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Coffee beverage preparation by different methods from an environmental perspective

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Abstract

Purpose Coffee is among the most appreciated beverages in the world, and there is a wide variety of methods of coffee consumption, inside and outside the home, with a significant growth in the coffee machine market for single serve. Due to this significant growth and in agreement with the current sustainability directives, the objective of the present article was to evaluate the environmental performance of the preparation step of the most representative methods of beverage preparation.

Methods The principles of the life cycle assessment (LCA) were applied to evaluate the environmental efficiency of the beverage preparation stage for the following methods: the traditional espresso, the French Press, the AeroPress, filtered coffee systems in coffee shops, the homemade filtration, and single-serve automatic machines. The boundaries of the study included the agricultural stage, the industrial roasting/grinding, and the beverage preparation up to final disposal of waste. Data were collected from 40 establishments among coffee shops, bakeries, and homes, with 153 individual data. The environmental efficiency was measured regarding energy, water consumption, waste generation, and the environmental impacts scores related to global warming, eutrophication, acidification, abiotic depletion, and human toxicity calculated by CML 2001 method.

Results and discussion Individualized data of coffee roasting/grinding from the industrial process was provided. The preparation of a single-serve soft pod (paper sachet) using an automatic machine resulted in the lowest emission of 14.3 g of CO_2 eq/50 mL of beverage in the monodose category, and also a non-biodegradable packaging waste to landfills about 11 times less than the single-serve plastic capsules with aluminum top seal, which had the highest consumption of energy, water, and waste generation in the single-serve category. In the category of consumption outside the home, espresso coffee, produced under pressure and higher temperatures, had the greatest impact, mainly due to its concentration, and the energy demanded by the automatic machines.

Conclusions The study identified that the concentration of coffee, as well as the ratio of packaging mass per volume of beverage prepared, has a significant effect on the calculated environmental impacts. The single-serve pods method using paper sachets can associate convenience with low environmental impact. The results obtained allow the consumer to include the environmental aspects in the choice of method for beverage preparation and also provide relevant information for public policy concerning residue generation.

Keywords Coffee beverage · Coffee brewing technique · Environmental impact · Life cycle thinking · Sustainability

1 Introduction

Scientific knowledge has been used for many years to increase food production for a growing global population. However, this progress has had environmental and social impacts such as depletion of natural resources, water scarcity, climate change, soil degradation, ecosystem stress, among many other changes observed in several parts of the planet. The planning of our future actions requires urgent revision of the ways in which the environment has been used. Given the close relationship between food and the planet, FAO has established guidelines to be pursued for sustainable food and agriculture to be followed by policymakers. For the food sector, actions are focused on soil protection, water use management, sustainable consumption promotion, and the adoption of measures to adapt and mitigate climate change (FAO 2018).

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The revolution in methods of coffee beverage preparation and introduction of individual doses generates an uncertainty regarding the environmental impacts of these new habits of consumption. The environmental interfaces of human activities with daily frequency, such as the coffee beverage, have been the subject of research due both to their potential for improvement and their associated impacts. A document developed to identify new packaging development guidelines identifies a consumer who is increasingly aware of and desirous of being environmentally responsible for their choices (Mourad and Jaime 2012).

1.1 Economic importance of coffee

Coffee is produced in about 60 countries, in the equatorial regions which have a favorable climate for plant growth, with Brazil, Vietnam, and Colombia being the main producers in the world market (USDA 2018). According to the Brazilian Ministry of Agriculture (MAPA 2016), Brazil is currently the largest producer and green coffee exporter in the world and the second largest consumer market, the first place belonging to the USA.

World coffee consumption exceeded 9.9 million tons in 2018, with most of the final product consumed in countries such as the USA, the European Community, and Japan, according to the International Coffee Organization (ICO 2019).

In the Brazilian harvest of 2016, where 51.37 million bags of 60 kg were produced, 84.4% were Arabica coffee (*Coffea arabica*) and 15.6% conilon coffee (*Coffea canephora*) (MAPA 2017).

The economic importance of coffee in Brazil comes from the time of colonization. After its introduction in the country in the eighteenth century (1727) in the State of Pará, the shrub has adapted very well to the climate and has been an essential source of income for hundreds of municipalities. According to the Brazilian Ministry of Agriculture, the coffee production chain is responsible for the generation of eight million jobs in the country, is present in the economy of more than 1900 municipalities distributed in 15 states, with about 287 thousand producers, predominantly mini and small, being part of cooperatives and associations (MAPA 2017).

Coffee is a beverage present in households and coffee shops in most countries. Billions of cups of coffee are appreciated every day by consumers around the planet. There are many ways to prepare the coffee beverage, and the number of consumers concerned about the environmental impact of the products consumed has grown.

Coffee culture in Brazil is closely linked to its own history, its economy and even its identity. The beverage is present in 98.2% of households according to a Nielsen survey of 2014 for ABIC (Brazilian Coffee Industry Association). According to this same research, about 75% of the beverage is consumed preferably inside the home. A true revolution has occurred in the methods of preparation of the drink since its introduction. In addition to the traditional filtered coffee, the consumption of espresso and single-serve coffee such as capsules and sachet-type soft pod has achieved significant market share in home consumption. Among Brazilians, the consumption of the single-serve products is still recent and of lower volume, compared with other more traditional forms of preparation such as filtered coffee, present in most Brazilian households. Instant coffee and ready-to-drink (canned or carton pack) are also alternative forms of drinking, but consumption has stagnated (EUROMONITOR 2017).

The MAPA reports on its website that, year after year, there has been an increase in the number of certifications related to environmental, ethical and social responsibility, adequate living conditions, respect for workers' rights, and rational use of resources. In addition, there are laws related to the preservation of forest resources and native fauna, erosion control, and water source protection (MAPA 2019).

Due to the importance of coffee in the daily life of 210 million Brazilians, knowledge of the environmental interfaces at the beverage preparation stage allows consumers to play an active role and contribute to reduce environmental impacts.

1.2 LCA coffee beverage studies

Life cycle assessment (LCA) has been one of the most widely used tools to evaluate the environmental performance of processes and products (Hellweg and Milà i Canals 2014). LCA is a methodology that compiles and evaluates the inputs, the outputs, and the potential environmental impacts associated with the production system considered throughout its life cycle. It can be said there is a general balance of withdrawals of resources from nature and the returns of resources after the transformations carried out. LCA is a useful tool to promote awareness and environmental education (Hoeskstra 2015; Nortanicola et al. 2016).

Several studies have already been conducted in the coffee chain and it is already well known that the agricultural stage is one of the most impacting stages, mainly due to the use of fertilizers and pesticides (Coltro et al. 2006; Busser and Jungbluth 2009; Pedrazzini et al. 2012; Hassard et al. 2014; Hicks and Halvorsen 2019. Irrigation, necessary in some regions of Europe, is also associated with considerable water consumption (Humbert et al. 2009). Among the studies carried out with the coffee drink, it is known that the packaging and the energy consumption for the preparation of the beverage also has significant impacts (Humbert et al. 2009; Brommer et al. 2011; Hassard et al. 2014; Hicks and Halvorsen 2019). According to Furfori et al. (2012), half of the impacts of the beverage are located in the life cycle stages under the control of coffee producers and their suppliers (agricultural stage, processing, packaging, and distribution) and the other half, under the control of users (equipment manufacturers, consumers, and final disposal). Several studies indicate that the methods of preparation of the beverage have a significant impact on this production chain (Busser and Jungbluth 2009; Humbert et al. 2009; Brommer et al. 2011; Pedrazzini et al. 2012; Hassard et al. 2014; Hicks and Halvorsen 2019). These studies have different boundaries and functional units, which makes direct comparison difficult. When analyzing the results of these studies, it is not possible to know about the efficiency of the preparation methods, since the numbers presented represent the sum of the steps considered in each study, besides being the result of the specificities of each place/region. In addition, the functional units vary greatly with doses from 30 to 275 mL.

There are several other studies carried out on the coffee chain (de Monte et al. 2005; Furfori et al. 2012, 2014; Geibler et al. 2016; Salomone 2003). Many of them merge local data with data imported from other studies. The use of external databases generates results that do not represent strictly the evaluated systems and also make the assessment of the efficiency of the beverage preparation methods even more difficult. The studies of Cetea - Packaging Technology Center have been characterized by the use of Brazilian data in the vast majority, due to the fact that the efficiency data are extremely dependent on the location, the technology and the time in which they are collected. A previous authors' study measured the impacts of the agricultural stage, in a large data collecting survey, including 56 farms (Coltro et al. 2006).

The objective of the present study was to put a spotlight on coffee preparation methods to better evaluate the difference between them, without the interference of other stages and in a way that the environmental efficiency and impacts related to the preparation stage of the coffee beverage could be identified, considering the most common brewing methods, using principles of the life cycle assessment and also the application of "Life Cycle Thinking" (LCT) approach.

2 Materials and methods

2.1 Boundaries of the study

The boundaries (Fig. 1) of this paper included the agricultural stage, the coffee cleaning and processing at farm level, transport of green coffee from farms to the processing unit, roasting and/or grinding of the bean, packaging, transport to the point of consumption, preparation of the beverage by different methods, and transport and disposal of post-consumer packaging waste. The following methods were evaluated: espresso, French Press, AeroPress, filtered coffee systems in coffee shops—Hario V60 and Kalita, filtered coffee using holder and filter paper model 103 for home, single-serve machine with soft pod, single-serve machine with capsule 1, and single-serve machine with capsule 2.

The average distance of 520 km between the farm suppliers and the industrial unit evaluated was considered. A distance of 100 km for the transport of roasted/grinded coffee up to the point of consumption was included. The final disposal of the post-consumer packaging waste was included considering also a distance of transport of 100 km.

2.2 Functional unit

The study was calculated in two functional units: "the dose as prepared" and "50 mL." The "prepared dose" is important because it represents the conditions in which the coffee beverage is offered to the consumer. However, as the objective of the study is to measure the environment efficiency of each method, LCA tool was modeled to allow selection of the best environmental choice, changing the "end of pipe" approach in a way to identify the opportunities to improve the environmental performance of this stage. The results showed here were normalized by 50 mL, the volume near the average of the coffees prepared in single-serve machines and consumed outside the home. The different methods prepare different doses, variable in volume, water content, and soluble solids.

2.3 Scope of the study

Data specifically raised in this study refer to the roasting and grinding stage (collected from the company located in São Paulo State) and the beverage preparation stages by the different methods. Data collection regarding the beverage preparation was carried out between February and November of 2017 (Table 1), through visits to coffee shops, bakeries, and coffee consumers in the cities of Campinas and São Paulo. This stage is the core of this study.

2.4 Roasting and grinding stage

A company located in São Paulo State provided data on the roasting and grinding stages regarding the consumption of energy, water, waste generation, transport of inputs, and transport distances of suppliers of green coffee.

The company does not have the energy consumption by step processing. Thus, an allocation of the total electric energy was used considering the individual power of each roaster and grinder and their productivities per hour.

For the calculation of the emissions resulting from the transport of green coffee to the analyzed company, the average distances by trucks were used. As the trucks come back empty, this distance has been doubled. The average consumption of 2.5 km/L diesel for a 15 to 30 ton truck was used.

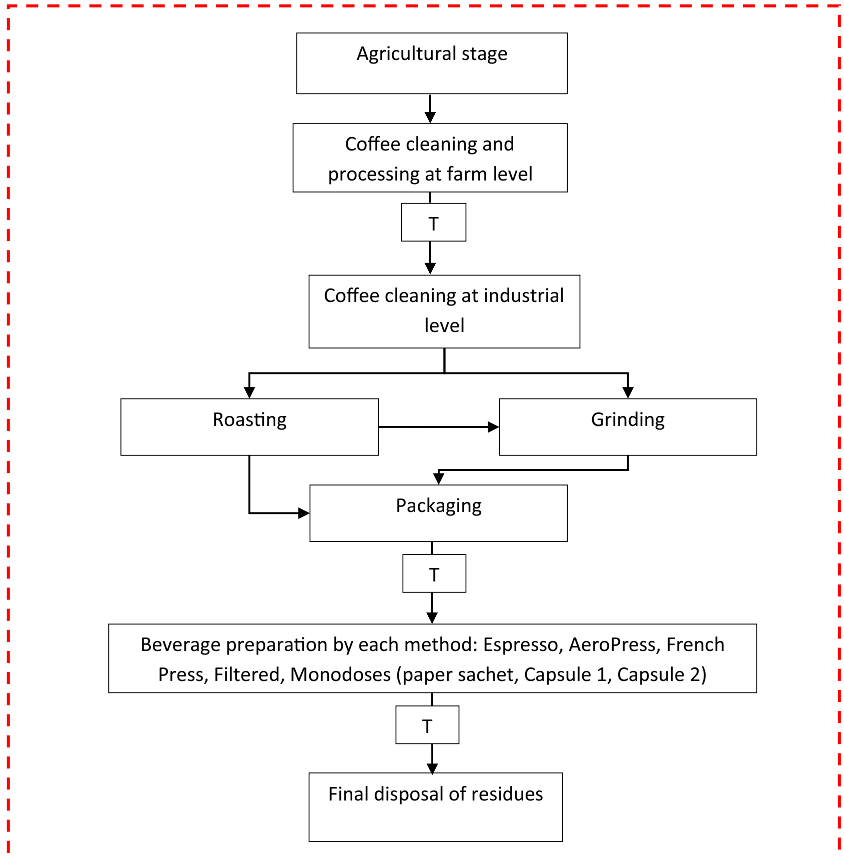

Fig. 1 Boundaries of the study

2.5 Beverage preparation

The study was conducted to understand the environmental interfaces of different beverage preparation methods. For this reason, a brief explanation of each is required prior to the data collection step.

2.5.1 Espresso

Italian espresso is a concentrated beverage obtained under high temperature and pressure in specific machines. A foam layer known as "cream" is also produced. According to ILLY et al. (1995), the typical parameters for the preparation of espresso coffee are 6.5 ± 1.5 g of coffee powder, water temperature around 90 ± 5 °C, machine pressure 9 ± 2 bar, and percolation time 30 ± 5 s. The average dose of the espresso is between 25 and 30 mL and can change between 15 to 50 mL.

2.5.2 French Press

In this method, medium-sized roasted and ground coffee is placed in direct contact with hot water in the French Press's cylindrical glass jar for about 4 to 5 min. The barista introduces a plunger, which has two sieves at its base, through which the solid part is left in the bottom and the extracted beverage migrates to the top of the jar and is ready to be served.

2.5.3 AeroPress

Roasted and ground coffee is placed in direct contact with hot water in one of the two cylindrical chambers of the AeroPress device. The paper filter is placed at one end and the beverage is withdrawn from the device by manually controlled pressure employed by the operator who pushes a plunger in the opposite end. The resulting beverage has an intermediate aspect between espresso and filtered coffee.

2.5.4 Homemade filtered coffee

Method traditionally used in Brazilian homes. Roasted and ground coffee is placed inside the paper or cloth filter supported by a filter holder. Boiling water is poured over the powder and the gravity filtered drink is either directly collected in cups or stored in thermos.

Roasted and ground coffee or whole beans are usually commercialized in 500- to 3000-g packs, and 1000 g is the most common size in flexible multilayer with aluminum packages.

Table 1 Sampling profile in 40 establishments among coffee shops, bakeries, and homes

Method	Number of establishments by method	City
Espresso	30	São Paulo/Campinas
AeroPress	16	São Paulo
French Press	16	São Paulo/Campinas
Filtered coffee coffee shop	8	São Paulo/Campinas
Filtered coffee HarioV 60	10	São Paulo/Campinas
Filtered coffee homemade	30	São Paulo/Campinas
Single-serve machine with soft pod	10	São Paulo
Single-serve machine with capsule 1	11	São Paulo
Single- serve machine with capsule 2	22	São Paulo
Total	153	

2.5.5 Hario V60

Similar to the homemade filtered method, it employs a filter holder made of plastic or porcelain which has internal spiral grooves and uses a paper filter specifically designed for this type of preparation. According to the manufacturer Hario, the design of the filter and filter holder facilitate the expansion of the coffee powder and a large opening in the base of the holder allows to control the speed and extraction of the beverage during the filtration.

2.5.6 Single-serve machines

In this system, individual doses of coffee are placed in machine compartments specially designed for each type of packaging and the beverage is obtained by passing hot pressure water that comes into contact with roasted and ground coffee. In this work, three types of individual packaging were evaluated. *Soft pod* packaging consists of tea-like paper bag as primary packaging packed in secondary packaging of bioriented polypropylene and metallized polyethylene terephthalate. Capsule 1 is made of aluminum and capsule 2 is made of aluminum and plastic, and both are sold in cardboard cartridges.

During the coffee shop visits, the following parameters were measured: masses of beans and/or ground coffee (depending on the method), the water used and the time of beverage preparation in electrical equipment. The °Brix of the prepared drinks was determined using an Atago refractometer. Analytical balance was used for packaging weight determination.

2.6 Final disposal

The final disposal stage was modeled according to the average waste management in the country.

According to ABRELPE—The Brazilian Association of Public Cleaning and Special Waste Companies, 78.4 million tons of solid waste were generated in the country, of which 91.2% were collected in 2017. Of the collected waste, 59.1% goes to landfills, 22.9% to controlled landfills, and 18% end up going to the dumps (ABRELPE 2019).

For modeling the final disposal of waste from these processes, the recovery rate of 66.2% was considered for cellulosic materials such as paper and board (IBA 2019). It was considered that in dumps, aerobic degradation predominates and in landfills, half of the carbon content generates carbon dioxide and the other half generates methane gas (Hunt 1995). Plastic materials and aluminum only weaken, but do not degrade under these conditions.

The implementation of the PNRS—Política Nacional de Resíduos Sólidos (National Policy on Solid Waste) in Brazil through Law 12305/2010 (BRASIL 2019) has required the environmentally appropriate final disposal of waste by the various actors in the production chains. Reverse Logistics Programs for coffee capsules have been encouraged by returning to voluntary delivery points (PEVs), post office mailing and collect through recyclable waste pickers cooperative in partnership with manufacturers. The recovery rate is still low, but efforts have been made to increase the recovery rate of coffee capsules after consumption. The sectoral agreement for implementing a reverse packaging logistics system signed between the MMA—Ministry of Environment and the Packaging Coalition—established a goal to reduce by 20% up to 2018 the dry mass of packaging destined to landfills, through a set of actions (CEMPRE 2019). Thus, it was adopted for the modeling of this work a recovering rate of 20% of the mass of post-consumption capsules. However, the exact rate is still unknown.

The energy for water heating and for grinding the whole roasted beans was calculated from the power of the equipment employed associated with the time for each operation, measured with a stopwatch.

2.7 Additional considerations for the modeling system

The data collected were organized in Excel Spreadsheets and the principles of mass balance used to analyze and validate them. The published inventory of 56 coffee farms in 5 Brazilian states for the years 2001 to 2003 (Coltro et al. 2006) was used to include the agricultural phase in the present study. Inventories of agrochemicals such as fertilizers and correctives were included from a Gabi software database. Emissions of nitrogenous compounds from synthetic and organic fertilizers were performed according to emission factors published by Nemecek (2013). Emissions of phosphorus-containing compounds and emissions due to the use of correctives and pesticides were estimated according to methodologies presented in Nemecek et al (2014). Data of electricity, natural gas, diesel, aluminum, polyethylene, and polypropylene were obtained from a CETEA private database from manufacturing companies in Brazil. The aluminum foil inventory used refers to one company's inventory for the 2012 base year and the polyethylene/polypropylene resin to another company analyzed in 2013.

Data of paper and cardboard inventories were obtained from the CETEA study (Mourad et al. 2014). The study was processed using a Gabi Software 4.3 version from Thinkstep.

2.8 Environmental efficiency of beverage methods

Energy, water consumption, residues generation, and greenhouse gases emission by the functional unit were selected to evaluate the environmental efficiency of each beverage method in a life cycle thinking approach. Results of eutrophication, acidification, abiotic depletion, and human toxicity scores calculated by CML 2001 (Guinée et al, 2002). This method was updated to Jan 2016 according to IPCC (2013). The CML method midpoint category was chosen as it is a method that includes the main relevant impact categories in environmental studies and can also be compared with several other studies where only the carbon footprint product is considered.

3 Results and discussion

3.1 Roasting and grinding coffee at industry level

Transportation is present in all stages of the life cycle and, in this study, the distances related to the transportation of the green coffee from the field and/or processing up to the industry were considered. The use of fossil fuels such as diesel is associated with depletion of natural resources and global warming.

In Brazil, the transportation of green coffee is carried out inside the country through a road network where diesel is the fuel mainly used.

In order to bring the green coffee from the producing and processing units to the factory, a weighted average distance of 520 km was calculated with an average volume transported of 494 bags of 60 kg with a total of 27,812 kg per truck.

Whole coffee beans are produced from roasting for medium to dark color. All data from this company are related to annual consumption in 2016. The average inventory of the roasting and grinding processes is shown in Table 2.

The analysis in Table 2 shows that most energy expenditure (93%) is for coffee roasting (1716 MJ/1000 kg of green coffee), when compared with (1838 MJ/1000 kg of green coffee) for roasting and grinding.

The water required for the roasting process represents 33% of the mass of the green coffee. It is observed that about 13% of the mass of green coffee is lost during roasting. Emissions of carbon dioxide from this process were not accounted for, just as the capture of this gas during photosynthesis was not included. About 10% of the green coffee mass generates solid waste and sent for aerobic composting. Roasting waste is pelletized to reduce volume and likelihood of sparks as it is aspirated at high temperatures. Residues generated in the roasting and ground processes are sent to the aerobic composting plant.

The energy of 1977 MJ/ton required for roasting in the manufacturing unit is about 22% higher than the consumption of 1621 MJ/t of green coffee estimated by Schwartzberg (2013).

The residues of this stage consist mainly of the pericarp, which forms the three outermost layers of the fruit and the skin surrounding the seed, known as silverskin. Pericarp is rich in fiber (35–51% cellulose) and can be used for other purposes such as the production of biogas, alcohol, and heavy metal absorber in aqueous solutions. Silverskin is a source containing antioxidants and dietary fiber and has been studied as a functional food ingredient (Blinová et al. 2017). For every 4 tons of processed coffee beans, about 30 kg of silverskin is obtained (Alves et al. 2017).

3.2 Beverage preparation

The beverage preparation methods have a large variation in quantity of coffee used, the serving size, and total of packaging mass, resulting, consequently, in different amounts of soluble solids in the beverage, as shown in Table 3.

Considering the dose as it is presented for consumption, it is observed that this measure is variable in content and volume, dilution and °Brix, but represents the way in which the coffee beverage is made available to consumers, and for this reason, it was considered in the general context.

In market research, it is known that the largest amount of coffee beverage is prepared at home, in quantities greater than will be consumed, and beverage discarded is observed. Single serve, most frequently consumed inside the home, allows to deliver only the amount to be prepared, avoiding the discarding of unconsumed coffee beverage.

The average consumption of the coffee shops surveyed was about 2.7 kg of roasted coffee beans per day.

3.3 Environmental efficiency of beverage methods

The analysis of the environmental efficiency of the different methods requires the standardization of the functional unit for the same volume of beverage. Energy, water consumption, and greenhouse gases emission were presented divided by each stage in order to also perform a contribution analysis. Results of eutrophication, acidification, abiotic depletion, and human toxicity scores calculated by CML 2001 (Guinée et al, 2002). This method was updated to Jan 2016 according to IPCC (2013).

The environmental impacts of transport were aggregated to subsequent stages and were not presented separately for figure simplification.

3.3.1 Energy consumption

The energy consumption for the stages of each method evaluated, combined with the mass of coffee and packaging used by the functional unit of 50 mL of beverage, is shown in Fig. 2.

The espresso method had the highest energy expenditure (0.43 MJ/50 mL beverage) which is mainly related to the energy for transport of green coffee and beverage extraction (0.25 MJ/50 mL), followed by the energy for agricultural stage (0.14 MJ/50 mL) and the roasting and grinding process. In the beverage extraction (0.16 MJ/50 mL), the energy consumption is related to the high energy demand of the automatic and super-automatic machines used in this brewing technique, added to the amount of energy used in the grinding of roasted coffee beans (0.04 MJ/50 mL) for the preparation of the coffee beverage.

The single-serve method with capsule 1 has the second highest energy consumption (0.38 MJ/50 mL beverage), followed by the same method with capsule 2 (0.29 MJ/50 mL beverage). In both cases, the consumption due to the packaging is significant and represents 0.28 MJ/50 mL and 0.12 MJ/50 mL respectively.

Homemade filtered coffee has a significant energy consumption concerning the use of LPG (liquefied petroleum gas) for water heating. This is the only method surveyed that does not use electric energy for coffee extraction.

The highest energy consumption for filtered coffee in shops is related to the packaging, with significant impact due to the use of aluminum cans for storage of 3 kg of whole roasted coffee beans and plastic packaging for product storage in bulk.

AeroPress is the method with smaller energy consumption per dose of 50 mL since the process of extraction is manual, and this method consumes a low quantity of ground coffee, and consequently, a smaller amount of energy for grinding.

It is noted that to obtain a difference of only 11% in the concentration of soluble solids between espresso and capsule 2 methods, a quantity of coffee 1.6 times greater is used, a fact that indicates that maybe the solubility of the coffee could be at its limit and that perhaps this concentration of soluble solids can be obtained with a lower mass and at a lower temperature as well. On the other hand, the pressure of espresso is around 9 bar and capsules is near 15 bar.

The energy consumption for the capsule espresso coffee method of 1.8 MJ/cup of 100 mL in Switzerland (Humbert et al. 2009), which is similar to capsule 1 of this study (0.32 MJ/50 mL), is higher than the present study. Besides the differences in inventory materials and mass proportions, the washing cycle, irrigation of plantation, and coffee maker manufacture is also included in the Swiss value.

3.3.2 Water consumption

Water consumption for the stages evaluated in each beverage method preparation per dose of 50 mL is shown in Fig. 3.

Water consumption due to agricultural stage is quite significant (13.45 mL/g of coffee). Thus, water consumption is also proportional to the concentration of coffee used by each method, besides the other determinant factors. The water consumed in packaging manufacturing is also significant. As capsule 2 prepares a concentrated coffee (9.61 g/50 mL) and also has a high packaging mass to volume ratio of prepared beverage (6.62 g/50 mL), this method demanded the highest consumption of this natural resource.

Espresso is the second demanding method of this resource. The first reason is due to its high concentration (15.5 g/50 mL) which requires in the agricultural stage 240 mL for the considered functional unit. The second reason is due to the higher consumption in the beverage preparation stage (107 mL/50 mL) in the automatic machines.

The preparation through the homemade filter was the method that least consumed water.

The reported water consumption by espresso coffee capsule of 21 L/cup of 100 mL in Switzerland's study (Humbert et al. 2009) is higher than the present results, mainly due to the irrigation of the coffee plantation. The lower water consumption in the present study is due to the fact that coffee is planted in Brazil almost entirely without the use of irrigation.

3.3.3 Residues into landfills and spent coffee grounds

One of the main current concerns regarding waste is the generation of waste that is not biodegradable and will take up space in landfills. For this reason, these residues were identified in the inventory and shown in Fig. 4.

Non-biodegradable packaging waste generated by the capsules 1 and 2 methods is much higher than packaging waste which has no single-dose oxidation barrier structure. Capsule 2 generates 3.25 g and capsule 1 generates 1.15 g, both for the preparation of 50 mL of beverage. In contrast, the packaging

Table 2 Average inventory of the roasting and grinding processes of the collaborating company

Roasting		Roasting and grinding	
Input	Unit/1000 kg	Input	Unit/1000 kg
Green coffee (kg)	1152	Green coffee (kg)	1203
Electricity (MJ)	275	Electricity (MJ)	435
Natural gas (MJ)	1702	Natural gas (MJ)	1777
Water (kg)	384	Water (kg)	401
Output	Unit/1000 kg	Output	Unit/1000 kg
Whole roasted coffee beans (kg)	1000	Roasted and ground coffee (kg)	1000
Pellets from roaster (kg)	13	Pellets from roaster (kg)	13
Mass loss at roasting (kg)	88	Grinding residues (kg)	88
Pre-cleaning residues (kg)	12	Pre-cleaning residues (kg)	12
Other organic residues (kg)	6	Other organic residues (kg)	6

residue of soft pods (paper sachet) represents only 9% of the former (0.3 g) and also has the convenience of a monodose.

The reuse of capsules after consumption has been the subject of several business initiatives, but the return of these packages after consumption requires high consumer commitment and an efficient collection and processing network, conditions that are not easily established.

Organic coffee residue remaining after beverage extraction may have the same destination of the organic waste from the industrial process and sent for composting, but the management of this destination depends on the coffee shops. Many coffee shops have reported that they have their own waste collect program, such as composting, especially for ground coffee. The paper filter is intended for ordinary waste as well as the primary and secondary packaging.

For household filtration, waste disposal is consumers' responsibility where it is necessary to separate the sludge, the paper filter, and the packaging and then give correct destinations for each of them.

The quantity of organic residue from coffee beverage preparation known as spent coffee ground (SCG) is quite significant since only 30% of coffee is solubilized. The SCG generation is proportional to the coffee concentration, ranging from 2 (filtered at home) to 12 g of dry mass/50 mL (espresso) of beverage. This residue is discharged into watercourses and landfills, leaching active biochemicals into the environment. A review of SCG characteristics found variations in hemicellulose composition of (32 to 42% w/w), cellulose (7 to 13% w/w), lignin (0 to 26% w/w), protein (10 to 18% w/w), lipids (2–24% w/w), chlorogenic acids (1–3% w/w), caffeine (0–2% w/w), and ashes (1–2% w/w). As SCGs contain significant amounts of bioactive chemicals, several researchers have pointed to recovery and valorization within the nutraceutical, pharmaceutical, food, and/or fine chemical industries (Massaya et al. 2019).

3.3.4 Global warming score

The greenhouse gases emission during the stages evaluated for each beverage method preparation per dose of 50 mL is shown in Fig. 5.

Table 3 Average characteristics of coffee beverage preparation in the survey done by the extraction method

Extraction method	Roasted coffee (g/serve)	Serving volume (mL)	°Brix	Total packaging (g/50 mL beverage)	Equipment
Espresso	12.0	42	6.50	0.61	Commercial Espresso machine (2 or 3 heads)
AeroPress	16.9	144	1.80	0.13	AeroPress
French Press	19.1	181	2.00	0.13	French Press
Filtered coffee coffee shops	22.5	167	1.90	0.17	Filter and holder (Kalita and others)
Filtered V 60 coffee shops	17.9	141	2.00	0.64	Filter and holder Hario V60
Filtered coffee homemade	46.2	574	1.97	0.42	Filter and holder 103 model
Single-serve soft pod (paper sachet)	7.0	54	2.75	0.69	Single-serve machine
Single-serve capsule1	5.1	41	3.70	2.98	Single-serve machine
Single-serve capsule 2	7.8	41	5.80	6.68	Single-serve machine

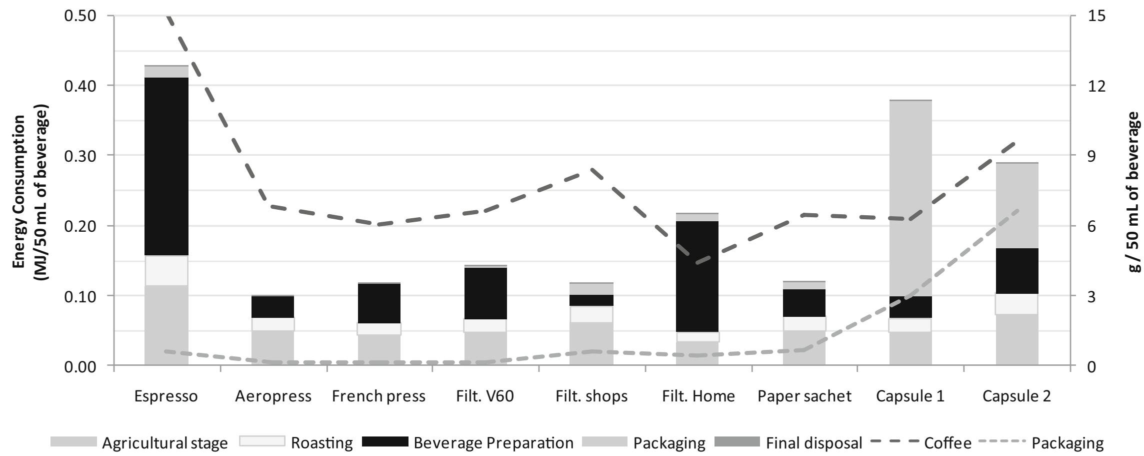

Fig. 2 Contribution analysis for energy consumption in different stages for each method and dashed lines showing the mass of coffee and packaging used by the functional unit of 50 mL of beverage

The agricultural stage is responsible for most of the global warming indicator, accounting for 38% to 86% of the calculated impacts.

The method that presented the greatest impact on GHG emissions was capsule 2: 35.6 g CO_2 eq/50 mL of beverage, with 46%% due to agricultural stage contribution and 36% due to packaging.

Espresso presented the second major environmental impact among the evaluated beverages: 32.2 g CO_2 eq/50 mL of beverage, with significant contribution of the agricultural stage: 78%.

The amount of packaging used per dose for the capsules is higher than that used for the other preparation methods, and there is more complexity of packaging materials, usually composed of different types of plastics, aluminum, and paper.

The product with the lowest environmental impact on greenhouse gas emissions was in French Press: 11.4 g CO_2 eq/50 mL of beverage.

The preparation of a single-serve soft pod (paper sachet) using an automatic machine resulted in the lowest emission of 14.3 g of CO_2 eq/50 mL of beverage, in the monodose category, associating the convenience of single serve and use of one automatic machine, with low environmental impact for coffee preparation, reaching a smaller global warming score than traditional home-brewed coffee (19.7 g CO_2 eq/50 mL), using a gas stove for water heating.

It is important that these data should be available to consumers so that they can understand the environmental impacts that they derive from their preferences.

In the study by Hassard et al. (2014), green coffee comes from Guatemala and Costa Rica and is transported to Japan, a fact that probably leads to a higher carbon footprint for espresso coffee (82 g CO_2 eq/50 mL) than that obtained in this study. In the study by Busser and Jungbluth (2009) for Espresso, it was considered that coffee was produced in Brazil (Coltro et al. 2006) and then exported to Europe, with a total emission of 150 g CO_2 eq/50 mL and 82% of greenhouse emissions originate from coffee cultivation and about 12% from the water heating for the preparation of espresso. This proportion is similar to the present results.

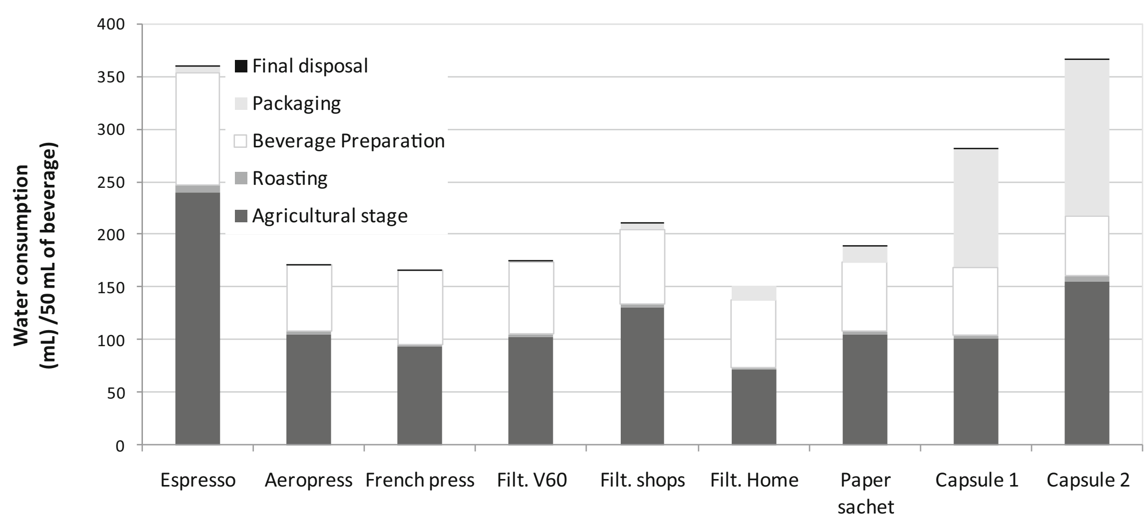

Fig. 3 Contribution analysis for water consumption in the different stages for each method of beverage preparation

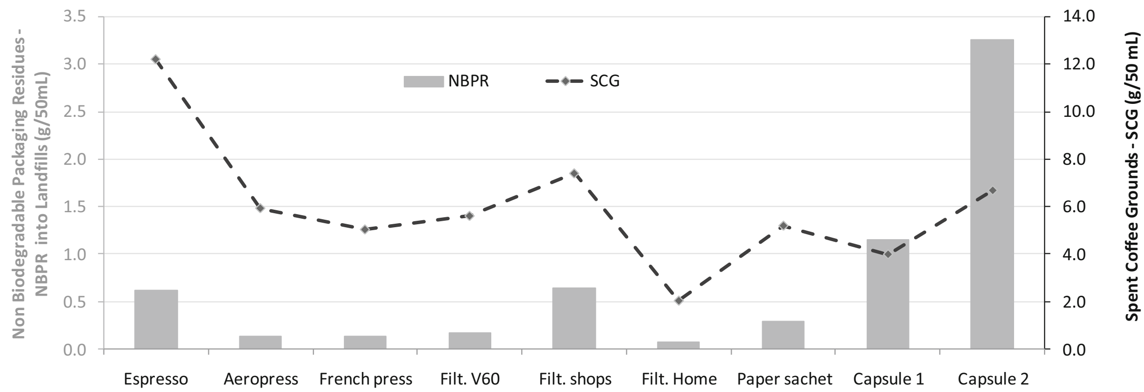

Fig. 4 Non-biodegradable packaging residues into landfills and spent coffee grounds by each method of beverage preparation

The reported global warming score by espresso coffee capsule of 110 g CO_2 eq/100 mL in a Switzerland's study (Humbert et al. 2009) is higher than 54 g CO_2 eq/100 mL calculated for capsule 1. By subtracting approximately 23 g CO_2 eq/100 mL from the value of the European study for steps not included in this study (coffee maker manufacture, overheads, and irrigation), the former still has a higher emission value, probably due to the agricultural stage.

Hicks and Halvorsen (2019) compare conventional (drip filter) with modern single-serve coffee pod brewing systems for coffee beverage and conclude that the differences found between them are also dependent on consumer behavior, with inversion of results. When equipment is connected to the energy in standby mode, the single-dose system has the greatest impact, but if it is turned off, it has a smaller impact than the conventional system. The boundaries of this work include the manufacture of coffee maker equipment.

3.3.5 Environmental impacts scores

In order to differentiate methods from the main environmental impact categories, Table 4 shows the contribution of each method by the functional unit of 50 mL of beverage.

The sum of the different impacts shows a profile similar to the energy consumption profile for the different methods.

In addition to the global warming category, already discussed in detail in Section 3.2.4, it is observed that the categories of human toxicity (HT) and acidification (A) are also significant, mainly due to the emission of nitrogen oxides in the agricultural (affect HT, A) and ammonia (affect HT). Thus, methods that use higher concentrations of coffee also have greater impacts of these categories. Abiotic depletion is also more intense in methods with higher coffee concentrations and methods that use larger amounts of packaging.

4 Conclusions

The alternative LCA approach adopted in this work allowed to identify clearly the environmental differences among the beverage methods currently in use in the country.

Agricultural cultivation, packaging production, and beverage preparation are stages of high environmental impact. So, the impacts of the different beverage preparation methods are mainly due to three factors: the beverage concentration, the

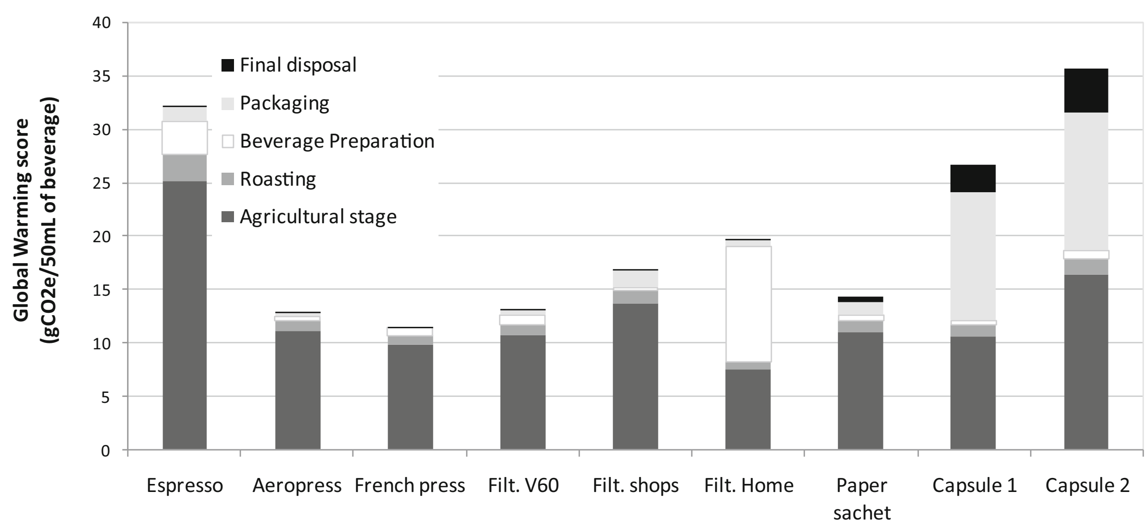

Fig. 5 Contribution analysis for GW score in the different stages for each method of beverage preparation

Table 4 Main environmental impact scores (EIS). Functional unit (g of each EIS by 50 mL of beverage)

Extraction method	GW	EU	HT	AD	A	POC
Espresso	32.21	0.131	0.927	0.157	0.504	0.021
AeroPress	12.81	0.043	0.235	0.056	0.142	0.005
French Press	11.40	0.043	0.219	0.049	0.152	0.006
Filtered V 60 coffee shops	13.08	0.049	0.310	0.060	0.180	0.007
Filtered coffee shops	16.79	0.051	0.411	0.085	0.165	0.006
Filtered coffee homemade	19.70	0.029	0.163	0.106	0.108	0.005
Single-serve soft pod (paper sachet)	14.28	0.045	0.352	0.067	0.154	0.006
Single-serve capsule1	26.60	0.058	0.349	0.101	0.262	0.013
Single-serve capsule 2	35.63	0.078	1.928	0.244	0.283	0.016

GW, global warming (gCO_2 eq); *EU*, eutrophication (gPO_4 eq); *HT*, human toxicity (g DCB eq); *AD*, abiotic depletion (g SB eq); *A*, acidification (g SO_2 eq); and *POC*, photochemical ozone creation (g ethene eq)

ratio of packaging mass per volume prepared, and the type of process for beverage extraction.

Capsule 2 is the method that presented the greatest impacts among the evaluated ones, because it combines high coffee concentration with high packaging ratio per volume of beverage.

Among the methods of preparation outside the home, the one that presented the greatest environmental impact was espresso, due to its high concentration and also the energy expenditure of the machine used for beverage extraction. Espresso is a traditional drink that has contributed to the growth of coffee shops around the world, a concentrated small dose with a consistent foam layer. It is suggested that future studies could explore the relationship between the amount of coffee employed and the soluble solids concentration of beverages obtained, associated with the perception and preference by consumers. A small reduction in espresso concentration may not be noticeable to the consumer and may represent a significant reduction in the impact of this brewing method.

AeroPress and French Press presented the lowest general environmental impacts among the methods evaluated.

The quantities of non-biodegradable packaging waste going to landfills are very different and this is of great environmental concern among single-dose methods due to the growing scarcity of available areas for these spaces. Capsule 2 generates 3.25 g/50 mL and capsule 1 generates 1.15 g/50 mL, which means that these methods generate 11 and 4 times more waste than soft pods (0.29 g/50 mL).

The single-serve pod with paper sachet (soft pod) was the best alternative for individual consumption, allowing the preparation of the coffee beverage with consistency, less effort, and time besides convenience for the consumer.

The present study focused on the environmental aspects from coffee beverage preparation. It is known, however, that the habit of coffee consumption is traditional in Brazil, and that the diversity of methods of preparation are linked to other aspects such as preferences of consumers regarding the soluble solids concentration of the beverage, type of coffee, roast degree, and aspects linked to preparation inside and outside the home. In this sense, the present study was able to measure important indicators related to the environmental profile of the preparation methods studied.

This study also allows us to observe that the disposal of coffee drink not consumed in the sink has at least the same environmental impact of its production, besides increasing the emission of organic compounds to water.

The development of public policy related to environmental education, recycling and circular economy, and projects including separation, destination, and disposal of waste must happen with the same intensity as the dissemination of machines for single-serve doses; otherwise, the production of solid wastes will significantly increase.

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