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Carbon Footprint of Different Coffee Brewing Methods

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The aim of this work was to assess which coffee brewing method was the most environmentally friendly one among a 3-cup induction Moka pot, and two single-serving coffee machines. To this end, a streamlined Life Cycle Assessment including the use of the above coffee machines, production, transportation, and disposal of all packaging materials used, and disposal of spent coffee grounds was carried out in compliance with the Publicly Available Specification (PAS) 2050 standard method. The production of one 40-mL coffee cup with the induction Moka pot gave rise to as low as 8 g CO_{2e}, these emissions being about 18% or 56% lower than those resulting from the use of a coffee capsule (10 g CO_{2e}) or pod (18.5 g CO_{2e}) coffee machine. These estimates might help the eco-conscious consumer to assess the environmental impact of his/her consumption habits.

1. Introduction

About 500 billion cups of coffee are consumed worldwide every year (Much Needed, 2020). Thus, coffee is one of the most popular beverages in the world. In 2019 the Italian consumption of roasted and ground coffee amounted to around 304,000 metric tons (Iascone, 2020). Of these, 84% were used to prepare the drink either at home and in the offices (54.6%) or in the hotel, restaurant, catering, and vending machine sector (29.4%). The remaining 16% was industrially used to formulate ice creams, yoghurts, soft drinks, desserts, etc. (Iascone, 2020). Roasted and ground coffee covered about 90% of the former, being followed by roasted coffee beans (6.7%), and instant coffee powders (3.3%). Such a coffee was chiefly packaged in flexible polylaminated bags with capacities ranging from 250 g to 3 kg (84.5%), followed by steel cans (7.5%), and single-serving coffee capsules or pods (5%). In the single-serving coffee sector, the request for aluminum capsules is growing by +11% since 2016, while that for plastic capsules and paper pods is declining (Iascone, 2020).
The environmental impact of coffee has been largely studied (Coltro et al, 2006; Hassard et al., 2014; Hicks et al., 2017; Humbert et al., 2009; Phrommarat, 2019) by accounting for different coffee varieties, conventional or organic farming, cultivation places, volumes of coffee from 40 to 237 mL, and brewing modes using roasted and ground coffee, roasted coffee grains, coffee pods or capsules. According to Brommer et al. (2011), who accounted for the cradle-to-grave greenhouse gas (GHG) emissions associated with the preparation of 2000 cups of coffee (125 ml each) averagely consumed in German houses on a year basis, the agriculture phase was responsible for 55.4% of the overall GHG emissions, followed by the consumer and post-consumer phases (36%), coffee roasting, packaging, and distribution (6.6%), and oversea transportation (1.9%).
In this context, the coffee brewing method used by the consumer, as well as the energy efficiency of the appliance used, exerts quite a significant effect on the environmental impact of the use phase. A great number of different coffee machines is nowadays used worldwide. Among them, it is worth citing the Moka pot, electric drip-filter coffee makers, French press, espresso machines, and single-serve pod or capsule coffee makers. Their market share varies from country to country. For instance, the electric drip-filter coffee machines still have a market share of 55 or 62% in the USA (Kraeutler et al., 2015) or Germany (Brommer et al., 2011), even if the sales of single-serve coffee makers is generally increasing. In Italy, 87% of home-brewed coffee is currently prepared with the Moka pot using pre-ground coffee (AGI, 2016).
The main aims of this study were firstly to measure the energy consumed to prepare a cup of coffee (40 mL) using the main coffee makers used in Italy (i.e., Moka pot, pod or capsule coffee makers), and secondly to perform a streamlined Life Cycle Assessment (LCA), that is a simplified LCA method, to identify the GHG

emissions associated just to the use and post-consumer phases in compliance with the Publicly Available Specification (PAS) 2050 standard method (BSI, 2011).

2. Materials and methods

Arabica coffee from Santos (Brazil) was used in 3 commercial formats, as kindly supplied by the company Caffè Aiello Srl (Rende, CS, Italy), namely ground coffee packed in 250-g multilayer bags (Package A), 44-mm Easy Serving Espresso pods (Package B), and Nespresso®-type capsules (Package C). The following three different coffee machines were used: i) a 3-cup induction Moka pot (IMP) cod. Linea-Moka-Induction-Oro (Bialetti Industrie SpA, Coccaglio, BS, Italy); ii) a coffee machine (PCM) Didì Borbone Blue Pods (Didiesse Srl, Caivano, NA, Italy) having a nominal power of 450 W; iii) a coffee machine (CCM) Nespresso D40 Inissia Black (De' Longhi Appliances Srl, Treviso, Italy) with a nominal power of 1200 W. The Moka pot was heated using a commercial 2-kW 190-mm induction-plate stove (Melchioni INDU, Melchioni Spa, Milan, Italy) set at a nominal power of 0.6 kW, as suggested by the Product Category Rules for Moka coffee preparation (EPD®, 2019a). When using the single-serving coffee machines, the energy consumption was determined according to the standard EN 60661 (CENELEC, 2014), by performing 5 sequential brewing cycles for as long as 100 min, as recommended by the Product Category Rules for espresso coffee preparation (EPD®, 2019b). In all brewing tests, the energy supplied was measured using a digital power meter type RCE MP600 (RCE Srl, Salerno, Italy) and referred to the overall number of coffee cups produced. The amount of ground coffee used in each test, as well as that of spent coffee residues, was measured using an analytical scale, while their corresponding moisture content was thermo-gravimetrically determined at 100 °C for 6 h (DPR, 1973). All brewing tests were replicated 3 times to evaluate the mean values and standard deviations of the dependent variables assessed, their statistical significance being assessed by the Tukey test at a probability level of 0.05.

3. Methodology

The streamlined LCA procedure was compliant with the Publicly Available Specification (PAS) 2050 standard method (BSI, 2011). The functional unit was specified as the preparation of one 40-mL cup of Moka or espresso coffee without any additional ingredients (e.g., sugar, milk) in accordance with the Italian Coffee Committee disciplinaries (Comitato Italiano del Caffè, 2018, 2020).

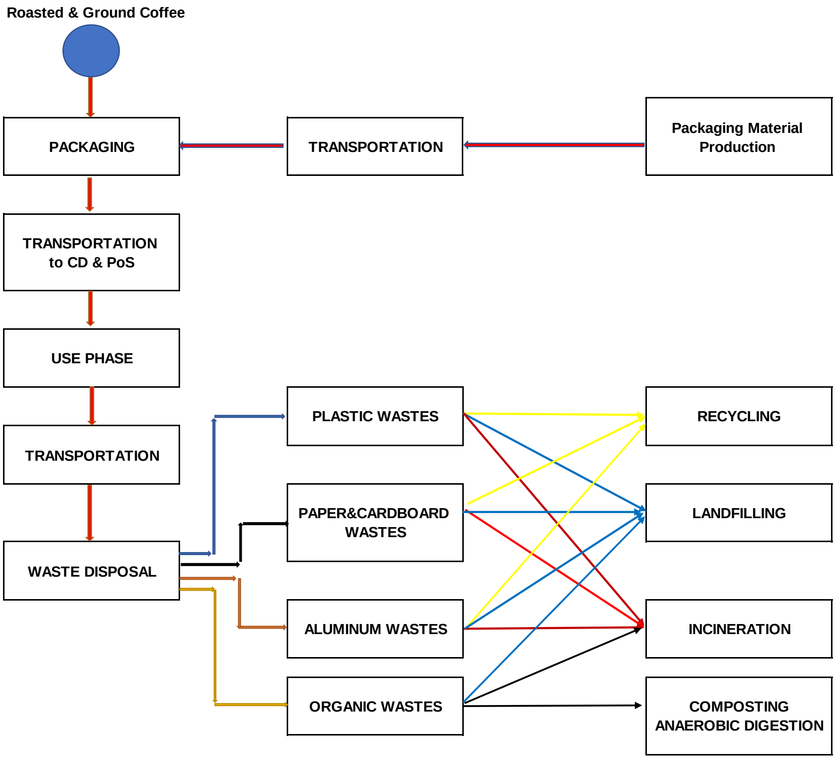

Figure 1: System boundary of the streamlined LCA study carried out to assess the carbon footprint of a 40-mL cup of coffee: CD, distribution centers; PoS, Points of Sale.

Fig. 1 shows the system boundaries of this LCA study, which included the use of the aforementioned coffee machines; production, transportation and disposal of all packaging materials used, as well as disposal of spent coffee grounds. These system boundaries did not include the GHG emissions arising from production of capital goods (i.e., coffee machines), as well as their cleaning and disposal (PAS 2050: Section 6.4.4), and the transport of consumers to and from the points of sale (PAS 2050: Section 6.5). The cultivation of coffee, coffee cherry transportation, production, and inland and oversea transportation of green coffee, as well as coffee roasting and grounding, were excluded from the system boundaries, as they were assumed to be the same for the different types of coffee formats and machines used.

3.1 Coffee packaging

Roasted and ground coffee was packaged in 3 different formats. Package A was a flexible multilayer bag (7.86±0.20 g) composed of polyethylene (PE: 0.735 g/g), aluminum (Al: 0.143 g/g) and polypropylene (PP: 0.122 g/g) and containing 250 g of coffee powders. Package B was a heat-sealable paper filter (0.180±0.002 g) gathering 7.23±0.02 g of ground coffee. The resulting coffee pad was wrapped in a PE-Al-PET pouch (1.51±0.01 g). Package C was a multilayer PE-Al-PET capsule (1.05±0.02 g), which contained 5.75±0.07 g of ground coffee thanks to two upper and lower aluminum lids (0.110±0.002 g both). The secondary packaging consisted of just a carton in the case of Package A, or of a corrugated paperboard box (CPB) containing 20 pods or 10 capsules each, which on turn was arranged in a cardboard master box (MB). Finally, the tertiary packaging included 95% reusable EPAL wood pallet (EWP) tightened by a stretch-and-shrink PE film and paper labeled. All details about the primary, secondary, and tertiary packages used are given in Table 1.

3.2 Transportation and distribution stage

The only transport modality for packaging materials from their production sites (PS) to the factory gate (FG), final product from FG to the distribution centers (DC) and points of retail purchase (PoS), EPAL wood pallets from the Euro pallet managing center (EPMC) to FG and from CD to EPMC, and post-consumer organic and packaging wastes from people's houses (PH) to the waste collection center (WCC) was by road using Euro 5 means, as specified in Table 2. Such logistics data were partly derived from the coffee processing plant, and partly from the Product Category Rules for Moka coffee and espresso preparation (EPD®, 2019a, b).

Table 1: Mass of any component of primary, secondary, and tertiary packages for roasted and ground coffee (RGC) as referred to the three packaging formats used: CB, cardboard box; EWP, EPAL wood pallet; MB, cardboard master box.

Coffee Packaging Format	**Ground Coffee Package A**	**Coffee Pod Package B**	**Coffee Capsule Package C**	**Unit**
Primary Packaging	*Polylaminated bag*	*Abaca Filter*	*PE-Al-PET Capsule*	
RGC mass	250	7.23±0.02	5.75±0.07	g
Vacuum pack mass	7.86±0.20	-	-	g
Paper filter mass	-	0.180±0.002	-	g
Overall capsule mass	-	-	1.16	g
Polylaminated pouch mass	-	1.51	-	g
Mass of primary package	*257.9*	*8.92*	*6.91*	*g*
Secondary Packaging A	-	*CPB*	*CPB*	
No, Pods or Capsules/box	-	20	10	-
Box mass	-	64.8	12.59	g
Mass of secondary package A	-	*243.2*	*81.69*	*g*
Secondary Packaging B	*MB*	*MB*	*MB*	
MB mass	318	1470	870	g
N° pouches or boxes/MB	20	48	156	-
Mass of secondary package B	*5.48*	*13.14*	*13.64*	*kg*
Tertiary Packaging	*EWP*	*EWP*	*EWP*	
No. MBs/layer	12	4	8	-
No. layers/pallet	12	4	4	-
PE film mass	0.82	0.91	0.91	kg
Pallet paper labels	3.1	3.1	3.1	g
R&G coffee mass	720	111.05	287.04	kg
Mass of tertiary package	*800.11*	*220.51*	*450.55*	*kg*

Table 2: Logistics of input/output materials with indication of the EURO5 means of transport used from the production sites (PS) or people's houses (PH) to destination (factory gate, FG; distribution center, DC; points of sale, PoS; EPAL wood pallet managing center, EPMC; waste collection center, WCC).

Input/output materials	**From**	**to**	**Means of transport**	**Load capacity** [Mg]	**Distance** [km]
Paper filter	PS	FG	Heavy rigid truck	7.5-16	860
Flexible bags & PE Film	PS	FG	Heavy rigid truck	7.5-16	270
Cartons	PS	FG	Heavy rigid truck	7.5-16	40
Pallet	EPMC	FG	Heavy rigid truck	7.5-16	200
	CD	EPMC	Heavy rigid truck	7.5-16	800
Palletized Coffee	FG	DC	Multiple axle lorry	>32	1000
	DC	PoS	Articulated truck	16-32	50
Organic& packaging wastes	PH	WCC	Light-medium rigid truck	3.5-7.5	50

3.3 Waste management

Post-consumer organic and packaging wastes were disposed of according to the overall Italian management scenarios of municipal solid waste (MSW) in 2018 (Ronchi and Nepi, 2019), as listed in Table 3. The organic residues from brewed coffee, as separated from Moka funnel or capsule, as well as used coffee pods, were discarded in the organic fraction of MSW. Since Demichelis et al. (2019) remarked that the organic fraction of MSW was on average submitted to biological treatment (38-72%), incineration with energy recovery (16-52%) and anaerobic digestion (7-32%), it was assumed that the recycled fraction (i.e., 52% of the overall organic fraction) was converted into compost or digested anaerobically in a 5:1 ratio (Table 3).

Table 3: Overall Italian waste management scenarios for packaging and organic wastes, as derived from the distribution and consumer phases in the year 2018.

Waste Management Scenarios	**Landfill** [%]	**Recycling** [%]	**Incineration** [%]	**Ref.s**
Organic wastes	28.0	52.0	20.0	SRD (2020)
Paper and cardboard wastes	11.3	81.1	6.6	Ronchi & Nepi (2019)
Wood wastes	34.2	63.4	2.4	Ronchi & Nepi (2019)
Plastic wastes	14.0	41.0	45.0	Ronchi & Nepi (2019)
Aluminum wastes	13.8	79.8	6.4	Ronchi & Nepi (2019)

3.4 Energy source

Electricity was the only energy resource used. It was withdrawn from the Italian medium or low voltage grid, its emission factor (512.9 g CO_{2e}/kWh) being extracted from the Ecoinvent v. 3.5 database.

3.5 Carbon Footprint assessment

The carbon footprint (CF) of the functional unit chosen was assessed by summing up all the GHG emissions associated to the coffee life cycles depicted in Figure 1 by accounting for a series of emission factors extracted from the databases (i.e., Agri-footprint v. 4.0, Ecoinvent v. 3.5) embedded in the LCA software SimaPro 9.0.0.41 (PRé Consultants, Amersfoort, NL).

4. Results and Discussion

4.1 Specific energy demand for coffee brewing

Table 4 shows the main results of the coffee brewing tests carried out using different coffee makers.
The amount of ground coffee (16 g) used to fill the 3-cup induction Moka pot was within the range (14-19 g) recommended the Moka coffee disciplinary (Comitato Italiano del Caffè, 2020). By referring to a single coffee cup, such amount was close to that contained in each coffee capsule (5.75 g), but less than that included in each coffee pod (7.23 g), which on turn fell within the range (7-9 g) recommended by the new espresso coffee disciplinary (Comitato Italiano del Caffè, 2018). The moisture content of ground coffee (x_{Wgc}) was independent of the commercial format, and definitively lower than the maximum level allowable (5% w/w) (DPR, 1973). The moisture content of spent coffee grounds (x_{Wscg}) ranged from 57% to 63% (w/w).
The energy consumed (E_{cons}) throughout the coffee brewing tests varied with the coffee machines in use. The induction Moka pot consumed about 20 Wh to yield 3 cups of coffee in an overall time of 272 s, that is 6.7 Wh per each coffee cup served. The single-serving pod or capsule coffee machine, respectively, consumed 60 or 32 Wh to produce 5 cups of espresso coffee in an overall time of 100 min, according to the EPD® procedure

(2019b). Thus, the specific energy consumption (E_{cc}) including the prefixed resting times was about 12.0 or 6.4 Wh per each single cup of coffee, and the average serving time was 30 s or 25 s, respectively. Despite E_{cc} for the induction Moka was not statistically different from that for the capsule coffee maker at the probability level of 0.05, their corresponding energy consumption scores per g of ground coffee (E_{gc}) were statistically different, owing to the slightly higher amount of ground coffee in each capsule used (Table 4). According to Brommer et al. (2011), the specific energy consumed to prepare a 125-mL cup of coffee using efficient pod or capsule machines with integrated auto power down function would be ~39 Wh, that is a little more than the triple of that consumed by the pod coffee machine used here (Table 4). On the contrary, use of very inefficient appliance with no integrated auto power down function would increase E_{cc} to as much as 109 Wh (Brommer et al., 2011).

Table 4: Main results of the coffee brewing tests carried out with different coffee makers (3-cup induction Moka pot, IMP; pod, PCM, or capsule, CCM, coffee machine): amount of ground coffee used (m_{gc}); number of 40-mL coffee cups prepared (n_{cc}); overall volume of coffee prepared (V_c); moisture contents of ground coffee (x_{Wgc}) and spent coffee ground (x_{Wsgc}); overall energy consumed (E_{cons}), specific energy consumed per single coffee cup (E_{cc}) and per unit of ground coffee used (E_{gc}); coffee preparation time (t_C). All tests were triplicated.

Coffee Maker	**m_{gc}** [g]	**n_{cc}**	**V_c** [mL]	**x_{Wgc}** [% w/w]	**x_{Wscg}** [% w/w]	**E_{cons}** [Wh]	**E_{cc}** [Wh/cup]	**E_{gc}** [Wh/g]	**t_C** [s]
IMP	16.01±0.01 [a]	3	119±1 [a]	0.68±0.12 [a]	61.0±0.1 [a]	20.3±0.6 [a]	6.7±0.2 [a]	1.25±0.04 [a]	272±5 [a]
PCM	7.23±0.02 [b]	5	200±2 [b]	0.56±0.21 [a]	56.6±0.9 [b]	60±3 [b]	12.0±0.6 [b]	1.66±0.08 [c]	30±5 [b]
CCM	5.75±0.07 [c]	5	200±2 [b]	0.54±0.22 [a]	62.6±0.9 [c]	32±1 [c]	6.4±0.2 [a]	1.11±0.03 [b]	25±4 [b]

4.2 Carbon footprint of different coffee brewing methods

Table 5 shows the GHG emissions associated to the main life cycle phases (i.e., transportation, packaging material production, use phase and post-consumer organic and packaging wastes disposal) of the functional unit accounted for.

When using the induction Moka pot, the primary hotspot coincided with the disposal of post-consumer organic and packaging wastes (42.2%), and the secondary one with the use phase (36.1%). When using the single-serving pod or capsule coffee machine, the primary hotspot was the production of packaging materials (51.6 vs. 55.3%), while the contribution of the second hotspot (use phase) reduced to about 28% in both cases. Owing to the high recycling aliquots of paper and cardboard and aluminum wastes (Table 3), the resulting CO_{2e} credits lowered the contribution of the post-consumer phase, especially in the case of coffee capsules. On the whole, the production of one cup of coffee with the induction Moka pot gave rise to as low as 8 g CO_{2e}/cup, these GHG emissions being about 18% or 56% lower than those resulting from the use of a capsule or a pod coffee machine. Obviously, these scores were related to the overall Italian waste management scenarios shown in Table 3. Provided that at the waste collection center the PE-Al-PET pouches used to protect each coffee pod, as well as the coffee capsules, were not disaggregated into their basic components to be recycled, but simply disposed of to landfill, as well as all the other organic and packaging wastes, the post-consumer disposal phase dominated the overall GHG emissions with a share ranging from 72% to 59% or 63% in the case of the induction Moka pot, pod or capsule coffee machine, respectively. Whereas the use phase continued to be the secondary hotspot (17.4%) when using the induction Moka pot, the packaging production became the secondary hotspot for the pod (22.9%) or capsule (21.2%) coffee machine. Consequently, the carbon footprint of a 40-mL cup of coffee increased by a factor of 2.1-2.6. Thus, contrary to Brommer et al. (2011), the use phase did not exhibit the largest share of the GHG emissions in comparison with the production and disposal of packaging materials, as well as disposal of spent coffee grounds.

Table 5: Contribution of the different life cycle phases to the carbon footprint of a functional unit of one 40-mL cup of coffee obtained using different coffee machines (same acronyms as in Table 4).

LCA Phase / **Coffee Maker**	**Transportation** [g CO_{2e}/cup]	**Packaging Material Production** [g CO_{2e}/cup]	**Use** [g CO_{2e}/cup]	**Post-consumer** [g CO_{2e}/cup]	**CF** [g CO_{2e}/cup]
IMP	0.9	0.9	2.9	3.4	8.1
PCM	2.4	9.5	5.3	1.3	18.5
CCM	1.4	5.5	2.8	0.3	10.0

5. Conclusions

The energy consumed to prepare a 40-mL cup of coffee using an induction Moka pot or single serving coffee machines was determined and used to estimate the carbon footprint associated with different coffee ground packaging formats, brewing methods, and post-consumer organic and packaging waste disposal scenarios.

Despite the quality of a cup of Moka coffee is highly dependent upon the skill of the preparer and maintenance of the equipment with quite a longer preparation time than espresso, the eco-responsible consumer should be aware that the use of ground coffee with the induction Moka pot instead of coffee pods or capsules would avoid as much as 10.3 or 1.8 g CO_{2e} per single serving. By accounting for the Italian daily consumption of coffee cups (70 million per day), these avoided GHG emissions would be equivalent to 180 or 32 daily circumnavigation of the Earth's equator with a Euro5 diesel city car emitting 100 g CO_{2e}/km.

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