considers the green beans production and delivery, the coffee and packaging manufacturing and distribution, the use phase (including washing the cup) and the end-of-life (Fig. 1).

2.2. Life cycle inventory

This study was performed in collaboration with the coffee producer, hence, easing the access to first hand foreground data. Primary data and information are obtained directly from the coffee producer, its production sites in Europe, its green coffee suppliers (Brazil, Colombia and Vietnam) as well as from our own measurements for the capsule packaging and the use phase. Secondary data are obtained from internal database, the scientific literature and the

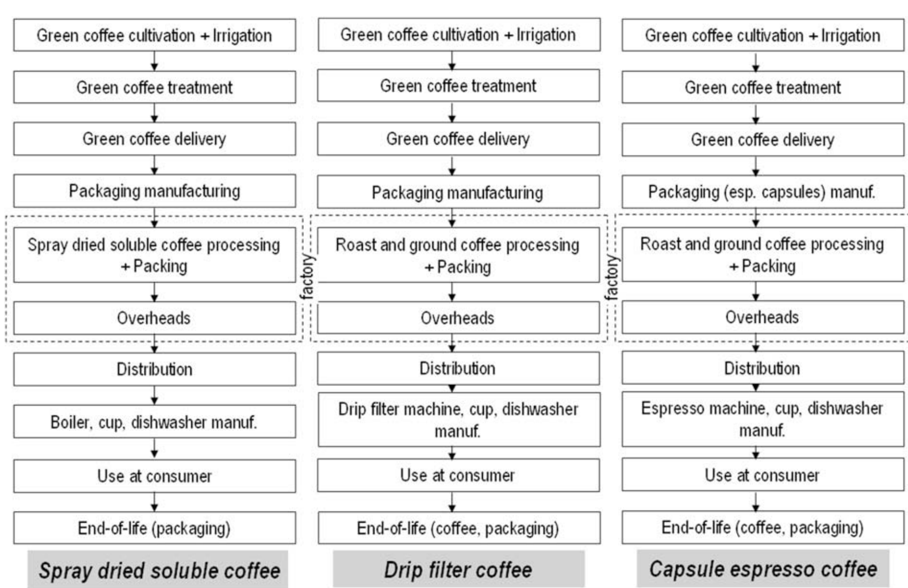

Fig. 1. Product system studied to provide a cup of coffee to the consumer.

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Table 2
Primary data collected on spray dried soluble coffee and roasted and ground coffee production sites.

Parameter	Value per kg spray dried soluble coffee produced	Value per kg roasted and ground coffee produced
Green coffee (in kg) (inverse of yield)	2.22	1.23
Electricity (in kWh)	2.3	0.14
Natural gas (in Nm^3)	0.8	0.07
Coffee grounds burned (in kg)	1.3	0
Glass (for packaging, in kg)	2.6	negligible
Laminate (for packaging, in kg)	0.014	0.016
Paper (mainly for packaging, in kg)	0.0042	n/a
Cardboard (mainly for packaging, in kg)	0.054	0.014
Freshwater (own source, in l)	11	n/a
Potable water (from public network, in l)	19	0.26
Processes taking place at the plant	1. Green coffee handling & cleaning 2. Roasting 3. Aroma recovery 4. Extraction 5. Evaporation 6. Spray drying 7. Agglomeration 8. Filling & packing 9. Conditioning	1. Green coffee handling & cleaning 2. Roasting 3. Grinding 4. Filling & packing 5. Conditioning

ecoinvent database [21,22]. The principal choices and hypotheses made at this stage are explained below.

2.2.1. Energy mix

The consumed electricity and natural gas at processing, use and end-of-life are assumed to be of the European mix.

2.2.2. Manufacturing

Table 2 presents the primary data collected at spray dried soluble coffee manufacturing plant in the UK for spray dried soluble coffee alternative as well as the roasted and ground coffee manufacturing plant in Spain for drip filter coffee alternative and capsule espresso coffee. Direct air and water emissions were not collected on-site but extrapolated using generic inventory datasets developed by ecoinvent.

2.2.3. Packaging

The default case packaging for spray dried soluble coffee is based on the packaging used in the manufacturing plant in the UK which is mainly based on glass and sticks. Table 3 presents the considered packaging alternatives for spray dried coffee. The stand-up pouch is a composite (PET/alu/LDPE) flexible packaging. The sticks are single portions also made of composite (PET/alu/LDPE) flexible packaging packed in a rigid cardboard box. At the end-of-life, the packaging disposal enables the substitution of the corresponding quantity of electricity and heat when incinerated and raw materials when recycled, using a system expansion approach as applied in the packaging study of Humbert and colleagues [23].

Table 3
Packaging alternatives for spray dried coffee.

Alternative (capacity)	Primary and secondary packaging Tertiary packaging
Glass jar (100 g)	242 g glass jar, 9.2 g PP cap, 1.1 g wad board, 0.2 g alu membrane, 0.9 g paper label 3.3 g cardboard, 1.5 g LDPE film, pallet
Metal can (100 g)	5.1 g LDPE cap, 1 g alu peel off, 44.2 g tin plate steel 4.1 g cardboard, 1.1 g LDPE film, pallet
Stand-up pouch (100 g)	9.4 g laminate (PET12/alu8/LDPE60) 16.3 g cardboard, 0.5 g LDPE film, pallet
Stick (in box) (45 g–1.8 g powder/stick)	12.8 g laminate (PET12/alu8/LDPE60), 14.2 g cardboard (25 sticks per box) 0.7 g cardboard, 1.2 g LDPE film, pallet

2.2.4. Transport

Mass weighted average supply distances are, respectively, 410 km by truck, 15,000 km by boat, and 133 km by truck for the delivery from dry/wet treatment plant to the export harbour, from the export harbour to the import harbour, and from the import harbour to the spray dried soluble coffee plant. The same delivery distances are assumed for the roast and ground coffee plant. Distribution distances from the coffee plant to the consumer are assumed to be 720 km by truck (420 km from filler to distribution center and 300 km from distribution center to retailer). Transportation inventory flows are calculated in ton·km units and associated with ecoinvent datasets developed for average load (transoceanic freight ship, 16–32 t lorry for distribution center to retailer and >32 t lorry for other truck transportation) [21,22].

2.2.5. Use

One cup of coffee contains 1 dl of water and coffee. However, due to process inefficiencies additional inputs are required in the use phase. In addition to these ingredients the preparation of a cup of coffee needs appliances and electricity. Table 4 provides the details and the main hypothesis adopted to model the use phase.

2.2.6. End-of-life

Independently from the packaging alternative, the end-of-life is modeled considering that glass, paper and cardboard are recycled, and all other materials are incinerated. Gross electric and thermal efficiency (LHV) for municipal waste incineration are assumed to be 10% and 20% respectively (reflecting a European average and being the one significant number values of the values used in ecoinvent [21,22]). Electricity and thermal production are assumed to displace European electricity mix and natural gas respectively.

2.3. Life cycle impact assessment

The life cycle impact assessment (LCIA) is performed using the IMPACT 2002+ method [25,26] (using 100 years time horizon for global warming), as well as the ecological scarcity method 2006 (expressing the impacts using the ‘UBP’ unit – i.e., ‘ecopoint’ in German) for water use impact score evaluation [27,28]. The later is a ‘distance-to-target’ method based on the concept of water scarcity: closer the total water withdrawal of a region from the total renewable water resources of that same region is, the higher the ecopoint is. Therefore, the less ecopoint the better. Characterization

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Table 4
Inputs needed per 1 dl cup of coffee.

	Spray dried soluble	Drip filter	Capsule espresso
Water for the coffee	2 dl (assuming that 200% the amount of water needed is boiled)	1.5 dl (assuming that 1/3 of the coffee made is wasted)	1 dl
Coffee	2 g of spray dried soluble coffee per cup	13.5 g of R&G coffee (includes 33% losses) (standard dose is assumed to be 9 g)	6.5 g of R&G coffee per capsule
Machine	Water boiler, 1 l/day, 2 cups/day, 300 days/year over 10 years	1 drip filter machine, 2 cups/day, 300 days/year over 10 years	1 espresso machine, 2 cups/day, 300 days/year over 10 years
Heating	0.125 kWh/l (own measurements)	0.125 kWh/l and 0.001 kWh/min for the stand-by (own measurements); 2 h stand-by	Stand-by of 2 h/day representing 0.028 kWh/cup (The electronic consumes 0.2 W the whole day, representing 0.0024 kWh/cup. However, these values are included in the stand-by values.)
Washing	Assumption is that the cup is used once before being washed. Dishwasher: lifetime is 3750 cycles; loading is 40 cups/cycle; 1.2 kWh/cycle (1.05–1.4 kWh/cycle [24]); 15 l of water/cycle (12–18 l/cycle [24]); 10 g of detergent/cycle (12–18 l/cycle [24]). Washing by hand is assumed to consume 0.5 l per cup with 40 °C water.		

factors for water use impact score evaluation are calculated using the equations developed by Frischknecht and colleagues [27,28] using data provided by AQUASTAT [29] on total water withdraw and total renewable water resources for each country of interest. Country-based characterization factors are used for processes situated in a clearly defined country (e.g., water used at the coffee manufacturing plant in the UK). However, generic characterization factors (based on OCDE average) are used for processes that have extended supply chain situated in undefined countries (e.g., transoceanic transport).

The LCA was implemented using the SimaPro 7 software [30].

3. Results and discussion

3.1. Life cycle inventory

The life cycle inventory of resource consumption and pollutant emissions is quantified for each of the three alternatives, by first gathering the core intermediary flows between unit processes, relating them to the functional unit and combining these with the generic life cycle inventory databases ecoinvent [21,22]. Details and explanations on the intermediary flows and life cycle inventory results can be found in Humbert and colleagues [18]. The life cycle inventory of water use is discussed below in parallel with the LCIA results.

3.2. Life cycle impact assessment

3.2.1. LCA of spray dried soluble coffee

The LCA results for spray dried soluble coffee are presented in Fig. 2 using the non-renewable primary energy consumption indicator.

The cultivation, processing and packaging are each responsible for approximately 10% of the total energy use. The cultivation is dominated by the use of fertilizers, with large variations in the amount of fertilizer used depending on the producer. The packaging impact is driven by the important amount of glass used for spray dried soluble coffee. Alternative packaging is presented, of which the pouch – and in a lesser extent the metal can – show a lower environmental burdens than the glass or the sticks (in cardboard box). The distribution represents only few percents as long as the road transport distances remain restricted to a few hundred km. The use phase represents between half and 75% of the total energy demand, with the heating of the water and the

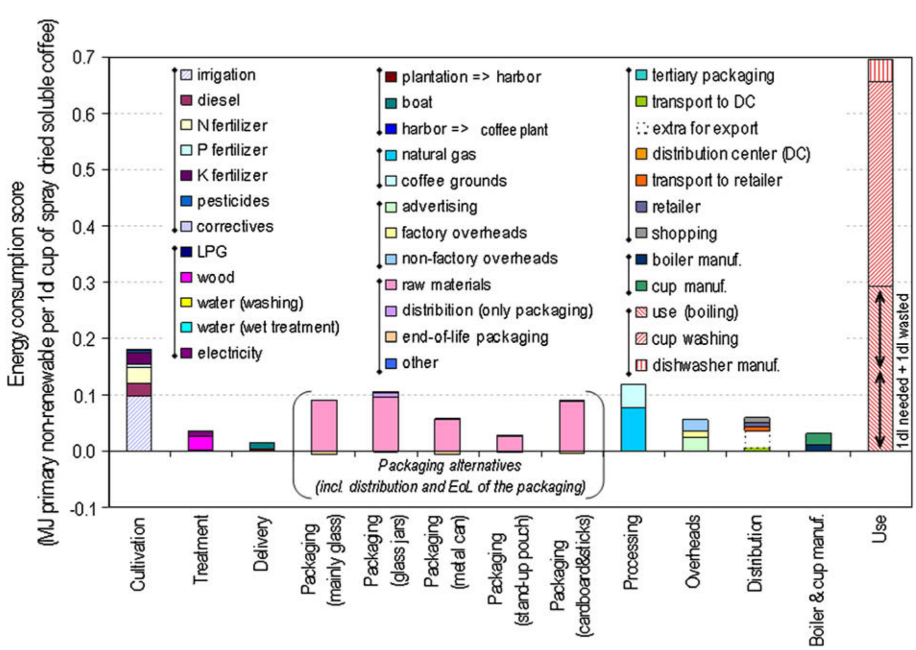

Fig. 2. Results detailing the different life cycle stages for one cup of coffee of spray dried soluble coffee, along with packaging alternatives.

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dishwasher being the main contributors. The large variability in consumer behaviors plays a major role in determining the uncertainty of the results. Excess boiled water is a key consideration for spray dried soluble coffee; the present case considers that double the amount of water needed is boiled. The efficiency of cup washing is another important factor, i.e., it is maximized when the dishwasher is fully loaded, or when no (hot) running tap water is wasted when washing by hand.

3.2.2. Spray dried soluble coffee compared with the other alternative

Fig. 3 presents (a) the non-renewable primary energy consumption, (b) the global warming score, and (c–e) the water use over the life cycle of the three alternatives considered. Water use is presented as for different indicators: (c) only considering non-turbined freshwater use inventory, (d) using regionalized characterization factors for non-turbined freshwater use, and (e) only considering turbined freshwater use inventory. Turbined water is the amount of water that is turbined from hydropower dams to produce electricity. Non-turbined water is the amount of water pumped from the environment (whether it is evaporated or released back), excluding the turbined water in hydropower dams. The later case (d) considers that a freshwater use of 1 l has different environmental impacts depending on the level of water stress in the region from which the water is exacted.

3.2.3. Energy

Overall, spray dried soluble coffee is less energy intensive than drip filter coffee or capsule espresso coffee (Fig. 3a). For each of the three alternatives, the use phase represents about one half of the overall non-renewable energy consumption. The time the water or coffee is kept warm and the number of coffees prepared per machine and per day are the two key factors for capsule espresso and drip filter alternatives. A higher frequency of coffee preparation leads to less energy per cup of coffee because of the allocation of the stand-by energy over more coffees. The excess boiled water or wasted coffee are important factors for both spray dried soluble and drip filter coffee, whereas for capsule espresso the packaging is

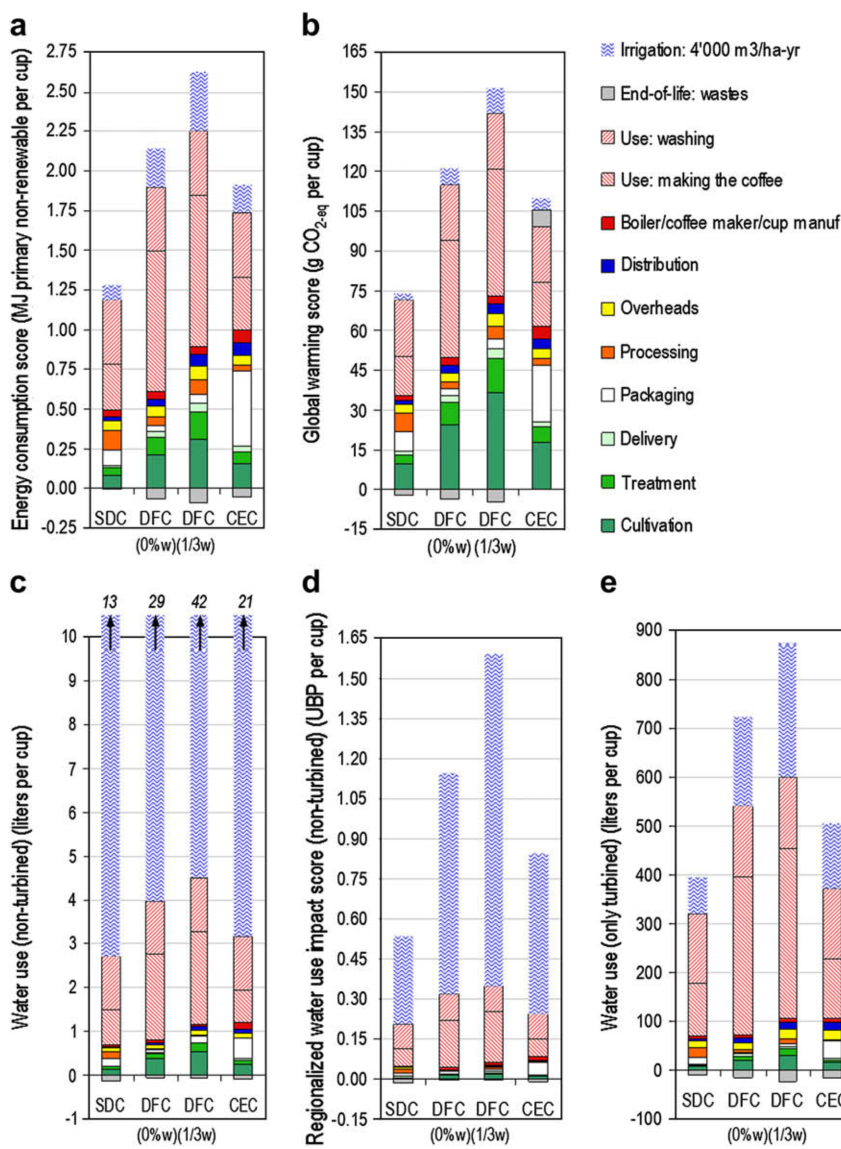

Fig. 3. (a) Energy consumption score, (b) global warming score, (c) non-turbined water use inventory, (d) non-turbined water use impact score, and (e) turbined only water use inventory presented in parallel, for the three alternatives: spray dried soluble coffee (SDC), capsule espresso coffee (CEC), and drip filter coffee (DFC) presented without (0% wasted coffee) and with wasted coffee (1/3 of the coffee wasted).

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energy intensive and comparable, in magnitude, to the use phase of this alternative. For the processes upstream of the coffee processing plant, the difference between the three alternatives is directly correlated to the amount of green coffee needed per cup of coffee, that is 17 g for drip filter against 4.4 g for spray dried soluble coffee and 8 g for capsule espresso coffee. These values are based on the ratios 'R&G coffee/green coffee' and 'spray dried soluble coffee/green coffee' of, respectively, 0.81 and 0.45 (Table 2).

3.2.4. Global warming score

Overall, the greenhouse gases emissions are correlated to the energy consumption (Fig. 3b). There is large uncertainty regarding the N_2O emitted during coffee cultivation. In this study we considered an emission factor of 0.017 kg N emitted as N_2O per kg of N input in the field.

3.2.5. Water

The ranking between scenarios is the same for the three water indicators and also corresponds to the previously described energy results: drip filter coffee leads to the highest water use score, followed by capsule espresso coffee and spray dried soluble coffee that shows the lowest water use. If the coffee plantation is irrigated, the amount of non-turbined water used can be up to 40 l per cup of coffee, dominating the overall life cycle water use (Fig. 3c). For the non-irrigated coffee, the total use of non-turbined water amounts to between 2.5 and 4 l per cup. A third of it is used upstream from the consumer (dominated by the cultivation and treatment of green coffee and its efficiency) and two third at the consumer house (equally distributed between brewing and cleaning water). Processing is not an important driver for water use. The impacts of non-turbined water use calculated with the generic factor (97 UBP/m^3) of the ecological scarcity method 2006 [27,28] directly reflect the non-turbined water use (not represented since the results have exactly the same shape as Fig. 3c but with the multiplicative factor of 97 UBP/m^3 [27,28]). Considering the local level of water stress and regionalizing the impacts of water use (Fig. 3d) significantly modify the relative importance of the different processes and phases: The water consumed in the use phase has an increased share of the overall impacts compared to the cultivation and treatment phases. This is related to the fact that, the level of water stress is on average lower in the coffee producing countries (33 UBP/m^3 as a weighted average value for Brazil (0.5 UBP/m^3, 14% of the origin), Colombia (0.25 UBP/m^3, 33% of the origin), and Vietnam (62 UBP/m^3, 53% of the origin), using the amount used in spray dried soluble coffee manufacturing plant as weighting factors) than in the average of OCDE countries (97 UBP/m^3) or in the UK (41 UBP/m^3). These results are based using national water stress indexes [29] and may change when considering water stress indexes at a more local level. In our irrigation scenario, a value of 4000 m^3/ha·yr is considered for the "extra water" provided to the field by the irrigation system. Should this value be 13,000 m^3/ha yr (i.e., if no water would be provided by the rain), the water footprint calculated in the present study would increase up to 130 l per cup. Chapagain and Hoekstra [31] report comparable figures, a cup of coffee (125 ml) requiring 140 l standard coffee and 80 l for instant coffee, once these figures have been corrected for the coffee yield and amount of roast and ground coffee per cup (both lower in [31] than in the present study). Chapagain and Hoekstra's approach primarily intends to show the amount of "embedded water" in internationally traded products, independently of their "scarcity", i.e., independently of whether it was "natural" rainfall or whether water was taken from other uses for irrigation. In our approach, as far as water is concerned, water use by the plants coming directly from the rain is considered to have no impact on water resources. The turbined water use (Fig. 3e) is mainly due to the electricity consumption during use phase. It approximately amounts to 900 l per cup for drip filter coffee, 500 for capsule espresso coffee and 400 for spray dried soluble coffee. It means that the volume of water used for electricity production is between 20 and 150 times higher that water volume used for all other processes. Overall, the key factors influencing water use are the irrigation process, if any, the amount of green coffee used per cup, the efficiency of coffee wet treatment, and the amount of water used to clean the cup.

3.2.6. Comparison between the different impact categories

Fig. 4 presents the environmental profile of the three alternatives calculated with the IMPACT 2002+ method [25]. In each impact category, each alternative is represented in proportion to the alternative that has the highest score for the considered impact category. This representation allows the identification of which alternative has the highest (respectively the lowest) impact in each of the impact category. Similarly to the above-described categories, spray dried soluble coffee shows systematically lowest impacts compared to both drip filter coffee and capsule espresso coffee.

3.3. Sensitivity analysis

3.3.1. Coffee cultivation

Coffee cultivation and consequences of N_2O for global warming scores are presented in Fig. 5. N_2O represents an important

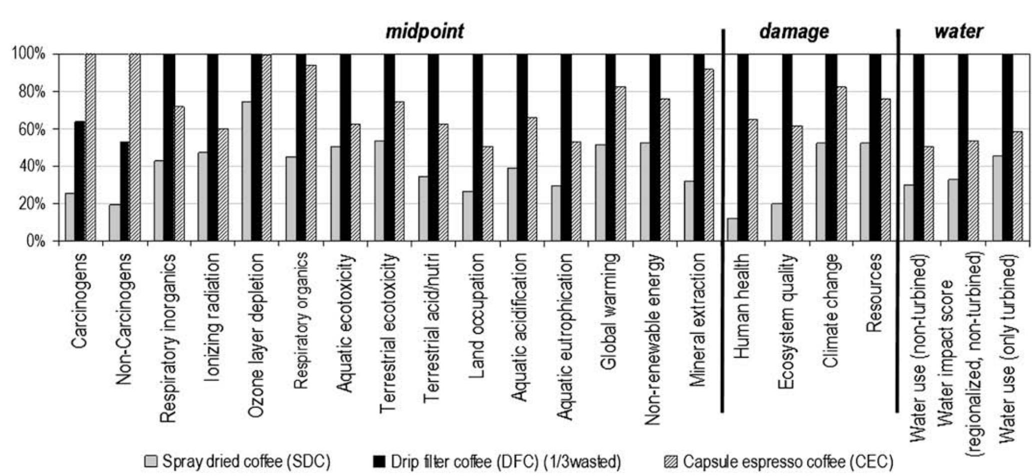

Fig. 4. Comparison between the different impact categories for the three alternatives.

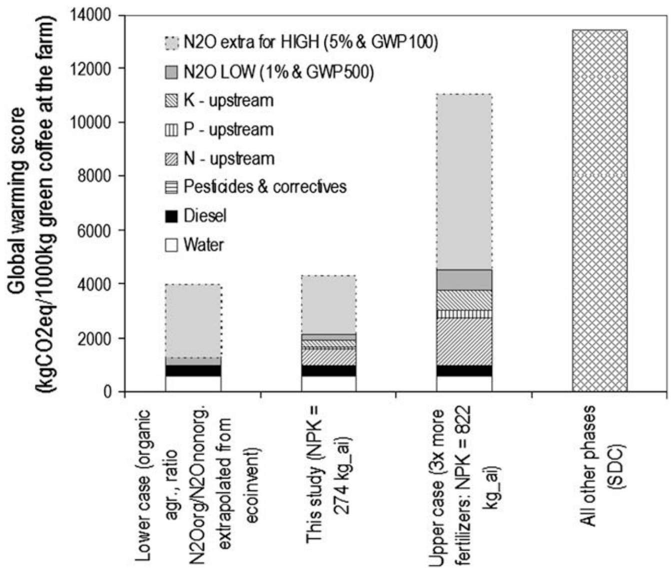

Fig. 5. Coffee cultivation and consequences of N_2O for global warming.

contributor to the global warming score. Organic agriculture also releases N_2O (from organic fertilizers), which, in some cases, can be higher than when using chemical fertilizers. In this study we considered an emission factor of 0.017 kg N emitted as N_2O per kg of N fertilizer input in the field. This value is extrapolated from Nemecek and Kägi [32], assuming no crop residues added, 4% of loss as ammonia, and 20% loss as nitrate. If larger releases of N_2O do occur, i.e., up to 0.05 kg N as N_2O per kg N input, as suggested by Crutzen and colleagues [33], the coffee cultivation could become the main contributor to the global warming scores. It is thus important to use only the minimum necessary amount of N fertilizers in the field. In a comparative analysis, the advantage of spray dried soluble coffee compared to drip filter or capsule espresso coffee would be further increased since spray dried soluble coffee is the alternative that requires the least amount of green coffee per cup.

3.3.2. Use phase

The impacts generated by the use phase typically vary up to a factor 2 because of the different consumers' behaviors. The amount of extra boiled water to prepare a cup of spray dried soluble coffee, the time the drip filter or capsule espresso coffee machine is switched on or whether the cup is washed using cold or warm water can significantly influence the overall results. The contribution and therefore relative influence of each parameter is shown in Fig. 3. However, as these behaviors are somewhat correlated to the consumer profile attitude, the ranking between the different alternatives are likely to stay the same.

3.4. Limitations

The scope of this LCA implies several limitations that could be supplemented by further studies, including: i) A systematic description of cut-off criteria and data quality assessment. ii) A systematic uncertainty analysis. iii) An improved identification of the representative user profile, since a preliminary sensitivity analysis highlighted that under the actual conditions, the use phase can significantly vary in relationship of the adopted hypothesis. iv) A detailed modeling of the direct impacts of fertilizers and pesticides on climate change, eutrophication, human toxicity and ecotoxicity that have to be interpreted with care in the present study. v) A detailed modeling of the actual location of water use for all the background processes to refine the water use impact score. vi) Improved methods to evaluate the impacts resulting from water use (e.g., physical impacts of turbined water use on ecosystems).

4. Recommendations for improvement of spray dried soluble coffee system

Several recommendations for improvements can be drawn from the present study: 1) Raise the ***consumer's awareness*** regarding ways to improve efficiency of the use phase. Do not boil more water than necessary for the cup of coffee, leading to a reduction of the overall impact of its cup of coffee by more than 15% compared to a consumer boiling twice the amount of water needed for the coffee. Reduce the impacts caused by the cup washing: reuse the cup before washing it and wash the cup efficiently, i.e., if possible with cold water, not wasting running warm water, or make sure that the dishwasher is fully loaded. 2) Encourage the ***suppliers of green coffee*** (or select suppliers) to: 2a) Use only the necessary amount of fertilizer in the coffee plantation. This is especially valid for nitrogen (N) fertilizer that significantly contributes to the global warming score through the release of N_2O into the atmosphere. 2b) Use efficient irrigation techniques. Irrigation is the main factor for water use throughout the life cycle of spray dried soluble coffee, only the necessary amount of water should be applied in the coffee plantation. 2c) Use wood from renewable (sustainable) forest for the green coffee treatment. The wood represents an important share of the treatment process, and 20% of the energy needed prior to the processing stage. This wood needs to be: 2ci) from sustainable grown forests (to avoid deforestation, which is responsible for important release of CO_2), 2cii) well managed forests (especially no monoculture or important clear cuts), to avoid erosion, and 2ciii) diverse forests, to avoid losing biodiversity. Forest Stewardship Council (FSC) certified wood is a possible solution. 3) Make sure that the ***energy use*** in the spray dried soluble coffee plant is optimized, since processing generates an important energy consumption. For example, only electricity efficient equipment and appliances should be used: all heat should be provided with natural gas or using heat waste from a nearby process or factory. Evaluate whether the coffee grounds that are burned in spray dried soluble coffee plants could be disposed of in a more beneficial way (e.g., biogasification or composting). Since a large amount of natural gas is used to produce steam, evaluate whether there is a possibility to add exchangers to preheat the water, using waste heat from other processes. 4) Rethink the ***packaging***: use less glass or replace it with lighter material since significant amounts of glass are used for the packaging (2.6 kg glass/kg spray dried soluble coffee). Using less packaging material would in addition reduce the mass to be distributed, this advantage being especially significant for long distance road transport. Options that may improve environmental performance of packaging include pouch or, in a lesser extent, metal cans.

5. Conclusions

5.1. Spray dried soluble coffee

The overall life cycle burdens for one cup of spray dried soluble coffee amounts approximately to 1 MJ of primary non-renewable energy demand, 0.07 kg of $CO_{2\text{-eq}}$, and 3–10 l of non-turbined water use depending on whether the coffee cultivation is irrigated or not. More than half of the environmental impacts of spray dried soluble coffee occur at the use phase. Cultivation, processing, and coffee packaging are of similar magnitude (10% each) and all together represent one third of the overall impacts. The use phase is

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dominated by the heating of the water and the dishwasher. The consumer behavior therefore plays an important role in determining the exact performance, for instance in terms of excess boiled water and efficiency of cup washing in term of dishwasher load or amount of running water used when washing by hand. The impacts from cultivation are dominated by the use of fertilizers despite large variation between producers. Irrigation is responsible for the largest share of water use. The packaging, while not a dominant component, cannot be neglected. Pouch and, to a lesser extent, metal can are packaging alternatives that have lower environmental burdens than glass or sticks. This study shows that it is important to consider the full life cycle, including the use phase when doing an LCA. Indeed, "side" or "end" stages, such as water boiling or cup washing are often neglected, which, if it is the case, misses up to half of the impacts.

5.2. Spray dried soluble coffee compared to drip filter coffee and capsule espresso coffee

Spray dried soluble coffee requires less energy than capsule espresso coffee and drip filter coffee, that represents the most energy intensive option. Spray dried soluble coffee is more energy intensive during the processing phase than the other two alternatives. However, since it requires less green coffee per cup of spray dried soluble coffee than for one cup of the two alternatives, spray dried soluble coffee scores better at the cultivation, treatment and delivery stage. Overall, spray dried soluble coffee uses less energy and has a lower environmental footprint than drip filter coffee or capsule espresso coffee.

5.3. Learning

This study shows that a broad LCA approach is needed to help the food manufacturing industry minimize the environmental burdens directly related to their products. Including all processes of the entire supply system of goods and packaging, distribution and final purchase transport, but also the consumption of goods, are necessary i) to get a comprehensive environmental footprint of the product system with respect to sustainable production and consumption, ii) to share stakeholders responsibility along the entire product life cycle (e.g., supplier vs producer vs consumer), and iii) to avoid problem shifting between different life cycle stages (e.g., optimizing the packaging at the expenses of a higher product losses or overconsumption by users).

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Appendix 1. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jclepro.2009.04.011.

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