Sustainability assessment of different types of coffee capsules

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This study was carried out by Wageningen Food & Biobased Research, subsidised by TKI BBE and funded by Advanced Technology Innovations, De Koffiejongens, Natureworks, Novamont, TotalEnergies Corbion and the Dutch Ministry of Infrastructure and Water.

Wageningen Food & Biobased Research
Wageningen, November 2023

Public

Report 2450
DOI: 10.18174/641509

WAGENINGEN
UNIVERSITY & RESEARCH

WFBR Project number: 6229117301
Version: Final
Reviewer: M. van der Zee
Approved by: J. Jetten
Carried out by: Wageningen Food & Biobased Research
Subsidised by: TKI BBE
Funded by: Advanced Technology Innovations, De Koffiejongens, Natureworks, Novamont, TotalEnergies Corbion and the Dutch Ministry of Infrastructure and Water
This report is: Public

The research that is documented in this report was conducted in an objective way by researchers who act impartial with respect to the client(s) and sponsor(s). This report can be downloaded for free at https://doi.org/10.18174/641509 or at www.wur.eu/wfbr (under publications).

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Executive summary

Aim and background of the study
The aim of this study is to compare different types of coffee capsules in terms of sustainability. The market for single-serve coffee products has expanded largely in last decades. One of the most successful products is the Nespresso-style coffee capsule. The use of these capsules in a dedicated coffee brewing machine provides a high level of convenience for consumers, enabling them to prepare a relatively high quality coffee product in a short period of time, with minimal water and energy use. Nowadays, multiple coffee companies offer various coffee products in the Nespresso format capsule, using not only aluminium as main material, but also polypropylene (PP), high-density polyethylene (HDPE), polylactic acid (PLA), polyhydroxyalkanoate (PHA) and poly(butylene adipate-co-terephthalate) (PBAT) based compostable compounds. The main research question in this study is: "What are the environmental impacts and sustainability profiles of the different types of coffee capsules when they are subjected to various end-of-life scenarios?". Reusable and refillable capsules are excluded from the scope, as these systems are not applied on large scale.

This report has been written by WFBR in the context of the project "Increase circularity by the use of biobased and/or industrially compostable materials" financed by TKI BBE (Topconsortium for Knowledge- and Innovation Biobased Economy). This Public-Private Cooperation project was further financed by the following industrial partners: ATI, De Koffiejongens, NatureWorks, Novamont and TotalEnergies Corbion. Also the Ministry of Infrastructure and Water funded part of the project.

Method: sustainability tool and working in scenarios
The sustainability analysis tool (MuDiSa[1] [22]) used in the project was developed within WUR to assess the environmental impact of packaged food products in multiple dimensions of sustainability, including circularity. Sustainability assessments are inherently complex, requiring methodological choices that inevitably will influence the results. A sensitivity analysis was executed to probe these leverages. Furthermore, with this tool we cover a broader scope in comparison to other LCA-based tools, resulting in a more balanced perspective. The system was fed with detailed data on the composition of the different types of coffee capsules, production process of the capsules and a lot of background data (i.e. emission factors of various materials and end-of-life routes). MuDiSa delivered the base results, which were analysed in the wider context of existing policies and the fit within the current waste management systems.

Sustainability and circularity are complex terms that can be assessed in different dimensions. Based on the collected data, the tool calculates and evaluates the contribution of the life cycle stages of coffee and packaging to a global warming potential over a period of 100 years (GWP-100) in terms of carbon dioxide equivalents. The global warming potential is often also referred to as the CO_2-impact, or as the greenhouse gas emissions. Among the environmental impact categories, global warming potential is considered as the most reliable and most relevant to assess food packaging systems. Among all calculated sustainability and circularity indicators, the material circularity indicator (MCI) [1] is considered a fairly complete indicator for material circularity. In the calculation of this MCI multiple factors contribute, including: recycling rates, recycled content, recycling process yield, biobased content, reusability and the average lifespan of a product. The combination of greenhouse gas emissions (GWP-100) and MCI provides a first high-level indication of the sustainability of a product-packaging combination.

The sustainability of many types of coffee capsules was assessed in relation to their specific end-of-life scenarios. Three main categories of coffee capsule materials were compared: compostable plastic capsules (PLA, PHA), conventional plastic capsules (PP, HDPE) and aluminium capsules (both with and without recycled content).

[1] Multi-dimensional sustainability assessment

The following what-if end-of-life scenarios were considered:

- All used capsules end up in Industrial composting – only for compostable capsules
- All used capsules end up in Recycling via light weight packaging waste (LWP) collection – for all capsules
- All used capsules end up in Incineration – for all capsules
- All used capsules end up in Landfill with energy recovery – for all capsules
- All used capsules end up in Mono-collection - only for aluminium capsules. Mono-collection is a voluntary collection system of consumed coffee capsules to recycle aluminium and to compost the coffee.

Results and discussion

Both the MCI and the contribution to greenhouse gas emissions were calculated for each of these capsule types in different potential end-of-life scenarios. It is important to note that the calculations have been done, based on theoretical what-if scenarios, assuming 100% of the capsules end up in a particular end-of-life route. This is done to compare the different routes from an ideal perspective. In reality capsules will also end up in other (non-targeted) end-of-life systems, but that is a different type of study.

To summarize the circularity potential of the different capsule materials, the MCI of the capsule is combined with the capsule-related greenhouse gas emissions (hence excluding the packed coffee) for the three main categories of capsule materials: compostable plastics, conventional plastics and aluminium. Please note that the X-axis is reverted, so the minimum emissions are on the right hand side of the graph. This way, the most circular/sustainable solution in terms of both MCI and greenhouse gas emissions will be on the top right corner of Figure 1.

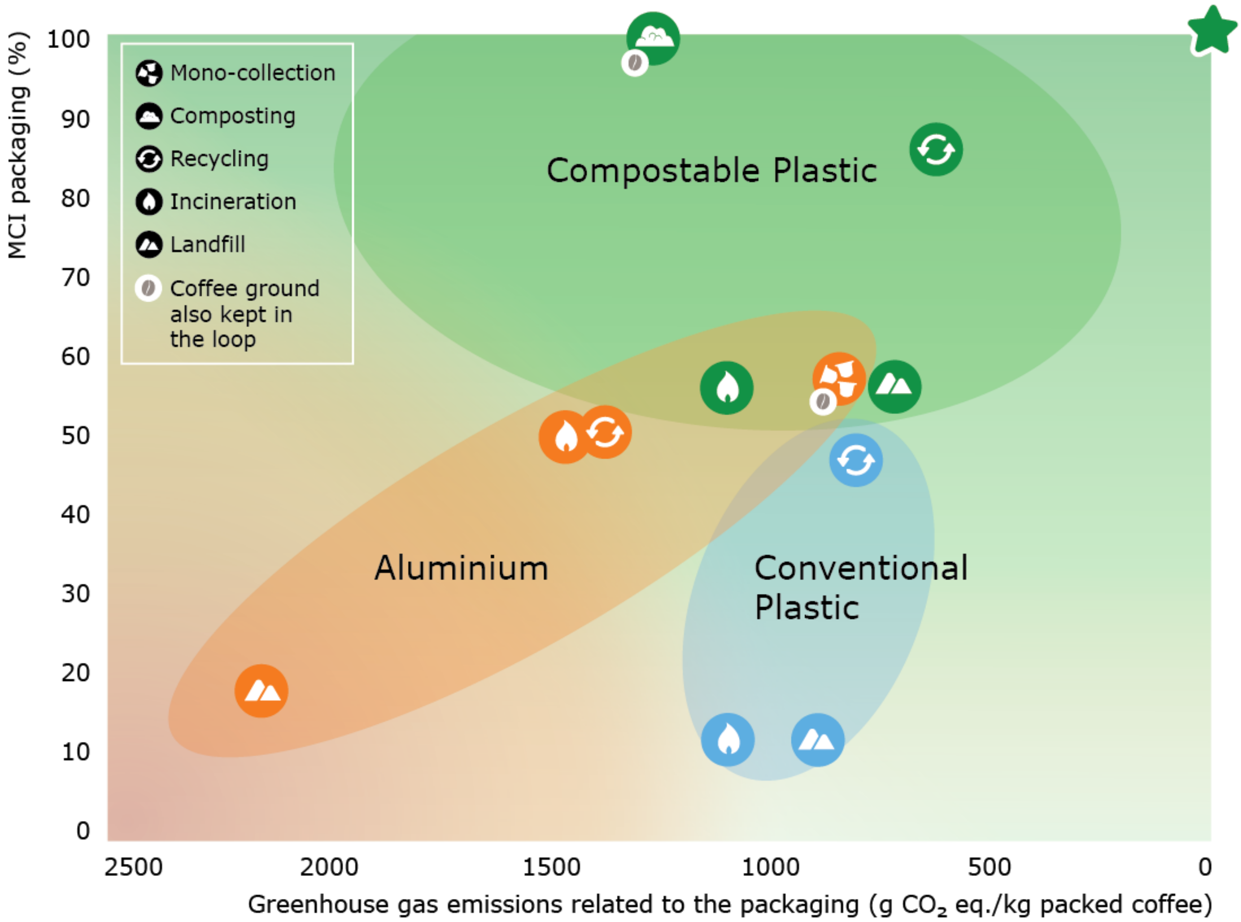

Figure 1: Combined overview of the MCI of the capsule [%] on the Y-axis and the greenhouse gas emissions related to the capsule [g CO_2 eqv./kg packed coffee] on the X-axis for different capsule materials and end-of-life options. Note that the X-axis is reverted, so minimum emissions are on the right hand side of the graph. Capsules included in this graph: PLA1, PLA2, PHA1, PP, PE, Al1, Al2.

Three different colours are used for the materials; green for the compostable capsules, blue for conventional plastic capsules and orange for aluminium based capsules. The 'clouds' represent the individual data points for the same scenario with different capsules of the same category. The capsule material category with potentially the lowest greenhouse gas emissions and highest MCI (100%) is the compostable material in case it is composted or recycled. A second best material for capsules is aluminium (made with recycled content) in case it is recycled via mono-collection. Conventional plastics are, based on MCI, the least circular and, based on greenhouse gas emissions, have mediocre carbon footprints. The production and end-of-life of the coffee grounds is excluded from this graph but the related greenhouse gas emissions will be discussed later in the report.
A large cloud means that there is a large bandwidth of the results. As example, the blue cloud for conventional plastics is small, because the results of the studied PP and HDPE capsules are very similar. The orange cloud related to the aluminium capsules is much bigger, as there is substantial variation in the MCI scores for aluminium capsules with 0% and with 40% recycled content. The detailed numbers and background of the data, which are the basis for this figure, can be found in chapter 4 of this report.

Although greenhouse gas emissions and MCI give a good quantitative picture, also other, more qualitative factors need to be considered. Table 1 shows per material the issues in the (current) waste management system, and what happens to both the capsules and the spent coffee grounds.

Table 1: The issues various capsule types encounter in the various after-use management systems and whether they support the recycling of the capsule material and of the contained coffee material. Color legend. Red: no recycling, material is lost. Orange: possible after adjustments. Green: material can be kept in the loop, either via recycling or composting.

Capsule type	**After-use management**	**Issues with the current waste management options***	**Capsule material recycling**	**Coffee grounds recycling**
Aluminium	Mono-collection	Low participation	Open loop recycling that depends on non-capsule feedstock	Composted, kept in loop via the biosphere
	Recycling (via LWP)	Some sorting facilities need adjustments	After adjustments, open loop recycling	No recycling, incinerated or pyrolysed
	Incineration (via MSW)	None, but doesn't support circularity	Partial aluminium recovery from bottom ashes, open loop recycling	No recycling, full incineration
	Landfill	None, but doesn't support circularity	No recycling	Organic material is lost
Conventional Plastic	Recycling (via LWP)	Some sorting facilities need adjustments	Partial plastic recycling possible after adjustments	No recycling, waste water treatment/ incineration
	Incineration (via MSW)	None, but doesn't support circularity	No recycling, full incineration	No recycling, full incineration
	Landfill	None, but doesn't support circularity	No recycling	Organic material is lost
Compostable Plastic	Organic waste	Currently not accepted by most organic waste processors	Composted, kept in loop via the biosphere	Composted, kept in loop via the biosphere
	Recycling (via LWP)	Some sorting facilities need adjustments	Currently not feasible, but closed loop recycling possible in the future after adjustments	No recycling, wastewater treatment/incineration
	Incineration (via MSW)	None, but doesn't support circularity	No recycling, full incineration	No recycling, full incineration
	Landfill	None, but doesn't support circularity	No recycling	Organic material is lost

* The term waste management options encompasses collection, sorting and recycling and waste processing technologies.

Currently only mono-collection of aluminium capsules and composting of biobased plastics via the organic waste provide circular solutions in which both the capsule materials and the spent coffee grounds are recycled and kept in their material loops. This is further elaborated per capsule material category:

Conventional plastics
Although the plastic coffee capsules generate relatively low greenhouse gas emissions, they do not fit in a circular economy as neither the plastic capsules nor the spent coffee grounds are recycled. The MCI is below 50%.

Aluminium
Mono-collection is a voluntary collection system of used coffee capsules. When capsules are collected, the coffee grounds can be anaerobic digested and composted and the aluminium can be recycled. Part of this material can be used to create new coffee capsules, however even in future, capsules cannot be made of 100% recycled content because untargeted trace elements will accumulate in the aluminium and make it less pliable in time. As aluminium is not a biobased material, the MCI will never reach 100%. The MCI reaches maximally 61% for capsules with 40% percent recycled content when they are mono-collected after use.
A main challenge is that the collection system also needs to become much more effective. Currently the participation rate in the Netherlands is unknown; a consumer survey gives a number around 29% [2], in reality this might be even lower. The required high participation rates for the voluntary mono-collection system are currently by far not attained and it will be very challenging to increase these numbers. This is the largest hurdle for this coffee capsule system to accomplish a high level of circularity.

Compostable plastics
The impact on global warming of the compostable capsules is quite low (especially when they are recycled) and their MCI is 100% (fully circular), in case all capsules are composted. Materials are biobased and biodegradable. Hence both coffee grounds and capsule material can be kept in the loop via the biosphere. Compostable options are also robust in case of misthrows: if compostable capsules end up in the municipal solid waste or the lightweight packaging bin, they will be incinerated.
Currently the majority of the Dutch organic waste management industry, however, does not accept compostable coffee capsules in the separately collected municipal organic waste. If this lock-in is resolved, this option provides the most circular solution for both the capsule material and the spent coffee grounds. There are two options to resolve this lock-in: 1) to come to a mutual agreement between the organic waste management sector and the coffee industry under which conditions these capsules can be allowed in the organic waste, similar to what was agreed for tea bags [43] or 2) to set-up a mono-collection system for compostable coffee capsules and to process them separately. For consumers it must be clear where to discard their used capsules, to avoid confusion. As tea bags and coffee pads can already be discarded with the organic waste, option 1 is preferred. The collection system is already in place for this and no changes to the waste treatment facilities are needed.

1 Introduction

The market for single-serve coffee products has expanded largely in last decades. One of the more successful products are the Nespresso-style coffee capsules. Originally these were marketed only by Nespresso using aluminium as main material for the capsules. The use of these capsules in a bespoke brewing machine provides a high level of convenience for the consumers, enabling them to prepare a relatively high quality coffee product in a short period of time, with minimal water and energy use. Nowadays, multiple coffee companies offer various coffee products in the Nespresso format capsule, using not only aluminium as main material (with or without recycled content), but also polypropylene (PP), high-density polyethylene (HDPE), polylactic acid (PLA), polyhydroxyalkanoate (PHA) and poly(butylene adipate-co-terephthalate) (PBAT) based compostable compounds. An overview of compostable capsules currently on the global market is provided in Annex 1.

Semantics
In the English language various terms are used for the capsules displayed in Figure 2. In US and UK the term "coffee pod" is used, whereas in continental Europe people refer to "coffee capsules". Coffee capsules are oval or taller containers, made of either plastic or aluminium with a foil top which is vacuum sealed to keep them fresh and can be customized for different companies[2]. In this study, we focus on the coffee capsules used by the Nespresso platform, because this platform is the most widely used and all studied capsules can be used in this Nespresso platform. Hence in this report the term "coffee capsule" is used to refer to these Nespresso-style format coffee capsules. In Figure 2 a photo is shown of such coffee capsules present on the Dutch market.

Figure 2: Photo of some Nespresso-format coffee capsules present on the Dutch market in 2023. From left to right: Alu-sense/Blokker (aluminium), De Koffiejongens (PHA), Nespresso (aluminium), Lidl (HDPE) and Bio-caps/Segafredo (PLA blends).

Imperative
With the market success of these capsules also came a waste management challenge. The exact market size for these single-serve Nespresso style capsules is unknown, but if we crudely estimate then roughly 1.5 billion capsules are discarded in the Netherlands annually and roughly 53 billion annually in the EU [48]. With an average wet weight of 12 grams per used capsule, this corresponds to a waste volume of 18 kton/a for the Netherlands. Consumers discard used capsules as whole objects, whereas the capsules and the spent coffee grounds would ideally be treated with separate waste management processes. The spent coffee ground is preferably organically recycled (anaerobically digested and/or composted) to minimise greenhouse gas emissions and to keep the organic materials including the nutrients in the biosphere. The aluminium is preferably recycled into a secondary aluminium and the plastics of the capsules would ideally be recycled into secondary materials. This is, however, difficult to accomplish in reality. In reality, the capsules are distributed over all the waste collection systems, as is apparent from waste analysis of the mixed municipal solid waste, organic waste and lightweight packaging waste. The precise distribution of the coffee capsules is unknown for the various types of capsules. The Dutch Coffee and Tea producers federation (Koffie en Thee Nederland) did, however, commission consumer research at Kantar to investigate the discarding behaviour of

[2] Coffee pods and coffee capsules - the difference | NovoCapsule

Dutch consumers with respect to the Nespresso-style coffee capsules [2]. Although this study doesn't discriminate between the various materials these capsules are made off, the overall data does show that the capsules are distributed over all waste bins; according to a consumer survey 29% is mono-collected, 44% is discarded in the mixed municipal solid waste, 4% is thrown in the organic waste and 21% is discarded with lightweight packaging waste. This non-ideal discarding behaviour not only results in a loss of recyclable materials (aluminium, plastics and organic matter) but also creates cross contamination of recyclable materials (aluminium and plastic in organic waste, coffee in non-ferrous metals, coffee in lightweight packaging waste (LWP), etc.). This situation is far from ideal and this has been recognised previously by multiple researchers and politicians as a waste problem that needs to be addressed [3], [4].
The discussion on coffee capsules got a new impulse In November 2022, when the European Commission released its proposal for a Packaging and Packaging Waste Regulation [5]. In this initial proposal it was mentioned that all "coffee or tea system single service units" should be compostable in industrially controlled conditions in bio-waste treatment facilities (article 3 and 8). The European Coffee Federation (association of coffee producers) responded that this proposal undermines the initiatives of the coffee industry to set up recycling schemes for all coffee pods [6].

Research questions
This study attempts to answer the following research questions:

- What is the environmental impact and sustainability profile of the different coffee capsules when they are subjected to various waste management treatments?
- Can compostable materials relieve the environmental impacts of these coffee capsules?

Scope
The study focusses on the Dutch situation and hence restricts itself to the waste management options and capsules that are available in the Netherlands in 2023. Therefore the end-of-life options studied are the mechanical recycling, the incineration and the industrial composting applying transfer coefficients based on the Dutch waste facilities. But since this study is also relevant for other European countries also the landfill end-of-life scenario is included, although this is not relevant for the Dutch situation.
This report focusses on giving the best technical description of the environmental impacts of coffee capsules when discarded in various waste bins. Also some other non-technical, qualitative aspects will be described in the discussion. This report does not intend to map opinions of stakeholders or to comprehend their motivations. Nevertheless, during the execution of this project we did speak to various representatives of Dutch coffee companies to gather technical data on Dutch coffee capsules.
This report focusses only on capsules as a coffee brewing method and hence excludes all other coffee brewing methods. The coffee brewing itself is excluded from the scope of this study as well.

Project information
This report has been written in the context of the project "Increase circularity by the use of biobased and/or industrially compostable materials" financed by TKI BBE (Topconsortium for Knowledge- and Innovation Biobased Economy). The aim of this project is to explore to what extent biobased and/or industrially compostable materials can contribute to a more circular economy by providing an alternative solution for products that currently cause issues in the waste management system. This Public-Private Cooperation project was further financed by the following industrial partners: ATI, De Koffiejongens, NatureWorks, Novamont and TotalEnergies Corbion. Also the Ministry of Infrastructure and Water funded part of the project.

Report
This report has been written by a group of researchers at Wageningen Food & Biobased Research. The report has been subjected to the same scientific rigour as all Wageningen reports and hence underwent an internal review.

2 Literature review

Methodology
Scientific literature on the topic of coffee pods and capsules was searched using several search engines and a combination of search terms. As the term "coffee pod" also refers to the biological husk in which the coffee bean grows, most literature found could be ignored. Also the term "coffee cups" has to be avoided as this refers to disposable beverage beakers. Only studies that relate to convenience single-serve coffee brewing concepts were included. The search engines used were: Web of Science, Scopus and Google scholar. Search terms used were "coffee pod", "coffee pod" AND "LCA", "coffee" AND "environmental impacts", "coffee capsules", "coffee capsules" AND "environmental assessment". After weeding out irrelevant papers a limited number of papers were found, see Table 2.

Table 2: Overview of the articles found on coffee capsules and prime categorisation.

Category	Number of articles found
Comparative LCA studies on different coffee brewing methods	5
Comparative LCA studies on different types of coffee capsules	3
Migration studies on coffee pods & capsules	4
Consumer behaviour and acceptance	2
Recycling of coffee pods / capsules	3

One review article has recently been written by Marinello et al., both on the environmental impacts of different coffee brewing methods and on coffee capsules [7]. They correctly conclude that the literature is very heterogeneous, both in relation to the type of capsules studied and the type of waste management options considered. The only over-arching conclusion that the authors could draw is that there is a need to find waste management solutions that separate the components of the capsules and process these components separately [7].

Comparative LCA studies on different coffee brewing methods
In past 12 years, five life cycle assessment (LCA) studies have been published that compare the environmental impacts of different coffee brewing methods. The outcomes vary per country and time period, as a result of a different local/actual situation regarding for example the brewing methods and the prevailing waste disposal system. Furthermore, also various aspects of consumer behaviour were found to influence the final result, such as the applied amount of coffee to water, the coffee wastage rate and leaving the coffee machine switched on in stand-by modus.

In 2011, Eva Brommer et al. compared the environmental impacts of five different coffee brewing methods with different preparation machines that are popular in Northern Europe, namely: conventional filter drip machines, filter pads machines, capsule machines, French press devices and fully automated machines that process whole roasted beans [8]. Although coffee cultivation has the largest environmental impacts (55% share of the overall emissions), the coffee preparation method also has a substantial impact (33%) which is mostly affected by the power consumption of the preparation device at home. Filter drip and espresso machines were found to have the lowest power consumption at home (and hence the lowest emissions), whereas fully automated brewing machines and capsule machines were found to have the highest power consumption, as consumers often leave these machines on in stand-by and sleep modes. Furthermore, the capsule machines contribute to the environmental impacts due to the use of aluminium and plastic materials and the automatic coffee machines contribute additionally due to the automatic cleaning and rinsing programmes. The system boundaries were coffee cultivation to consumption and the disputable assumption was made that all coffee was drunk, whereas it is common sense that a substantial fraction of the filter drip coffee is wasted [8].

In 2018, Andrea Hicks re-examined the environmental impacts of similar coffee brewing methods, but did take coffee wastage into account in her study. This gave opposing results; now the drip filter system was found to have the highest environmental impacts, whereas the pod style systems were found to have the lowest impacts in six impact categories. This is an American study with system boundaries from coffee cultivation to landfill as waste management option [9]. In 2019, she reanalysed her own study and took "human behaviour" also in consideration, with which she implies the additional power consumption by keeping coffee machines in stand-by modus and the phantom power consumption when equipment is plugged in but not in active use. Coffee pod preparation was still found to result in the lowest environmental impacts when only the phantom energy use was considered, but when stand-by power usage was also considered, the drip filter preparation method was found to create less impacts. Hence, the human factor determines which brewing system is best [10].

In 2020, Maria de Figueiredo Tavares and Mourad studied the behaviour of Brazilian households when preparing coffee and measured coffee, water, electricity usage and waste production. They used this data in a LCA study with coffee cultivation and landfill as system boundaries and found that paper-based pads gave the least environmental impacts [11].

In 2021, Matteo Cibelli et al. published an Italian study on the environmental impacts of different coffee brewing methods under Italian conditions. The system boundaries were coffee cultivation to landfill or incineration. Moka-Pot brewing was compared with espresso brewing, brewing in capsules and with pod machines. The Italian traditional Moka-Pot brewing method resulted in the least environmental impacts, especially when this pot was heated with an induction plate. The environmental impacts of espresso preparation, capsule and pod preparation were much higher and the latter two also contributed to more material usage and waste production [12].

Comparative LCA-studies on different type of coffee pods & capsules
Three studies have hitherto been published that compare coffee pods & capsules made from different materials. Again these studies relate to different countries (Italy, Canada and the USA) with different types of coffee pods on the market and different waste management options, which all influence the final result. Since, the coffee pods on these markets are offered in different secondary packages, varying from simple cardboard boxes to PET trays to multi-layered flexible packages, also the secondary packaging was found to be an important factor to influence the overall environmental impacts of the coffee pod systems.

In 2018, Annachiara Tonelli et al. published a conference paper in which three different coffee capsules were compared that were offered on the Italian market; biodegradable coffee pods, aluminium coffee pods and PP-based coffee pods [13] .The biodegradable coffee pods were made from PLA and sold in modified atmosphere packaged rigid PET trays with a barrier coating. After use, the biodegradable coffee pods were assumed to be discarded in the organic waste bin and composted. Whereas the secondary PET tray was assumed to be discarded with the lightweight packaging waste and recycled. This is a bold assumption, since as far as we can recollect, PET trays were even in 2022 not recycled in Italy. The aluminium-based coffee pods were nitrogen-gas-flushed prior to closing and sold in cardboard boxes. After use, only 7% of the aluminium cups were separately collected in Italy for recycling, the rest was assumed to be landfilled with mixed municipal solid waste. The cardboard boxes were assumed to be separately collected with paper & board waste and recycled. The PP-based coffee pods have aluminium foil lids and are sold in BOPP/Aluminium based multi-layered flexible pouches that were gas flushed (40% nitrogen and 60% carbon dioxide) prior to sealing. After use both the coffee pods and the multi-layered film are assumed to be landfilled with mixed municipal solid waste. Based on these assumptions, the LCA showed that the PP-based coffee pods created the largest environmental impacts in all impact categories. Both the biodegradable and the aluminium coffee pods had slightly lower environmental impacts than the PP based pod and the biodegradable pod even proved slightly better than the aluminium pod with respect to the impact categories: acidification, photochemical oxidation and abiotic depletion. Furthermore, in the sensitivity analysis they report that in case the biodegradable pods are not composted but anaerobically digested and composted, the environmental impacts will even be lower.

In 2017, Li Jingxi wrote a thesis on the comparative LCA between three different coffee pod systems available on the Canadian market. Three types of single-serve coffee pods were compared: polystyrene (PS)-based pods with aluminium lids and a paper filter, aluminium-based pods and biodegradable pods. All these pods are offered in cardboard boxes on the Canadian market [14]. For the Canadian situation in 2018 it was assumed that all PS-based pods were discarded with mixed municipal solid waste and landfilled, 24% of the aluminium pods were separately collected and recycled and hence 76% were landfilled, 40% of the biodegradable pods were collected with organic waste and composted, the remaining 60% were landfilled. Furthermore, 62.5% of the cardboard boxes were separately collected for recycling and the rest (37.5%) was landfilled. This cradle-to-grave LCA excluded several parts of the life cycle that were deemed to be equal for all pod systems, namely: coffee cultivation, retail, transport, manufacture and use of the brewing machines. In this study the aluminium pods were found to have the highest impacts for all categories. The PS and biodegradable pods had lower and fairly comparable impacts. The PS pod had slightly higher impacts as compared to the biodegradable pod in the following categories: global warming, smog, acidification and respiratory effects. Conversely, the biodegradable pods had slightly higher impacts for ozone depletion, eutrophication and ecotoxicity [14].

In 2020, Kooduvalli reported a comparative LCA study of PP-based versus PLA based coffee pods used in an American university setting [15]. It is a cradle-to-gate study with transportation and End-of-Life phases also considered and excluding coffee cultivation and brewing. Within the American setting, it was assumed that PP-based pods will be landfilled and all PLA-based pods will be either composted or landfilled. The environmental impacts were found to differ marginally between both pods. The biodegradable pod had a slightly higher amount of embodied energy. But landfilling as an end-of-life option did create negative environmental impacts with regard to ecotoxicity, eutrophication and non-carcinogenicity, hence the composting of the biodegradable pods did help to alleviate those impacts [15].

Reflection on the literature of environmental impacts

In summary, the LCA-studies report differing outcomes that are the result of different factors considered within the system boundaries, different consumer behaviour and different waste management options. Hence, we reconfirm the conclusion of Marinello et al. that the public literature on this topic is heterogeneous [7], although most of the studies considered the environmental impact categories mentioned in Table 3. Overall, coffee cultivation itself causes substantial environmental impact. The various methods of coffee brewing further increase these impacts, depending on whether all prepared coffee is consumed or wasted (consumer behaviour), the amount of energy consumed in the coffee preparation method, any additional material used for single-serve pods / capsules and the coffee machines. The environmental impacts can be slightly reduced by recycling the spent coffee grounds with organic waste, either by anaerobically digestion or composting. Impacts can also be reduced in case the used pods/capsules are separately collected and both the materials and the coffee are recycled. The effectivity of this mitigation strategy is hampered by the reported low separate collection rates of these pods/capsules (or by low capture rates of alternative recovery strategies).

Table 3: Environmental impact categories often used in publicly available LCA studies on coffee capsules.

Global warming	Eutrophication
Ozone depletion	Acidification
Fossil fuel depletion	Ecotoxicity
Carcinogenic (Human toxicity)	Non-carcinogenic (Human toxicity)
Respiratory effects	Smog

Migration studies

Coffee pods/capsules are subjected to hot water at high pressures during the brewing process. These are ideal conditions for the migration of small molecules from the various components of the coffee pods/capsules to both the coffee beverage and to the spent coffee grounds. In 2014, Di Bella et al. found plasticisers in freshly brewed coffee made in various brewing machines, including machines using coffee pods [16]. Various phthalate esters such as dimethyl phthalate and di(2-ethylhexyl)adipate were found to migrate in sub-microgram levels to the brewed coffee per pod. Some large plastic coffee pods showed slightly higher migration levels than aluminium & normal plastics capsules, along with the detection of few other plasticisers, but the levels remain at the low sub-microgram level for each serving made. The level of migration of these plasticisers is low in comparison to the tolerable dietary intake levels and hence this exposure has a low priority for the public health [16], [17]. Nevertheless, individuals might argue that this

exposure is unnecessary and might want to avoid it. These individuals are advised that similar exposures are produced with alternative coffee brewing techniques (for instance from rubber sealing rings) [16], [17].
All coffee brewing machines add metal ions to the spent coffee grounds. The level at which metal ions migrate into the coffee is exacerbated after decalcification [18] but thorough rinsing after decalcification helps to reduce this migration. When rinsed properly, these migrated amounts of metal ions entail only very limited risks for the public health [18]. But metal ions do not only migrate to the coffee, they also migrate to the spent coffee grounds. The concentration of aluminium in coffee was found to increase from roughly 2.5 ppb to 8.5 ppb from the aluminium seals of the coffee capsules before and after coffee brewing in a Nespresso machine, which might have consequences for the organic recycling of the spent coffee grounds [19].

Consumer acceptance/behaviour studies in the context of a circular economy
Coffee pods/capsules offer convenience to consumers to brew a high quality coffee product on any location that offers a power connection and fresh water. The downside of using pods/capsules is that a waste flow is generated. Initially consumers could only discard used pods in the mixed municipal solid waste, which resulted both in increasing waste volumes and in discontent among consumers with regards to the waste. To mitigate this, recycling programs were started for consumers to send in their used pods (Nespresso recycling programme, Podback scheme, etc.), which aimed to recover both the pod materials (aluminium, plastics) and the spent coffee grounds separately. Furthermore, the compostable and biodegradable pods were developed and marketed, which were intended to be discarded in the organic waste bin and processed with the organic waste. This can result in recovered biomethane if the organic waste is digested or compost if it is composted.
For these recycling schemes to be successful, the consumers need to participate. To encourage participation Abuabara gives several recommendations, including a convenient collection system, an incentive program and the sharing of results [20].
Visser and Dlamini studied the purchasing behaviour of South African coffee pod users and sought relationships between their values, knowledge and to which extent these consumers purchase compostable coffee pods. No relationship was found between knowledge and purchase behaviour, but social context and altruistic values positively influenced the environmental attitude, which in turn impacted the purchase behaviour; these individuals were more inclined to purchase compostable coffee pods [21].

3 Methods

3.1 Selection of alternatives for coffee capsules

There are several types of coffee capsules available on the Dutch market, the most common being Nespresso type capsules. Hence, this study focuses on the most commonly applied coffee capsules in the Netherlands; the Nespresso style format and not any other (often larger) formats. Nespresso style capsules represent a format that fits into the concomitant coffee brewing machines. The most common material used for these capsules is aluminium, but there are also Nespresso-style capsules made from different materials on the market, including high density polyethylene, polypropylene and compostable materials. Multiple types of compostable capsules available in the Netherlands are considered in this study: capsules based on PLA (converted by Flo and ATI) and capsules based on a PHA blend (from De Koffiejongens).

This study excludes reusable and/or refillable capsule formats and paper capsules, as these systems are hardly applied in reality. Although these systems were (and perhaps still are) offered on the market, it is impossible to get data on their actual use in Dutch households. The inconvenience for consumers to fill and clean each capsule is probably the main cause of their limited use.

In this report we will first compare the main categories of coffee capsules (aluminium, conventional plastics and compostable plastics) to explore the main differences in impacts. In a subsequent later stage of this study, more variants per category of coffee capsules are studied in detail in a sensitivity analysis, see Table 4.

Table 4: Selected coffee capsule types studied in this study.

Code	**Material**	**Company**
PLA1	Polylactic acid	NatureWorks (raw material producer) FLO (converter)
PLA2	Polylactic acid blend	ATI (converter)
PHA1	PHA blend	De Koffiejongens (converter)
PP	Polypropylene	ATI (converter)
PE	High density polyethylene	Lidl (supplier)
Al1*	Aluminium (0% recycled content)	Blokker (supplier) Alu-sense (converter)
Al2	Aluminium (40% recycled content)	Nespresso (supplier)

* it will be 80% recycled content in Q1 2024, which most likely implies 40% post-industrial and 40% post-consumer recycled aluminium

3.2 Tool for sustainability analysis

The sustainability analysis tool (MuDiSa[3]) used in the project was developed within WUR to assess the environmental impact of packaged food products in multiple dimensions of sustainability and circularity [22]. Traditionally, most of the other LCA-based tools focus more to environmental and human impact assessments including different impact categories, but ignore important sustainability and circularity dimensions. With this tool we cover a broader scope in comparison to other LCA-based tools.

The tool includes specific data of the packaging material and food product. We can make the distinction between primary/foreground data, like for example the packaging components, and background data, like for example emission factors of material production and recycling processes. This collected input on the life cycle of the packed product consists of the life cycle inventory (LCI, see section 3.4) and can be different,

[3] Multi-dimensional sustainability assessment

depending on the type of product-packaging combination, and the end-of-life scenarios. The foreground data that are necessary for the calculation of the environmental impact and the indicators are:

- Type of product (coffee)
- Packaging volume
- Food losses [%]
- Packaging components: weight, material, production method
- Amount of loops (in case of reusable packaging)
- Packaging waste scenario
- Binary operators for indicators of recyclability: Recyclable (yes/no), Circular recyclable (yes/no), with respect to the Dutch waste management system
- Binary operators to establish the littering potential: BI -use (in home/out of home) is yes when the packaged food product is likely to be consumed out-of-home and BI – sup (yes/no) is yes when the article is listed in EU Single Use Plastics directive [3].

The tool calculates the greenhouse gas emissions/global warming potential after 100 years in terms of carbon dioxide equivalents of the packaged product and the indicators for the other dimensions of sustainability based on information of the life cycle of the packaged product. Background information is used to be able to execute these calculations. This background information is available in databases that are part of the calculation too. For the following products and processes greenhouse gas emission factors are included in the databases:

- Food products (kg CO_2 eqv. / kg)
- Materials (kg CO_2 eqv. / kg)
- Production processes (packaging) (kg CO_2 eqv. / kg)
- End-of-life processes (kg CO_2 eqv. / kg)

Based on these data, the tool calculates and evaluates the contribution of the life cycle stages of the product (in this case packed coffee) and the packaging into global warming potential over a period of 100 years (GWP-100) in terms of carbon dioxide equivalents. Among the environmental impact categories, global warming potential is considered the most relevant to assess the environmental impact of a food packaging and it is the category calculated with lower uncertainties compared with the others. The calculated emission of greenhouse gases is split in five life stage contributions:

1) Emissions due to the production of the food product
2) Emissions due to the production of the packaging (material and production process)
3) Emissions reuse process (applicable only for reusable packaging, therefore not applicable in this study)
4) Emissions due to the end-of-life treatment of spent coffee grounds and packaging
5) Avoided emissions due to the use of recycled materials or recovered energy from incineration process or produced compost as a fertilizer

Additionally, several indicators are calculated to assess the overall sustainability and circularity of the packaging. These indicators fill the gap for the environmental impacts that can currently not be calculated with a basic LCA method, such as potential contribution to litter, recyclability and circularity. The calculation of these indicators do not consider the spent coffee grounds or the production of coffee beans, as they are packaging-focused indicators. The following six indicators are relevant for this study:

1) Recycled Content Indicator (ReConI): This is an indicator that describes the share of post-consumer recycled material that is used to produce the capsule. The use of post-industrial recycled material is excluded from the calculation of the indicator. It is expressed with a percentage. It equals 0% in case no recycled content is present and 100% is case the entire capsule is made of recycled material.
2) Renewable Content Indicator (ReNewI): This indicator expresses the share of renewable material of which the capsule is made. The unit is percentage and it runs from 0% (no renewable content) to 100% (completely made from renewable materials). A renewable material means: not based on fossil feedstock.
3) Recyclability Indicator (RI): It is used to identify the recyclability of the packaging material within mechanical recycling processes and to quantify the mass fraction of the packaging that is made of a

recyclable material. It is expressed in a percentage, where 100% implies that the capsule is fully recyclable, while 0% means the packaging cannot be recycled.

4) Recycling Chain indicator (RCI): It expresses the recycling chain efficiency for a specific type of packaging. It is calculated by multiplying the collection, sorting and recycling efficiency of the primary material which can be converted into a secondary material. In case each packaging is made of several components, this indicator is calculated separately for each component and the sum of all gives the total value.
5) Organic Recyclability Indicator (ORI): ORI describes the recyclability of the capsule material within organic waste treatment processes and quantifies the mass fraction of the capsule that is completely transformed in biomethane, CO_2 or humus. It is expressed in a percentage, where 100% implies that the packaging is fully recyclable organically, while 0% means the packaging remains unaltered and cannot be recycled organically.
6) Litter Prevention Indicator (LPI): LPI indicator is used to articulate the likelihood the capsule contributes to the formation of persistent road-side and/or marine litter. The likelihood of littering is small for coffee capsules, however this indicator gives information on what would happen if the capsule would end up in nature. The indicator does not take incorrect waste separation behaviour by civilians into account (so-called misthrows). It is expressed in the form of a percentage, where 100% means that the package doesn't form persistent litter and 0% means that the chance that this package will be littered is maximal.
7) Material Circularity Indicator (MCI): This indicator was developed by Ellen MacArthur Foundation and it is expressed in a percentage [1]. This indicator has 10% as lower limit unlike other indicators where it is 0%. So, a 100% score signifies that the capsule is fully circular, while 10% signifies that the capsule is fully linear. The MCI indicator takes into account the capsule recycling (both mechanical and organic), recycling efficiencies, reuse/life-span and material origin. A subfactor within the MCI named 'Utility factor' was set to 1. This subfactor describes both the life span of the product and the amount of loops a reusable product is used. Since the capsules are single-serve products it was set to 1. Compared to the other indicators, MCI is the most complete one, taking diverse information into account. For this reason, the results of MCI were chosen to be presented in the result chapter of the main text and the rest of indicators can be found in the appendix.

The MuDiSa tool takes multiple dimensions of sustainability into account. Nevertheless, there are other more qualitative factors regarding coffee capsules, that cannot be calculated but only described. These relate for example to behavioural aspects, fit within the legal landscape and possible contamination of waste types. These potential consequences are discussed in the discussion chapter.

3.3 Sustainability analysis methodology

Scope and System boundaries

The scope of this sustainability assessment is formed by the system boundaries. These run from the production of the capsules and coffee to the end-of-life management of both. This is depicted in Figure 3.

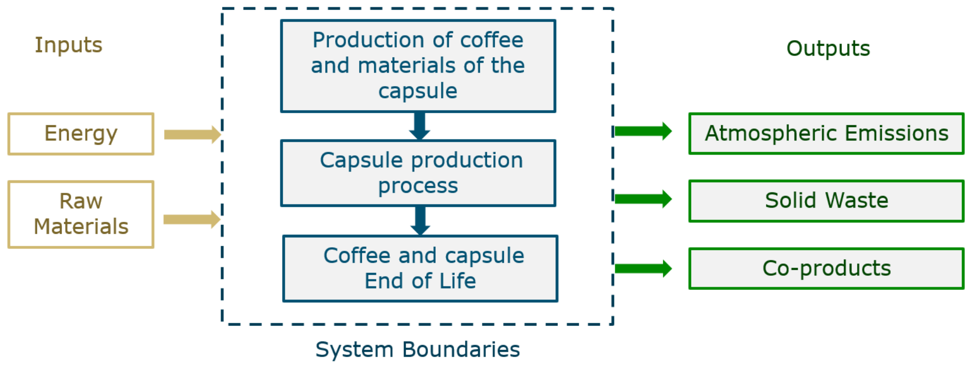

Figure 3. The system described in this study is within the system boundaries. The inputs and outputs to this system are taken into account in the sustainability assessment.

The distribution and the transportation of coffee capsules, coffee brewing using a Nespresso machine, and production of Nespresso machine are excluded. The functional unit for the assessment of the greenhouse gas emissions is 1 kg packed coffee and the results are presented in kg CO_2 equivalents per kg of packed coffee. Some other studies define 1 or 100 capsules or the coffee dosage after brewing as functional unit. The coffee capsules, however, all include similar amounts of coffee and the variety in coffee content of the capsules is not capsule material specific, but producer specific (see section 3.4.1). Therefore, functional unit of 1 kg and 1 cup or dosage are expected to have similar results in this comparative study. The scores of the environmental performance indicators are expressed in percentages, as described in section 3.2. Furthermore, a sensitivity analysis is performed on the most uncertain data.

Some main assumptions were made in this study:

- The study is executed with the waste collection and management practises that are common in the Netherlands in 2023. Landfill has been included as end-of-life (EoL) scenario, although it is not practised in the Netherlands for municipal waste, however it is in other European countries. As the data on the fate of coffee capsules in different EoL systems is scarce, it was decided to execute a theoretical study with a 100% collection rate for each EoL scenario.
- The transfer coefficients for recycling coffee capsules and incinerating aluminium capsules are based on the performance of Dutch infrastructure.
- From discussions with the industrial incumbents it became apparent that although there are quality differences between coffee brewed from the different types of capsule materials, it is not likely that coffee in capsules is wasted. Therefore, it was decided to use food waste rates of 0% for the coffee in all types of capsules.
- The calculation of the emissions during the EoL of the spent coffee ground is based on the dry mass of the packed coffee.

Modelling Approach

As explained in the previous section, greenhouse gas emissions/global warming potential is calculated in terms of carbon dioxide equivalents. To calculate this, emissions and avoided emissions of different processes are combined. This can be done in different ways. This section explains which modelling approach is used and why this has been selected.

The assessment follows in essence an attributional modelling approach, considering the actual environmental impacts of the processes directly related to the production and disposal of coffee capsules. However, elements of a consequential approach (applied when you want to investigate the consequences of a change compared to a baseline situation) are considered as well, such as the fact that we are working with different what-if scenarios (see section 3.5).

Examples of such scenarios include mechanical recycling, industrial composting and incineration. In these processes/scenarios products are made, i.e.: recycled products that could substitute virgin materials, compost that is used as soil conditioner, and also heat and electricity. To calculate the global warming potential over 100 years an allocation method has to be chosen to account for the credits and burdens of these processes correctly. Since the research question of this study relates to the environmental impacts of different coffee capsules that are subjected to various end-of-life scenarios, the selected allocation approach should focus on end-of-life burdens and credits. Therefore, for this study the closed loop approximation allocation approach is used, otherwise known as the 0:100 approach. In this allocation approach the credits (and burdens) for the generation of recycled product, that avoids the production of a future virgin material, are fully assigned to the producer of the primary product. With this approach, the user of the recycled product does not get any credit, so the use of recycled content in a product is not burden free and has the same attached burden as a virgin material. There is no single allocation approach that is generically recommended for such complex circular systems. However, this closed loop approximation approach is commonly used for materials for which it is already common to use recycled content, such as metals and glass. The selected approach is well-justifiable in the context of this study, as the focus of this study is on the end-of-life-options for the different coffee capsules. Nevertheless, it should be noted that the selection of the allocation approach influences the result of the assessment.

Furthermore, the punching scrap (sometimes referred to as skeleton) generated inside the system boundaries is included in the GWP calculations. We assumed that this scrap is 100% collected and recycled. As an example, Figure 4 represents the closed loop approximation allocation approach of burdens and credits during the cradle-to-gate assessment of an aluminium capsule and including the recycling of the scrap materials.

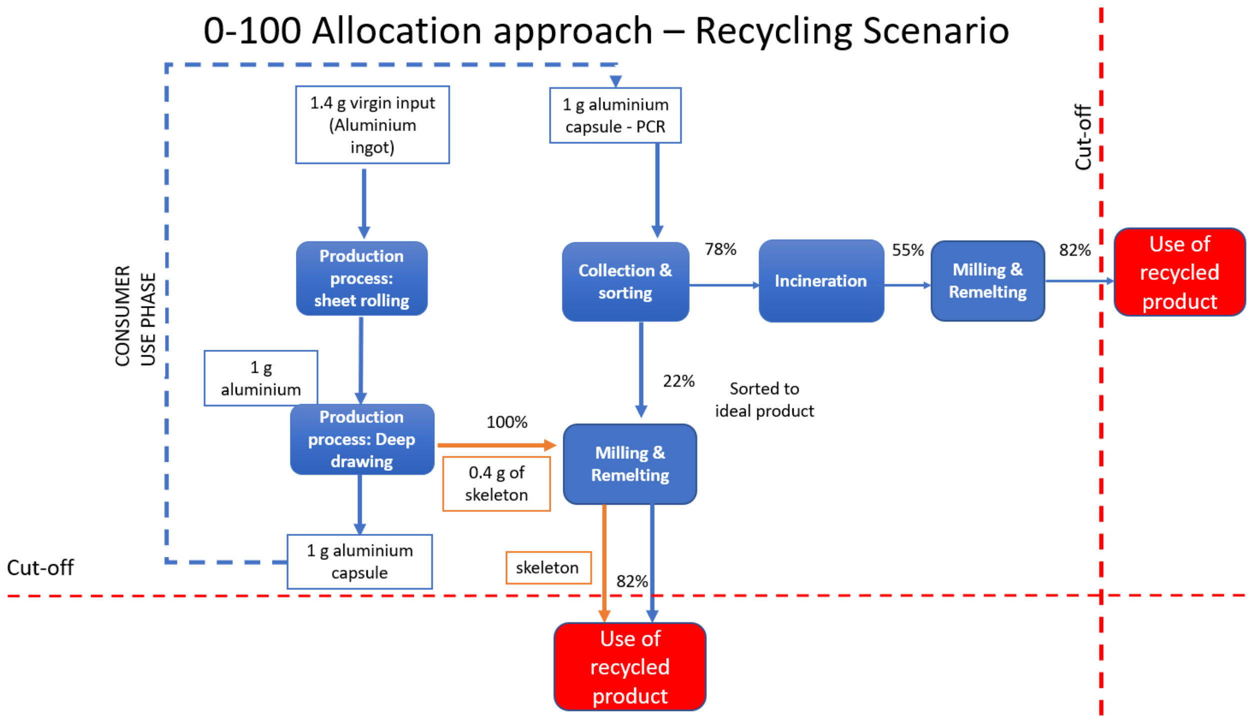

Figure 4. The applied 0-100 approach to allocate burdens and credits during the cradle-to-grave assessment of an aluminium capsule. In the 0-100 approach the environmental burden of virgin and recycled material is considered the same, so therefore only virgin input is shown in this scheme. The use of recycled product itself is outside the system boundaries, however credits are given for the production of the recycled product.

Also for the other sustainability and circularity indicators (like MCI), methodological choices need to be made. These indicators are meant to show the other dimensions of sustainability that relate to the different packaging types. Their calculation methodology directly prescribes how recycled content and/or recycling of the materials is included in the indicator. For instance, the MCI considers both the benefit of using recycled input in the production stage and the generation of recycled material in the end of life of the product. The calculation of the indicators (excluding global warming potential over a period of 100 years) excluded the scrap or skeleton generated inside the system boundaries during the coffee capsule production stage.

Recycled content

The use of recycled materials in the production of capsules influences the calculation of the sustainability indicators. Two types of recycled aluminium are distinguished: post-industrial (pre-consumer) and post-consumer. The post-industrial aluminium is mostly the so-called punching scrap or skeleton (see section 4.4.2). The post-consumer aluminium is both the recycled aluminium from the mono-collection of capsules and the recycled aluminium from beverage cans. The recycling processes are very comparable for both types of aluminium waste; first the scrap is de-coated, re-melted, rolled in new sheets, coated and used again. The GWP is not affected from the presence of post-consumer recycled content, as the recycled input has the same burden as the virgin material in the closed loop approximation approach. The recycled content does however influence the calculation of MCI and ReConI. For these indicators only the post-consumer recycled content is included as recycled content in the calculation.

Biogenic carbon

In this study biogenic carbon is taken into account as this is a relevant aspect of the comparison between biobased and fossil-based materials. Biogenic implies that atmospheric CO_2 has been taken up during the cultivation of food stuffs and biobased materials through photosynthesis. Hence, the biogenic carbon calculation is relevant only for the biobased materials, in this case only for biobased plastics (PLA, PHA) and paper components included in the studied coffee capsules. The biogenic carbon related to use of electricity coming from biomass or background processes including land use, is excluded. Additionally, the biogenic carbon related to the production and end-of-life of the coffee is excluded as well. As the amount of packed coffee is the same for all different capsules, it will not add any value in the comparison of different capsule materials. The uptake calculation is based on the biomaterial storage approach expressed from the following equation:

$$CO_2\,uptake = \frac{Material\ carbon\ content}{Carbon\ molecular\ weight} \times Carbon\ dioxide\ molecular\ weight$$

For example, if the carbon content of PLA is 0.5 kg/kg PLA and the carbon and carbon dioxide molecular weight is 12 and 44 accordingly, the carbon storage during the production of 1 kg of PLA pellet equals to 1.83 kg CO_2 . In order to properly account the biogenic carbon through all life stages it is important to carefully identify the emissions during EoL. During incineration there is a full oxidation and emission of biogenic carbon; during industrial composting the majority of biogenic carbon is oxidized during the biodegradation and emitted and a small part is stored in the compost; during landfilling the biogenic carbon is partially oxidized as well and becomes carbon dioxide and methane; and during mechanical recycling the biogenic carbon is stored in the recycled material. The incineration of sorting rejects of a recycling process results in biogenic carbon emissions.

Data collection
The material composition of the four types of Nespresso style capsules were provided by the participating entrepreneurs or by measurements done by WUR. Numbers are listed in life cycle inventory, section 3.4.

The emission factors of the produced materials, transport and waste management were mostly taken from the EcoInvent database [38] and literature, although some deviations were made, see Annex 2. The data in the EcoInvent database relates to market data (so including unit processes to be able to put these materials on the market such as transport, factories, etc.) and are generated with the IPCC 2013 GWP 100a V1.03 method. Data from literature or own estimates are used to fill the database in case the data was unavailable in Ecoinvent (see Annex 2).

Limitations
To perform the sustainability assessment using the MuDiSa tool, it was necessary to augment the background database with emissions from production and end-of-life (EoL) treatments for compostable plastics used in coffee capsules. It was challenging to properly extract useable data from various literature sources. Various functional units are being used, which hinder the conversion of emissions to kilograms of CO_2 equivalent per kilogram. Many studies calculated emissions using different impact methods, allocation approaches, system boundaries, assumptions, and modelling decisions. For instance, some studies opted to include the modelling of land use effects during industrial composting, while others excluded emissions related to land use changes for compost application. It was impossible to recalculate and convert such data in data that could be used in this study. Additionally, numerous studies exhibited differences in the valuation in terms of positive credits of generated compost and recycled material. Some studies concluded that specific parameters, such as the credits for compost and recycled material, as well as electricity production efficiency from incineration, were sensitive and could significantly influence the results. Consequently, extracting comparable emission data proved to be a challenge, especially given that this study addresses innovative materials like compostable plastics. Therefore, we extracted data from sources that were best suitable for this study and included that data in the background database.

3.4 Life Cycle Inventory (LCI)

3.4.1 Capsule composition

The material composition of the various capsules was obtained from two sources. We received confidential compositional information of the producers involved in the study. This data is shown in a simplified manner in Table 5. Additionally, several capsules were purchased in supermarkets and taken from consumers and disassembled. All components and the amount of contained coffee grounds were weighed. The chemical identity of some components was verified with Infrared spectroscopy. The material composition of the studied capsules is listed in Table 6.

Table 5: Simplified composition of the coffee capsules sold by the participating companies.

Code	Capsule	Lids	Other components	Company
PP	1.27 g PP, 0.03 g EVOH*	0.02 g Al, 0.01 g PP	-	ATI (converter)
PLA1	1.20 g PLA	0.1 g paper & PLA	-	Flo (converter), NatureWorks (raw material producer)
PLA2	2.40 g PLA blend	0.05 g cellulose & biopolymer	0.22 g PLA & PBAT (ring)	ATI (converter)
PHA1	1.56 g PHA blend	0.12 g cellulose & biopolymer	0.14 g paper, 0.002 ink (label)	De Koffiejongens

*: EVOH: poly(ethylene-co-vinyl alcohol)

Table 6: Simplified composition of purchased and disassembled coffee capsules.

Code	Capsule	Lids	Other components	Company
Al1	1.01 g Al	0.13 g Al	Not detected	Alu-sense (converter) Blokker (supplier)
Al2	0.87 g Al	0.09 g Al	0.09 g EVA* (diffuser)	Nespresso (supplier)
PE	0.98 g HDPE	0.11 g Al		Lidl (supplier)

*: EVA: poly(ethylene-co-vinyl acetate)

The precise amount of coffee per capsule was weighed, see Table 7.

Table 7: dry weight of coffee per capsule as measured (n=3)/assumed for several capsule types.

Code	Weight of coffee per capsule, [g]
Al1	5.31
Al2	5.61
PP	5.5[B]
PE	6.01
PLA1	5.5[A]
PLA2	5.5[B]
PHA	5.66

A: according to the producer, not measured

B: assumed based on PLA1 data, not measured

3.4.2 Production process of capsules

In the sustainability calculations the production process of the coffee capsules is also relevant. These processes are listed per type of capsule in Table 8. Note that not all production processes are available in the literature and background databases. Therefore in some instances simplifications had to be made; and either coating processes could not be included or the most similar processes had to be picked from the database.

Table 8: Production processes of each coffee capsule scenario.

Code	Production Process	Reference
Al1	Sheet rolling of aluminium and deep drawing of steel	Adjusted process based on the production process of small aluminium products
Al2	Sheet rolling of aluminium and deep drawing of steel	Adjusted process based on the production process of small aluminium products
PP	Sheet extrusion followed by thermoforming	Assumption based on production process of small rigid plastic products
PE	Sheet extrusion followed by thermoforming	Assumption based on production process of small plastic rigid products
PLA1	Sheet extrusion followed by thermoforming	Provided by the company
PLA2	Injection moulding	Provided by the company
PHA1	Injection moulding	Provided by the company

3.5 Scenarios

The environmental impact of different types of coffee capsules including spent coffee grounds is studied for various end-of-life treatments. The scenarios are therefore combinations of specific coffee capsules with specific waste management practises for capsules and spent coffee grounds as they are common within the Netherlands and Europe. Since coffee is being prepared with the single-serve capsules and it has been assumed that no coffee is wasted, the use-phase is constant and does not require additional scenarios. Directly after brewing, the water content of spent coffee grounds is high. However, the collection and end-of-life treatment of coffee capsules does not take place right after the disposal and the water content is decreasing with time. This time period varies and hence the moisture content of the capsules at the point of waste processing will vary as well. For simplicity, the tool is using the dry mass of spent coffee grounds to calculate the impact of end-of-life processes.

It is assumed that civilians will separate out the used coffee capsules 100% correctly in the appropriate waste bin. Through collection these used capsules will be directed towards a specific intended waste management practise. This, however, does not imply that the capsules also end-up in the correct facilities, since the sorting losses and recycling losses that are common in the Dutch waste management systems are taken into account as well. Hence, a scenario in which the capsules are intended to be separately collected with lightweight packaging waste, will imply that indeed all capsules are collected with LWP, but due to sorting and recycling losses still some of these capsules are incinerated.

The transfer coefficients of the sorting, recycling and recovery after incineration are selected based on background knowledge from previous projects. Depending on data availability, data is used for the Netherlands, or otherwise for Europe. The transfer coefficients for the plastic capsules were based on the data for other rigid PP packages in the Netherlands [39]. The transfer coefficients for the aluminium capsules were based on previously reported data for the Netherlands [40]. Table 9 presents these transfer coefficients per type of material. The chosen parameters and scenarios are discussed further in section 4.4.

Table 9: Transfer coefficients of coffee capsules recycling and incineration. Recycled products for aluminium are ingots and for plastics are pellets.

Capsule type	Collection via	Sorting	Sorting residues for incineration	Metal product in bottom ashes after incineration	Recycling to product
Aluminium	Mono-collection	100%	0%	-	97%
	Recycling	22%	78%	55%	82%
	Incineration	-	-	55%	82%
Conventional & Compostable plastics	Recycling	51%	17%	-	90%

The data required for calculating the greenhouse gas emissions for the industrial composting scenario was retrieved at European level from Hermann et al [41] and comprised the carbon and energy content of the biobased materials. According to this source the typical biodegradation rates under aerobic conditions and high temperatures (50°C-60°C) for PLA, PHA, and paper are 80%, and for PBAT 70%. Moreover, the composting will transform 56.89% of the carbon present in these biodegradable polymers in carbon dioxide gas, 43% in humus and 0.11% in methane gas. The boundary of the system is the exit gate of the industrial composting process, so credits are given for the production of compost as a replacement for peat.
The Dutch organic waste scenario included in the sensitivity analysis is a combination of anaerobic digestion and industrial composting, where 30% of the collected organic waste is treated by facilities that make use of an anaerobic digestion process preceding the aerobic composting process. The other 70% of the collected organic waste is processed by industrial composting without anaerobic digestion. The data required for calculating the greenhouse gas emissions of the anaerobic digestion part of this scenario was also retrieved from Hermann et al. [41].
The calculation of incineration burdens and emissions is based on the carbon and energy content of the materials. In the case of biobased materials, the carbon content is biogenic. The extracted data of the biobased materials from Hermann et al. [41] are based on the average European incinerators with energy recovery. The credit for the produced heat (22%) and electricity (11%) is based on the heating value of each material. The electricity replaces the average European electricity mix and the heat replaces the use of natural gas.

The main what-if scenarios that are considered, are listed in Table 10.

Table 10: Main scenarios.

Scenario	Main Capsule material	End-of-life treatment	
		Material	**Coffee**
PLA1-C	PLA (Flo)	100% Industrial Composting	100% Industrial Composting
PLA1-R		100% Recycling	100% Incineration
PLA1-I		100% Incineration	100% Incineration
PLA1-LE		100% Landfill with energy recovery	100% Landfill with energy recovery
PHA1-C	PHA (De Koffiejongens)	100% Industrial Composting	100% Industrial Composting
PHA1-R		100% Recycling	100% Incineration
PHA1-I		100% Incineration	100% Incineration
PHA1-LE		100% Landfill with energy recovery	100% Landfill with energy recovery
PP-R	Polypropylene (ATI)	100% Collection with LWP & recycling	100% Incineration
PP-I		100% Incineration	100% Incineration
PP-LE		100% Landfill with energy recovery	100% Landfill with energy recovery
Al2-M	Aluminium (Nespresso) 40% RC	100% Mono-collection	100% Industrial Composting
Al2-R		100% Collection with LWP & recycling	100% Incineration
Al2-I		100% Incineration	100% Incineration
Al2-LE		100% Landfill with energy recovery	100% Landfill with energy recovery

To assess the effect of other choices, a sensitivity analysis has been carried out on different elements, like the composition of the capsule, but also on a variation in the end-of-life treatment. In this more detailed analysis, more types of capsules per material type are compared. The comparisons include:

- Different conventional plastic capsules,
- Different compostable plastic capsules,
- Different aluminium capsules,
- Different organic waste treatment options for the compostable plastic capsules,
- Difference in PLA pellet production data

The list of the more detailed scenarios which are used for the sensitivity analysis is given in Table 11.

Table 11: Scenarios for Sensitivity analysis.

Scenario	Main Capsule material	End-of-life treatment
Different conventional plastic capsules		
PP-R	Polypropylene (ATI)	Collected with LWP & recycled
PP-I	Polypropylene (ATI)	Incineration
PP-LE	Polypropylene (ATI)	Landfill with energy recovery
PE-R	High-density polyethylene (Lidl)	Collected with LWP & recycled
PE-I	High-density polyethylene (Lidl)	Incineration
PE-LE	High-density polyethylene (Lidl)	Landfill with energy recovery
Different compostable plastic capsules		
PLA1-C	PLA (Flo)	100% Industrial Composting
PLA1-R	PLA (Flo)	Recycling
PLA1-I	PLA (Flo)	Incineration
PLA1-LE	PLA (Flo)	Landfill with 0% biodegradation of bioplastic and energy recovery
PLA2-C	PLA (ATI)	100% Industrial Composting
PLA2-R	PLA (ATI)	Recycling
PLA2-I	PLA (ATI)	Incineration
PLA2-LE	PLA (ATI)	Landfill with 0% biodegradation of bioplastic and energy recovery
PHA1-C	PHA (De Koffiejongens)	100% Industrial Composting
PHA1-R	PHA (De Koffiejongens)	Recycling
PHA1-I	PHA (De Koffiejongens)	Incineration
PHA1-LE	PHA (De Koffiejongens)	Landfill with 0% biodegradation of bioplastic and energy recovery
Different aluminium capsules		
Al1-M	Aluminium (Alu-sense/Blokker) 0% RC*	Mono-collection
Al1-R	Aluminium (Alu-sense/Blokker) 0% RC*	Collected with LWP & recycled
Al1-I	Aluminium (Alu-sense/Blokker) 0% RC*	Incineration
Al1-LE	Aluminium (Alu-sense/Blokker) 0% RC*	Landfill with energy recovery
Al2-M	Aluminium (Nespresso) 40% RC	Mono-collection
Al2-R	Aluminium (Nespresso) 40% RC	Collected with LWP & recycled
Al2-I	Aluminium (Nespresso) 40% RC	Incineration
Al2-LE	Aluminium (Nespresso) 40% RC	Landfill with energy recovery
Difference in organic waste management methods		
PLA1-C	PLA (Flo)	100% Industrial Composting
PLA1-AD-C	PLA (Flo)	A mix of anaerobic digestion and industrial composting (Dutch organic waste scenario)
PLA2-C	PLA (ATI)	100% Industrial Composting
PLA2-AD-C	PLA (ATI)	A mix of anaerobic digestion and industrial composting (Dutch organic waste scenario)
PHA1-C	PHA (De Koffiejongens)	100% Industrial Composting
PHA1-AD-C	PHA (De Koffiejongens)	Anaerobic digestion and industrial composting (Dutch organic waste scenario)
Difference in PLA pellet production data		
PLA1a-C	Ecoinvent / IPCC 2013 GWP 100a V1.03	100% Industrial Composting
PLA1a-R	Ecoinvent / IPCC 2013 GWP 100a V1.03	Recycling
PLA1a-I	Ecoinvent / IPCC 2013 GWP 100a V1.03	Incineration
PLA1a-LE	Ecoinvent / IPCC 2013 GWP 100a V1.03	Landfill with 0% biodegradation of bioplastic and energy recovery
PLA1b-C	Total Energies Corbion	100% Industrial Composting

Scenario	Main Capsule material	End-of-life treatment
PLA1b-R	Total Energies Corbion	Recycling
PLA1b-I	Total Energies Corbion	Incineration
PLA1b-LE	Total Energies Corbion	Landfill with 0% biodegradation of bioplastic and energy recovery

* it will be 80% recycled content in Q1 2024, where 40% will be from post-industrial and 40% will be from post-consumer recycled aluminium

4 Results

4.1 Sustainability assessment of the capsules

The calculated greenhouse gas emissions results (GWP-100) of the four main types of coffee capsules with the contained coffee product are presented in Figure 5. These results are provided in relation to the waste management options that are relevant for these types of capsules, as explained in the list of scenarios, see Table 10. The impact on greenhouse gas emissions of the production of roasted coffee beans is constant across all scenarios and can be ignored in the following analysis when we focus on differences between the various capsules. Nevertheless, it is also clear from Figure 5 that coffee production has by far the largest impact of all. The impact of coffee production is almost six times higher compared to the impacts of the conventional plastic and biobased plastic coffee capsules in their various scenarios. The emission factor for roasted coffee production has, however, a substantial uncertainty. According to Usva et al. it varies between 1.1 to 6.6 kg CO_2 eqv./kg [24]. For this study, the high impact value was selected for the model, as the worst case scenario.

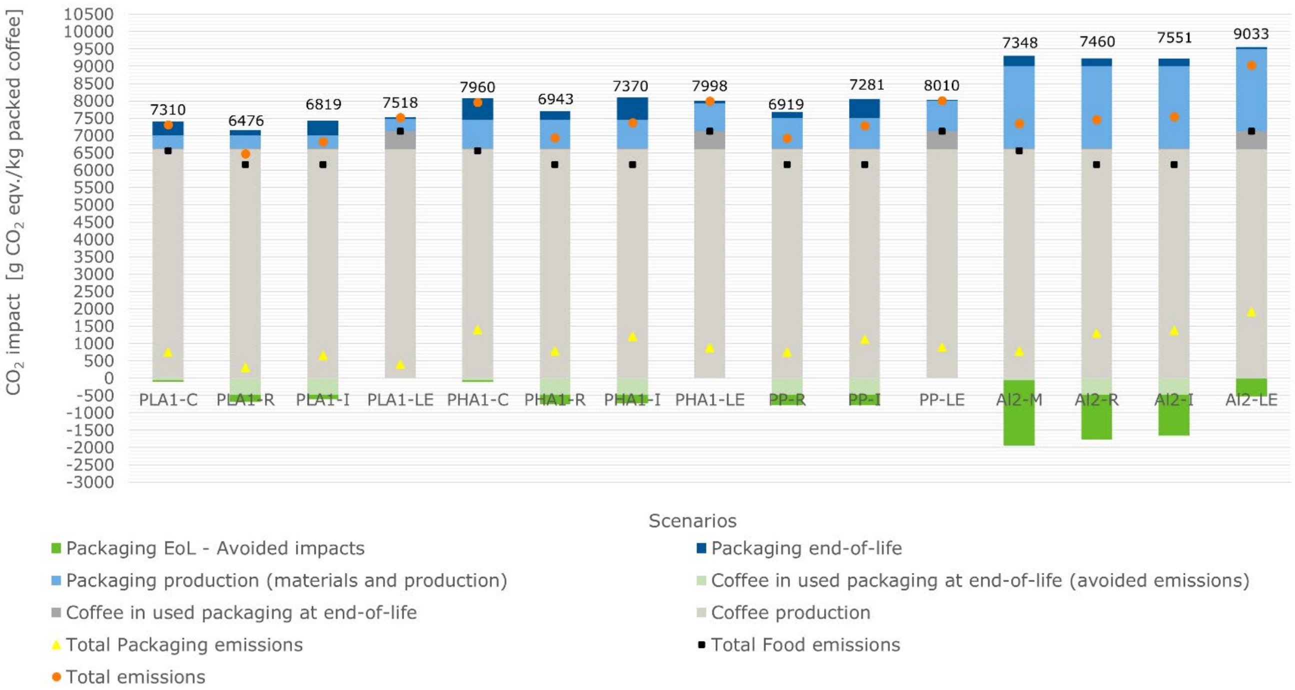

Figure 5: Contribution to the greenhouse gas emissions for the main four capsule types in relation to the waste management options that are relevant. The results are shown per life cycle stage for the capsule and the coffee in [g CO_2 eqv./kg packed coffee].

The impact on greenhouse gas emissions of the end-of-life of contained spent coffee grounds is different and is obviously dependent on the type of end-of-life treatment of the capsules. Figure 5 indicates that the landfill of coffee grounds has the highest negative impact due to high rate of biodegradation (in dark grey) compared to the other scenarios and increases the total contribution of coffee capsules to the greenhouse gas emissions (depicted as orange dots). On the other hand, the industrial composting and incineration of coffee, decrease the total impact of the capsules. For industrial composting (in the composting and mono-collection scenarios) the impact decrease is small. Especially during the incineration of spent coffee grounds (taking place in the incineration and recycling scenarios) there is avoided impact (in light green) because of the energy recovery (heat and electricity mix).

The greenhouse gas emissions results of the four main types of coffee capsules in relation to the relevant waste management options during their packaging life stages are shown in Figure 6. It also includes the total

packaging emissions, which are depicted as yellow triangles in the figure. Overall, compostable plastics (PLA, PHA) and conventional plastics (PP) show lower CO_2 impacts than aluminium capsules.
For the compostable capsule types, the overall greenhouse gas emissions are lowest when the capsules are recycled or landfilled and slightly higher in case they are industrially composted or incinerated. For the conventional plastic capsules recycling is a better end-of-life pathway than incineration and landfill. The preference for recycling both capsules materials can be understood as recycling renders high credits for the substitution of virgin materials. The low value for landfilling is deceptive, as these greenhouse gas emission numbers only regard the contributions of the capsule material. If also the contained spent coffee grounds are taken in consideration, the greenhouse gas emissions during landfill are higher than for composting, recycling and incineration and then landfilling is a less favoured option.

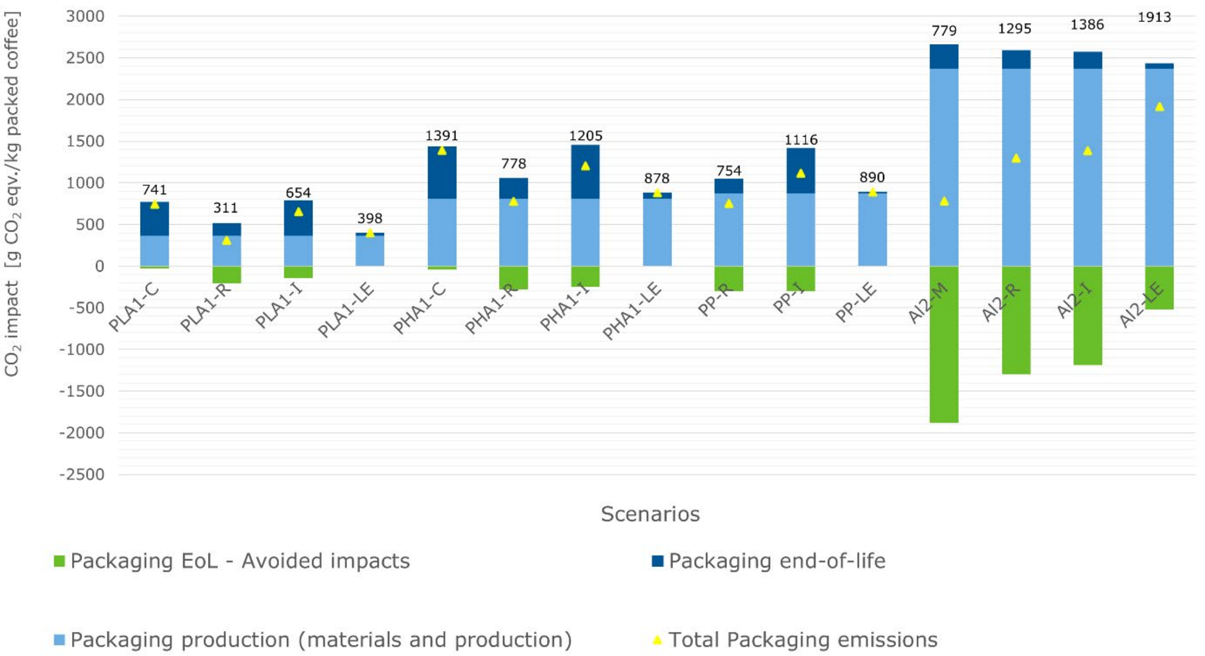

Figure 6: Contribution to the greenhouse gas emissions for the main four capsule types in relation to the relevant waste management routes per life cycle stage, and the total emissions of each packaging in [g CO_2 eqv./kg packed coffee].

Figure 6 also exhibits the avoided impact on greenhouse gas emissions of each scenario in green. The avoided impact (credit) of incineration, recycling and mono-collection of both types of aluminium capsules is significantly larger than for the other materials, with the mono collection scenario showing the highest avoided impact. This is related to the substitution of newly produced aluminium with the recycled aluminium from the recycling process. The avoided impacts related to the substitution of conventional plastic with recycled plastics are much lower.
Recycling of plastics results in lower greenhouse gas emissions than composting and incineration due to substitution of virgin material and energy recovery after the incineration of rejected materials. However, it should be noted that these emissions are influenced by sorting efficiencies which are sensitive parameters and can significantly affect the results.
Incineration scores better compared to composting because the credits in kg CO_2 eqv. for the recovery of energy is approximately 6 times higher compared to the credits for using the compost as soil conditioner replacing peat.

4.2 Sensitivity analysis in greenhouse gas emissions

A limited set of scenarios was studied in the sustainability assessment of section 4.1. To get an idea of the sensitivity of the results to the influence of different capsule materials, different waste management practises and of several assumptions, a more elaborate analysis was conducted involving multiple aspects in relation to the greenhouse gas emissions. Section 3.5 describes the scenarios that have been used in the sensitivity analysis.

Different conventional plastic capsules

The greenhouse gas emissions of the two type of coffee capsules made from conventional plastics (PP and HDPE) are shown in Figure 7. The difference in emissions between the two type of conventional plastic capsules is minimal. The differences in impact and avoided impact related to packaging waste is mainly attributed on the difference on the mass and the secondary components of the capsules. In this case, the polypropylene coffee capsule is slightly heavier and contains more secondary materials. In Annex 3 the graph including coffee grounds is presented.

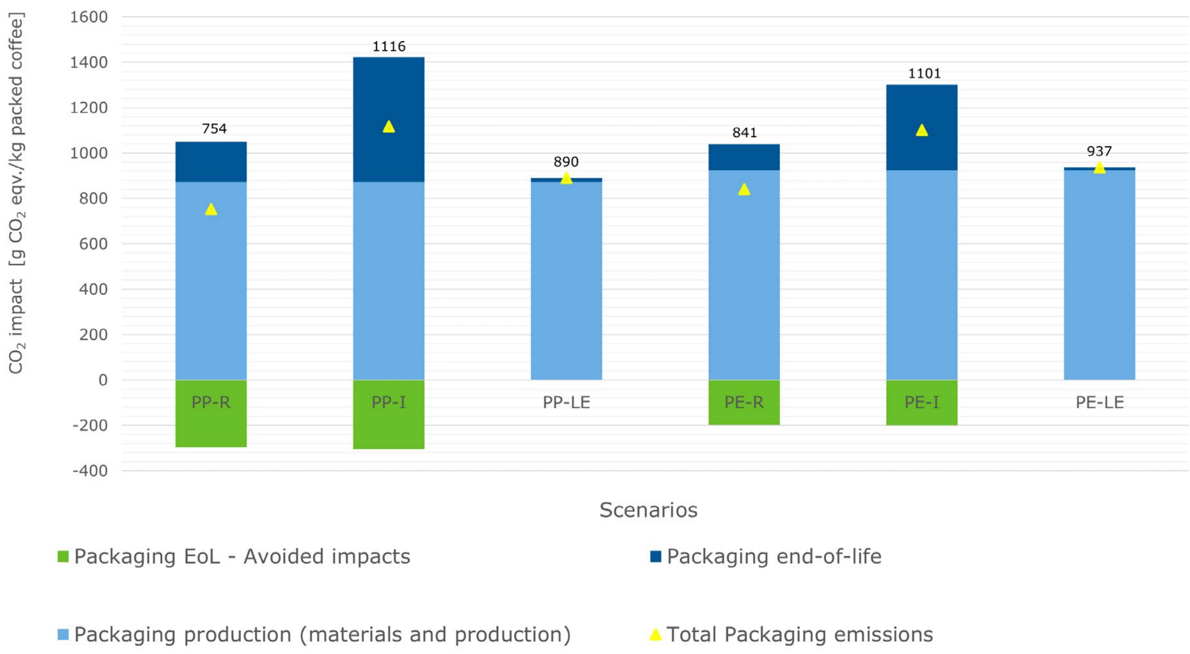

Figure 7: Comparison of contribution to the greenhouse gas emissions between different conventional plastic capsules materials per life cycle stage in [g CO_2 eqv./kg packed coffee].

Different compostable plastic capsules

Just as with the conventional plastic capsules, the impact of the compostable plastic capsules during the packaging waste stages is influenced by the mass of the capsule and the type of different components present in the capsule. The packaging waste and production impact of PLA2 is for all scenarios almost double that of PLA1 since the mass of the capsule is also twice as high. This shows that the mass of the capsule has a more substantial impact on the greenhouse gas emissions than the type of compostable plastic.

For all compostable coffee capsules recycling is the waste management pathway having the lowest greenhouse gas emissions, due to the credits for substituting virgin materials. The avoided impact (in green) derived from the substitution of virgin PLA by recycled PLA is quite high, so it balances the total packaging impact. For completeness, in Annex 3 the graph including coffee grounds is presented.

In case composting is compared with incineration, the much lower avoided emissions for composting are noticeable, which relates to the lower credit for replacing peat with compost than the credits for energy recovery from incineration.

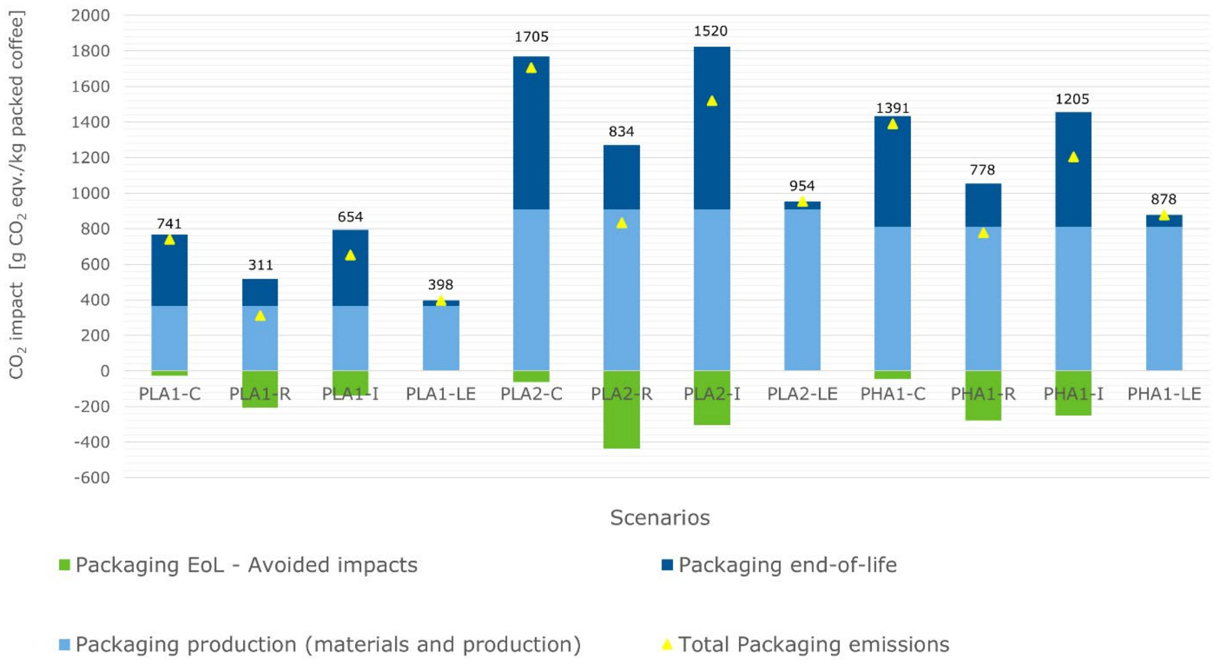

Figure 8: Comparison of contribution to the greenhouse gas emissions between different compostable plastic capsules materials per life cycle stage in [g CO_2 eqv./kg packed coffee].

Different aluminium capsules

The differences in greenhouse gas emissions between the two types of aluminium capsules in the various end-of-life pathways are shown in Figure 9. The differences are limited and can be largely understood by the slightly lighter weight of the Al2 capsule in comparison to the Al1 capsule. It should be noted that the recycled content does not have any effect here due to the selected modelling approach (0-100 approach). This choice is explained in section 3.3. To avoid double-counting of credits for the calculation of greenhouse gas emissions, the production of recycled material at the end of life gets credits, but not the use of recycled content in a capsule.

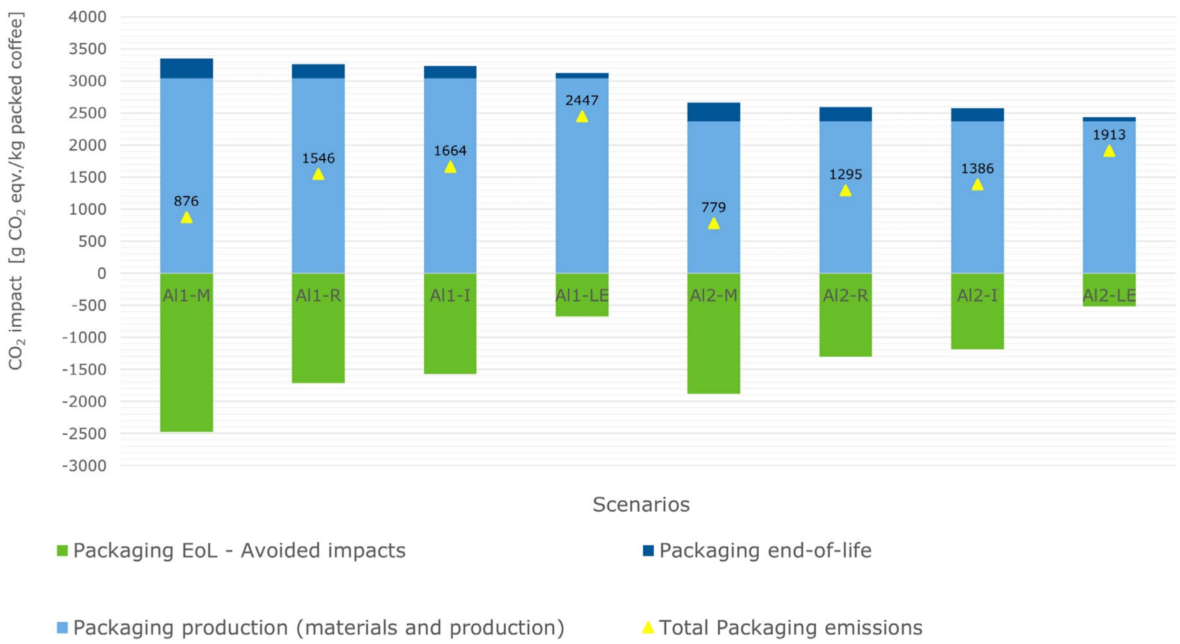

Figure 9: Comparison of contribution to the greenhouse gas emissions between different aluminium capsules materials per life cycle stage in [g CO_2 eqv./kg packed coffee].

Difference in organic waste management methods
Two organic waste management options have been compared for the three compostable coffee capsules: conventional industrial composting versus Dutch organic waste scenario in which a part of the organic waste is also anaerobically digested (AD-C), see Figure 10. As can be observed, the emissions due to the processing of the capsule material waste as well as the avoided impacts are both slightly larger for the Dutch organic waste scenario. The difference is minor but 100% industrial composting does result in a little lower greenhouse gas emissions, as it is assumed that the capsules are not much affected by the anaerobic digestion process.

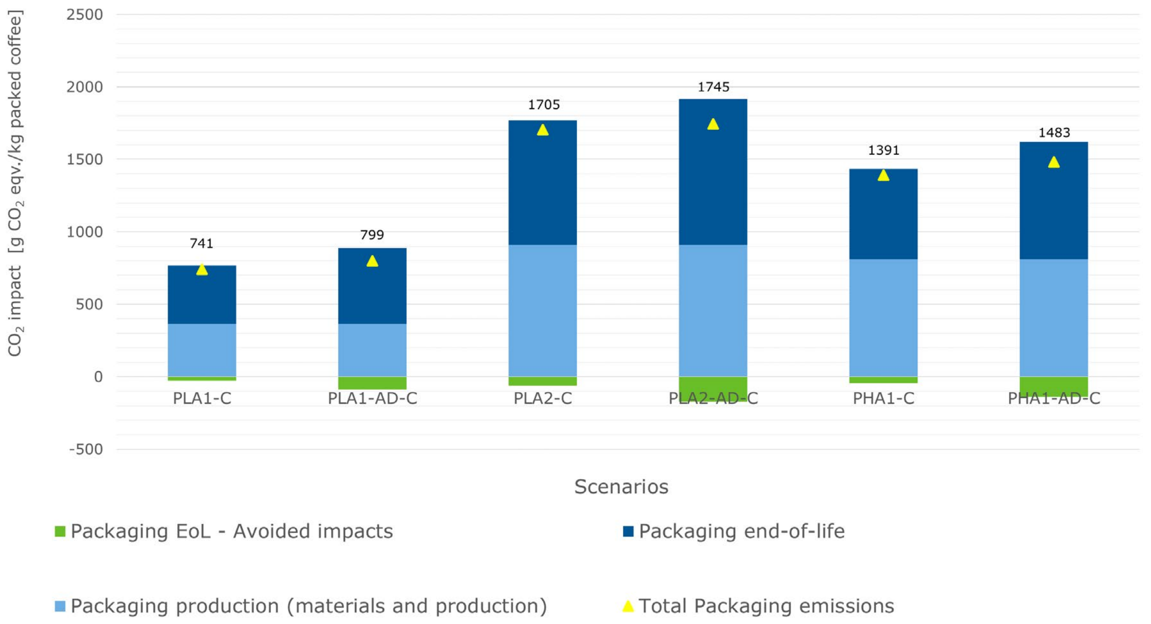

Figure 10: Comparison of contribution to the greenhouse gas emissions between 100% industrial composting and Dutch organic waste scenario (combination of industrial composting and anaerobic digestion) of biobased plastic capsules per life cycle stage in [g CO_2 eqv./kg packed coffee].

Difference in PLA pellet production data
Figure 10 exhibits the effect of using different emission factors for PLA extracted from various sources. The PLA1 emission factor is the baseline data used in this report and includes PLA pellet production data from Vink and Daves et al. [32]. This is representative for the Ingeo biopolymer based on NatureWorks data and the Ingeo production system for biopolymers from industrial corn located in the area between Nebraska and Iowa (US). No renewable energy certificates are used, and the electricity used is from the local grid. The emission factor PLA1a is retrieved from the Ecoinvent database, calculated using the IPCC 2013 GWP 100a V1.03 impact assessment method. Ecoinvent based its analysis on data obtained from a NatureWork's production facility situated in Nebraska, where carbon dioxide emissions are balanced out with wind power certificates. Nevertheless, Ecoinvent made several adjustments, including the addition of infrastructure and alterations to the electricity production method, to ensure the data's general applicability. The emission factor PLA1b is retrieved from data of Morão et al. [42] and is based on the TotalEnergies Corbion PLA production process. The emission factor PLA1a is slightly higher compared to PLA1 and PLA1b. This relates to data processing method of Ecoinvent, that uses for instance European electricity mixes in its calculation to ensure general applicability of the data.

On the other hand, emission factor PLA1b exhibits a slightly lower contribution to climate change. The production is based on sugarcane corn and is located in Thailand, with electricity supplied from the local grid. It is representative only for TotalEnergies Corbion PLA. Compared to NatureWorks data used in PLA1, the TotalEnergies Corbion PLA production process receives credits from the use of by-products of the sugar mill. Also, other differences in the data can be attributed to the differences in the local electricity mix.

These results show that although the greenhouse gas emissions vary between the different type of compostable materials (which relate to local production conditions), the relative impact on the overall sustainability analysis is limited.

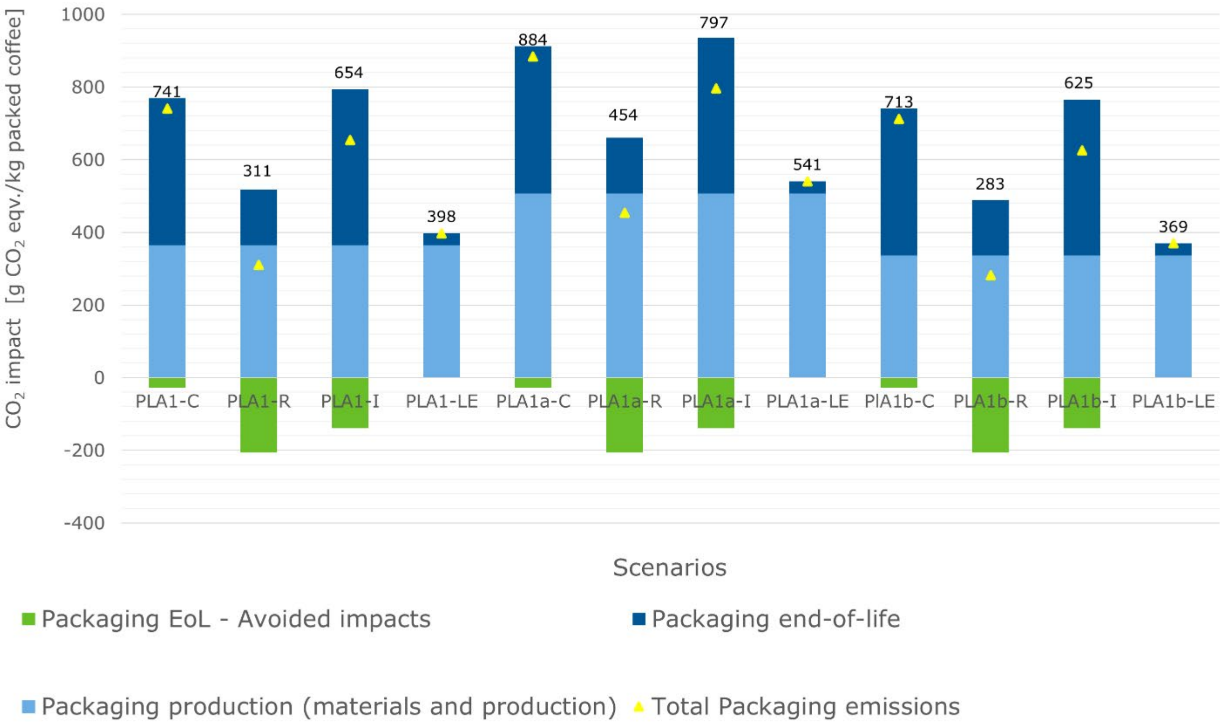

Figure 11 Effect of using different PLA pellet production data (including biogenic carbon) extracted from various sources on the results of the total packaging contribution to greenhouse gas emission.

4.3 Circularity indicators

The material circularity indicator (MCI) [1] is a fairly complete, but hence also complex indicator for material circularity that yields scores that range from 10% (completely linear) to 100% (completely circular). In the calculation of this MCI multiple factors contribute, including: recycling rates, recycled content, recycling process yield, biobased content, reusability and the average lifespan of a product. It should be pointed out that the indicator is calculated based on the material of the packaging only and the coffee grounds are excluded. The MCI scores for the various scenarios are given in Figure 12. The highest MCI scores are for the compostable capsules that are composted after use, reaching 100%, in other words being completely circular.

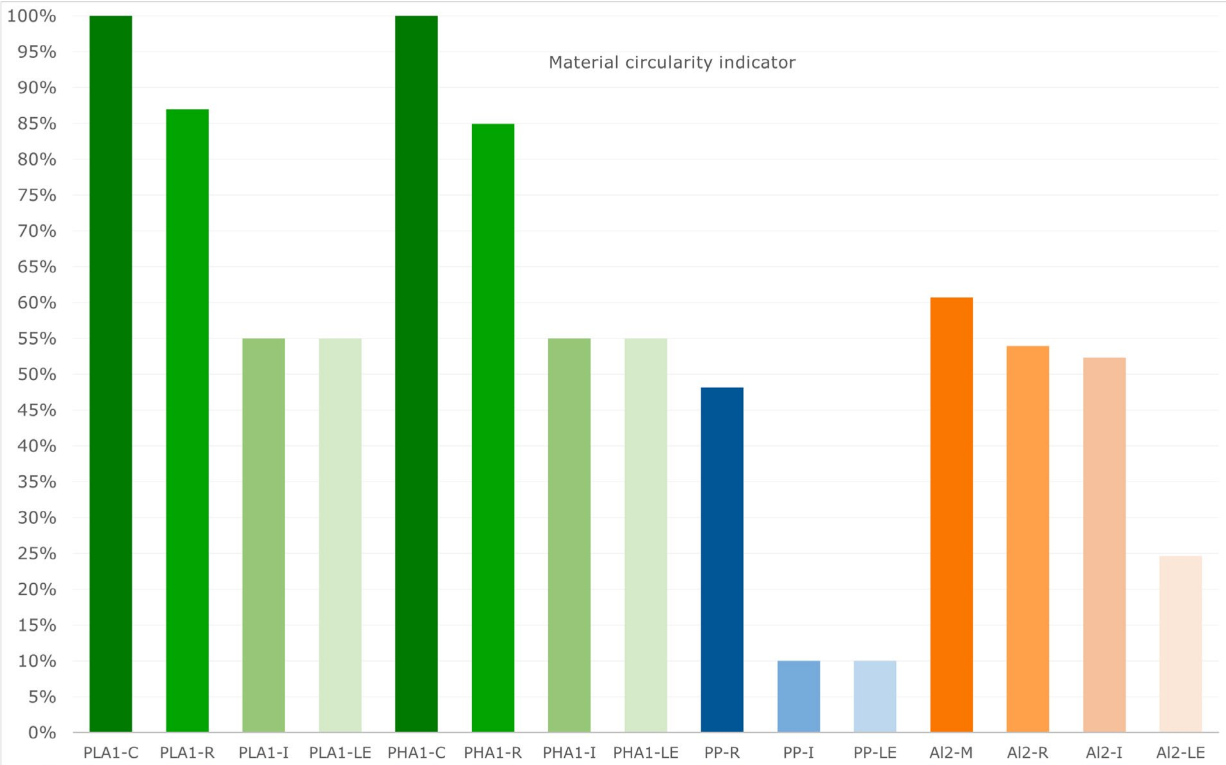

Figure 12: Material circularity indicator score of different coffee capsule main scenarios, assuming a 100% collection in a certain stream. C: industrial composting, R: recycling, I: incineration, LE: landfill with energy recovery. M: mono-collection. Compostable materials are displayed in green, conventional plastic in blue and aluminium in orange.

The MCI scores for all other scenarios are much lower. The lowest scores are awarded to the conventional plastic and aluminium capsules without recycled content that are landfilled after use and the conventional plastic capsule that is incinerated after use. These score 10%, meaning that they are completely linear: made from virgin materials and used only once.
All other scenarios score mediocre MCI values, implying that they only encompass some elements of circularity, but are not considered fully circular. The only slightly elevated MCI value is for scenario Al2-M, which is the aluminium capsule that is made from 40% recycled content that is completely mono-collected and recycled.

In order to draw a broader and more holistic conclusion regarding the sustainability and circularity performance of coffee capsules, both the GWP-100 (greenhouse gas emissions) and MCI must be considered. Otherwise, unbalanced conclusions could be drawn. For instance, landfilling compostable capsules does contribute less to greenhouse gas emissions compared to industrial composting because landfill serves as a carbon sink. From this perspective, landfilling can be viewed as an environmentally benign waste management practise. However, the MCI score for landfilling of compostable plastics is significantly lower than for composting the same type of capsules: 55% vs. 100%, indicating that landfill is a less circular end-of-life option than composting.
Hence, to obtain a more complete understanding of the sustainability assessment. we summarized in Figure 13 the circularity potential of the different capsule materials by combining the MCI of the capsule with the greenhouse gas emissions related to the capsule material for the three main categories of capsule materials: compostable plastics, conventional plastics and aluminium. Please note that the X-axis is reverted, so the minimum emissions are on the right hand side of the graph. This way, the most circular/sustainable solution in terms of both MCI and greenhouse gas emissions will be on the top right corner of the Figure 13.

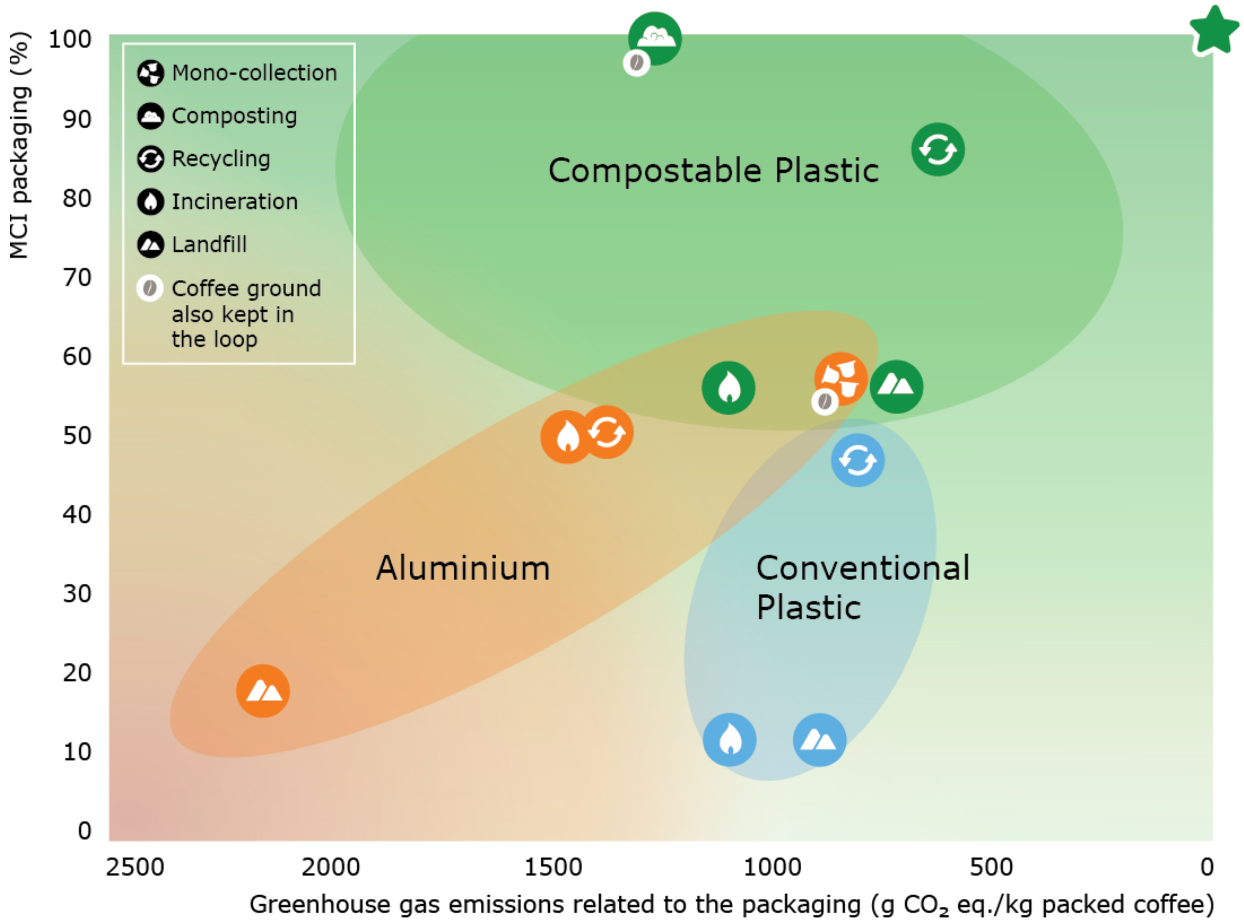

Figure 13: Combined overview of the MCI of the capsule [%] on the Y-axis and the greenhouse gas emissions related to the capsule [g CO_2 eqv./kg packed coffee] on the X-axis for different capsule materials and end-of-life options. Note that the X-axis is reverted, so minimum emissions are on the right hand side of the graph. Capsules included in this graph: PLA1, PLA2, PHA1, PP, PE, Al1, Al2.

Three different colours are used for the materials; green for the compostable capsules, blue for conventional plastic capsules and orange for aluminium based capsules. The 'clouds' represent the individual data points from the various scenarios. The capsule material category with potentially the lowest greenhouse gas emissions and highest MCI is the compostable material in case it is composted or recycled. A second best material for capsules is aluminium (made with recycled content) in case it is recycled via mono-collection. Conventional plastics are, based on MCI, the least circular and based on greenhouse gas emissions, have mediocre carbon footprints. Moreover, even though the greenhouse gas emissions for landfilling compostable capsules is lower than composting the same capsules, figure 12 clearly shows that the composting of these capsules is the more sustainable option.

The scores of all other indicators that were investigated in this study are included in Annex 4 along with their graphs. A summary overview is given in Table 12. An explanation of the various indicators can be found in section 3.2.

Table 12: Overview of total greenhouse gas emissions and other indicators for the main scenarios.

Code	Total Emissions (incl. coffee) [g CO2 eqv./kg packed coffee]	Emissions (capsule only) [g CO2 eqv./kg packed coffee]	MCI	ReConI	ReNewI	RI	RCI	ORI	LPI
PLA1-C	7310	741	100%	0%	100%	0%	0%	100%	88%
PLA1-R	6476	311	87%	0%	100%	92%	59%	0%	88%
PLA1-I	6819	654	55%	0%	100%	0%	0%	0%	88%
PLA1-LE	7518	398	55%	0%	100%	0%	0%	0%	88%
PHA1-C	7960	1391	100%	0%	100%	0%	0%	100%	100%
PHA1-R	6943	778	85%	0%	100%	86%	55%	0%	100%
PHA1-I	7370	1205	55%	0%	100%	0%	0%	0%	100%
PHA1-LE	7998	878	55%	0%	100%	0%	0%	0%	100%
PP-R	6919	754	48%	0%	0%	96%	61%	0%	75%
PP-I	7281	1116	10%	0%	0%	0%	0%	0%	75%
PP-LE	8010	890	10%	0%	0%	0%	0%	0%	75%
Al2-M	7348	779	61%	32%	0%	81%	79%	0%	75%
Al2-R	7460	1295	54%	32%	0%	81%	44%	0%	75%
Al2-I	7551	1386	52%	32%	0%	81%	37%	0%	75%
Al2-LE	9033	1913	25%	32%	0%	0%	0%	0%	75%

MCI: Material Circularity Indicator, ReConI: Recycled content indicator, ReNewI: Renewable content indicator, RI: Recyclability indicator, RCI: Recycling chain indicator, ORI: Organic recyclability indicator, LPI: Littering prevention indicator

The indicators linked to traditional recycling (RCI and RI) score high for aluminium capsules and low for compostable capsules, however, for the organic recycling indicator (ORI) this is the opposite. Even if coffee capsules do not have a high risk to end up in the litter, the LPI shows that if it happens, PLA (and even more so for PHA) is less of a problem for nature than aluminium, as it will (eventually) biodegrade. The aluminium capsules use recycled content so the ReConI indicator is higher, whereas the compostable capsules use 100% renewable feedstock and no fossil feedstock, resulting in a higher ReNewI indicator for the compostable solution. This clearly shows sustainability can be perceived from multiple perspectives.

4.4 Origin and fate of coffee and capsule materials

For a thorough understanding of the circularity of coffee capsules, the origin and the fate of both the coffee and of the capsule materials was mapped. The system perspective approach of the scenarios was followed, implying that we assume that the collection rates are 100% in the chosen scenarios (what-if approach). Per group of capsule materials we will discuss what happens in the different end-of-life scenarios. The results are summarised in Table 13.

4.4.1 Conventional plastic capsules

The applied plastics in the capsules (HDPE or PP) are virgin plastics, produced from crude oil. The recycled content is 0%, since there is no food grade recycled feedstock available in sufficiently large quantities. After-use the capsules in our scenarios are either incinerated, recycled or land-filled.

Incineration

During incineration the capsule material and the SCG are converted in CO_2 and nutrients from the SCG are lost.

Recycling
During recycling only a small share of the capsules ends up in the PE or the PP sorted product and these are sent to recycling facilities at which the aluminium foil is removed and coffee is washed out. This means that most of the coffee capsules that are collected for recycling are ending-up in rejects that are incinerated and a small fraction that is actually open-loop recycled into either rPE or rPP which is used in cable lining, battery box housings, etc. The coffee from the capsules that are collected for recycling will be incinerated and turned into CO_2 and the nutrients are lost. Either these SCG will end-up in the fine rejects or in the waste water. In the Netherlands the sludge of waste water treatment plants is mechanically dried and incinerated.

Landfill
During landfilling, the SCG will slowly degrade and either be converted in methane that could be captured or in CO_2. The plastic capsule itself will not degrade and also the aluminium foil will remain.

4.4.2 Aluminium capsules

Aluminium used in capsules is often newly produced and of a specific alloy that allows for press moulding. But since freshly produced aluminium contains so much embodied energy, producers seek for recycled content to lower the carbon footprint of the aluminium. However, only very specific alloys can be used. Either recycled beverage cans, internal production scrap and recycled coffee capsules. In the common production process of aluminium capsules there is substantial amount of punching scrap (named skeleton in the recycling trade). The roll of aluminium is unrolled and fed into a punching machine that produces discs that can further be shaped into capsules. To minimise the risk of tearing the thin sheet during punching safety distances between the outside rims and the punch holes have to be respected. According to process operators the weight of a skeleton roll is roughly 40% of a new sheet roll. Since this punch scrap is already coated internally and externally, it has to be de-coated first, then remelted and converted into a new roll of aluminium sheet, coated and re-used. Therefore, large coffee capsule manufacturing operations will have a recycled content of at least 40%, and this is post-industrial recycled scrap. When the recycled content exceeds 40% it will likely originate from post-consumer beverage cans or coffee capsules. Since the amount of recycled aluminium originating from coffee capsules is small, most will originate from beverage cans. For the Nespresso aluminium capsules we were informed that they contain 80% recycled content, which likely implies that 20% virgin aluminium is used, 40% post-industrial scrap and 40% recycled beverage cans or coffee capsules. As the collection rate of all Nespresso-style capsules in The Netherlands is maximum roughly 29% (according to a consumer survey) and there are losses during recycling, we can only crudely estimate that this 40% post-consumer recycled content is likely 20% capsules and 20% beverage cans. The Blokker capsules are produced at Alu-sense in Belgium [35]. Currently, these capsules have 0% recycled content, but the expectation is that in Q1-2024 80% recycled content will be used. If indeed Alusense manages to attain this level of recycled content in 2024, than it is likely that it will be comprised of similar contributions of post-industrial and post-consumer aluminium as for the Nespresso capsules.

Mono-collection
After mono-collection, most aluminium from the capsules is recovered, pyrolysed and remelted to ingots. The aluminium losses are relatively low and the alloy composition is largely maintained. The SCG are separated off and composted. Hence, a large part of the SCG is converted into CO_2 and a small share into humus and the nutrients are maintained. Composting of the SCG from the aluminium capsules is likely to be executed in a mixture with other organic waste. The lid of the capsule is sorted out as sorting residues and is directed to incineration where a part of it is recovered from bottom ashes and remelted.

Recycling (collection via LWP)
In case the coffee capsules are collected with LWP, a share will end-up in the non-Ferrous fraction and be recycled. The rest will end-up in the sorting residue fraction. The sorting distribution depends on the equipment used in the sorting facility. The aluminium in both fractions (NF and residue) will undergo several process steps after which aluminium products are recovered. The lid is ending up in the sorting residues, which will be incinerated. The elemental composition has changed, making this iron and silicon rich type of alloy more suitable for casting applications and not for thin sheet applications. The SCG present in the aluminium capsules in either sorting product (NF or residue) will end-up being incinerated, hence be converted in CO_2 and the nutrients are lost.

Incineration
In case the coffee capsules are incinerated, roughly half will oxidise and be lost and the rest can be recovered as a casting alloy. This recovered aluminium is accounted for in the calculation of the avoided emissions in Figure 6. The SCG are converted in CO_2 and the nutrients are lost.

Landfill
In case the aluminium coffee capsules are landfilled, the aluminium will remain, whereas the SCG will slowly decompose in either methane or CO_2. The nutrients are lost.

4.4.3 Compostable plastic capsules

PLA is produced from sugar or starch rich agricultural feedstocks such as sugar cane and corn respectively. PHA is produced by bacteria that are fed with sugars or fats. There is no real competition with food production, due to the production locations which have excess of these agricultural feedstocks. After use the capsules are composted, recycled, incinerated or landfilled.

Composting
In case the compostable capsules are collected with municipal organic waste and composted, most of the capsule material and the SCG is converted in CO_2, some is converted in humus and the nutrients of the coffee are maintained.

Recycling
Recycling of PLA is possible in different ways. In this study mechanical recycling is modelled, even if it is not yet happening at scale in the Netherlands. The sorting challenges related to the small size of capsules, that have been described for conventional plastic capsules in LWP, are valid for compostable coffee capsules in this stream as well.
In case the compostable capsules are recycled via depolymerisation, the capsule material can be retrieved. Since this recycling is not operational yet, we cannot determine the quality of the recycled capsule material. In case this material will be depolymerised, purified and repolymerised the quality should be comparable to virgin. The paper fibres and the SCG will end-up in the waste water, after which the sludge will be dried and incinerated and the nutrients in this sludge are lost.

Incineration
In case the compostable capsules are incinerated both the capsule material and the SCG are converted to CO_2 and the nutrients are lost.

Landfill
In case the compostable capsules are landfilled SCG will slowly decompose to form CO_2 and methane and the nutrients are lost. The compostable capsules exhibit almost a zero biodegradation rate inside [36].

Table 13: Overview of the origin of the capsule materials and the fates of the capsule materials and the spent coffee grounds (SCG) in various scenarios.

Scenario	Origin Capsule material	Fate capsule material	Fate SCG
PLA1-C	Corn/sugar cane	CO_2, humus	CO_2, humus, nutrients kept
PLA-R		Some rPLA, CO_2	CO_2, nutrients lost
PLA1-I		CO_2	CO_2, nutrients lost
PLA1-LE		Lost	CO_2, CH_4 , nutrients lost
PHA1-C	Plant oils*	CO_2, humus	CO_2, humus, nutrients kept
PHA1-R		Some rPHA, CO_2	CO_2, nutrients lost
PHA1-I		CO_2	CO_2, nutrients lost
PHA1-LE		Lost	CO_2, CH_4 , nutrients lost
PP-R	Crude oil (fossil based)	Some rPP, CO_2	CO_2, nutrients lost
PP-I		CO_2	CO_2, nutrients lost
PP-LE		Lost	CO_2, CH_4 , nutrients lost
Al1-M	100% new Al	Recycled Al partially suited for closed loop	CO_2, humus, nutrients kept
Al1-R		Recycled Al open-loop	CO_2, nutrients lost

Scenario	Origin Capsule material	Fate capsule material	Fate SCG
Al1-I		Small amount of recycled Al open-loop	CO_2, nutrients lost
Al1-LE		Lost	CO_2, CH_4 , nutrients lost
Al2-M	20% new Al +	Recycled Al partially suited for closed loop	CO_2, humus, nutrients kept
Al2-R	40% PI scrap +	Recycled Al open-loop	CO_2, nutrients lost
Al2-I	20% PC beverage cans +	Small amount of recycled Al open-loop	CO_2, nutrients lost
Al2-LE	20% PC capsules	Lost	CO_2, CH_4 , nutrients lost

*: The data in the tool relates to corn

4.4.4 Circularity of coffee capsules

From this overview, it is apparent that only the compostable coffee capsules are completely circular with respect to both their capsule material and the coffee when they are composted. Both are recycled via the bio-spherical loop. Two parameters are critical in this looping strategy. First of all, it needs to be ascertained that the whole capsule is composted during the operation and secondly that the agricultural feedstocks used for the production of either PLA or PHA do not compete with food production and secondly that the agricultural feedstocks used for the production of either PLA or PHA are produced in a sustainable, responsible way.
Also the mono-collection system for aluminium coffee capsules has circular elements but is not completely closed loop circular. First, production of the capsule material will require some new virgin aluminium for each loop. Looping with 100% recycled capsule material is currently not possible due to the low participation rates of the mono-collection system and due to the unavoidable accumulation of foreign elements during closed loop recycling which will make the recycled aluminium after multiple closed-loops less suitable for capsule production. The spent coffee grounds can be recycled closed loop via composting, and this is preferably done by mixing in other types of organic waste, to manage the aluminium concentration of the compost.
The conventional plastic capsules are not circular at all. In the most favourable case some HDPE or PP can be recycled via the LWP collection and sorting system, but the resulting recycled plastics are not food-grade and hence not suited for coffee capsules. Also the SCG within the plastic capsules is completely lost.

5 Discussion

5.1 Methodology

This study used the MuDiSa tool to assess the sustainability of commonly applied Nespresso style coffee capsules in different waste management practises. This tool has been developed to ascertain the sustainability impacts of food packages and was practical to map out the impacts of these coffee capsules in the various dimensions of sustainability. Although other tools could have been used that perhaps would have rendered a more detailed impression of some specific aspects of sustainability, this tool gives a first high level overview of a wide range of sustainability indicators and the required data could be acquired within the time frame of this project.

Nevertheless we had to make subtle adjustments to the tool to evaluate coffee capsules. In the coffee capsule case, the food product remains inside the package after consumption in the form of spent coffee grounds (SCG) and this is markedly different than most other food-packaging cases. As the product and the packaging cannot be separated when discarded, they will undergo the same end-of-life route. Consequently, for the coffee capsule case it is especially relevant to focus on the after-use processing of both the capsule material and of the SCG. Directly after brewing, the water content of spent coffee grounds is high. However, the collection and end-of-life treatment of coffee capsules does not take place right after the disposal and the water content is decreasing with time. Therefore for simplicity, the tool is using the dry mass of spent coffee grounds to calculate the impact of end-of-life processes. In reality there will still be some moisture in the coffee, and during incineration of capsules, the contained moisture will evaporate and this will reduce the credits allocated to the greenhouse gas emissions by avoided production. This reduction in avoided production is not taken into account, meaning that in reality greenhouse gas emissions during incineration will be somewhat higher.
During composting, most of the spent coffee grounds are likely converted to either CO_2 or to humus. Over the time scale at which the global warming potential is calculated (100 years) it is very likely that all coffee grounds are completely converted into CO_2, but in the intermediate period the humus originating from the coffee grounds will become part of the compost product. The benefits of the use of compost are difficult to capture in unambiguous numbers for sustainability indicators, but include for example:

- Improving the structure and health of the (agricultural) soil by adding organic matter.
- Helping the soil retain moisture and nutrients.
- Attracting beneficial micro-organisms to the soil and reducing the need for pesticides and fertilizers.
- Reducing the potential for soil erosion.
- Sequestering carbon in the soil.
- Building resiliency of the soil to the impacts of climate change.

Because of the difficulty in translating these benefits into parameters such as emission factors, current LCA models do not take them into consideration. The only benefits that are accounted for in the current study is when the produced compost is used to replace peat, which results in some avoided emissions and avoided use of fossil resources.

It should be noted that the calculation of the greenhouse gas emissions for the various end-of-life options involves many different modelling choices and approaches that have a profound influence on the final results. We found only 2 papers in which the same methodology was applied to all the materials and all the end-of-life options we investigate in this study, in particular Moretti et al [44] and Hermann et al [41]. In both articles significantly different choices are that, though seemingly small, can have a notable effect resulting in substantial difference in values. Some examples are:

- For the greenhouse gas emissions of industrial composting, one critical distinction is that Moretti's article considers the incineration of rejected material (30%) and provides a credit for energy recovery, which significantly reduces CO_2 emissions (by almost 30%).
- Moretti also opts to calculate with compost replacing not only soil conditioners but also fertilizers, which have higher credits.

- Moretti chooses to include the impact of compost application on the land, while Hermann excludes this process. Moretti credits the application of compost due to the reduction in field emissions resulting from the avoidance of synthetic fertilizer application. Hermann, on the other hand, excludes emissions of nitrous oxide resulting from fertilizer application, considering them solely dependent on nitrogen content. The land use stage contributes 25% to the GWP of industrial composting impact.
- The contribution of construction and operation varies.
- Moretti provides a credit for the difference in diesel consumption of a powered spreader during compost application.

In other words, the two studies are not easily comparable because Hermann's study is based on the carbon and energy content of the material, while Moretti's study includes many other processes contributing to the global warming potential. In general, the energy mix in the process is traditionally one of the most sensitive parameters. There is no good or wrong in these choices, as long as they are used consistently when the aim is to compare the calculated emissions of different materials for the various end-of-life scenarios.

All considering, the data from Hermann et al is selected for this study because it is most in line with the background of other data used in this study.

These observations underscore the importance of not taking greenhouse gas emission results for granted. It's essential to closely examine not only the final results but simultaneously the methodology used, before drawing conclusions. It also justifies why we use multiple sustainability indicators besides the calculated greenhouse gas emissions to compare different types of coffee capsules for different end-of-life scenarios in terms of sustainability.

An imperfection of the tool is that emission factors for recycled aluminium from other origins than recycled beverage cans are not publicly available and hence the emission factors of recycled beverage cans had to be used for recycled content in the aluminium capsules, although we expect that also recycled content with a different origin is used in these capsules (see section 4.4.2).

5.2 Consequences of shifting policy objectives

Governments and companies have their own policies to reduce the environmental impacts of consumer goods and these do not necessarily align. For most food companies a reduction of the greenhouse gas emissions is paramount and consequently they often have self-imposed carbon footprint reduction targets. And since in the vast majority of the packaged food products, the food itself causes more emissions than the package, most companies focus on reducing the food-related emissions, including those related to food-waste. Many companies also embrace circularity goals for packages, but often regard these as secondary in comparison to the higher sustainability objectives. For example, most companies have pledged to make all their packages recyclable, reusable or compostable in either 2025 and 2030 via Plastic Pacts. Furthermore, in a response to the newly proposed recycled content policies in the PPWR we currently witness a shift in several companies, to focus more on getting their 'own' packaging materials back and keeping them in the loops they manage, and hence to focus less on lowering the overall environmental impacts of the whole packaged food product. The ramifications of this shift is further discussed at the end of this section.

Currently, governments do not only want to address climate change, but also littering and pollution issues through packaging waste legislation but this hasn't been the priority up to a few years ago. In 1992, the EU initiated packaging waste policies with the first packaging and packaging waste directive 62/94 [25]. They set out with demanding recycling targets to limit the negative impacts of packaging wastes. Over the years, this directive has been revised multiple times, which effectively meant that the recycling targets were raised in time [26]. Only in 2019, with the Single Use Plastics (SUP) directive, product bans were added to the legal tool box [27]. In 2022, the UK implemented a virgin tax for plastic objects containing less than 30% recycled content. In the proposed PPWR we see multiple proposed policies: recycling targets, recycled content targets, reuse targets, product bans, consumption reduction, etc.[5] Hence, nowadays for the governments, not the packaged food products are in the focus of the environmental policies, but only the packages themselves. With this shift in policies, the overall sustainability of the packaged food product is lost out of

sight and the focus shifts to circularity indicators such as recycling targets, reuse targets and recycled content targets. As the legislators perceive these circularity indicators to offer more tangible results than carbon emission reduction policies. But striving for circularity of only packaging materials doesn't guarantee sustainable outcomes for packaged food products and risks the chance of cementing frameworks that hinder progress towards more sustainable solutions.
This is especially true for this specific case, as a coffee capsule-after use contains more spent coffee grounds than capsule material and it therefore would make sense to find solutions that would keep both the organic matter of the SCG and the capsule materials in their respective loops, in such a manner that the greenhouse gas emissions would be minimal.

When stakeholders only focus on the retrieval of their own packaging material and use this as recycled content in new packages, it is likely that these companies will opt for reuse or recycling systems in which they have control over the packaging material. In the case of coffee capsules, the aluminium capsules with a mono-collection system are then ideal. Looking from this perspective of having control over the packaging material, compostable capsules could be regarded as a non-circular solution, because the manufacturer does not get its own capsule-material back for another loop. And although this is correct, it ignores that with compostable capsules both circles are completely closed and new coffee and capsule material can be obtained from agriculture via the bio-spherical loop.[4] As long as food companies are legally obliged to keep packaging materials in loops, whereas they are not encouraged to keep the contained food products in the bio-spherical loop, this bias will not be resolved.

The current focus of the FMCG industry to get control over their own packaging materials is the consequence of the recycled content targets for PET bottles in the SUPD [2019/904/EC] and the further elaboration to all plastic packages in the proposed PPWR [396/2022/EC]. In preceding waste management legislation such as the WFD [98/2008/EC] and the PPWD [852/2018/EC] the focus of the legislator was on attaining recycling targets, hence on the quantity of the recycled material and not on the quality. Consequently open-loop recycling systems were erected and issues such as emptiability of packages, leakage to the environment and cross-contamination of the various separately collected materials were not addressed. Future waste legislation should promote long-term, highly circular solutions and avoid the pitfalls of rebound effects.

5.3 The fit of coffee capsules in the current waste management practises

Coffee capsules were invented to offer convenience to consumers, they were not designed to fit in an existing waste management scheme. This implies that the capsules will need to fit in somewhere and preferably be an asset to that waste fraction (hence delivers more material of a similar composition) and doesn't obstruct or hinder the processing. Alternatively, dedicated collection schemes have to be set-up to deal with the used capsules. For coffee capsules in principle the following waste management schemes are potentially relevant: (a) separate mono-collection and recycling, (b) collection with lightweight packaging waste, sorting and recycling, (c) collection with organic waste and composting, (d) collection with mixed municipal solid waste (MSW) and incineration and finally (e) collection with MSW and landfilling. For most combinations of these waste management schemes with the main capsule materials there are, however, challenges and issues. For (d) and (e) there is a "fit", as almost anything can be incinerated or landfilled, but these are final resort / dead-end strategies that are contrary to circularity and will no longer be promoted in European policies. This is explained below for the combinations of capsule material and waste management systems for which this is relevant and this information is summarised in Table 14 near the end of this section.

5.3.1 Aluminium capsules and mono-collection

Aluminium capsules fit the best in a mono-collection system, since this has been designed for these capsules and renders the lowest greenhouse gas emissions (Figure 6) and the highest MCI values (Figure 12).

[4] Legally,composting is regarded as a form of recycling of organic substances, see Annex II of Waste framework Directive [49]

Consumers fill collection bags at home with used capsules and send these via the regular mail service to national cross-docking stations, from which lorry freights are sent to large central processing facilities. Additionally, there are collection points in various shops from which it is forwarded to the same central processing facility. Here the plastic bags are opened and the contents are milled, air-classified and treated with an Eddy current separator to yield three fractions: aluminium, spent coffee grounds and plastics. All three fractions are processed separately. The aluminium is remelted to ingots. The coffee grounds are composted and the plastics are converted in rLDPE pellets. The fit of this process method is obviously optimal since it was purposely designed for it. The self-evident downside is that it is a new and additional collection system that requires civilians to participate and it has turned out to be far from simple to accomplish high return rates with a voluntarily mono-collection system via the regular post. The results of the Kantar consumer behaviour study reconfirms this general notion; of all the types Nespresso-style capsules only 29% of consumer participate in the mono-collection scheme [2]. This relative low participation rate is not considered in the calculated greenhouse gas emissions data in Figure 6 and Figure 9, since these calculations have been executed under the assumption of 100% participation. When realistic participation rates would have been used in the calculation, the overall greenhouse gas emissions would have been higher (higher direct emissions and lower avoided emissions).

5.3.2 Aluminium capsules in LWP

Aluminium capsules that are collected with LWP will be sorted in a sorting facility and it will depend on the configuration of the sorting facility whether the aluminium coffee capsules end-up in the non-Ferrous-metal product (NF) or in the sorting residues. The decisive aspects are the sieve size of the drum sieve and the presence of Eddy Current separators over only the middle-sieve fraction or also over the fine-sieve-fraction. With this respect we see a gradual development in the design of sorting facilities. The more modern sorting facilities in for example Belgium and in Zwolle all have Eddy current separators over both sieve fractions and therefore they will recover aluminium coffee capsules from the LWP at relative high efficiencies of roughly 80%. The NF fraction is subsequently traded with metal processors. This is a heterogeneous group of companies. The older dry mechanical recyclers will not be very happy with the presence of coffee in the NF product. They typically will mill, sieve and purify the metal with Eddy current separators to yield a cleaned NF product. For them the presence of coffee capsules results in more sieving losses that needs to be incinerated. Whereas, dedicated pyrolysis plants for NF (for instance Prezero Pyral) will not have much issues with the presence of coffee grounds, it can only result in slightly longer process times. The most modern NF sorting plants that use density separation technologies to sort the NF metals, cannot work with organic impurities and will need the NF fraction to be mechanically pre-treated first. In all cases the aluminium can be retrieved, but the spent coffee grounds are either incinerated or pyrolyzed and are hence lost. An important difference with the mono-collection system is that the recycled aluminium from LWP contains more trace elements as iron and silicon which makes this recycled aluminium alloy suited for casting applications but unsuited for the production of new capsules. Hence, the collection of aluminium capsules with LWP will effectively result in the open-loop recycling of aluminium.

A few years ago, the EPR-organisations regarded the aluminium coffee capsules in the LWP as contaminants. Capsules didn't qualify legally as packages (since they are discarded full) and hence the producers didn't have to pay EPR fees (extended producer responsibility – producer paying for the end-of-life of their packaging) and no actions were taken to improve their recycling by the EPR organisation. Formally, they were regarded as contaminants and were placed on negative lists (those objects that should not be added to the LWP). This, however, changed. Civilians did throw the aluminium capsules in the LWP and after a few years, the producers had to pay EPR fees, although the capsules formally were still not accepted in the LWP. In Belgium the Fost-Plus EPR operator is currently embarking on a series of tests to improve the sorting of these capsules and to optimise the recycling of the produced NF product in which the aluminium capsule is contained. For the EPR organisers in general, the challenge is to incentivise the sorting facilities and the recycling facilities to accept the capsules in the LWP and the NF product and to adjust their processes accordingly. As most of these companies invested in expensive facilities to sort or recycle, this is either a quick fix or an expensive upgrade and can form a barrier.

5.3.3 Conventional plastic capsules in LWP

Plastic coffee capsules are present in the Dutch LWP, although in small shares, according to own observations during sorting of LWP and sorted products PE and PP. Depending on the sieve size of the drum sieve they will either be present in fine sieve fraction or the middle sieve fraction. Most of them will be present in the fine sieve fraction and currently, there is no technology to recover them from this waste stream, implying that these will be incinerated. The relatively small share of capsules that end-up in the middle sieve fraction can make it to the cascade of NIR sorting machines and be positively sorted out into the PE or PP sorting fraction. This sorting fraction will be traded with either PE or PP recyclers that will mill, sieve and wash the plastic packages. The coffee capsules will be a minor constituent, but still it will reduce the processing yields, since the main mass of these capsules is coffee grounds that is either sieved out or washed out. Furthermore, these plastic capsules have aluminium sealed lids that are difficult to remove completely, so it is likely that a part of these lids make it to the intermediate product of washed milled flakes. Since, metals are detrimental for extruders and can clog melt filters, often an Eddy current metal separator is placed before the feed hopper of the extruder. These metal separators blow out generously to protect the equipment, hence one piece of metal is blown out with dozens of neighbouring plastic flakes. Hence a small metal contaminant can cause substantial material losses that need to be incinerated. Not all recyclers are fully aware of the presence of this minor constituent of their feedstock and hence only a few recyclers are not very enthusiastic about the presence of these coffee capsules in the sorted PE and PP products.

Most EPR organisations have more urgent concerns than conventional plastic coffee capsules. Nevertheless in Belgium, Fost-Plus will attempt several tests in 2023 to recover the plastic capsules from the sorting fines with NIR separation technologies. Based on the composition of the sorting fines and limited efficiency of NIR sorting for smaller objects, this is deemed to be challenging.

5.3.4 Compostable capsules in organic waste

Although compostable coffee capsules are made from compostable plastics, most Dutch organic waste processing companies are opposed to their presence in the organic waste. To our knowledge, only DAR Nijmegen accepts compostable capsules in the organic waste. To understand the opposition we need to explore the current status quo of the organic waste industry.

In the Netherlands, municipal organic waste (i.e. household kitchen/vegetable/fruit and garden waste) is collected separately and processed by 21 different installations into compost. 11 of these organic waste treatment facilities (processing about a third of the total volume of source separated organic waste) have an anaerobic digestion process as pre-treatment before the aerobic composting process. The various composting technologies can be roughly categorized into 4 types; tunnels, halls, open air, and pacom (table composting under roof). Each facility has its own unique processing scheme.

Separately collected organic waste from Dutch households still contains contaminants such as plastics, glass and metals [28]. Most of the plastics present are conventional fossil-based plastics that occasionally have some relation to organic matter, such as plant pots, plant labels, etc. These contaminants need to be removed during the process to obtain a compost that is saleable and fulfils the low contamination threshold values [29]. Separately collected organic waste is a heterogeneous wet material with aggregated/entangled pockets that is difficult to sort and process. The 21 composting companies have developed different processes and strategies to process this organic waste, but all have to remove contaminants. In general, most companies loosen the collected material by modest bruising and sieve the material to remove over-sized objects that are subsequently sorted. In some cases these pre-treatment sorting residues are discarded and sent to incineration, in other cases contaminants such as stones, glass, metals, plastics are removed with a variety of pre-treatment technologies and the remaining over-sized objects that are organic in nature (branches, wood) are recirculated into the process. After this pre-treatment, the organic waste is composted in an industrial setting in which the temperature of the process needs to be well-managed. The temperature needs to exceed 55°C for sanitation (killing pathogens and seeds of weeds), but it should also not exceed 70°C for too long to keep the microorganism responsible for the decomposition alive. At the end of the composting phase (with an average residence time of 18 days, but varying between facilities from 5 to 70 days), the process is steered to dry the material to facilitate sieving and removal of contaminants. In a well-managed process this will result in a compost that is well-suited for agriculture and domestic use in gardens. The post-treatment sieving residues are in some cases discarded and incinerated, and in some facilities recirculated into the process where they are mixed with freshly arrived organic waste to undergo the next composting cycle. Overall, composting organic waste is sensitive for disruptions, with large technical and financial consequences. Accepting a contaminated load of organic waste will not only result in compost that is too contaminated to be marketed, but it will also result in high additional incineration costs. On top of that, it is difficult to notice contaminants in organic waste during the acceptance procedure. Therefore, it is well-understandable that the organic waste management industry is concerned with the rise in average contamination levels in Dutch organic waste from 0.85% in 2000 to 3.9% in 2019 [27]. Consequently, 13.8% of the separately collected organic waste is removed during the composting and cleaning process and is incinerated.

In short, the Dutch organic waste management sector is against the recycling of compostable plastic objects to compost with separately collected organic waste, because they fear that it will result in the further contamination of the organic waste with plastics, because civilians will find it difficult to make the distinction between conventional non-degradable plastic objects and compostable plastic objects. They worry that accepting the presence of compostable coffee capsules in the organic waste will not only result in the presence of the targeted compostable capsules, but also of conventional plastic and aluminium based capsules, that will finally boil down to higher costs for its industry and less marketable compost being produced. Furthermore, the sector wants to convey, simple and easy to understand messages to the general public on how domestic waste should be separated. It is therefore important for this industry that only homogeneous categories of consumer goods are accepted that are easily distinguished by individuals. For example in the recent past, the whole category of used tea bags and coffee pads was accepted for organic waste treatment, after the Dutch Coffee and Tea industry committed to switching to compostable components only for the whole product category and refraining from placing non-compostable alternatives on the Dutch market [43]. In our perspective as independent scientists, this is a valid point of the waste management industry. On the other hand, in Ireland and Italy the compostable capsules are already treated with the organic waste and no issues have been reported, as far as we are aware.
Another minor downside of organic recycling of compostable coffee capsules is for the time being the incomplete coverage rate for separate collection systems of organic waste. Legally, all Dutch municipalities have to offer a separate collection scheme for organic waste, but a few exemptions are given in case it is excessively expensive or technically infeasible [30]. Especially in the large urban centres there are still a few neighbourhoods in which the organic waste is not separately collected. These are predominantly areas with high-rise buildings.
In the original PPWR text, the European Commission proposes an obligation to make all coffee capsules from compostable materials. Either such a legal intervention or a voluntary agreement could resolve the current lock-in.

In conclusion, the processing of compostable coffee capsules with organic waste is blocked by a lock-in caused by the waste industry and the coffee industry. This lock-in effectively disables the closing of the cycles for both the capsule material and the spent coffee grounds. Resolving this lock-in could, however, result in the closing of both material cycles simultaneously. One of the critical conditions of the waste management industry to allow these compostable capsules is that the whole coffee industry will only use this type of capsules and no other. As long as this condition is not met, this lock-in will perpetuate, implying that both industries contribute to the lock-in whereas both are needed to resolve it.

5.3.5 Compostable capsules in LWP

The sorting challenges related to the small size of capsules, that have been described for conventional plastic capsules in LWP, are valid for compostable coffee capsules in this stream as well. Additionally, the compostable materials are currently not targeted in the LWP. So even if they can be sorted, there is currently no recycling process available at scale. This could change in future, but currently all capsules will end up in the sorting residues that are incinerated.

5.3.6 Overview fit in waste management system

None of the combinations of capsule materials and current after-use management systems are ideal. Two combinations enable some level of circularity of the capsule material and the contained coffee material, and would hence match with the Dutch waste policy. However, both encounter different practical issues. The mono-collection system for aluminium capsules suffers from low participation rates, open-loop recycling and the composting of compostable capsules suffers from the rejection by the organic waste management industry. This is further clarified in an overview of capsule material types and waste management options in Table 14. In this table it is easy to grasp what we mean with the recycling of the capsule material, namely that new secondary material is retrieved from it. For the recycling of the spent coffee grounds we specifically refer to keep the organic material in the bio-spherical loop, so nutrients are returned to the natural environment and not locked-in in land-fill sites for either MSW or bottom ashes of incinerators.

Table 14: The issues various capsule types encounter in the various after-use management systems and whether they support the recycling of the capsule material and of the contained coffee material. Color legend. Red: no recycling, material is lost. Orange: possible after adjustments. Green: material can be kept in the loop, either via recycling or composting.

Capsule type	After-use management	Issues with the current waste management options*	Capsule material recycling	Coffee grounds recycling
Aluminium	Mono-collection	Low participation	Open loop recycling that depends on non-capsule feedstock	Composted, kept in loop via the biosphere
	Recycling (via LWP)	Some sorting facilities need adjustments	After adjustments, open loop recycling	No recycling, incinerated or pyrolysed
	Incineration (via MSW)	None, but doesn't support circularity	Partial aluminium recovery from bottom ashes, open loop recycling	No recycling, full incineration
	Landfill	None, but doesn't support circularity	No recycling	Organic material is lost
Conventional Plastic	Recycling (via LWP)	Some sorting facilities need adjustments	Partial plastic recycling possible after adjustments	No recycling, waste water treatment/ incineration
	Incineration (via MSW)	None, but doesn't support circularity	No recycling, full incineration	No recycling, full incineration
	Landfill	None, but doesn't support circularity	No recycling	Organic material is lost
Compostable Plastic	Organic waste	Currently not accepted by most organic waste processors	Composted, kept in loop via the biosphere	Composted, kept in loop via the biosphere
	Recycling (via LWP)	Some sorting facilities need adjustments	Currently not feasible, but closed loop recycling possible in the future after adjustments	No recycling, wastewater treatment/incineration
	Incineration (via MSW)	None, but doesn't support circularity	No recycling, full incineration	No recycling, full incineration
	Landfill	None, but doesn't support circularity	No recycling	Organic material is lost

* The term waste management options encompasses collection, sorting and recycling and waste processing technologies.

5.4 Likely end-of-life fates of coffee capsules

This study has compared various combinations of coffee capsule materials with end-of-life management routes and made the inherent assumption that all capsules were treated with the chosen end-of-life management process. This gave insights in what could be the most ideal combination of materials and waste management process.
In reality, however, disposed consumer articles never end-up completely in one waste bin. Usually they are mostly thrown in the targeted waste bin and simultaneously present in other non-targeted waste bins. Accurate end-of-life-fates or distribution coefficients of disposed consumer articles over the various waste bins are seldomly available or measured, as they involve laborious analysing of multiple samples of waste. This is also the case for the current coffee capsules; there is no independent study that has determined the actual end-of-life fates of coffee capsules. This raises three questions; 1) what is the targeted waste bin for coffee capsules, 2) what is known of the discarding behaviour of Dutch citizens with respect to coffee capsules (and is it different in other European countries), and 3) what is the potential impact of capsules that are discarded in wrong waste bin?

5.4.1 What is the targeted waste bin for coffee capsules?

In most European countries coffee capsules are only allowed in separate collection schemes and mixed MSW and not in LWP waste, organic waste, etc.. There are several exceptions as plastic and aluminium capsules are allowed in LWP in Belgium and Germany. Furthermore, in Ireland and Italy compostable capsules are allowed in the organic waste. The separate collection schemes for coffee capsules include Nespresso, Podback, Terracycle, Blokker to name a few. These separate collection schemes are only present in a few European countries and rely on the voluntary participation of citizen.

5.4.2 What is known of the discarding behaviour of European citizens with respect to capsules?

No thorough study based on waste analysis has been executed, hitherto. The only data available are self-reported collection rates of companies and one study based on consumer research. Some coffee companies have stated that they retrieve about a quarter of the capsules with their voluntary collection system in personal communications to researchers of WFBR, but these numbers have never been reported officially. Remarkably this number (of about 25%) corresponds reasonably well with participation rates determined for drop-off collection of LWP in the Netherlands [39]. In a recent conference a representative of the European Coffee Federation stated that "the highest collection rate with a dedicated recycling scheme is 14%, however in some trials the actual recycling rate is below 5%" [47]. This would suggest that the collection rate is substantially less than 25%. Additionally, the Dutch association of coffee and tea companies conducted a consumer survey with respect to the disposal of coffee capsules (Nespresso format) in the Netherlands. 44% of the consumers said that they dispose them in the mixed MSW. 29% of the consumers claim they hand in the capsules via a dedicated collection system, and 21% dispose them in the bin for LWP waste. 4% of the consumers think that capsules can be disposed in the organic waste bin [2]. Although self-reported data is inherently unreliable, due to the proclivity of humans to give socially desired answers, this study does confirm that a large share of these capsules end-up in the mixed MSW and only a few are currently recycled. In Italy, where the compostable capsules are allowed in the organic waste, the collection and processing rate of compostable capsules via the organic waste has been estimated to be 52% [45, 46https://www.italianpost.news/bioplastics-recycling-reaches-61-of-the-italian-population/], which is exceptionally high, since the coverage rate for organic waste collection in Italy is 61%.

5.4.3 What is the potential impact of capsules ending-up in the wrong bin?

The impact of coffee capsules ending-up in the wrong waste bin is strongly dependant on the acceptation criteria and processing details and hence inherently complex. This is further discussed below case by case.

Compostable capsules in LWP
These capsules will most likely end-up in the sorting residues of the sorting facility and will be incinerated.

Conventional plastic capsules in organic waste
These are likely to enter the composting process and some contained coffee will actually be composted along the way. Any intact plastic capsules are likely to be sorted out by sieving or by ballistic solid separators used to remove stones near the end of the process. Nevertheless, due to mechanical handling during the composting process, the capsules are likely to fragment into small pieces and these smaller pieces cannot be removed efficiently with either sieving or ballistic solid separators. Consequently, the presence of plastic coffee capsules in the organic waste is likely to result in contamination of the compost.

Aluminium capsules in organic waste
Some of these capsules will be removed in the final sieving step or by ballistic solid separators near the end of the process, but due to fragmentation of the capsules, they will also contribute to the contamination of the compost.

5.5 Overall assessment

Of only two types of coffee capsules both the capsule material and the contained spent coffee grounds can be managed circularly, as discussed in the previous section. The impacts of the these two types of coffee capsules in relation to the after-use management methods are shown in a condensed manner in Table 15.

Table 15: Concise comparison between the two potentially most circular combinations of coffee capsule materials and waste management practises in relation to all indicators.

Impact	Compostable Capsules that are composted	Aluminium capsules mono-collected with recycled content
GWP-100 [g CO_2 eqv./kg] incl. coffee	7310	7348
GWP-100 [g CO_2 eqv./kg] excl. coffee	741	779
MCI	100%	61%
LPI	88%-100%	75%
Fit in the current waste management system	Currently not allowed due to lock-in	Good fit, but low participation
Circularity of the capsule material	Fully circular	Open-loop recycling
Circularity of the coffee	Fully circular	Fully circular

Two capsule scenarios score the best. The compostable capsules that are composted have low impact on global warming (in terms of greenhouse gas emissions), highest material circularity indicators (MCI is 100%), very little chance to contribute to litter formation and fit in a complete closed loop circular system for both the capsule material and the coffee. The mono-collected aluminium capsules with recycled content also have a low impact on global warming, a moderate material circularity indicator, a low chance to contribute to litter formation, fit in an open-loop recycling system for the capsule material and a closed loop recycling system for the contained coffee. But these two types of capsules/end-of-life combinations only perform relatively good under specific conditions. First of all, the aluminium capsules under the condition that they are maximally produced with recycled content and after-use mono-collected and recycled. Secondly, the compostable capsules under the condition that they are collected with organic waste and composted. But it is important to stress that both types of capsules will only perform ideally under these specific conditions, which also relates to solving systemic barriers. This will discussed in detail below, but let’s get the overview complete and shortly discuss what does not work.

The worst performers on the circularity indicators are the conventional plastic (HDPE or PP) capsules; a) they do not fit in a circular system b) currently they are not recycled (neither the capsule material nor the contained coffee) c) although the chance that they will be littered is small, in case they are, they will contribute to the formation of persistent microplastics. Although recycling can help to lower the greenhouse gas emissions slightly, these capsules are not ideal for conventional mechanical recycling processes; they are relatively small, often contain aluminium components and contain SCG. Some improvements for the plastic coffee capsules are feasible in the future in case sorting companies succeed in sorting them from LWP and recycling companies are able to deal with the contaminants they bring in the system. Nevertheless, this will require substantial efforts from these companies, whereas they will hardly benefit from making such improvements. Additionally, the contained (moist) spent coffee grounds are mostly incinerated and this will not only result in greenhouse gas emissions but also in the loss of nutrients. Currently, there are no technologies and recycling pathways foreseeable in which both the capsule material and the contained SCG are recycled and kept in their respective loops. Perhaps in the future effective mono-collection systems combined with dedicated recycling technologies could be established as a last-resort option for these plastic capsules. But even for such a system it will technically difficult to remove pieces of plastic from spent coffee grounds and avoid pollution of the resulting compost. This is inherently easier for aluminium, which can selectively be removed with an Eddy current separator.

The outcome of this study compares well with the only comparative European study on coffee capsules of Tonelli in 2018 [13]. And although this Italian studied slightly different capsules, with different secondary packages and a different LCA-tool, the final result is nearly identical; conventional plastic capsules scored the worst and compostable and aluminium capsules performed better.

5.5.1 Critical conditions for reaching the assessed what-if situation

Aluminium coffee capsules
The two critical conditions at which aluminium capsules cause least greenhouse gas emissions, prevent littering most effectively and do contribute to the circular economy for capsule materials and SCG are: 1) an effective mono-collection system and 2) the use of high levels of recycled content in newly produced capsules. Both are, however, challenging to accomplish and not self-evident.
The Achilles-heel of the current mono-collection system is the low participation rate. According to the consumer survey of Kantar, maximum 29% of the Nespresso-style capsules are mono-collected [2]. This implies that roughly 70% of these aluminium capsules are lost. Still some aluminium will be recovered from the LWP and the bottom ashes, but the SCG are completely lost. Ideally this participation rate should be near 100% to maximise circularity, minimise leakage and minimise greenhouse gas emissions. This, however, is not realistic to approach with a voluntary collection system and additional incentives are necessary, ranging from a deposit-refund system to financial reductions at re-orders. More effective mono-collection systems should be a prime concern of all incumbents and is essential to progress towards more circularity with aluminium capsules. Due to the low participation rates for mono-collection systems, the coffee and tea industry is moving away from these kinds of systems and tries to optimize collection via LWP systems (personal communication).

The use of recycled content in newly produced coffee capsules is essential to lower the carbon footprint and increase the circularity of the aluminium capsules. Not all types of secondary aluminium are, however, suitable for the production of new capsules as it requires a specific alloy. Since the amounts of collected capsules are currently insufficient to supply sufficient feedstock, most of this recycled content has to originate from different sources such as recycled beverage cans. This effectively makes it an open-loop recycling system. The precise level of recycled content in the capsules is not known for all brands and only reported by some companies. Ideally, such critical data for sustainability analysis would be verified by an independent authority in the future. Finally, a fully closed circular system for aluminium coffee capsules is not realistic, as in closed metal recycling systems trace metals are known to accumulate. For this type of aluminium alloy an increase of environmental iron and silicon implies reduced pliability. Therefore, there is currently a maximum in the share of recycled content that can be applied and hence a continuous need for a share of freshly produced new aluminium alloy in the system.

Compostable coffee capsules
Compostable coffee capsules keep both the capsule material and the SCG in the biological loop, but to successfully contribute to the circular economy it obviously entails their collection for composting. Currently the Dutch association of waste treatment companies (VA) is opposed to discarding the compostable capsules to the organic fraction of municipal waste and composting them with the organic waste, which is a major obstacle to progress towards a more circular system for coffee capsules. There are two options to resolve this lock-in: 1) to come to a mutual agreement between the organic waste management sector and the coffee industry under which conditions these capsules can be accepted in the organic waste, similar to what was agreed for tea bags [43] or 2) to set-up a mono-collection system for compostable coffee capsules and

to process them separately. There are many advantages to the first option. One of the clear and valid conditions of the waste management industry is that the whole category of a specific product should be compostable before the whole category can be allowed in the organic waste. This requires consensus of the coffee industry on this matter. Hence, this lock-in is maintained by both industries and can only be resolved by both as well. Alternatively, the European Commission could resolve this lock-in with its proposed PPWR.

Diverging opinions
The scientific perspective is that coffee capsules only fit in a circular economy in case both the capsule material and the contained SCG are recycled. Furthermore, to keep the whole system sustainable these looping systems should be executed in such a manner that a minimal amount of energy is used. Obviously, this scientific perspective diverges from the interests of stakeholders, that have invested in specific capsule technology, waste management practises, etc. or have company policies that influence the selection of capsule materials. We duly respect those interests, but safe-guarding industrial interests is not our primary duty as scientists.

6 Conclusions and recommendations

The sustainability of coffee capsules production, use and waste management was assessed for different combinations of capsules and end-of-life treatment options with a dedicated tool for packaged food products. Theoretical scenarios in which the capsules are all treated in the same manner are compared with each other to comprehend the influence of both the capsule material and the waste management method. Coffee capsules are a special type of “food package”, since it is discarded with the contained food residue; the spent coffee grounds. Furthermore, the dry matter weight of these spent coffee grounds is typically five to six times larger than of the capsule material, emphasising its relative importance. It should be noted that in any sustainability assessment methodical choices must be made, which affect the final results. This is inevitable and care has been taken by conducting a sensitivity analysis to probe these leverages. Moreover, in this study multiple sustainability indicators are assessed simultaneously and by combining them a more complete and balanced picture emerged . The production of the coffee contributes significantly to the total greenhouse gas emissions. The contributions of the capsule materials is relatively small for plastic and compostable capsules and is high for capsules made from newly produced aluminium that are not recycled. However, in case the capsule is produced from secondary aluminium and completely mono-collected and recycled, the contributions to greenhouse gas emission reduce to levels that are comparable to those of the conventional plastic and compostable capsules. Most combinations of capsule materials and end-of-life treatment options have low or limited recycling indicators, since either no materials are recycled, or only the capsule material is recycled and the contained spent coffee grounds are lost. There are two exceptions in which both the capsule material and the contained spent coffee grounds are recycled in a circular way and that have consequentially relatively high material circularity indicators. The compostable capsules that are composted score high as they can keep both the capsule material and the contained coffee in the organic loop. The mono-collected aluminium capsules also score fairly high as they can keep the coffee in the organic loop and can recycle the aluminium in a predominant open-loop. Unfortunately, both these most circular combinations of capsule materials and end-of-life treatment options have their own set of challenges. The compostable coffee capsule can only accomplish this high level of circularity when it is composted. The largest hurdle in this case is the lock-in created by the organic waste management industry in the Netherlands that does not accept these capsules in the separately collected organic waste. For the other high scoring capsule material/end-of-life treatment combination, the aluminium capsules will need to be mono-collected with very high participation rates and then both the aluminium and coffee grounds need to be recycled separately into secondary aluminium and compost. The required high participation rates for the voluntary mono-collection system are currently by far not attained. Furthermore, the likelihood that high participation rates will ever be reached for voluntary mono-collection system is minute. Only mono-collection systems with clear financial incentives are known to attain such high levels of participation. This is the largest hurdle for the aluminium coffee capsule system to accomplish a high level of circularity.

In short in the current waste management system in the Netherlands no combination of capsule material and end-of-life scenario is ideal with respect to all dimensions of sustainability. The aluminium capsules only can have acceptable low carbon emissions when they are effectively mono-collected and the recycled material is used to produce new capsules and this is only partly the case. The conventional plastic coffee capsules have lower greenhouse gas emissions compared with the aluminium ones but these do not fit in a circular economy and neither the plastic capsules nor the spent coffee grounds are recycled. The compostable coffee capsules also contribute little to the greenhouse gas emissions, but they are currently not accepted in the organic waste and hence capsule material and the spent coffee grounds can also not be recycled circularly. If this lock-in will be solved, for instance with the obligation to use compostable materials as is written in the proposed PPWR, this option provides the most circular solution for both the capsule material and the spent coffee grounds. The collection system is already in place for this and no changes to the waste treatment facilities are needed.

We have several recommendations:

- In order to create an improved overview of the emissions, reliable emission factors are required for the different waste management options for spent coffee grounds and for the recycling of the capsule materials. With these factors the current analysis can be elaborated and improved.

- In case stakeholders want to improve the sustainability of aluminium capsules, the only full circularly pathway for both capsule material and spent coffee grounds is the mono-collection system. This system is currently impaired by the low participation rates and stakeholders are recommended to incentivise collection with deposit refund systems that could potentially achieve the required near 100% collection rates.
- Compostable coffee capsules are a promising solution in terms of sustainability but require multi-stakeholder consensus. We therefore recommend that the national government initiates negotiations between the coffee industry, the waste management industry and material producers to define the conditions at which the compostable capsules can be accepted to be treated with separately collected municipal organic waste. Alternatively, the European Commission could proceed with the PPWR and demand the use of compostable materials for coffee capsules and pods and their processing with organic waste.
- In more general terms we recommend that all involved parties, including industry, policy makers, waste management, and local governments, should thoroughly explore and assess possibilities to achieve the utmost circularity for both materials and spent coffee grounds, while minimizing environmental impact. This evaluation should encompass a comprehensive analysis of short- and long-term strategies, reviewing existing barriers and determining the necessary policies, investments, and other requisites to surmount them.
- In general policy makers should be aware that setting policy targets only for packaging materials can result in non-sustainable outcomes, especially when the products concerned are composed of packaging materials and food residues at the moment of discarding, such as is the case for coffee capsules. In these instances a more appropriate policy should ideally include targets for the contained food product as well.

Finally we conclude with a more general reflection on the methodology. This study used a dedicated tool for packaged food products in which not only the greenhouse gas emissions/global warming potential but also circularity indicators are calculated. This combination proved to be vital to render meaningful insights in not only reducing the greenhouse gas emissions but also in approaching a more circular economy. Without the circularity indicators we would have probably concluded that the differences between the capsule materials are negligible, but by including them more meaningful differences emerged.

Literature

1. Foundation EM. Circularity indicators - an approach to measuring circularity. Cowen: Ellen MacArthur Foundation, 2019:64.
2. van Thiel L. Weggooigedrag koffiecapsules. Amsterdam: Kantar Public, 2023:13.
3. Carlin C. Coffee Pods Challenge, Producers and Consumers. PLASTICS ENGINEERING 2020;**May**:28-31
4. Thoden van Velzen EU, Molenveld, K., Brouwer, M.T., van der Zee, M., Smeding, I. Issue paper: Recycling of different waste streams. Wageningen: WFBR, 2021:23.
5. Commission E. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC. Brussels: European Commission, 2022:118.
6. Federation EC. ECF POSITION ON THE DRAFT REGULATION PROPOSAL FOR PACKAGING AND PACKAGING WASTE (PPWR). Secondary ECF POSITION ON THE DRAFT REGULATION PROPOSAL FOR PACKAGING AND PACKAGING WASTE (PPWR) 10/2/2023 2023. https://www.ecf-coffee.org/publications/ecf-position-on-the-draft-regulation-proposal-for-packaging-and-packaging-waste-ppwr/.
7. Marinello S, Balugani E, Gamberini R. Coffee capsule impacts and recovery techniques: A literature review. Packaging Technology and Science 2021;**34**(11-12):665-82 doi: 10.1002/pts.2606.
8. Brommer E, Stratmann B, Quack D. Environmental impacts of different methods of coffee preparation. International Journal of Consumer Studies 2011;**35**(2):212-20 doi: 10.1111/j.1470-6431.2010.00971.x.
9. Hicks AL. Environmental Implications of Consumer Convenience: Coffee as a Case Study. Journal of Industrial Ecology 2018;**22**(1):79-91 doi: 10.1111/jiec.12487.
10. Hicks AL, Halvorsen H. Environmental impact of evolving coffee technologies. The International Journal of Life Cycle Assessment 2019;**24**(8):1396-408 doi: 10.1007/s11367-018-1575-0.
11. de Figueiredo Tavares MP, Mourad AL. Coffee beverage preparation by different methods from an environmental perspective. The International Journal of Life Cycle Assessment 2020;**25**(7):1356-67 doi: 10.1007/s11367-019-01719-2.
12. Cibelli M, Cimini A, Cerchiara G, Moresi M. Carbon footprint of different methods of coffee preparation. Sustainable Production and Consumption 2021;**27**:1614-25 doi: 10.1016/j.spc.2021.04.004.
13. Tonelli A, Mosna, D., Vignali, G. COMPARATIVE LIFE CYCLE ASSESSMENT OF DIFFERENT PACKAGING SYSTEMS FOR COFFEE CAPSULES. 4th International Food Operations and Processing Simulation Workshop, FoodOPS 2018. Budapest, Hungary, 2018:9.
14. Li J. Comparative LCA of single serve coffee packaging in Ontario. University of Waterloo, 2017.
15. Kooduvalli K, Vaidya UK, Ozcan S. Life Cycle Assessment of Compostable Coffee Pods: A US University Based Case Study. Sci Rep 2020;**10**(1):9158 doi: 10.1038/s41598-020-65058-1.
16. Di Bella G, Potortì AG, Lo Turco V, Saitta M, Dugo G. Plasticizer residues by HRGC–MS in espresso coffees from capsules, pods and moka pots. Food Control 2014;**41**:185-92 doi: 10.1016/j.foodcont.2014.01.026.
17. Velotto S, Squillante J, Nolasco A, Romano R, Cirillo T, Esposito F. Occurrence of Phthalate Esters in Coffee and Risk Assessment. Foods 2023;**12**(5) doi: 10.3390/foods12051106 .
18. Muller FD, Hackethal C, Schmidt R, Kappenstein O, Pfaff K, Luch A. Metal release from coffee machines and electric kettles. Food Addit Contam Part A Chem Anal Control Expo Risk Assess 2015;**32**(11):1959-64 doi: 10.1080/19440049.2015.1086929 .
19. Iscuissati IP, Galazzi RM, Miró M, Arruda MAZ. Evaluation of the aluminum migration from metallic seals to coffee beverage after using a high-pressure coffee pod machine. Journal of Food Composition and Analysis 2021;**104** doi: 10.1016/j.jfca.2021.104131[published Online First: Epub Date]|.
20. Abuabara L, Paucar-Caceres A, Burrowes-Cromwell T. Consumers' values and behaviour in the Brazilian coffee-in-capsules market: promoting circular economy. International Journal of Production Research 2019;**57**(23):7269-88 doi: 10.1080/00207543.2019.1629664[published Online First: Epub Date]|.
21. Visser R, Dlamini S. Green Purchasing Behaviour towards Compostable Coffee Pods. Sustainability 2021;**13**(12) doi: 10.3390/su13126558 .
22. Brouwer MT, Thoden van Velzen, E.U. Multi-dimensional sustainability assessment of product-packaging combinations. Wageningen: WFBR, 2023:24.
23. European Commission, Joint Research Centre, Gervasio, H., Dimova, S., Model for Life Cycle Assessment (LCA) of buildings, Publications Office, 2018, https://data.europa.eu/doi/10.2760/10016

24. Usva K, Sinkko T, Silvenius F, Riipi I, Heusala H. Carbon and water footprint of coffee consumed in Finland—life cycle assessment. The International Journal of Life Cycle Assessment 2020;**25**(10):1976-90 doi: 10.1007/s11367-020-01799-5 .
25. European COUNCIL. EUROPEAN PARLIAMENT AND COUNCIL DIRECTIVE 94/62/EC on packaging and packaging waste. Official Journal of the European Union 1994;**L 365/10**:14
26. European COUNCIL. DIRECTIVE (EU) 2018/852 amending Directive 94/62/EC on packaging and packaging waste. Official Journal of the European Union 2018;**L 150 / 141**:14
27. European COUNCIL. DIRECTIVE (EU) 2019/904 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the reduction of the impact of certain plastic products on the environment. Official Journal of the European Union 2019;**L 155/1**:1-19
28. Vereniging Afvalbedrijven. BETERE GFT-KWALITEIT VEREIST KETENSAMENWERKING; KWALITEIT GFT NEEMT STERK AF. 2019. https://www.verenigingafvalbedrijven.nl/nieuws/betere-gft-kwaliteit-vereist-ketensamenwerking.
29. RWS. Onder welke voorwaarden mag compost worden toegepast onder de Meststoffenwet? Secondary Onder welke voorwaarden mag compost worden toegepast onder de Meststoffenwet? https://www.bodemplus.nl/onderwerpen/wet-regelgeving/bbk/vragen/compost/faq/welke-voorwaarden/.
30. VANG-HHA. Gescheiden inzameling vanaf nu wettelijk verplicht. Secondary Gescheiden inzameling vanaf nu wettelijk verplicht 2020. https://vang-hha.nl/nieuws/2020/gescheiden-inzameling-vanaf-wettelijk-verplicht/#:~:text=Gemeenten%20zijn%20sinds%201%20juli,gevaarlijke%20afvalstoffen%20gescheiden%20worden%20ingezameld.
31. David A. Turner, Ian D. Williams, Simon Kemp, Greenhouse gas emission factors for recycling of source-segregated waste materials, Resources, Conservation and Recycling, Volume 105, Part A, 2015, Pages 186-197, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2015.10.026.
32. Erwin T.H. Vink and Steve Davies.Life Cycle Inventory and Impact Assessment Data for 2014 Ingeo™ Polylactide Production.Industrial Biotechnology.Jun 2015.167-180.http://doi.org/10.1089/ind.2015.0003
33. European Commission, Directorate-General for Research and Innovation, Environmental impact assessments of innovative bio-based product . Task 1 of "Study on Support to R&I Policy in the Area of Bio-based Products and Services ", Publications Office, 2019, https://data.europa.eu/doi/10.2777/251887
34. Daniel Maga, Markus Hiebel, Nils Thonemann, Life cycle assessment of recycling options for polylactic acid, Resources, Conservation and Recycling, Volume 149, 2019, Pages 86-96, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2019.05.018
35. Ximena C. Schmidt Rivera, Alejandro Gallego-Schmid, Vesna Najdanovic-Visak, Adisa Azapagic, Life cycle environmental sustainability of valorisation routes for spent coffee grounds: From waste to resources, Resources, Conservation and Recycling,Volume 157, 2020,104751, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2020.104751
36. Alu-sense website https://www.alu-sense.com/en
37. Jeffrey J. Kolstad, Erwin T.H. Vink, Bruno De Wilde, Lies Debeer, Assessment of anaerobic degradation of Ingeo™ polylactides under accelerated landfill conditions, Polymer Degradation and Stability, Volume 97, Issue 7, 2012, Pages 1131-1141, ISSN 0141-3910, https://doi.org/10.1016/j.polymdegradstab.2012.04.003
38. Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: <http://link.springer.com/10.1007/s11367-016-1087-8>
39. Brouwer, M., Picuno, C., Thoden van Velzen, E. U., Kuchta, K., De Meester, S., & Ragaert, K. (2019). The impact of collection portfolio expansion on key performance indicators of the Dutch recycling system for Post-Consumer Plastic Packaging Waste, a comparison between 2014 and 2017. Waste Management, 100, 112-121. https://doi.org/10.1016/j.wasman.2019.09.012
40. Thoden van Velzen, E. U., & Smeding, I. W. (2020). Potentie voor de recycling van aluminiumverpakkingen eind 2020: Studie naar de mogelijkheden voor de recycling van aluminiumverpakkingen en verwante consumentenartikelen in Nederland eind 2020. (Wageningen Food & Biobased Research report; No. 2060). Wageningen Food & Biobased Research. https://doi.org/10.18174/525699
41. Hermann, B.G., L. Debeer, B. De Wilde, K. Blok, M.K. Patel (2011). To compost or not to compost: Carbon and energy footprints of biodegradable materials' waste treatment. Polymer Degradation and Stability 96 (2011) 1159-1171

42. Morão, A., de Bie, F. Life Cycle Impact Assessment of Polylactic Acid (PLA) Produced from Sugarcane in Thailand. J Polym Environ 27, 2523–2539 (2019). https://doi.org/10.1007/s10924-019-01525-9
43. Website https://www.greendeals.nl/sites/default/files/2021-05/Green%20Deal%20on%20coffee%20pads%20and%20tea%20bags%20in%20organic%20houshold%20waste.pdf consulted on 02-11-2023
44. Christian Moretti, Lorie Hamelin, Line Geest Jakobsen, Martin H Junginger, Maria Magnea Steingrimsdottir, Linda Høibye, Li Shen, Cradle-to-grave life cycle assessment of single-use cups made from PLA, PP and PET, Resources, Conservation and Recycling, Volume 169, 2021, 105508, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2021.105508.
45. Website https://biorepack.org/comunicazione/news/bioplastiche-compostabili-superati-obiettivi-di-legge-2025.kl consulted on 08-11-2023
46. Website https://www.italianpost.news/bioplastics-recycling-reaches-61-of-the-italian-population/ consulted on 08-11-2023
47. Presented by European Coffee Federation at AMI Single-Serve Capsules conference 26-28 September 2023, Barcelona Spain
48. AMI Consulting, Single Serve Capsules, Global Market overview 2020, September 2020 (confidential)
49. European COUNCIL. DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives. Official Journal of the European Union 2008;**L 312/3**
50. Kim, S., Dale, B. Life Cycle Assessment Study of Biopolymers (Polyhydroxyalkanoates) - Derived from No-Tilled Corn (11 pp). Int J Life Cycle Assessment 10, 200–210 (2005). https://doi.org/10.1065/lca2004.08.171
51. Brouwer, M. T., Thoden van Velzen, E. U., Augustinus, A., Soethoudt, H., De Meester, S., & Ragaert, K., 2018. Predictive model for the Dutch post-consumer plastic packaging recycling system and implications for the circular economy. Waste Management, 71, 62-85. https://doi.org/10.1016/j.wasman.2017.10.034

List of acronyms

Al	Aluminium
BOPP	Biaxially oriented polypropylene
EoL	End-of-life
EPR	Extended producer responsibility
EVA	Poly(ethylene-co-vinyl acetate)
EVOH	Poly(ethylene-co-vinyl alcohol)
GWP	Global warming potential
HDPE	High-density Polyethylene
LCA	Life cycle assessment
LCI	Life cycle inventory
LPI	Litter prevention indicator
LWP	Lightweight packaging waste
MCI	Material circularity indicator
MSW	Mixed Municipal solid waste
ORI	Organic recyclability indicator
NF	Non-Ferrous metals
PET	Poly ethylene terephthalate
PHA	Poly hydroxy-alkanoates
PLA	Poly lactic acid
PP	Polypropylene
PPWR	Packaging and packaging waste regulation
RCI	Recycling chain indicator
ReConI	Recycled content indicator
ReNewI	Renewable content indicator
RI	Recyclability indicator
SCG	Spent coffee grounds
SUP	Single use plastics

Annex 1 Examples of compostable coffee capsules on the global market

In the table below, examples of existing compostable coffee capsules are listed. The information below, like material and disposing/composting conditions, is provided by the brand owner on their websites. This list is in random order.

No.	Brand and/or supplier (Country)	Material	Disposing/ Composting conditions	Launch year	Other details	Reference (digital link)
1	Nespresso (Switzerland)/ Huhtamaki	Compostable paper	At Home with garden composter	Nov 2022, to be piloted with consumers in spring 2023	Capsules packed in paper sachet have a shelf life of 6 months. On opening the sachet, capsules to be consumed within 2 weeks	Coffee capsule based on compostable paper | Nespresso Huhtamaki's proprietary breakthrough high-precision technology delivers home compostable paper-based coffee capsules for Nespresso and millions of coffee lovers
2	St Remio (Australia)	Corn based	Industrially compostable	2020	Entire capsule including lid is biodegradable/ compostable	Biodegradable Coffee Pods | Compostable & Recycling Coffee Pods | St Remio Coffee
3	Lavazza (Italy)	Compostable	Industrially compostable	2019	Vacuum sealed Up to 7.5g coffee in each capsule	A Modo Mio ¡Tierra! Bio Organic - Espresso Coffee Capsules | Lavazza
4	Coffee-Up (Germany)	Corn, cellulose and sugarcane based (Bioplastics)	Bio- and/or residual waste (Industrial composting/ Incineration) Decompose in 3-18 months	-	-	Compostable organic coffee capsules - the largest selection | Coffee-Up! ☕
5	My Coffee Cup (Germany)	-	Garden compostable	2022	Shelf life of at least 18 months	Coffee capsules for Nespresso®³ from MY COFFEE CUP
6	Eurospin (Italy)	Renewable sources	Disposed in the wet of separate collection	-	-	Don Jerez compatible compostable coffee capsules | Eurospin
7	Pellini (Italy)	Plant material, food waste	-	-	Self-protected – fully sealed	Nespresso compatible capsules: compostable, self-protected capsules | Pellini (pellinicaffe.com)
8	La Natura (Switzerland)	-	Biodegradable and home compostable	-	-	Organic Coffee Capsules - La Natura Lifestyle (lanaturacoffee.com)
9	Rejuvenation water (UK)	Plant-based	Disposable in food and general waste Decompose within 18 weeks	2021	Healthy plant based drinks	Nespresso© compatible Matcha Pods & Keto Coffee – Rejuvenation Water Rejuvenation Water Introduces First-Of-Its-Kind Plant-based Immunity Health Pods - Vegan Kind

No.	Brand and/or supplier (Country)	Material	Disposing/ Composting conditions	Launch year	Other details	Reference (digital link)
10	Röststätte (Berlin, Germany)	Wood-fibers and lactic acid	Industrially compostable	-	-	Compostable capsules from Röststätte Berlin (roeststaette.com)
11	Caffé Vergnano (Italy)	Biodegradable and compostable polyesters, partly from renewable sources	Organic waste bin	2017	-	Compostable coffee capsules | Caffè Vergnano (caffevergnano.com)
12	Hema (Netherlands)/ Beyers	Renewable plant-based	Organic waste bin, Decompose within 6 months	2022	-	Coffee, good for people and the environment. | Beyers
13	Wakuli (Netherlands)	-	Home compostable	-	-	Wakuli – Wakuli Koffie
14	Moyee (Netherlands)	Plant based (maise and cellulose)	Biodegradable, decomposes within 8 weeks	-	-	First FairChain capsules in the world (moyeecoffee.com)
15	Smit & Dorlas (Netherlands)	Biobased - Sugarcane, beetroot PLA	Compostable, decomposes after 12 weeks	-	-	SIGNATURE LUNGO CAPSULES - Smit & Dorlas | Smit & Dorlas Caribbean N.V. (smitdorlascaribbean.com)
16	Koffievoordeel.nl (Netherlands)	-	Compostable	-	Shelf life greater than 12 months	https://www.koffievoordeel.nl/highlands-gold
17	Café Launay (France)	-	Compostable, Biodegradable	-	-	Café Launay (cafelaunay.com)
18	Lidl/ Bellarom (Germany)	-	Home compostable	-	-	Bio compostable coffee capsules - lidl.ch
19	Boutique Lobodis/ Honduras (France)	Vegetable materials	Home (garden) compostable, Industrially compostable in 3 months	-	-	French Torrefaction (lobodis.com) Organic and fair trade coffee from Honduras - Nespresso® Compatible Caps - Lobodis (bienmanger.com)
20	Méo (France)	Sugarcane-based with paper seal	Home compostable within 3 months	-	-	Zero-waste objective! Compostable coffee capsules at home (meo.fr)
21	Moka premium (France)	Corn starch, GMO-free coconut and rapeseed vegetable oils	Home compostable in 24 weeks at 20ºC	-	-	Moka Premium | 100% biodegradable capsules with 0% aluminum
22	Les cafés sati (France)	Cellulose and vegetable oils	Home/ Garden compost within 6 months at 20-30ºC	2021	-	Compostable capsule at home: the novelty ☕🌱 | Sati Cafes (cafesati.com)
23	Terramoka (France)	Cellulose, coconut and rapeseed oils	Home compostable in 24 weeks at room temperature	-	-	Terramoka organic coffees in Nespresso® compatible capsules
24	Café San Marco (Italy)	Renewable raw materials (62%)	Industrially compostable	-	Produced exclusively using green energies	Our coffees - Nespresso® compatible

No.	Brand and/or supplier (Country)	Material	Disposing/ Composting conditions	Launch year	Other details	Reference (digital link)
						capsules - BIO N°8 - Café San Marco
25	Mövenpick, Green cap capsules (Switzerland/ Germany)	Renewable raw (vegetable) materials	Industrially compostable	2021	Biodegrade up to 90% within 12 months and 100% in few more months	Green Cap Long Cream - Mövenpick Fine Food (moevenpick-finefood.com) Environmentally Friendly Mövenpick Green Cap Coffee Capsules - Travel Style Fun
26	Coop (Italy)	-	Compostable	-	Coop is a supplier for several compostable capsules brands	Coffee capsules 100% arabica raffaello x15 COOP - FIOR FIORE - Coop Shop
27	Caffé Corsini (Italy)	-	Industrially compostable	2019	-	Caffè Corsini introduces new compostable capsules at Host and Anuga (comunicaffe.com)
28	Gimoka (Italy)	-	Organic waste bin, Industrially compostable	-	-	Intenso - Gimoka Capsules compatible with Lavazza A Modo Mio® Compatible System of Compostable Capsules and Coffee
29	Prosol (Spain)	-	Organic waste bin, Home compostable	-	-	Prosol - Supplier and manufacturer of Nespresso Compatible capsules
30	Novell (Italy)	Biodegradable plastic compostable (Ecoflex) and corn PLA	Organic waste bin, Industrially compostable within 12-20 weeks	2017	-	Zero Waste - Cafès Novell (cafesnovell.com) Novell Launches New Compostable Coffee Capsule with Certified Organic Coffee (linkedin.com)
31	Dualit (UK)	Corn starch	Home compostable, Industrially compostable	2023	-	Compostable Coffee Pods – Dualit Website
32	Gordon St Coffee (UK)	Solinatra®, made from agricultural plant waste	Home compostable, Industrially compostable	2021	-	Complete Guide to our Solinatra Compostable Coffee Capsules – Gordon Street Coffee (gordonstcoffee.co.uk)
33	Halo coffee (UK)	Sugarcane and paper pulp	Home compostable within 90 days in ambient temperature	2017	(world's first fully compostable coffee capsules)	Nespresso Compatible Compostable Coffee Pods | Halo Coffee Why Halo – Halo Coffee Former Creative Chairman of Grey London Launches Compostable Coffee Pod | LBBOnline
34	Segafredo (Italy)	-	Compostable	2019	Oxygen sealed to preserve taste and aroma. Produced using green energies	Compostable capsules | Segafredo Webshop (segafredoshop.nl)
35	Glorybrew (US)	-	Industrially compostable in 12 weeks	2021	In 2017 developed compostable capsules compatible with Keurig machines	About Glorybrew Compostable Pods for Nespresso & Keurig Coffee Makers

No.	Brand and/or supplier (Country)	Material	Disposing/ Composting conditions	Launch year	Other details	Reference (digital link)
36	De Koffiejongens (NL)	PHA and cellulose	Home compostable, Industrially compostable	2020	CO2 neutral since 2021 and B Corp certified since 2023	De Koffiejongens
37	FLO (Italy), NatureWorks (raw material producer)	Gea capsule consists of PLA Ingeo and paper	Industrially compostable	2019	PLA is ISCC-certified to guarantee sustainable soil use and ensures that farmers' welfare is protected	Flo group| Coffee capsules|GEA-Compostable ones(flo.eu)
38	Plant-based coffee capsule, ATI (Netherlands)	Made from sugarcane, bioplastics, and plant rests	After use they can be discarded in the organic waste bin, fully compostable (21 days)	2010	-	Advanced Technology Innovations, The best sustainable single serve coffee capsule on the market today.

Annex 2 Source and adjustments of background data

Food product	Source	Comment/Adjustments
Roasted coffee beans	Usva, 2020 [24]	High impact value was selected as the worst case scenario

Materials	Source	Comment
Aluminium, PP and HDPE granulate, paper	Ecoinvent / IPCC 2013 GWP 100a V1.03 [38]	
EVA	Ecoinvent / IPCC 2013 GWP 100a V1.03 [38]	adhesive for metal as a proxy
EVOH	Ecoinvent / IPCC 2013 GWP 100a V1.03 [38]	Ethylene vinyl acetate copolymer as proxy
PLA pellet	Erwin T.H. Vink and Steve Davies 2015 [32]	Used in PLA1
PLA pellet	Morão, A. and de Bie, F., 2019 [42]	Used in PLA2, PLA1b
PLA pellet	Ecoinvent / IPCC 2013 GWP 100a V1.03 [38]	Used in PLA1a
Cellulose	Ecoinvent / IPCC 2013 GWP 100a V1.03 [38]	Tissue paper as proxy
PBAT	European Commission, 2019 [33]	PLA/PBAT film as a proxy
PHA pellet	Kim and Dale, 2005 [50]	derived from No-Tilled Corn,based on Metabolix production process

Production processes	Source	Comment
All other production processes in database / used in cases,	Ecoinvent / IPCC 2013 GWP 100a V1.03 [38]	

End-of life (EOL) processes	Source	Comment
All other EOL processes in database / used in cases	Ecoinvent / IPCC 2013 GWP 100a V1.03 [38]	
All other EOL processes in database / used in cases	Ecoinvent / IPCC 2013 GWP 100a V1.03 [38]	
Incineration processes of fossil-fuel plastics	Own estimate based on carbon and energy content	Excluding transportation, construction and operation of the plant
Recycling of PE, PP, aluminium	Turner, 2015 [31]	Sorting, disassembly/dismantlement, treatment, transportation and reprocessing of waste materials are included. Substitution of virgin PP and PE production is based on 10% material quality loss. Substitution of virgin aluminium production is based on 0% material quality loss.
Recycling of PLA	Mega et al., 2019 [34]	Based on pilot scale plant, sorting and transportation are included. The correction factor for substitution of virgin PLA is 51%
Recycling of PHA	Mega et al., 2019 [34]	PLA as a proxy
Industrial composting, anaerobic digestion and incineration of biobased materials	Hermann et al., 2011 [41]	Based on mass, (dry) carbon, energy balances of each material input excluding transportation and

End-of life (EOL) processes	Source	Comment
		construction and operation of the plants
Landfill of fossil plastics and paper (including energy recovery)	ELCD database 2.0, IPCC 2013 GWP 100a	including landfill gas utilisation and leachate treatment and without collection, transport and pre-treatment
Landfill of paper and aluminium	ELCD database 2.0, IPCC 2013 GWP 100a	Inert waste as a proxy
Landfill of biobased plastics	ELCD database 2.0, IPCC 2013 GWP 100a	Fossil-fuel plastics as a proxy
Incineration, industrial composting, anaerobic digestion and landfill of coffee grounds	Rivera et al., 2020 [35]	

Recycling processes / efficiencies		
All data	Background knowledge of researchers of WFBR based on previous projects, such as: [39], [40], [51]	

Annex 3 Sustainability assessment supplementary figures

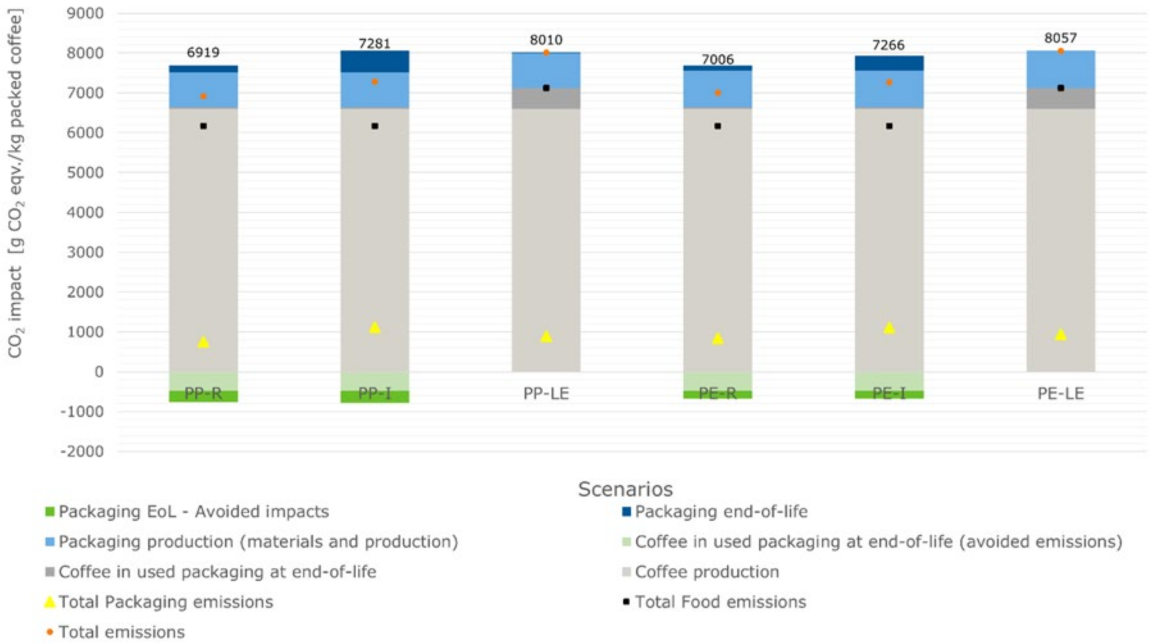

Figure 14 Comparison of contribution to the greenhouse gas emissions between different conventional plastic capsules materials, including coffee, per life cycle stage in [g CO_2 eqv./kg packed coffee].

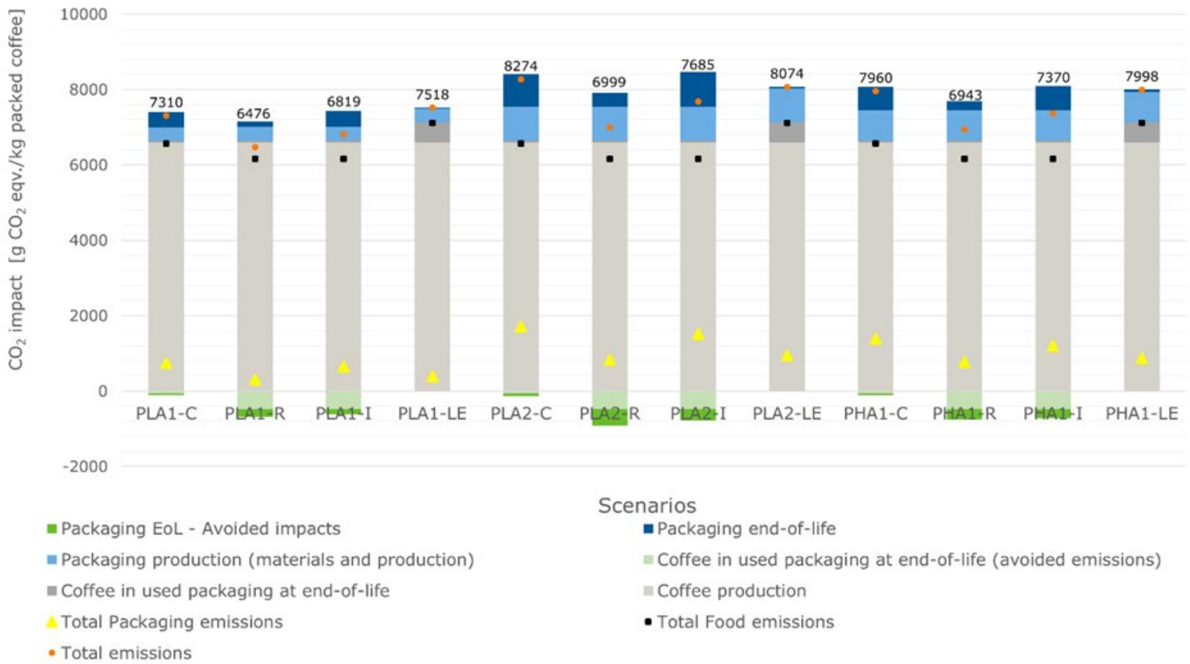

Figure 15 Comparison of contribution to the greenhouse gas emissions between different compostable plastic capsules materials, including coffee, per life cycle stage in [g CO_2 eqv./kg packed coffee].

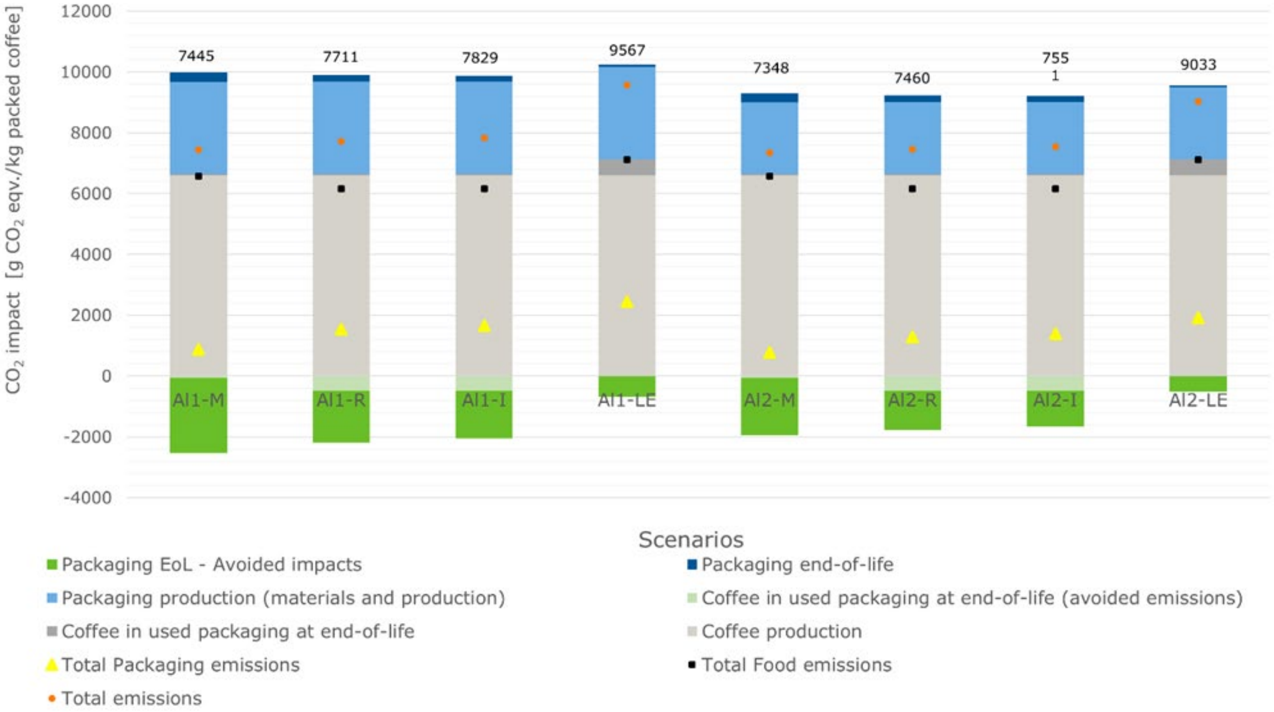

Figure 16 Comparison of contribution to the greenhouse gas emissions between different aluminium capsules, including coffee, materials per life cycle stage in [g CO_2 eqv./kg packed coffee].

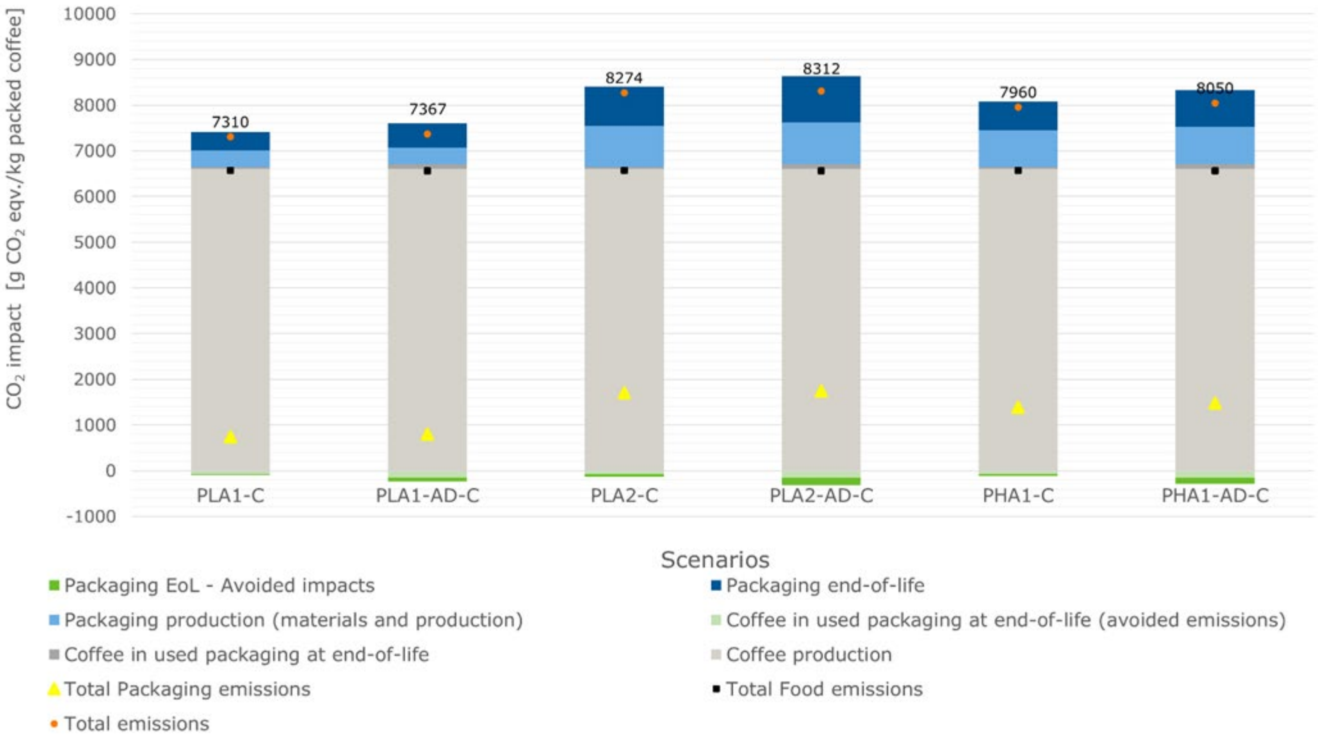

Figure 17 Comparison of contribution to the greenhouse gas emissions between 100% industrial composting and Dutch organic waste scenario (combination of industrial composting and anaerobic digestion) of biobased plastic capsules, including coffee, per life cycle stage in [g CO_2 eqv./packed coffee].

Annex 4 Sustainability indicators

Recycled content indicator (ReConI):
This indicator describes the share of post-consumer recycled material that is used to produce the capsule. The use of post-industrial recycled material is excluded from the calculation of the indicator. It is expressed with a percentage. It equals 0% in case no recycled content is present and 100% is case the entire capsule is made of recycled material.
The recycled content indicator for Al2 is 32%. The 40% post-consumer recycled content assumed in this scenario, is for the capsule material only. The ReConI calculates the recycled content percentage based on the total capsule weight, including the other components like the lid.

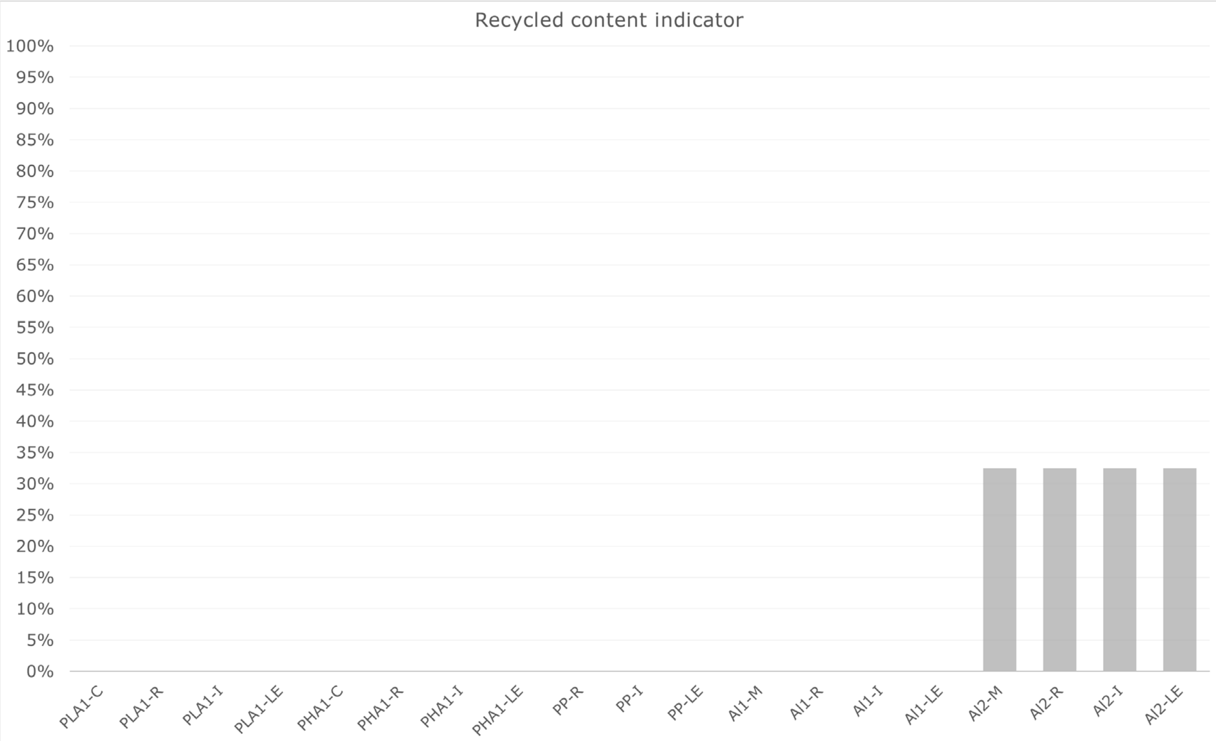

Figure 18 Recycled content indicator score of different coffee capsule main scenarios.

Renewable content indicator (ReNewI):
This indicator expresses the share of renewable material of which the capsule is made. The unit is percentage and it runs from 0% (no renewable content) to 100% (completely made from renewable materials). A renewable material means: not based on fossil feedstock.

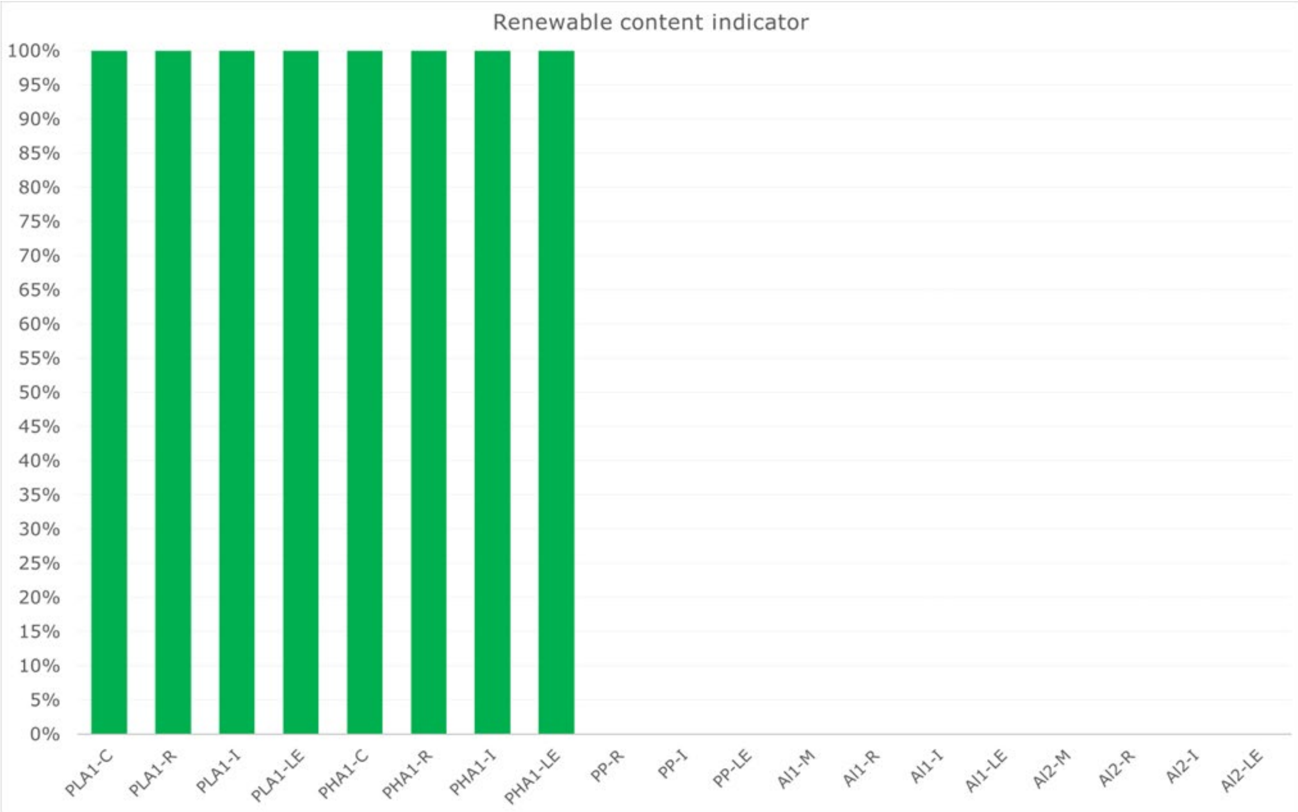

Figure 19 Renewable content indicator score of different coffee capsule main scenarios.

Recycling chain indicator (RCI):
It expresses the recycling chain efficiency for a specific type of packaging. It is calculated by multiplying the collection, sorting and recycling efficiency of the primary material which can be converted into a secondary material. In case each packaging is made of several components, this indicator is calculated separately for each component and the sum of all gives the total value. The indicator was calculated assuming that there is 100% collection coffee capsules for all the scenarios.

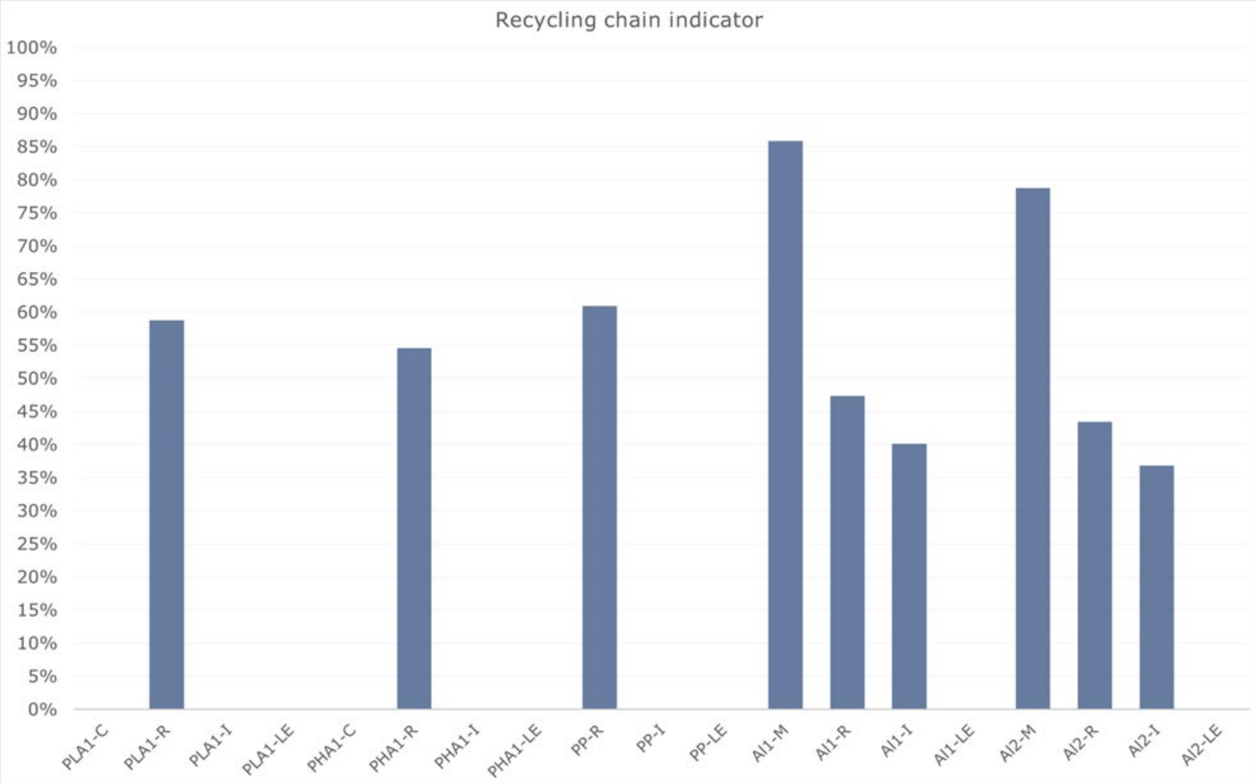

Figure 20 Recycling chain indicator score of different coffee capsule main scenarios.

Organic recyclability indicator (ORI): ORI describes the recyclability of the capsule material within organic waste treatment processes and quantifies the mass fraction of the capsule that is completely transformed in biomethane, CO_2 or humus. It is expressed in a percentage, where 100% implies that the packaging is fully recyclable organically, while 0% means the packaging remains unaltered and cannot be recycled organically.

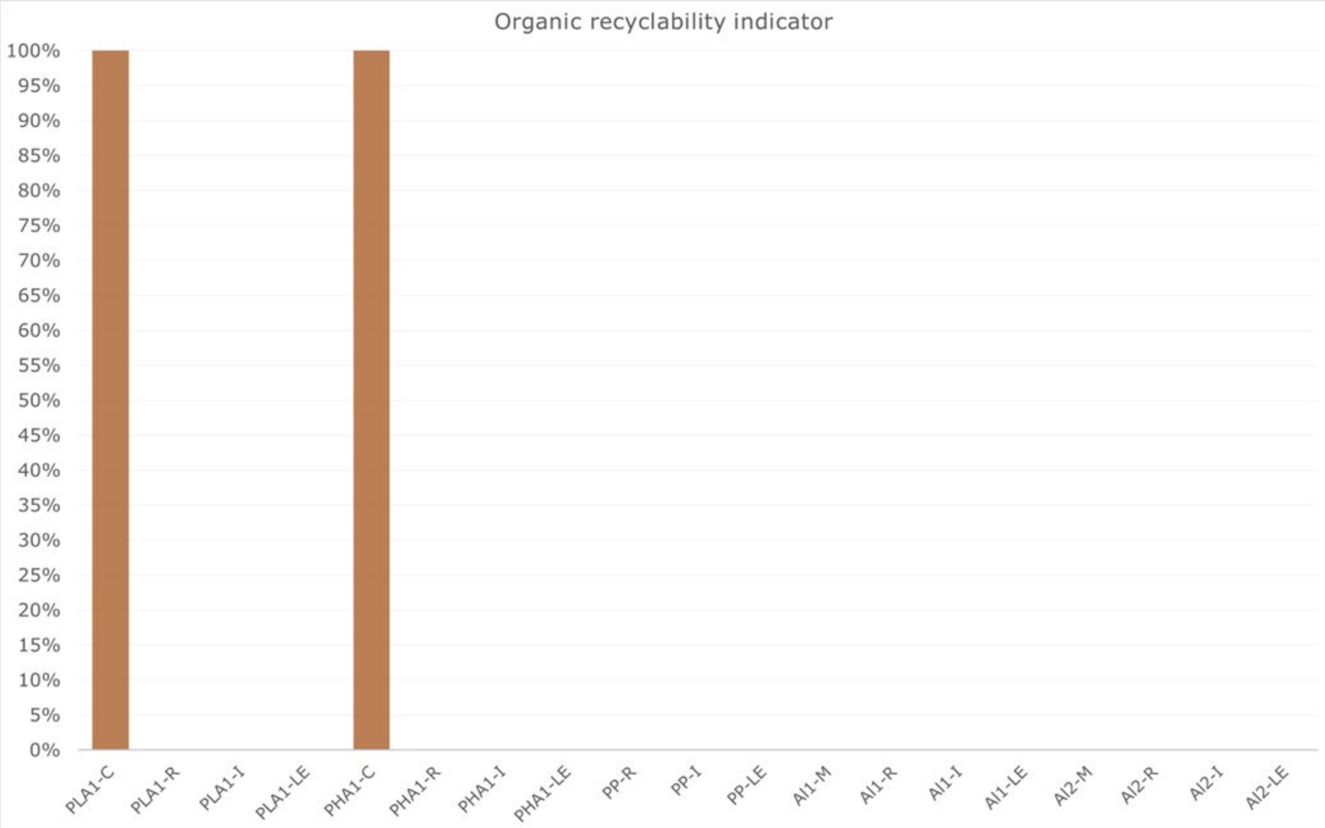

Figure 21 Organic recyclability indicator score of different coffee capsule main scenarios.

Littering prevention indicator (LPI): LPI indicator is used to articulate the likelihood the capsule contributes to the formation of persistent road-side and/or marine litter. The likelihood of littering is small for coffee capsules, however this indicator gives information on what would happen if the capsule would end up in nature. The indicator does not take incorrect waste separation behaviour by civilians into account (so-called misthrows). It is expressed in the form of a percentage, where 100% means that the package doesn't form persistent litter and 0% means that the chance that this package will be littered is maximal.

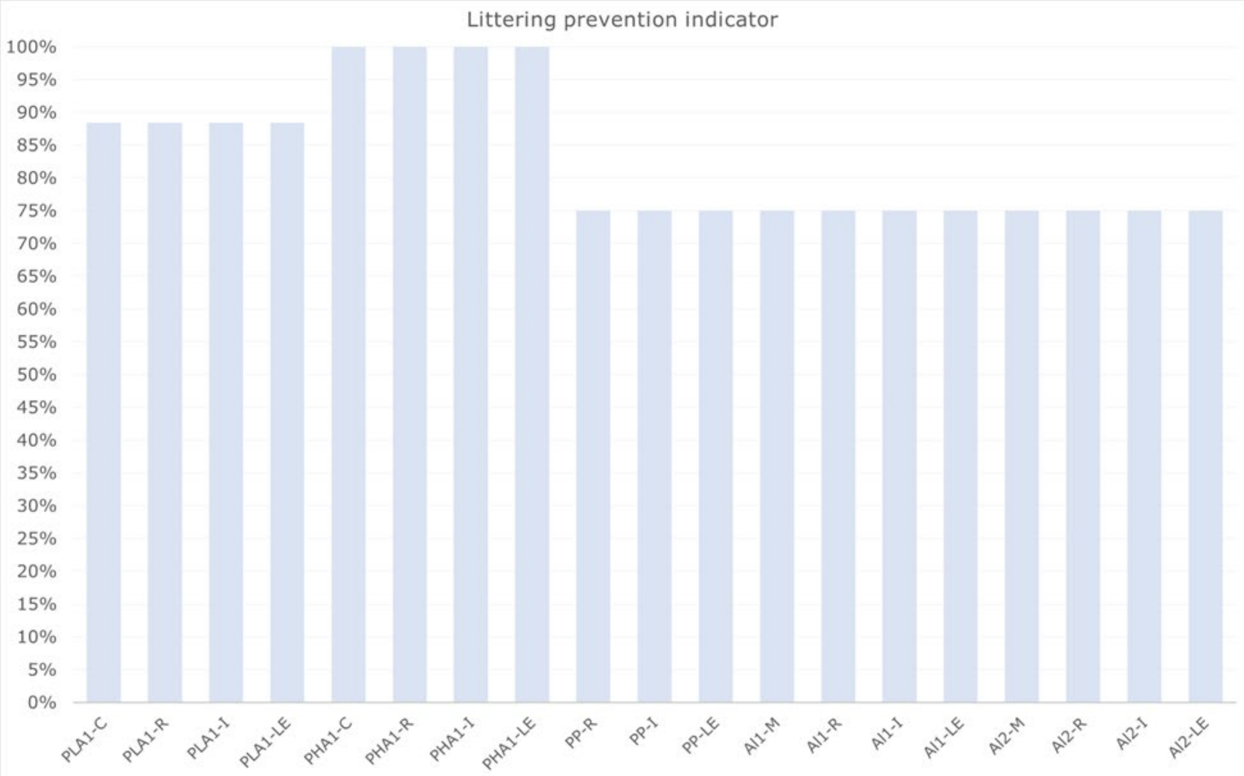

Figure 22 Littering prevention indicator score of different coffee capsule main scenarios.

Recyclability indicator (RI):
It is used to identify the recyclability of the packaging material within mechanical recycling processes and to quantify the mass fraction of the packaging that is made of a recyclable material. It is expressed in a percentage, where 100% implies that the capsule is fully recyclable, while 0% means the packaging cannot be recycled.

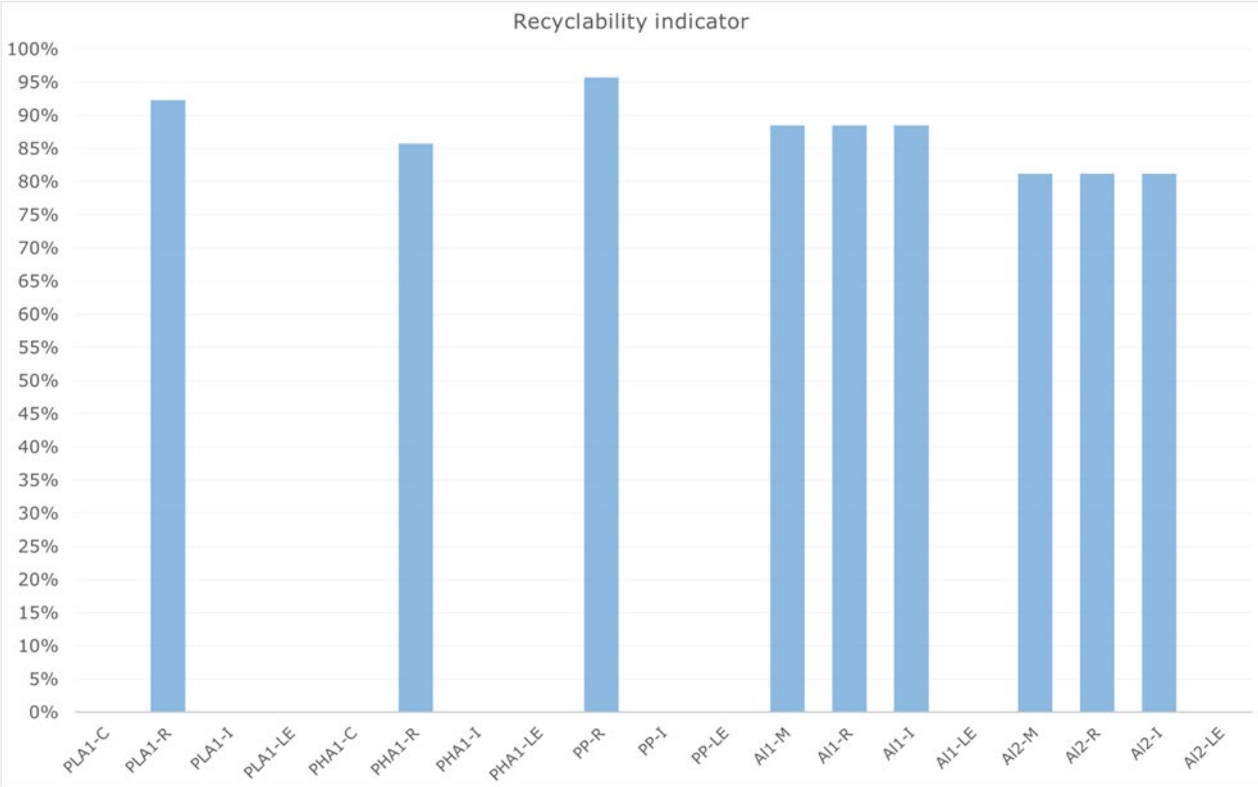

Figure 23 Recyclability indicator score of different coffee capsule main scenarios.

Table with sustainability indicators for all scenarios

Code	Total Emissions (incl. coffee) [g CO2 eqv./kg packed coffee]	Emissions (capsule only) [g CO2 eqv./kg packed coffee]	MCI	ReConI	ReNewI	RI	RCI	ORI	LPI
PLA1-C	7310	741	100%	0%	100%	0%	0%	100%	88%
PLA1-AD-C	7367	799	100%	0%	100%	0%	0%	100%	88%
PLA1-R	6476	311	87%	0%	100%	92%	59%	0%	88%
PLA1-I	6819	654	55%	0%	100%	0%	0%	0%	88%
PLA1-LE	7518	398	55%	0%	100%	0%	0%	0%	88%
PLA2-C	8274	1705	100%	0%	100%	0%	0%	100%	88%
PLA2-AD-C	8312	1745	100%	0%	100%	0%	0%	100%	88%
PLA2-R	6999	834	86%	0%	100%	89%	57%	0%	88%
PLA2-I	7685	1520	55%	0%	100%	0%	0%	0%	88%
PLA2-LE	8074	954	55%	0%	100%	0%	0%	0%	88%
PHA1-C	7960	1391	100%	0%	100%	0%	0%	100%	100%
PHA1-AD-C	8050	1483	100%	0%	100%	0%	0%	100%	100%
PHA1-R	6943	778	85%	0%	100%	86%	55%	0%	100%
PHA1-I	7370	1205	55%	0%	100%	0%	0%	0%	100%
PHA1-LE	7998	878	55%	0%	100%	0%	0%	0%	100%
PP-R	6919	754	48%	0%	0%	96%	61%	0%	75%
PP-I	7281	1116	10%	0%	0%	0%	0%	0%	75%
PP-LE	8010	890	10%	0%	0%	0%	0%	0%	75%
PE-R	7006	841	46%	0%	0%	90%	57%	0%	75%
PE-I	7266	1101	10%	0%	0%	0%	0%	0%	75%
PE-LE	8057	937	10%	0%	0%	0%	0%	0%	75%
Al1-M	7445	876	51%	0%	0%	88%	86%	0%	75%
Al1-R	7711	1546	46%	0%	0%	88%	47%	0%	75%
Al1-I	7829	1664	45%	0%	0%	88%	40%	0%	75%
Al1-LE	9567	2447	10%	0%	0%	0%	0%	0%	75%
Al2-M	7348	779	61%	32%	0%	81%	79%	0%	75%
Al2-R	7460	1295	54%	32%	0%	81%	44%	0%	75%
Al2-I	7551	1386	52%	32%	0%	81%	37%	0%	75%
Al2-LE	9033	1913	25%	32%	0%	0%	0%	0%	75%

To explore the potential of nature to improve the quality of life

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Report 2450

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