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Coffee capsule impacts and recovery techniques: A literature review

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Abstract

The recently developing coffee market has been characterized by profound changes caused by new solutions and technologies for coffee preparation. The polylaminate materials that compose most popular capsules make them a type of waste that is difficult to manage and recycle. This paper analyses the scientific references that deal with studying and improving the management processes of waste coffee capsules, as well as the studies that have analysed their environmental impact. Through a bibliographic review, some encouraging aspects emerged in the recovery of materials that can be adequately recycled (plastics and metals), as well as their possible use for the production of biogas and energy recovery. The need to manually separate the components that make up the capsule still represents one of the main challenges. Many efforts are still needed to favour the environmental sustainability of this waste from a strategic, technological and consumer empowerment point of view.

KEYWORDS
circular economy, coffee capsules, recycling, sustainability, waste treatment

1 | INTRODUCTION

The recently developing coffee market has been characterized by profound changes caused by the advent of new solutions and technologies for coffee preparation, which have led to new habits in consumers who have gradually turned to single-serving coffee. Coffee is a globally traded commodity (the second most traded after oil) and an integral part of many people's daily lives, as it is used as a drink in quantities that are second only to those of water consumption.[1,2] Global trends of coffee production and consumption are periodically measured and described by the International Coffee Organization (ICO), a multilateral intergovernmental organization that represents 98% of the world's coffee production. The data indicate that in 2019, global production of raw coffee beans was at roughly 170 million 60-kg bags, and the global consumption was estimated at approximately 168 million 60-kg bags.[3]

From the point of view of environmental impacts, the coffee supply chain is responsible for significant effects during all the phases that form the supply chain[1,4]: on the protection of natural resources, water pollution, biodiversity conservation, deforestation, waste generation and labour exploitation.

Table 1 reports, for each phase, the main potential impacts associated with the activities that are carried out.

In the scientific literature, various contributions are available that analyse, also applying the Life-Cycle Assessment (LCA) approach, the environmental impact due to the different phases that make up the supply chain and that allow to identify the activities and factors of greater pressure on territories and natural resources.

Hicks[5] reports the significant impact due to the use of fertilizers and pesticides, the high use of water and energy, as well as the emissions of air pollutants. Brommer et al[6] evaluate the environmental impacts of different methods of coffee preparation. In their study, they analysed only the phases related to packaging and related disposal, production of coffee machines and their use for the preparation of coffee, disposal of the filter pads/capsules/coffee ground. The paper confirms that, among all these phases, the use of the coffee makers is the one that determines the greatest impacts (expressed as global warming potential) and highlighting the use of energy as one of the main causes of these performances. Interesting are the results relating to the disposal phase of the filter pads/capsules/coffee ground which indicate the most impactful solution in the capsule machines compared to other solutions (e.g. French Press and filter drip coffee maker). The same result was also obtained for the production of the filter pads/capsules. Hassard et al[7] evaluate the carbon footprint and energy analysis of alternative coffee products in Japan, evaluating the entire supply chain of different products, identifying in the farming and processing, brewing and packaging phases those most critical for the carbon footprint and for energy consumption. The waste management and disposal phases have a more significant impact on the carbon footprint, while energy recovery solutions from waste make it possible to reduce the impact on energy consumption.

TABLE 1 Coffee supply chain and main environmental impact

Phase	Main environmental impact
Coffee production and treatment	Land use and deforestation Fertilizers and pesticides Use of water Use of energy Atmospheric emissions Residues Solid waste and wastewater
Packaging	Use of natural resources and raw materials Use of energy Atmospheric emissions Solid waste and wastewater
Transport and distribution	Atmospheric emissions
Use stage	Use of water Use of energy Waste generation
End of life	Atmospheric emissions Soil and water pollution Waste generation

Phrommarat[8] evaluates the environmental impact in the different supply chain phases and with respect to the numerous impact classes that characterize the LCA studies. This study also confirms the greatest impact during the cultivation and use phases for most impact categories. The disposal phase has significant impacts especially for the freshwater and marine ecotoxicity. Arzoumanidis et al,[9] through the use of simplified LCA assessment tools, assessed the impacts of the roasted coffee product system along the entire supply chain, identifying the phases of use of coffee for the preparation of beverages as the one with the greatest impact in all impact categories analysed (due to electricity consumption), followed by the production phase (also including packaging) and transport. The end-of-life phase has a less significant impact. Similar results have also been described by Humbert et al,[10] Salomone[11] and Giraldi-Diaz et al.[12]

Figure 1 shows, as an example, the contribution to greenhouse gas (GHGs) emissions from several LCA studies available in the literature.[13]

To overcome some of these critical issues, the companies that produce, process and market coffee apply solutions that help improve the sustainability of their activities, trying to reduce the environmental impact of their supply chain. As an example, the results of the Bager[1] study are shown: the author analysed a sample of 513 companies, identifying the types of actions taken, which are shown in Figure 2.

Coffee consumption trends have also evolved rapidly over time, favouring growth in demand for single-portion coffee relative to that of bulk coffee. This reflects a new philosophy among consumers and

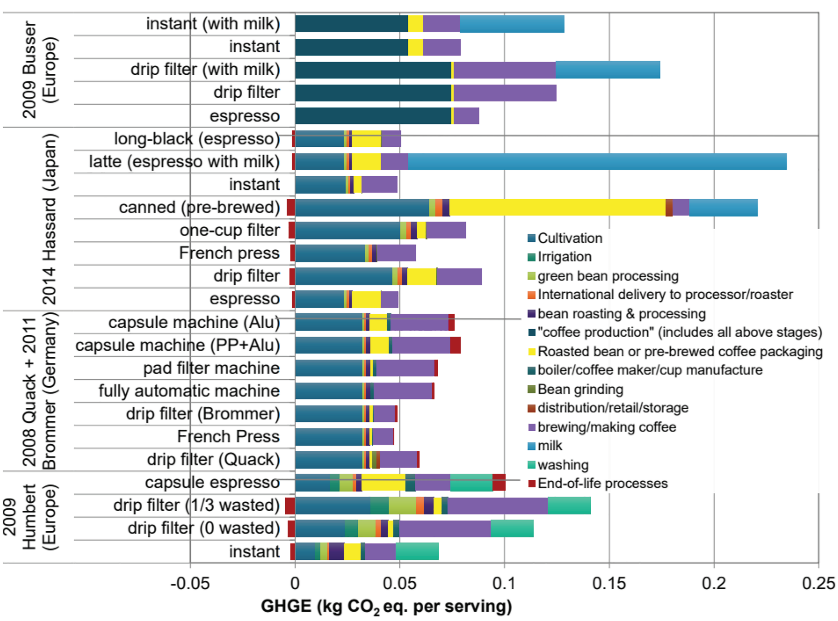

FIGURE 1 Greenhouse gas emissions across the life cycle of coffee[13]

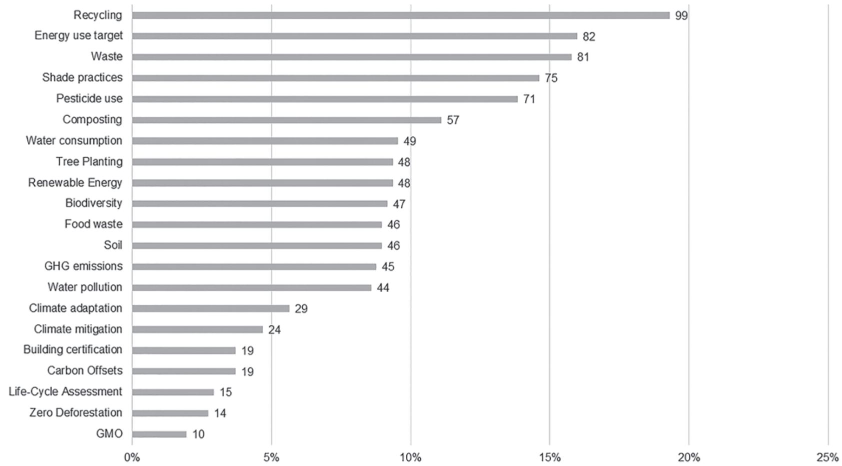

FIGURE 2 Environmental practices of companies operating in the coffee supply chain[1]

in their behaviours, who are increasingly in search of comfort, practicality, optimization and instant gratification. These factors are described in the works of Samoggia and Riedel,[14] which identifies in personal preferences, economic attributes, attributes of the coffee product, consumption context and socio-demographic issues the elements that determine the behaviour of consumers towards coffee. Maciejewski and Mokrysz[15] indicate the recent consumer behaviour trends as strongly influenced by the following aspects: naturalness and sustainability, health and nutrition, multisensory experiences and convenience, digitalization and individualization. Many of these factors are met by single-serving capsules and pods, as reported by Gandia et al.[16]

As reported by Maciejewski and Mokrysz,[15] the US and Western European markets have already been saturated with single-serve coffee, but over the next years, it is likely to spread to Asia and in particular in China and South Korea. The capsule exhibits rapid and growing diffusion, particularly among households.[17] A coffee capsule consists of a truncated cone-shaped shell made of plastic, metal or bioplastic material. To date, this form is the most used for single-portion coffee. The capsule is filled with approximately 5–7 g of ground coffee and then sealed with a protective film (the laminated sheet). The most popular capsules on the market are plastic or aluminium caps. Today, there are also biodegradable capsules made from bioplastic material, but they are still far less commonly used than the traditional ones. Gandia et al[18] demonstrated great resistance to the acquisition and consumption of generic and nonbranded capsules.

The capsules are made from several different materials. This operation should be done by the consumer, allocating each individual material for disposal according to the correct ways: aluminium and plastic in the appropriate collections, as well as coffee residues in the wet. However, dividing the plastic part from the aluminium part and the coffee residues is not a simple operation, which is why, generally, the capsules end up in the undifferentiated collection that are still frequently and in large percentages disposed of in landfills or incinerators. Here, a further potential solution to the problem could intervene, thanks to the use of appropriate waste sorting equipment which, however, is not designed to work with such small objects. Therefore, the available solutions are still far from the market.

Although the end-of-life phase typically has a low environmental impact compared to the other phases of the coffee supply chain, the study of the best solutions to adequately treat scraps and waste from use and the preparation of coffee are important, trying to identify the best practices to ensure prevention in their formation and in their sustainable and circular use. In particular, this aspect appears relevant especially in the case of solutions that are currently not (or still scarcely) recyclable like most of the coffee capsules used in the domestic and commercial sectors, since:

- single-portion coffee and capsules are a growing trend globally;
- the solutions available for their recovery and recycling are limited and, often, present only in local and delimited territorial areas;
- the lack of solutions for their recovery and valorization, determines negative environmental impacts (e.g. Figure 1) during the end-of-life phase of the supply chain which are less significant if the waste deriving from the preparation can be valorized in another way: for example, spent coffee grounds (SCGs) as studied by Atabani et al,[19] Banu et al,[20] Dattatraya Saratale et al[21] and Shin et al.[22]

For our best knowledge, few scientific studies are dedicated to analysing the impact assessment of coffee capsule, despite the growing numbers on their use and the limited solutions for their sustainable management: the European LIFE-PLA4COFFEE project n. ENV/IT/000744[23] quantify the global market at 48 000 000 000 units sold in 2016 (approximately 27% metal and 73% plastic), mainly concentrated in Western European countries and North America (representing approximately 70% of the global market). These quantities of capsules correspond to approximately 576 000 t of global waste (based on the average weight of a capsule of 12 g), currently with low levels of recovery and treatment and consequent recourse to landfill and waste-to-energy disposal.[24] Despite the marked privileges of using single-portion coffee, their proper management and possible recycling at the end of their life are still not easily addressed. In fact, some of the main problems associated with single-portion coffee are related to the recovery and recycling capacity of materials that compose the capsules and to their environmental impact.

Several project initiatives have been launched to address this problem and to develop compostable and more sustainable capsules. To cite a few examples, some major international manufacturers use compostable capsules. Others developed dedicated reverse logistic approach for its capsules which are collected through various recycling points and recycled in a sustainable way. The literature highlights how packaging measures that save food could support the fulfilment the United Nations Sustainable Development goal.[25]

However, there are insufficient solutions for the treatment of this waste on a global scale from its appropriate collection to the treatment and enhancement of materials that can be recovered (plastics, metals and SCGs), capable of supporting waste management even in particular moments.[26] The lack of effective solutions for the end-of-life management of coffee capsules is also found in the scientific literature which appears to be scarce of studies on alternatives for the treatment and recycling of coffee capsules, as well as on the evaluation of their impact environmental. Therefore, the goal of this paper is to describe the approaches and methodologies available in scientific literature for studying the environmental impact of coffee capsules and the recovery and recycling of the materials that compose them. The results can have a double practical value: to encourage the dissemination of available practices and to stimulated the scientific literature in the description of further innovative and effective processes.

2 | RESEARCH METHODOLOGY

From the works described above, the objective of this research was to analyse scientific evidence available in the scientific literature on the coffee sector. Specifically, the research was aimed at identifying articles that analyse the sustainability of single-portion coffee capsules and specifically addressing their postconsumer treatment and recycling.

To facilitate our search for scientific evidence, research protocols, evaluation and selection were applied (Table 2). The search was completed on 24 January 2021 using ScienceDirect and Scopus without restrictions. The keywords used were divided into two distinct groups and then coupled to combine the groupings. The first group focuses

TABLE 2 Research, evaluation and selection protocol

A	Database						
	A1.	ScienceDirect					
	A2.	Scopus					
B	Search criteria						
	B1.	Journal		All			
	B2.	Year		All			
	B3.	Article type		All			
	B4.	Last date of search		24 January 2021			
C	Keywords						
		Group A		Group B	ScienceDirect	Scopus	Total
		Coffee capsules	AND	Recovery	2288	15	2303
				Treatment	4982	37	5019
				Disposal	557	3	560
		Coffee single serve	AND	Recovery	6407	0	6407
				Treatment	14 558	0	14 558
				Disposal	2651	2	2653
		Total			31 443	57	31 500
D	Steps for material selection						
	D1.	Duplicate removal					
	D2.	Keyword and abstract assessment					
	D3.	Application of inclusion criteria					
			D3.1	Single-dose treatment		OR	
			D3.2	Assess the capsules		OR	
			D3.3	Assess the sustainability and the treatment approach			
	D4.	Full text assessment					
E	Other paper sources						
	E1.	Informal approach					
	E2.	Snowball method					

on research on the portioned coffee sector, while the second group focuses on research on sustainability and the recovery and recycling of materials.

With this approach, we examined trends of the research and its numerical results (Figure 3).

3 | RESULTS AND DISCUSSION

In this section, the papers selected are described with the aim of providing a useful basis on which to develop and disseminate new knowledge on this topic. Overall, 24 papers published between 2003 and 2021 were selected.

The results are divided into two subsections: the first dedicated to the description of the available studies that apply the LCA approach to assess the environmental impacts resulting from the different ways of preparing coffee, reporting when the use of the capsules has also been analysed; the second dedicated to identifying studies that intend to study the possible use of capsules according to sustainable and circular approaches.

3.1 | LCA studies

Table 3 reports the main objective of each study, the main assumptions considered and the main results obtained. Table 4 indicates the boundaries and main assumptions of each study. The papers are included in the tables in chronological order. Overall, 15 articles were selected. They have been published by authors from Europe (7), United States (3), Asia (2) and Central and South America (2) between 2009 and 2020.

Humbert et al[10] were the first to address the capsule issue. The authors analysed the environmental impacts of different ways of preparing coffee over the entire life cycle. The study compares solutions using spray dried soluble, drip filter and capsule espresso coffee. Through their quantification of impacts, the authors attribute less energy use and a lesser environmental footprint to spray dried soluble coffee than to capsule espresso or drip filter coffee. Drip filter coffee is found to have the greatest impact on a per cup basis. Brommer et al[6] evaluated the environmental impacts of different methods of coffee preparation, demonstrating the effects of the method chosen for coffee preparation, the user behaviour and the efficiency of the appliance used for coffee preparation.

Tonelli et al[28] compare the environmental impacts of three different coffee capsule systems (compostable, aluminium and polypropylene capsules) using the LCA approach. Polypropylene capsules are found to have the most impact across all of the categories considered, followed respectively by aluminium and biodegradable capsules. Hicks and Halvorsen[30] and Hicks[5] compare a conventional (drip filter) brewing system to a novel (single-serve coffee pod) brewing system using the LCA approach with different budgets applied to different impact categories. These studies highlighted how the capsule system does not have an exceptionally greater environmental impact than the two conventional systems and how energy consumption (and consumer habits) has a strong impact in determining performance. Kooduvalli et al[32] examine the effectiveness of composting compostable coffee pods within a local industrial-scale composting facility applying the LCA approach. Their comparison to conventional plastic coffee pods demonstrates the benefits of compostable coffee pods (reduced composting time and reduced costs of waste disposal). In the study described by de Figueiredo Tavares and Mourad,[31] the LCA approach is applied to compare different ways of preparing coffee: the traditional espresso method, the French Press method, the AeroPress method, filtered coffee systems used in coffee shops, home filtration, and single-serve automatic machines. Among these approaches, methods using capsules made from aluminium and capsules made from aluminium and plastic (both are sold in cardboard cartridges) were analysed. Their results identify the use of single-serve pods with paper sachets as the solution with the least environmental impact. The capsules tested used the most energy and water, second only to espresso coffee, and were found to be the least sustainable from the discarding of non-biodegradable packaging residues and SCGs into landfills. Aluminium and plastic capsules were found to have the worst effects in terms of contributing to global warming, followed by espresso coffee and aluminium capsules.

3.2 | Recovery and recycling approaches

Table 5 reports the identified studies, describing the objective and methodological approach adopted by the authors. Nine articles were selected, published by authors from Brazil (5), Australia (2) and Europe (2) between 2018 and 2020.

Ktori et al[34] investigate the possible use of SCGs separated by exhausted coffee capsules via the pyrolysis approach for the production of fuels and carbon materials used as fertilizer in arid fields. To obtain the quantities of SCGs needed for the process, the authors employ used coffee capsules by separating the organic content from the plastic containers. Abuabara et al[35] define a framework for managing the problem of capsule recovery to support the recycling of

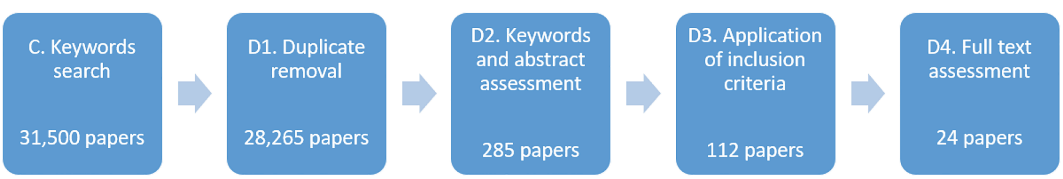

FIGURE 3 Results of the selection approach

TABLE 3 Main aspects characterizing the selected articles

Study	Objective	Functional unit (FU)	Supply chain phases	Software used	Use of the capsules considered	Main results
Salomone[11]	Identification of the 'hot spots' in the coffee production in which environmental improvements were easily achievable	1 kg of packaged coffee delivered to the final consumer	From cultivation to disposal	TEAM 3.0 by Ecobilan	No	Cultivation and transport are the most impacting phases on the life cycle
Humbert et al[10]	Environmental impacts of different ways of preparing coffee over the entire life cycle. The study compares solutions using spray dried soluble, drip filter and capsule espresso coffee	1-dl cup of coffee ready to be drunk, at the consumer's home	From cultivation to disposal	SimaPro 7	Yes	Cultivation and use are the most impacting phases on the life cycle
Brommer et al[6]	Environmental issues along the life cycle of coffee and to compare the different preparation methods of coffee	Preparation of 2000 cups of coffee (125 ml each)	From Manufacturing of the coffee makers to use of the coffee makers	PROSA study	Yes	Use of the coffee makers and production of the filter pads/capsules are the most impacting phases on the life cycle
Schiesser et al[27]	Comparison of impact of seven pods were chosen for comparison	A cup of 40-ml espresso coffee	From cultivation to use	Simapro 7.3.3	No	Cultivation and use are the most impacting phases on the life cycle
Hassard et al[7]	Assessment of product carbon footprint (PCF) and energy usage for six alternative coffee products	One serve of the respective hot coffee product	From cultivation to disposal	n.a.	No	Cultivation, brewing and packaging are the most impacting phases on the life cycle
Arzoumanidis et al[9]	Evaluate simplified LCA assessment tools for food products	1 kg of packaged roasted coffee	From cultivation to disposal	eVerdEE and SimaPro 7.2.4	No	Use is the most impacting phase on the life cycle
Giraldi-Diaz et al[12]	Assess the carbon, energetic and water footprints of supply chain and production of grounding and roasting coffee	1 kg of ground Arabica coffee produced during a crop year	From cultivation to commercialization	SimaPro	No	Cultivation is the most impacting phase on the life cycle
Hicks[5]	Compare a conventional (drip filter) brewing system to a novel (single-serve coffee pod)	0.275 L of coffee	From cultivation to disposal	SimaPro 8.0.1	Yes	Growing and processing the coffee are the most impacting phases on the life cycle
Tonelli et al[28]	Comparison of the environmental impacts of three different coffee capsule packaging systems (compostable, aluminium and polypropylene capsules)	One coffee capsule	From cultivation to disposal	SimaPro 8.3	Yes	Cultivation and packaging are the most impacting phases on the life cycle

TABLE 3 (Continued)

Study	Objective	Functional unit (FU)	Supply chain phases	Software used	Use of the capsules considered	Main results
Diyarma et al[29]	Analyse the direct impact of Gayo coffee production	1000 kg of the product	From cultivation to packaging	n.a.	No	Cultivation is the most impacting phase on the life cycle
Hicks and Halvorsen[30]	Compare a conventional (drip filter) brewing system to a novel (single-serve coffee pod)	Coffee maker lifetime	From cultivation to disposal	SimaPro 8.0.1	Yes	Cultivation and use are the most impacting phases on the life cycle
Phrommarat[8]	Life cycle assessment of ground coffee	A cup of hot, black Arabica coffee (13.5 g of ground coffee brewed in 150 ml of hot water)	From cultivation to disposal	n.a.	No	Cultivation and use are the most impacting phases on the life cycle
de Figueiredo Tavares and Mourad[31]	Evaluation of the environmental efficiency of the beverage preparation stage	Two functional units: 'the dose as prepare' and '50 ml'.	From cultivation to disposal	CML 2001 method	Yes	Cultivation and use are the most impacting phases on the life cycle. Packaging for capsules production
Kooduvalli et al[32]	Tests the degradation rate of capsule samples within the composting environment	Pod packaging that serves an 8 oz. (236.6 ml) serving of coffee	From plastic shell to disposal	SimaPro	Yes	Plastic shell and landfill are the most impacting phases
Usva[33]	Assess the carbon and water footprint of coffee	1 L of consumed coffee	From cultivation to disposal	n.a.	No	Fertilizer production, fertilizer use and packaging are the most impacting phases on the life cycle

TABLE 4 Main boundaries and assumptions

Study	Main assumptions	Study boundaries
Salomone[11]	• Use of a lot of literature data • Average yield of 4.25 quintals/hectare • Commercially available databases have been used for the manufacturing of packaging materials	• System boundaries were defined to include all life cycle steps from coffee cultivation through to its distribution to consumers, consumption and disposal • Production of machinery and equipment are excluded from the system • Data for the international market refer to two different filter coffee machines used by households throughout Europe: an electric aluminium coffee machine with a thermos jug and a coffee maker for use on an ordinary gas stove. The authors assumed that 50% of the coffee delivered onto the international market was prepared with the first kind of machine and 50% with the second • The use of professional coffee machines is not included because they are far more complicated (they generally have other accessories that consume more energy) • Water consumption (for coffee preparation and for cleaning the machine) and sugar are also excluded as they are assumed to be of little importance to the whole life cycle of the product • Transports considered only for some phases of the process • Disposal without any recycling
Humbert et al[10]	• Use of a lot of literature data • Direct air and water emissions were not collected on-site but extrapolated using generic inventory • 1-dl cup need: 2 g of spray dried soluble coffee, or 13.5 g of R&G coffee, or 6.5 g of R&G coffee per capsule • Primary data for green coffee, electricity, natural gas, coffee grounds burned, glass, laminate, paper, cardboard, freshwater, potable water	• The product system covers the full life cycle needed to provide a cup of coffee • Cultivation sites in Brazil, Colombia and Vietnam • Production sites in Europe • European energy mix (electricity and natural gas) • Transport by truck and boat • Different input for use phase (water and coffee needs, machine, heating, and washing) • Glass, paper and cardboard are recycled, and all other materials are incinerated

TABLE 4 (Continued)

Study	Main assumptions	Study boundaries
Brommer et al[6]	• According to the strict principle of life cycle analysis, all material and energy inputs within the system boundaries sketched earlier were inventoried and traced back to natural resources • Coffee machines without power down function are left in idle mode for 12 h per day, for the filter drip coffee maker, 30 min of keep warm function (hot plate) is assumed • Various assumptions were made for the calculation of energy consumption in relation to the type of approach and machine for preparing coffee	• The production of the coffee machine was based on its material composition (no manufacturing data were available) • Use of the coffee machine for the preparation of 2000 cups of coffee in 1 year • Production and disposal of the filter pads and capsules including their packaging • The filter paper and the packaging of the coffee beans/coffee powder • Disposal of coffee grounds and sewage • Cleaning and decalcification of the machines, disposal and/or recycling of the coffee makers, cultivation of coffee as well as the provision of (cold) water, distribution were excluded from the study
Schiesser et al[27]	n.a.	• Pods production has always been realized in France
Hassard et al[7]	• Use of a lot of literature data • Use data from previous studies, in particular for cultivation and fertilizer • Different data about basic serving sizes, water, milk and coffee requirement for each coffee product evaluated	• Conventional inorganic, mono-culture and unshaded coffee farms are considered • Guatemalan and Costa Rican coffee beans in a 1:4 ratio • The cleaning and grade separation, and bagging and container packaging are omitted due to lack of data • Transport by truck and boat • Coffee roasting and use in Japan • Mechanical grinding • Japanese electricity mix for all activities • Energy incurred by this storage was estimated on the basis of 1 day and 1 week of storage per serve prior to consumption • Some of the waste was recycled, others incinerated
Arzoumanidis et al[9]	n.a.	• Coffee cultivation in Brazil • Transportation to Italy • Process in Italy • Distribution in Italy and abroad • Data regarding the agricultural phase in Brazil were retrieved from the literature • Primary data for treatment

(Continues)

TABLE 4 (Continued)

Study	Main assumptions	Study boundaries
Giraldi-Diaz et al[12]	• Use of a lot of literature data • Different data about water, raw materials and power for each phase have been considered	• Capital goods were excluded • The allocation procedures for multiple streams, co-products and products were established by mass and economic causality as per ISO 14044. In the case of energy processes, such as the drying and roasting of coffee beans, allotted flows were based on energy balances from each production stream, including intermediate flows
Hicks[5]	• Use of a lot of literature data • The raw materials data were acquired through disassembly and measurement of coffee pods and the components of the other coffee brewing systems • The yield varies with the method of coffee production utilized • Different data about coffee, filter, water, electricity and yield have been used • Energy consumption was found using a device-specific energy metre	• The system analysed includes the raw materials acquisition, manufacturing, transportation, use and end-of-life stages • Plastic cup used in the production of pod coffee is a proprietary mix of different plastic • The French press makes slightly more; however, with this method of coffee production, it is not possible to make a smaller quantity than the press is designed for and have the product be optimal. The coffee machine used with the single-serve coffee pod has three yield settings; the largest was selected • Coffee grounds, filter, cup, foil, and residual water are disposed of in a municipal landfill
Tonelli et al[28]	• Data of the transport of coffee beans from the producer country to Europe was obtained • The average Switzerland electricity mix is used • Less than 1% of the energy and mass flows of the inputs and outputs was excluded from this analysis	• The phase of domestic preparation of coffee was excluded from the analyses because it is equal for all the three types of coffee capsules, so it is not significant for the comparison • The main differences between the life cycles of the three kinds of analysed capsules concern the packaging materials and their disposal after consumption
Diyarma et al[29]	• Wet processing • Energy requirement in coffee production has been calculated	

TABLE 4 (Continued)

Study	Main assumptions	Study boundaries
Hicks and Halvorsen[30]	• Use of a lot of literature data • The electricity needed to manufacture the conventional coffee brewing machine has been estimated at 27 MJ or 14 MJ/kg of material • The data on the energy consumed by each of the coffee maker technologies were determined utilizing a Kill-a-Watt energy metre (The drip filter was found to consumer 6.04e−4 kW per hour [kWh] of phantom energy, while the pod style coffee maker consumed 2.0e−3 kWh)	• The two brewing systems were disassembled and their materials characterized (e.g. metal, plastic and packaging) • Transportation of the coffee brewing machines is taken into account, with both coffee makers assumed to be manufactured in Southeast Asia, in particular Shenzhen, China. Transportation by sea, rail and road • Recycling has been excluded
Phrommarat[8]	• Use of a lot of literature data • Average coffee cherry yield of 5000 kg/ha • Different data about water, power, resources has been used in different stages of the coffee life cycle	• The considered product system comprised five main phases, namely, coffee cultivation, bean processing, distribution, use and disposal. • Three brewing scenarios have been considered as dependent by consumer's preference • Carbon dioxide emissions from land-use change were negligible • Chemical fertilizers and insecticides were not used • Transport by truck and boat • Thailand energy grid mix has been used • The roasted beans were ground by electric coffee grinding machines at the consumers' homes or offices • Used coffee grounds and packaging were discarded as household waste
de Figueiredo Tavares and Mourad[31]	• Use of a lot of literature data • 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 • Different data (coffee, water, pressure and energy) have been used for each beverage preparation method	• Transport by truck and boat

(Continues)

TABLE 4 (Continued)

Study	Main assumptions	Study boundaries
Kooduvalli et al[32]	• Use of a lot of literature data	• Injection-moulded polypropylene (PP) coffee pods were used • Both circular lids are assumed to be produced by sheet rolling, calendaring, and extrusion • Global market data have been used for modelling most raw materials across both supply chains • Transport of finished products and EOL disposal occurs through trucks and municipal waste collection trucks for municipal waste transport to both landfill and compost facilities
Usva[33]	• Use of a lot of literature data • Different data (water use, coffee beans, filters and electricity) have been used for two types of coffee machines considered	• Theoretical irrigation rates for agricultural products have been estimated • Direct and in-direct N_2O emissions from coffee cultivation were calculated • The coffee roastery uses renewable electricity • The main raw materials for the coffee • package were polyethylene (PE), aluminium and nylon • Transport by truck and boat • Some scenarios with different consumer behaviour at home were calculated. For drip-brewed coffee, scenarios with increasing heating standby time up to 120 min instead of 37 min were calculated. For using a French press, some extra hot water may be used to warm up the French press and 'pot heating' scenarios included this option

TABLE 5 Studies on the recovery and recycling of capsules

Study	Objective	Approach	Main results
Ktori et al[34]	Starting from capsules, the study use SCGs with a circular approach for the production of fuels and carbon materials such as biochar	Laboratory experiment	Conversion of spent coffee grounds into bio-oil (36 wt%) when pyrolysed at 540°C, whereas the corresponding values for biochar and biogas product yields can reach 29 and 9 wt%, respectively
Abuabara et al[35]	The study define a framework for managing the problem of capsule recovery to support the recycling of aluminium and used coffee	Study of the approach also through customer interviews	The ambition for a reverse supply chain in coffee capsule manufacturing presents real challenges to achieving circular practice
de Bomfim et al.[36]	Recovery of plastic materials that compose coffee capsules and the mechanical recycling of this material to use it as a matrix of a bio-composites reinforced with natural fibres	Manual approach and mechanical treatment	Thermogravimetric approach shows no significant thermal stability loss
de Bomfim et al[37]	Exposes plastic waste made from espresso capsules to different types of degradation and identify the influence of exposure on material properties	Laboratory experiment	Capsules showed a good weathering resistance, no thermal changes, no significant visual, thermal and chemical changes
De Souza et al[38]	Effect of coffee capsules on wastewater filtering	Experiment	
Al Mahmood, Hossain, Bhattacharyya, and Sahajwalla[39]	Recycling of polymer-laminated aluminium packaging (PLAP) materials	Three physicochemical approaches	Polymer-laminated thin aluminium packaging waste was transformed into solid Al, graphitic carbon, bio-oil and finally Al microparticles
Domingues et al[40]	Analyse the chemical, physical, thermal, mechanical and morphological characteristics of the recyclable materials obtained from coffee capsules.	Laboratory experiment	The mechanical characterization of the material obtained by mixing the recyclable materials of the disposable capsules showed that the polypropylene filter and the body of the capsule are the most interesting materials to be recycled, and those present good properties
Gokelma et al[24]	Recovery of metals from recycling capsules	Laboratory experiment	The degradation of organics has an important influence on the metal yield. Water vapour seems to have the largest impact on the metal yield. The remelted aluminium had the purity of 99 wt% Al
Al Mahmood, Hossain, Bhattacharyya, Privat, et al[41]	Recycling of polymer laminated aluminium packaging (PLAP) materials	Three physicochemical approaches	Polymer-metal multilayer food packaging materials were recycled by the single-stage smelting process and a combination of thermal disengagement and rapid transformation technique in a controlled environment

aluminium and used coffee. de Bomfim et al,[36] to improve understanding of the performance of the recycling of materials that compose coffee capsules, evaluate their thermal properties through thermogravimetric analysis (TGA) and differential scanning calorimetry. The results obtained from recycled materials are compared to those of virgin polypropylene and the capsules before recycling. The capsule treatment process employed in this study involves manual separation followed by mechanical recycling. In the other study by de Bomfim et al,[36] the authors analyse polypropylene stabilization and degradation initiators due to the exposure of plastic waste obtained from espresso coffee capsules. By modifying the environmental conditions of exposure, the assessments use real applications in a composting environment. De Souza et al[38] use coffee capsule waste to test the capacity to treat sanitary sewage through experiments conducted at a treatment plant of the Federal University of Lavras. The study demonstrates how coffee capsules can serve as support material in anaerobic reactors, providing satisfactory pollutant removal efficiencies. Al Mahmood, Hossain, Bhattacharyya, and Sahajwalla[39] and Al Mahmood, Hossain, Bhattacharyya, Privat, et al[41] describe three different ways to recycle laminated metal packaging into multiple products, with encouraging results. Domingues et al[40] analyse the chemical, physical, thermal, mechanical and morphological characteristics of the recyclable materials obtained from coffee capsules. The coffee capsule and inner filter were identified as the most fruitful products for reuse due to their unique properties. Gokelma et al[24] describe an approach to recycling capsules that involves remelting under a salt flux. The study employed used capsules filled with residual moist coffee granules and unused capsules with and without dry coffee inside as a reference. The analysis evaluates metal yields and coalescence efficiency levels, demonstrating an ability to recover aluminium with a purity level of 99%.

Table 6 describes which are the approaches applied by the analysed papers for the sample collection phases, which are the materials that have been recycled and which have been sent to landfill. The use of materials for energy recovery (through their combustion) is also described. It is clear that the collection phase does not yet have a consolidated approach. Only Tonelli et al[28] provide for the involvement of producers through the collection of capsules. In the other studies, only timely and purposeful collections were conducted. SCG, plastic and metals are the materials that are most recycled. All the selected studies foresee the recovery of some material. All materials that have not been recycled are disposed in a landfill. Few examples describe incineration with the possible recovery of energy.

TABLE 6 Approaches to study the capsule collection and treatment phases

Study	Collection	Recycling	Energy recovery	Disposal
Humbert et al[10]		Glass, paper and cardboard are recycled	Other materials are incinerated	
Brommer et al[6]			Some materials are recycled	Some materials are sent to incinerators and landfills
Hicks[5]		SCGs		Materials are disposed of in a municipal landfill
Tonelli et al[28]	Collection by producer	Aluminium, plastic and SCGs	Biogas instead of compost from the organic waste collected after consumption	
Abuabara et al[35]		Aluminium and SCGs		
de Bomfim et al[36]		Separate the PP		
de Bomfim et al[37]	Collected at local university	Separate the PP		
De Souza et al[38]		Capsules used as filter material		
Hicks and Halvorsen[30]		SCGs		Materials are disposed of in a municipal landfill
Al Mahmood et al[39]	Collected from community cafes	Physical degradation process of the metal capsules to generate microparticles		
de Figueiredo Tavares and Mourad[31]		Recovering rate of 20% of the mass of post-consumption capsules		Landfill
Domingues et al[40]		Evaluation of the separation process		
Gokelma et al[24]		Aluminium		
Kooduvalli et al[32]		Composting for compostable capsules		Landfill for traditional capsules
Al Mahmood, Hossain, Bhattacharyya, Privat, et al[41]	Collected from community cafes	Physical degradation process of the metal capsules to generate microparticles		

Abbreviations: SCGs, spent coffee grounds; PP, polypropylene.

Table 7 reports some main key messages related to the processes and results described by some of the analysed authors. These aspects are very important as they provide useful information on the effectiveness of the studies and contribute to the dissemination of this evidence.

In addition to these works, further technical studies are available. In particular, we report two studies prepared by Quantis commissioned by Nespresso and the PAC Packaging consortium. The first study by Quantis[42] describes the results of a comparative life cycle

TABLE 7 Key messages from some of the papers analysed

Study	Key messages
Humbert et al[10]	• Their results attribute approximately 50% of the environmental footprint to the phases under the control of the coffee producer or of its suppliers and the other 50% to stages controlled by the user. • Drip filter coffee is found to have the greatest impact on a per cup basis. • Packaging contributes 10% of the overall life cycle impacts. • The use phase represents between half and 75% of the total energy demand • Overall, spray dried soluble coffee uses less energy and has a lower environmental footprint than drip filter coffee or capsule espresso coffee • LCA is a technique that can help the food industry minimize the environmental burdens directly related to their products
Hicks[5]	• The study found that the capsule system did not have an exceptionally greater environmental impact than the other conventional systems • The consumption of electricity in standby (leaving the coffee machine in ready to brew mode) can determine a significant increase in the environmental impact, suggesting the significant importance of consumer habits
Ktori et al[34]	• Spent coffee grounds pyrolysis could be the solution to valorize wastes • Need for an automatic approach to coffee separation
Tonelli et al[28]	• Polypropylene capsules are found to have the most impact across all of the categories considered, followed respectively by aluminium and biodegradable capsules. • Aluminium capsule is the best food packaging material in terms of oxygen barrier properties compared to the thickness of packaging • Aluminium capsule cannot be recycled if it is not separated from the coffee • The Aluminium production è molto energivora • The PP capsule is the most impactful one for all the categories considered, due to the packaging system
Abuabara et al[35]	• Diverse policies and strategies for resource recovery from used coffee capsules are needed to achieve some key results: behavioural change, expansion of urban collecting points, incentive program, communicate and commit to customers
de Bomfim et al[36]	• Coffee capsules plastic waste can be mechanical recycled to biocomposites application • There is not significant thermal stability loss, difference melting and crystallization temperatures comparing with virgin PP
de Bomfim et al[36]	• PP capsules showed good resistance to atmospheric agents
De Souza et al[38]	• It is possible to use coffee capsules in anaerobic reactors for the removal of waste pollutants • This system allows to reach organic matter removal efficiencies higher than 80% • Coffee capsules have similar characteristics to commercial and research materials
Hicks and Halvorsen[30]	• The drip filter coffee had the greatest environmental impact of all of them
Al Mahmood, Hossain, Bhattacharyya, and Sahajwalla[39]	• It is possible to manufacture microparticles from packaging materials • It is possible to synthesize bio-oil from polymer laminates
de Figueiredo Tavares and Mourad[31]	• Agricultural cultivation, packaging production and beverage preparation are stages of high environmental impact • The combination of high coffee concentration with high packaging ratio by volume of beverage causes a high environmental impact
Domingues et al[40]	• PP filter and the capsule body are the most interesting materials to recycle, and those with good properties • A process is required that reduces time and manpower for separating the aluminium and the lid from the rest of the parts of the capsule
Gokelma et al[24]	• Different coloured capsules have different metal yields during remelting • The behaviour of the coatings play a role in oxidation during remelting • Presence of coffee that dropped the yield drastically (tends to zero with full coffee residue) • Water vapour seems to have the largest impact on the metal yield
Kooduvalli et al[32]	• Need to evaluate different impacts to get an accurate assessment • From the combination of lower impacts related to composting and lower costs in terms of net purchase and disposal showing cost savings of up to 21%.

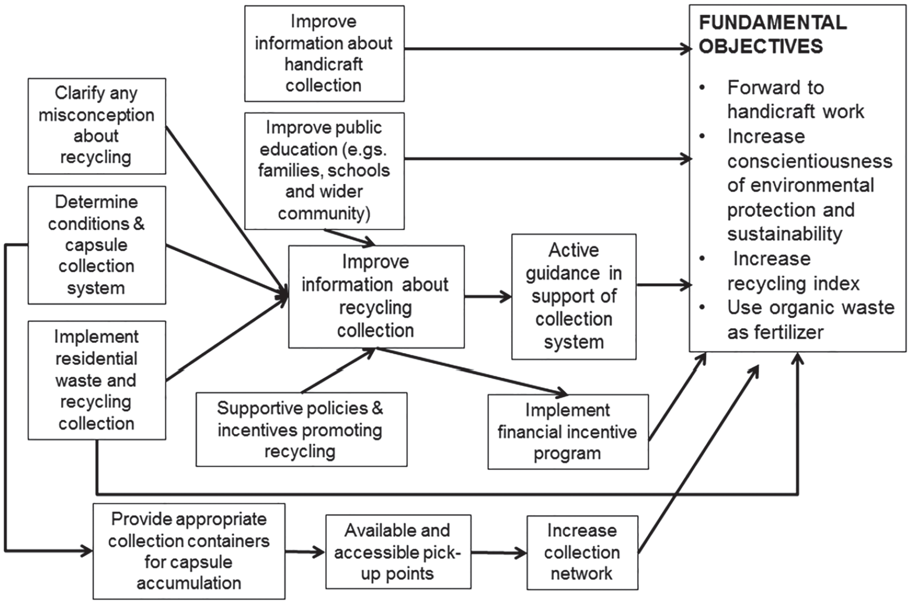

FIGURE 4 Some enablers of the development of sustainability in the treatment of the capsule[35]

assessment of a 40-ml cup of espresso based on a packaging and distribution system employed by Nespresso Espresso and three generic products. The results find the Nespresso Espresso product to have the least overall environmental impact when capsules are sent for recycling than the other alternatives studied. The second study[43] compares single-serve to bulk coffee brewing through a formal ISO 14040-44-compliant LCA study. The results find the single-serve best case scenario to exhibit better environmental performance than the drip brew system in terms of the systems' full life cycles.

Since these studies were funded by stakeholders directly affected by the coffee market, these results have not always been met with scientific approval.

Finally, some possible future developments are reported as elements to encourage the development and dissemination of studies dedicated to the correct treatment of capsules as waste:

- Improve end-of-life analysis of the products that make up the capsules, some of which have shown interesting potential as secondary raw materials.
- Study the possibility of adopting materials and management procedures that may have a lower environmental impact (e.g. substituting plastic materials with bio-polymer and by producing biogas instead of compost from the organic waste collected).
- Explore the potential of unconventional management practices (e.g. cryo-milling).
- Adequate separation of the capsules by users and effective segregation and collection by the authorities responsible for waste management is necessary.
- Encourage consumer awareness and participation.
- Investigate policies with incentives.

In particular, the study by Abuabara et al[35] shows a schematic representation that well expresses some of the enabling processes towards sustainable practices for the management of coffee capsules, as shown in Figure 4.

4 | CONCLUSIONS

It is evident from the research conducted that, despite progressive increase in quantities of single-serve coffee capsules that characterizes the current market, studies published on this issue are limited and heterogeneous. Good practices and commitments from international manufacturers are constantly improving, as is the growing launch of biocompatible and compostable solutions.

This research made it possible to identify some papers available in the literature that analyse the aspects of the management and environmental impact of coffee capsules, isolating some interesting elements. It has been shown that capsules are not always the choice that has the greatest environmental impact, highlighting how energy aspects and consumer habits can significantly change performance. Useful processes have emerged for the recovery and treatment of the plastics and metals present inside the capsules, as well as their use as filter material.

In general, the aspect shared by all the authors is the need to find a solution capable of separating each component that forms the capsule, relieving the consumer of this task that he is not willing to do.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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