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Japan-UNIDO-CSIR-Wits project:
Supporting the transition from conventional plastics to more environmentally sustainable alternatives

Life Cycle Sustainability Assessment (LCSA) of material alternatives for food take-out containers and cups

Final report

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Prepared by:

Dr Valentina Russo

Prof William Stafford

For:

Nahomi Nishio, UNIDO

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Authored for	CSIR	Signature	Date
By	Dr Valentina Russo	Valentina Russo	15/05/2023
Designation	CSIR Scientist: Lead author		
Moderated for	CSIR	Signature	Date
By	Prof Suzan Oelofse	SHHOelofse	22/05/2023
Designation	Principal Scientist and Project Manager		
Approved for	CSIR	Signature	Date
By	Anton Nahman	ANahman	24/05/2023
Designation	Research Group Leader: Sustainability, Economics and Waste		
Approved for	UNIDO	Signature	Date
By	Nahomi Nishio		
Designation			

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Executive summary

This Report forms part of a project titled **Supporting the transition from conventional plastics to more environmentally sustainable alternatives**, funded by the Government of Japan through the United Nations Industrial Development Organization (UNIDO) and carried out by the Council for Scientific and Industrial Research (CSIR) in collaboration with the University of Witwatersrand (WITS). The overall purpose of the project is to support South Africa's transition from conventional plastics to more environmentally sustainable alternatives; with the ultimate goal of reducing the amount of plastic leaking into the environment. Specifically, this report falls under Activity 1.2, namely "*Identify material substitution opportunities for identified product(s) with a Life Cycle Sustainability Assessment (LCSA)".*

Polystyrene take-out containers and cups are used for take-out meals and perform a valuable function in containing and insulating hot meals and drinks. However, these single-use plastic items are also increasingly being found in the environment, contributing to the growing problem of marine litter. Polystyrene take-out containers and cups were identified (Activity 1.1) as high-priority products for which alternatives should be sought. However, the proposed alternatives should not only reduce the problem of material pollution and marine litter, but also not have any other unintended environmental impacts.

The life cycle impacts of polystyrene take-out containers and cups (meal-kits) and various alternatives were assessed using life-cycle assessment (LCA) and the ReCiPe 2016 Midpoint(H) and Endpoint(H) method, which considers a broad range of environmental impact categories at both mid- and end-point level.

In addition, given the lack of a plastic pollution impact category in existing LCA methods, we have developed two additional indicators, namely 1) Persistence of leaked material ($\text{Persistence}_{\text{LM}}$) and 2) Material Pollution Indicator (MPI) to assess the pollution potential of plastic (and other materials more generally) in the environment. Specifically, $\text{Persistence}_{\text{LM}}$ refers to how long a specific item of a given type of material will stay in the environment once it has leaked. The Material Pollution Indicator (MPI) describes the degree to which an item of a given material type is likely to cause pollution due to its potential to leak into the environment and cause damage in the environment; as a combination of its cost (likelihood of being recovered from the environment and recycled), material density (likelihood that he material disperses from management systems and leaks into the environment) and persistence (timer remaining in the environment where it can cause harm). At different scales, the two indicators are intended to approximate the impacts on the environment in terms of the likelihood of items to end up in the environment and, once there, for how long the impact will persist.

Finally, to broaden the LCA analysis further, two socio-economic indicators have also been considered: Cost, which in this study is based on the cost of materials to the manufacturer of the product; and Jobs, which refers to the labour-intensity of each product and therefore their contribution towards employment.

With the inclusion of the two socio-economic indicators and other new indicators, the study goes beyond the scope of a conventional environmental LCA (E-LCA) study and could be considered a Life Cycle Sustainability Assessment (LCSA) study. LCSA, as compared to E-LCA, is characterised by the inclusion of social and economic indicators in addition to only environmental indicators.

The functional unit for the study was based on the estimated consumption of take-out meals in South Africa (which then requires 12 meal-kit per year), and particular attention was placed on modelling the end-of-life stage to represent the South African context. Economic-based allocation was applied to ensure correct allotment of burdens to products. A business-as-usual scenario (BAU), which included only landfilled and mis-managed end-of-life flows, was analysed first. Increased recycling rates, different geographies for polymer production and manufacturing of finished goods, as well as different coating materials, where applicable, were explored through scenarios (see Appendices).

The main findings from the LCSA study are as follows:

- The raw material extraction and polymer production stages in the product life cycle are responsible for the bulk of the environmental impacts associated with meal-kit use in South Africa (see **Figure 1**). This is true both for plastics and alternatives (paper, bagasse and bioplastics), but plastics have a particularly high raw material resource footprint as a result of the coal-to-liquids (CtL) process used for South African plastic polymer production (BAU Scenario).

- For all investigated options, locally sourced raw materials and local conversion has greater environmental impacts, compared to equivalent imports. This is a consequence of South Africa's electricity being supplied mainly by coal, as well as the CtL process used for local plastic polymer production.

- A standard environmental LCA with 18 end-point impact categories (based on the ReCiPe 2016 methodology) to compare polystyrene to ~10 other alternatives (other conventional plastics, coated paper, coated bagasse and several bioplastics); showed that polystyrene has the lowest overall impacts (BAU scenario) (see **Figure 1**). However, this excluded the newly developed persistence and material pollution indicators aimed at assessing the impacts associated with material pollution of plastic (and other materials) in the environment, as well as cost.

- Polystyrene is at least four hundred times worse in terms of material pollution than paper. Biodegradable plastics, biobased plastics, bagasse, and paper are all less persistent in the environment than conventional plastics.

- Alternatives to Polystyrene with lower material pollution include coated paper/cardboard; bagasse; and several bioplastics such PBS, PHB, PBAT+PSM (Mater-Bi®) and expanded PLA (Bio-foam PLA)[1]. However, unlike many of the other options, PLA products can only be composted effectively in dedicated industrial composting. Given the lack of industrial composting in South Africa, home compostable paper and bioplastics (e.g., PBS, PBAT etc) are the recommended alternatives due to their higher degradability characteristics, which reduces their persistence and material pollution in the environment.

- While paper/cardboard and bagasse can be composted in home and industrial composting systems, these materials are commonly coated with polyethylene (PE) to act as a moisture/grease barrier. Although the coating may constitute only between 3-5% by mass, it can hinder biodegradation and increase material persistence. Therefore, it would be preferable if the coating was made from compostable bioplastics (i.e. PBS, PBAT+PSM (Mater-Bi®), PHB or PLA), but preferably not bioplastics requiring industrial composting systems (e.g. PLA).

- It is unlikely that paper/cardboard and bagasse meal-kits would be recycled mechanically due to limited separation at source in South Africa, separation at source challenges with meal-kit containers, and the food-contamination of material recycled from meal-kit containers. However, increasing recycling rates of currently available meal-kits in accordance with the five-year targets under the recent Extended Producer Responsibility (EPR) Regulations (2023-2028), as well as composting of biodegradable and compostable alternative materials, will improve the overall environmental performance by about 40% for both conventional plastic alternatives and for biodegradable and compostable alternative materials.

- Both extruded polystyrene (XPS) clamshells and expanded polystyrene (EPS) cups are clearly more affordable than the other options investigated. The XPS and EPS material in the clamshell or cup has a very low material price, as well as a very low material weight (e.g. expanded polystyrene products are >95% air). The alternatives such as paper, bagasse and bioplastics are at least twice as costly. Bioplastic materials such as PLA, PBAT and PBS cost

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[1] Definitions of this acronyms can be found in the List of Abbreviation Table (pg 13).

about five times more than polystyrene, while PHA and PHBH are about forty times the cost of polystyrene.

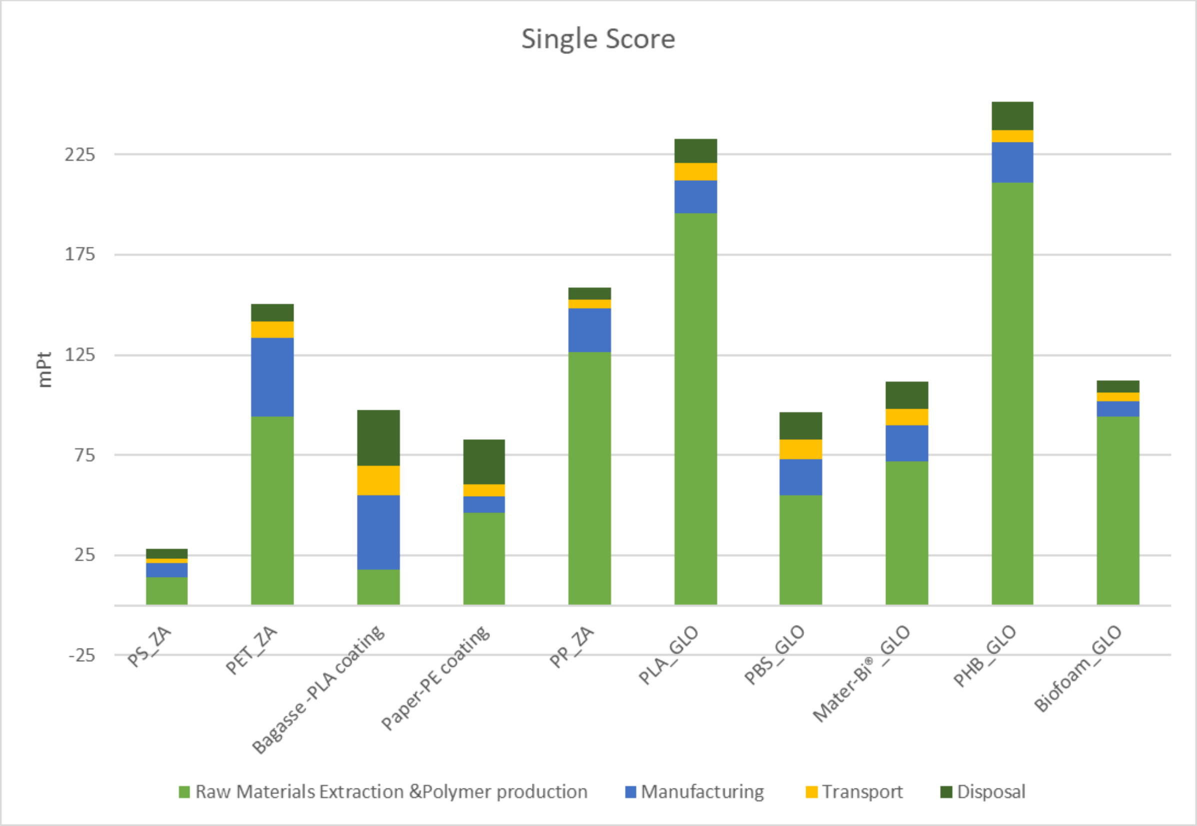

Figure 1: LCIA ReCiPe 2016 Single Score results for the BAU scenario

Considering all the environmental and socio-economic indicators and attempting aggregation to a single metric using min-max scaling, suggests that Polystyrene (PS) meal-kit (cup and clamshell) has the lowest overall environmental impacts; followed by expanded PLA, and then coated paper and bagasse. However, such aggregation is not recommended by LCA standards (ISO 14044), as the weighting of indicators becomes extremely contentious (for example, equal weighting assumes that each indicator has equal importance or value); while such aggregation also fails to assess meaningful end-point impacts (raw material depletion, human and ecosystem health) that are most useful for policy and decision making.

As such, different weighting options were explored, both to test the methodology's robustness and to understand when a shift in the ranking would occur to favour a particular meal-kit alternative (**Table 1**). It was observed that even when the Material Pollution Index (MPI) is assigned 50% of the total weighting, PS still comes out at the preferred option. A change in the ranking of the preferred option was only observed when 75% of the weighting is assigned to the MPI, with the PLA Bio-foam being the preferred option to the PS meal-kit in that case.

These results are generally well aligned with those from international LCA studies on single-use take-out containers and cups. In addition, other studies have shown that single-use cups, for example, have similar environmental impacts regardless of the material they are made of.,. When considering single-use food-packaging products, polystyrene (PS), extruded polystyrene (XPS) and paper have often been shown to have a better environmental performance than other packaging materials (PET, PLA, PP and Aluminium). This is largely a result of the low density of expanded and extruded polystyrene. Since the environmental performance of packaging is to a large extent influenced by the type and amount of material, the light-weighting (or rather ‘right-weighting’) of packaging (without compromising its functionality) also results in improvements in the environmental performance.

A main limitation of LCAs undertaken in South Africa is the lack of South African specific LCA datasets., This study has included recent relevant South African data, which highlights the energy intensity of material production, particularly plastics, and the potential to avoid impacts by minimising the use of materials, through re-use and substitution with alternative materials.

In addition, a limitation of LCA studies relating to plastics globally is the lack of an indicator to assess the impacts of material pollution (plastics and other materials in the environment impacting human-health, biodiversity and ecosystems). To overcome this issue, the study has included two indicators (Persistence of leaked material ($\text{Persistence}_{\text{LM}}$) and the Material Pollution Indicator (MPI)), which were recently developed by the CSIR team, to account for the impacts of plastics and other materials in the environment. These indicators reveal the extremely slow degradation of plastics, and hence their persistence and accumulation in the environment. They also highlight the additional problem of increased leakage and littering of low-density materials such as polystyrene, which have several orders of magnitude greater material pollution compared to bioplastic and paper alternatives (per Functional Unit of the study, i.e. 12 meal-kit per year). Therefore, a switch from polystyrene to compostable materials (paper, bagasse, and certain bioplastics) will substantially reduce plastic pollution, but may incur additional environmental burdens. Among the bioplastics, Bio-foam (from expanded PLA) is potentially the best option, but PLA requires industrial composting with dedicated infrastructure to control moisture and temperature; and there is a lack of these systems in South Africa. Therefore, switching to bioplastic alternatives that require industrial composting requires investment in infrastructure and associated separation and collection systems. In contrast, other types of bioplastics (e.g. PBS, PHB and PBAT+PSM) can be composted in both home and industrial composting systems; and is preferred option to reduce material pollution at a low added infrastructure cost (see **Table 1**).

As part of the broader project, a market study has been conducted aimed at investigating the potential for replacement of polystyrene with blended bioplastic (bagasse and PLA) in cups and clamshells used in the food takeaway packaging industry in South Africa. The study found that several issues need to be addressed before market penetration can be achieved. These include:

i. setting up production and manufacturing facilities, as well as industrial composting facilities;
ii. pricing is regarded as a barrier to entry - the applications of polystyrene cups and clamshells in the food takeaway industry indicates that cost will be an issue for many small businesses using the products;
iii. some of the stakeholders consulted, expressed concerns about the potential socio-economic consequences of switching to alternatives, such as job losses; and finally,
iv. South African legislation seems to favour the recycling of conventional plastics, without sufficient accommodation of biodegradable / compostable plastics to enable separation and effective treatment of these alternatives.

Table 1: Overall Score based on the Min-Max normalisation method and alternative approaches to weighting

Meal-kit type	**Overall score** **(equal weighting)**	**Meal-kit type**	**50% weighting to MPI**	**Meal-kit type**	**75% weighting to MPI**
PS (ZA_manufacture, 0%recycling)	1.03	PS (ZA_manufacture, 0%recycling)	0.51	Bio-foam - expanded PLA (GLO_ZA_imported)	0.67
Bio-foam - expanded PLA (GLO_ZA_imported)	2.70	Bio-foam - expanded PLA (GLO_ZA_imported)	1.35	PS (ZA_manufacture, 0%recycling)	0.76
Paper - PE coating	3.43	Paper - PE coating	1.72	Paper - PE coating	0.86
Bagasse -PLA coating (GLO-ZA_imported)	4.65	Bagasse -PLA coating (GLO-ZA_imported)	2.33	Bagasse -PLA coating (GLO-ZA_imported)	1.16
PSM-Mater-Bi (GLO_ZA_imported)	5.29	PSM-Mater-Bi (GLO_ZA_imported)	2.65	PSM-Mater-Bi (GLO_ZA_imported)	1.32
PBS (GLO_ZA_imported)	6.88	PBS (GLO_ZA_imported)	3.44	PBS (GLO_ZA_imported)	1.72
PLA (GLO_ZA_imported)	7.79	PLA (GLO_ZA_imported)	3.90	PLA (GLO_ZA_imported)	1095
PHB (GLO_ZA_imported)	11.96	PHB (GLO_ZA_imported)	5.98	PHB (GLO_ZA_imported)	
PP (ZA_produced, 0% recycling)	1297	PP (ZA_produced, 0% recycling)	6.49	PP (ZA_produced, 0% recycling)	.2.99
PET (ZA_produced, 0% recycling)	13.29	PET (ZA_produced, 0% recycling)	6.65	PET (ZA_produced, 0% recycling)	3.33

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List of Abbreviations / Glossary

BAU	Business-as-usual
Biodegradable	The term biodegradable refers to any material that can be broken down by microorganisms (like bacteria and fungi) and assimilated into the natural environment. Biodegradation is a naturally occurring process; when an object degrades, its original composition degrades into simple components like biomass, carbon dioxide, water.
Compostable	The term compostable refers to a product or material that can biodegrade under specific, human-driven circumstances. Unlike biodegradation, which is an entirely natural process, composting requires human intervention.
CtL	Coal-to-Liquid. It refers to the Fisher-Tropsh process to produce liquid fuels and chemical from a coal source.
E-LCA	Environmental Life Cycle Assessment
EoL	End-of-life
EPS	Expanded polystyrene
FU	Functional Unit
GLO	Global, abbreviation used in ecoinvent database
LCC	Life cycle costing
LCA	Life Cycle Assessment
LCSA	Life Cycle Sustainability Assessment
PBAT	Polybutylene adipate terephthalate
PBS	Polybutylene succinate
PET	Polyethylene terephthalate
PHB	Polyhydroxybutyrate
PLA	Polylactide
PP	Polypropylene
PRO	Producer Responsibility Organisation
PS	Polystyrene
PSM	Polymer starch material
ReCiPe 2016	ReCiPe 2016 (H) method
Recovery	Recovery, as a broader term, is here used to refer to both “recycling and composting” to imply material recovery and nutrient recycling.
rPET	Recycled PET
RoW	Rest of the World, abbreviation used in ecoinvent database
Safripol	Safripol (Pty) LTD -major polymer producer in South Africa
SCP	Sustainable consumption and production
S-LCA	Social life cycle assessment
XPS	Extruded polystyrene
ZA	South African country code

1 INTRODUCTION

1.1 Project background

The overall aim of the project is to support South Africa's transition from conventional plastics to more environmentally sustainable alternatives; with the ultimate goal of reducing the amount of plastic leaking into the environment (including the marine environment) in South Africa. It aims to strengthen the local bioplastics and sustainable alternative material industry and build up capacities for plastics recycling through informal collection. This will be achieved through two distinct outputs, namely:

- *Output 1*: Development of an Action Plan to support sustainable transition to alternative material, including strengthening of local industry (including the bioplastics industry).
- *Output 2*: Strengthening of capacity for plastics recycling through encouraging waste separation at source and integration of informal collectors.

The aim of *Output 1* is to support the identification and implementation of alternative materials for problematic plastic products. More specifically, Output 1 plans to evaluate and suggest alternative materials that provide the best social, economic, and environmental solutions compared to traditional problematic plastic product(s). To inform the Action Plan under *Output 1, Activity 1.2 was tasked to identify material substitution opportunities for identified product(s) using Life Cycle Sustainability Assessment (LCSA).*

1.2 Why Take-out Containers?

In a previous task (*Activity 1.1 - Identification of single-use plastics with opportunity for replacement*), polystyrene take-out containers and cups were identified (based on literature and expert consultations) as one example of problematic plastics with low recycling rates and a high probability of leaking into the environment.

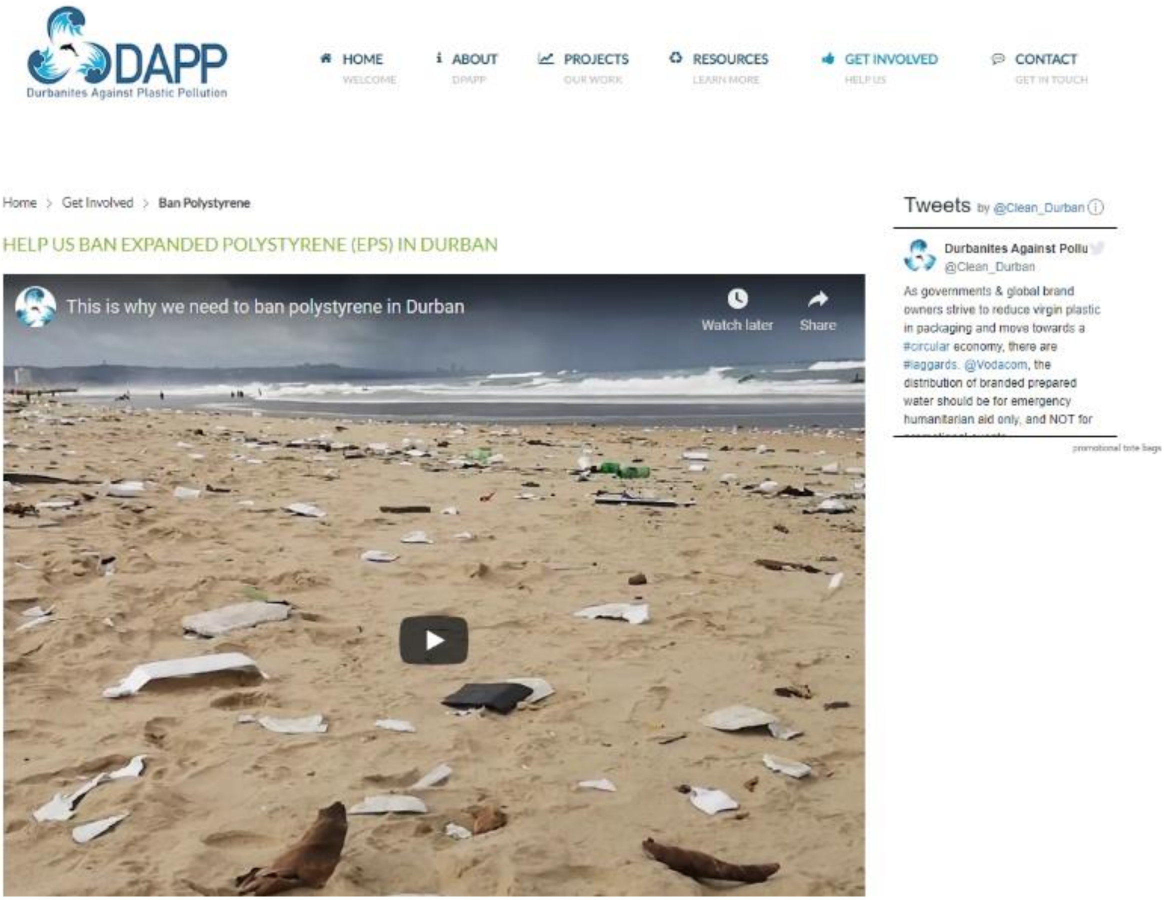
Polystyrene is commonly reported as one of the top items of 'litter' or marine debris recovered from shorelines and beaches worldwide (Garrity and Levings, 1993; Bravo *et al*., 2009; Lee et al., 2013; Ocean Conservancy, 2017), including in Antarctica (Convey *et al.*, 2002) as well as South Africa (Chitaka and von Blottnitz, 2019). Notably, the polystyrene is often found as pieces or fragments during beach clean-ups as the material has a propensity to disintegrate and disperse and is a challenge to recover and recycle due to high collection and transport costs and a low material value. Polystyrene has also been found on the surface of the open ocean (Morét-Ferguson *et al*., 2010) and on the seafloor (Keller *et al.*, 2010).

Currently, there is a global trend away from the use of polystyrene, particularly in food and single-use applications; with several towns (e.g. Portland (Oregon, USA), Toronto (Canada), Muntinlupa (Philippines), Paris (France), and Tainan (Taiwan)) prohibiting their use. The problem with polystyrene beach litter and material polluting of environment is also highlighted by the local Durbanites Against Plastic Pollution (DAPP) which has lobbied for a ban on polystyrene (see **Figure 2**).

Therefore, this study focussed on assessing the life cycle impacts of Polystyrene take-out containers and cups; and of various alternatives, using attributional life-cycle assessment (LCA). The impact assessment was carried out using the ReCiPe 2016 (H) method that considers 18 environmental impact categories at mid-point level, and 3 damage categories at end-point level. Although not recommended by the ISO standards (ISO 14044), we also aggregate the results to a single score to facilitate a comparison between the various alternatives.

In addition, a number of additional indicators were developed and applied in the study; namely:

- Two indicators, namely Persistence$_{LM}$ and a Material Pollution Indicator were developed to address material pollution and marine litter;
- Two socio-economic indicators were applied: 'Cost' was considered to account for the cost associated with the materials to the manufacturers, while an indicator around 'Jobs' was applied to assess the net job losses or gains in the transition from conventional plastics to biodegradable alternatives.



HELP US BAN EXPANDED POLYSTYRENE (EPS) IN DURBAN

This is why we need to ban polystyrene in Durban

Tweets by @Clean_Durban

Durbanites Against Pollu
@Clean_Durban

As governments & global brand owners strive to reduce virgin plastic in packaging and move towards a #circular economy, there are #laggards. @Vodacom, the distribution of branded prepared water should be for emergency humanitarian aid only, and NOT for

promotional tote bags

Figure 2: Web-page of a South African activist, education and outcome based programme driven by a group of experienced non-government implementation partners in Durban. Durbanites Against Plastic Pollution (DAPP) https://dpapp.org/get-involved/ban-polystyrene

2 LITERATURE REVIEW

Internationally there is a growing concern around the environmental impacts of plastic packaging and other single use plastic products. Several LCA studies have assessed the impacts of single-use take-away food packaging (UNEP, 2020) and beverages cups (UNEP, 2021). In the case of beverage cups, ten (10) LCA studies were compared, which looked at both single-use and reusable cups for hot and cold drinks. Regarding take-away food packaging, eleven (11) LCA studies were analysed (UNEP, 2020) and beverages cups (UNEP, 2021), which compared single-use plastic and other material alternatives, as well as reusable food packaging. The results showed that single-use cups have similar environmental impacts regardless of the material they are made of (whether bio-based plastic, fossil-based plastic, or paper); and that reusable options are preferable. Paper is the preferred alternative and when recycling rates increase up to 80% is also preferable over reusable alternatives. Regarding single-use food-packaging, extruded polystyrene (XPS) and paper tend to have a better environmental performance than alternatives made from other materials (PET, PLA, PP and Aluminium). Lightweighting of packaging (without compromising its functionality, i.e., 'rightweighting') also impacts positively on the environmental performance.

Recently, UNEA 5.2 acknowledged the significant impacts of plastic pollution on the marine environment and the importance of evaluating the impacts of plastic through a full life cycle approach, considering national circumstances and capabilities. Furthermore, it recognised the wide range of approaches, sustainable alternatives and technologies to address the full life-cycle of plastics; and underlined *"the importance of promoting sustainable design of products and materials so that they can be reused, remanufactured or recycled and therefore retained in the economy for as long as possible along with the resources they are made of, as well as minimizing the generation of waste, which can significantly contribute to sustainable production and consumption of plastics*." (UNEA 5.2, 2022).

Regarding some of the other problematic plastic products identified in Activity 1.1 of this project, some Life Cycle based studies have been conducted to date in South Africa, for example:

- *Cotton Bud Sticks:* Chitaka (2020) illustrates the potential environmental impacts associated with switching from plastic (polypropylene) to paper cotton bud sticks, via a comparative life cycle assessment. Both imported and locally manufactured paper cotton bud alternatives were investigated, and the study concluded on imported paper cotton bud sticks had the lowest emissions across most of the impact categories. This was mainly due to the use of coal as a primary feedstock in the production of propylene (unique to South Africa) and as a primary energy source for electricity production. Also from a retailer perspective, substituting plastic cotton bud sticks with paper was viewed as a simple and quick way to appease consumers.
- *Grocery Bags:* Russo et al. (2020) and Stafford et al. (2022) conducted a Life Cycle Sustainability Assessment of 16 carrier grocery bag material options potentially available in South Africa. Life Cycle Sustainability Impact Assessment results across all impact categories ranked fossil-based reusable bags as the best performing. Overall, re-usable bags were top ranked from an E-CLA point of view; the reference bag of the study, HDPE 24 µm with 100% recycled content was the best fossil-based single-use bag, whereas among the biodegradable bags the best performing across all impact categories is the imported PBAT+Starch. Persistence$_{LM}$ (persistence of leaked material) indicator to measure plastic pollution provides evidence on options (biodegradable bags) having the least potential impacts on environment due to their degradability, overtaking the re-usable alternatives.
- *Plastic drinking bottle and tops:* Chitaka (2020) investigated the Bottle Vs Lids issue when it comes to proneness of leakage into the environment. Although not an LCA study, she explored the challenges hindering the collection and recycling of lids and concluded that lid tethering as possible intervention would increase the collection rate of lids as they would remain attached to the widely recycled bottles.
- *Straws:* Chitaka et al. (2020) compared the environmental impacts associated with five straw material options available in South Africa. The study concluded that paper straws have the least

impacts in most impact categories when compared with other disposable options and glass is favoured over steel as reusable option. In terms of marine pollution, reusable straws were deemed to pose the least risk due to their reusable nature. Paper was associated with the least potential impacts at disposal, due to its degradability.

It is worth noting that only two of the above-mentioned studies tried to go beyond a conventional LCA: Chikata et al. (2020), which included a proxy indicator (Leakage Rate) to account for marine pollution; and Russo et al. (2020) and Stafford et al. (2022), which conducted a Life Cycle Sustainability Assessment (LCSA), including the development of a proxy indicator (called $\text{Persistence}_{\text{LM}}$) to account for plastic pollution (and material pollution more generally) in the environment; as well as two socio-economic indicators (impacts on employment, and on cost for consumers).

At the international level, UNEP has compiled meta-studies on several single-use and reusable alternatives for the following items: shopping bags, beverage bottles, takeaway food packaging, beverage cups, tableware, nappies, menstrual products, and face masks (UNEP, 2021b). The findings emphasize that products intended for single use are the problem, regardless of their material.

Nappies were also studied by *Aumônier et al.* (2008), who conducted a comparative LCA for disposable and reusable nappies in the UK. The study concluded that the manufacture of disposable nappies has greater environmental impact in the UK than their waste management by landfill. For reusable nappies, the study showed that the impacts are highly dependent on the way they are laundered.

None of the studies reviewed in the analysis or carried out by *Aumônier et al.* (2008) took a LCSA approach.

2.1 Polystyrene as a problem plastic

Polystyrene is a petroleum-based plastic made from the styrene (ethenylbenzene) monomer. Polystyrene was first commercially produced in 1931, and is used in a wide range of commercial, packaging and building applications. Polystyrene products are produced through the polymerization of rigid plastic or expanded with a gas to create a foam prior to polymerisation. Rigid polystyrene is used in appliances such as television and computer cabinets, as well as for disposable cutlery, and plates. Polystyrene foam has excellent insulating properties and is available in two forms: Expanded polystyrene (EPS) is used for cups for drinks, food storage and cushioning in packaging; while extruded closed-cell polystyrene foam (XPS) is used in building and construction, cushioning in packaging, and for food trays and take-out containers.

The use and indiscriminate disposal of plastics can create hazards to all biodiversity and ecosystems. Plastics have a potential to cause harm in two ways:

- Chemically, when monomers, plasticisers and other hazardous additives leach from polystyrene products; and
- Physically, when plastic enters the environment and breaks down from macro-plastics to micro- and nano-plastics.

The composition of polystyrene products, as well as the context in terms of manufacture, use, disposal and fate in the environment, is a critical aspect when determining the hazard (Liboiron, 2015). The monomer of polystyrene, styrene, is a known carcinogen and toxin, and listed under Category 1 potential endocrine disruptors (European Commission 2016; Linther 2011). When the polymerization of styrene during manufacturing is complete, the resulting styrene is unlikely to be released, even following degradation in the environment. However, if styrene is not completely polymerised during the manufacture of polystyrene, residual styrene could leach into food and beverages - particularly hot food and beverages containing fats that will likely increase chemical leaching. The World Health Organization (WHO) lists the maximum permissible limit at 20 parts per billion (ppb) for styrene (World Health

Organization, 2004). The reported amount of styrene that leaches from polystyrene into food and drinks varies in the literature (from about 1 to 300 ppb) depending on the experimental design , using various foods and/or solvents, varying time periods, and varying temperatures (Tawfik and Huyghebaert, 1998; Ahmad and Bajahlan, 2007; Sanagi *et al*., 2008). Many studies at *ambient temperature* indicate very low levels of leaching (nano-grams), that do not raise a safety concern for the consumer (EFSA CEF Panel, 2014; Bejgarn *et al*., 2015). However, leaching experiments from polystyrene with common foods at *relevant temperatures* (70 °C and 95°C) revealed that leaching from EPS does occur. The levels of leachate are very low and at the limits of current chemical detection methods, but bioassays have clearly demonstrated that this leachate is toxic to aquatic invertebrates (Thaysen *et al*., 2018; Aljaibachi and Callaghan, 2018). Furthermore, there is at least one study that identified volatile styrene monomers found in shells of eggs after they were stored for 2 weeks in polystyrene containers at supermarkets; with seven times more ethylbenzene and styrene compared to eggs not packaged in polystyrene (Matiella and Hsieh 1991).

As mentioned earlier, if polymerization is complete, the biodegradation of polystyrene is unlikely to produce styrene. However, styrenes have been detected in ocean water and sediments globally (Kwon *et al*., 2015; Kwon *et al*.,2017); and since man-made polystyrene plastic is thought to be one of the only sources of styrenes to the environment, the styrene is thought to be from the slow weathering of polystyrene in the environment.

Plastics in the environment present physical hazards, and polystyrene has been found to impact diverse biodiversity and ecosystems. Plastic pollution can cause entanglement, suffocation and reduced feeding ability of biota, resulting in reduced fitness, fecundity and lifespan. Hundreds of marine and freshwater species are known to have ingested or become entangled in plastics (Gall *et al*., 2015; Rochman *et al*., 2016; Huerta *et al*., 2017; de Souza *et al*., 2018). Plastic degrades in the environment extremely slowly; taking decades (or longer) to break down physically and chemically. Even when a plastic item degrades under the influence of weathering, it first breaks down into smaller pieces of plastic debris or micro-plastics that are increasingly found in biota and the human food chain (Woodall *et al.,* 2014; Conkle *et al.,* 2018; Barnes *et al*., 2009; Gregory, 2009; Oehlmann *et al*., 2009; Ryan *et al*., 2009; Teuten *et al*., 2009; Thompson *et al*., 2009; Barboza *et al*., 2018; Peixoto *et al*., 2019).

Plastic pollution also has socio-economic impacts, by affecting fishing stocks, reducing the aesthetics of beaches and natural areas (Wyles *et al*., 2016), blocking drainage and wastewater treatment plants (Fobil *et al*., 2009), and providing a breeding ground for water-borne diseases (Wyles *et al*., 2016; Boelee *et al*., 2019; UNEP, 2014).

In addition to the physical hazards they pose, hydrophobic plastics such as polystyrene have an ability to adsorb persistent organic pollutants (POPs), which can be released following ingestion of polystyrene microparticles by animals (e.g. fish). For example, seabirds that have consumed plastic waste have been found to have POPs in their tissues at 300% greater concentrations than in similar birds that have not eaten plastic. Polystyrene is particularly good at absorbing hydrophobic chemicals, with concentrations of POPs adsorbed by polystyrene at up to a million times greater than in the surrounding water. Due to the known toxicity and persistence of POPs in organisms and food webs, these chemicals can disrupt key physiological processes and cause disease and reduce the fitness and reproductive ability of organisms. As a result of these risks, several scientists have recommended the reclassification of polystyrene and several other plastics as hazardous, so that they could be more effectively regulated by environmental protection agencies (Rochman *et al.,* 2016).

Lastly, incomplete combustion of polystyrene at temperatures and aeration that is typical of household burning of wastes produces many toxic products; including styrene and other polyaromatic hydrocarbons that are likely to be carcinogenic (IARC, 2018). In summary, high rates of polystyrene production and consumption, inadequate waste management and slow environmental degradation, with the formation of microparticles and adsorption of hydrophobic toxic chemicals, has led to large quantities of polystyrene waste transporting adsorbed toxins and impacting terrestrial, aquatic and marine biodiversity and ecosystems.

2.2 Polystyrene take-out Containers

Polystyrene take-out containers can refer to either a “clamshell” food tray (made from XPS), or a cup (made from EPS) (**Figure 3**).

Thus, for the purpose of comparing alternatives to Polystyrene take-out containers, a “**Meal-kit” was defined as being composed of both a clamshell food container and a cup**. The baseline Meal-kit against which the alternatives will be compared consists of an XPS clamshell and an EPS cup. A variety of meal-kit materials type were considered as possible alternatives to the Polystyrene meal-kit, as per Table 2.

Figure 3: PS meal kit: take-out clamshell (left) and cup (right)

2.3 Biodegradable options

Biodegradable plastic, which can be produced from either bio-based or fossil-based feedstock, refers to polymers that undergo biodegradation under specified environmental conditions and within specified degradation times (EN 13432). Even when polymers are bio-based, i.e., the polymers are manufactured, in part or in whole, from renewable biological resources, most often from vegetable sources; plastics labelled as biobased, and biodegradable can also contain plasticisers and additives. A comparison with conventional plastics indicated that bioplastics and plant-based materials can pose an equal – if not greater – risk to conventional plastics when they break down in the environment (Zimmerman, 2020).

Also, results of field studies concluded that when biodegradable plastics end up outside industrial or controlled composting conditions, some can persist for many years once they are in marine environments without showing any signs of biodegradation, and, as litter, they can pose similar environmental risks as conventional plastics to individuals, biodiversity, and ecosystem functioning (UNEP, 2021c). Other potential problems of biobased and biodegradable plastics include heavy reliance on agriculture and associated resources (land, fertiliser, water), disruption of recycling of conventional plastics if not correctly separated, and a risk that they may be more prone to littering due to consumer perceptions about biodegradability in the environment.

Thus, when products are labelled as “compostable”, “biodegradable”, “oxodegradable” or “biobased”, these terms can be confusing and misleading. Any claim of compostability or biodegradability should be clearly related to the conditions under which the properties apply. Precise communication with consumers is needed to explain that these claims do not give “permission to litter”, and to give them the appropriate information for the correct way to dispose of products. However, such labels have become an appealing marketing term and are very misleading. To help address this, there are several new standards and schemes for treatment of bioplastic products, such as EN 13432 and EN 14995 for industrial or municipal compostable materials and other certificates based on AS 5810-2010 for home composting (European Bioplastics 2015, European Bioplastics 2015). A number of standards have been developed to test and assure biodegradability under certain conditions and include composability under industrial, home, marine and anaerobic conditions; namely:

- **Biodegradable: DIN 38412:30 -** This standard describes a method for determining the toxicity of water constituents towards Daphnia magna, a water flea species. It simulates the effect of biodegradable materials on aquatic life (Deutsches Institut für Normung 1991).
- **Biodegradable: ISO 14855-1 -** This standard determines the ultimate aerobic biodegradability of plastic materials under controlled composting conditions, which involves monitoring evolved carbon dioxide from plastic materials in contact with soil (International Organization for Standardization 2012).
- **Compostable: ISO 17088 -** This standard outlines the criteria for compostable plastics and products made from them under industrial conditions. It specifies necessary test methods, properties, and limits for determining compostability (International Organization for Standardization 2008).
- **Compostable: EN 13432 -** This standard defines the criteria for packaging recoverable through composting and biodegradation under industrial conditions. Materials should biodegrade, disintegrate, and not negatively impact the composting process or the quality of the compost (European Committee for Standardization 2000).
- **Compostable: ASTM D6400 -** This standard details the specifications for plastics suitable for composting in municipal and industrial aerobic composting facilities. It includes tests to confirm that the plastic will compost satisfactorily (ASTM International 2019).
- **Oxo-biodegradable: ASTM D6954-04 -** This standard provides a guide for testing plastic materials that degrade when exposed to oxygen (oxo-degradable), and subsequently biodegrade under aerobic composting conditions (ASTM International 2004).
- **Home Compostable: AS 5810 -** This Australian standard specifies requirements and methods for the control and verification of biodegradable plastic materials which are suitable for processing in home composting systems (Standards Australia 2010).
- **Marine Biodegradable: ASTM D7081-05 -** This standard covers the biodegradability of plastics in the marine environment by aerobic microorganisms. The standard specifies criteria to determine if a plastic that will sink in seawater is biodegradable (ASTM International 2005).
- **Home Compostable: NF T 51-800 -** This French standard is for the compostability of plastics and products made from them in domestic composting conditions. It includes a test scheme and evaluation criteria for the final acceptance of the material (Association Française de Normalisation 2015).
- **Marine Biodegradable: ASTM D6691 -** This standard test the degree and rate of aerobic biodegradation of plastics when exposed to seawater under controlled composting conditions (ASTM International 2015).
- **Marine Biodegradable: ISO 18830 -** This standard specifies a method for determining the degree of disintegration of plastic materials in seawater under laboratory conditions (International Organization for Standardization 2016).
- **Marine Biodegradable: EN 14987 -** This standard outlines a method for the pre-treatment and ultimate aerobic biodegradability of plastic materials in seawater (European Committee for Standardization 2006).
- **Landfill Biodegradable: ASTM D5511 -** This standard test the anaerobic biodegradation of plastic materials under high-solids anaerobic-digestion conditions, which simulate landfill conditions (ASTM International 2016).

- **Landfill Biodegradable: ASTM D5526 -** This standard **is a** method for determining the rate and extent of aerobic biodegradation of synthetic plastic materials in a controlled composting environment under hiconditions (ASTM International 2016).
- **Biodegradable: ISO 17556 -** This standard determines the ultimate aerobic biodegradability of plastic materials in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved (International Organization for Standardization 2012).

In addition to the above, standards and schemes are needed for the separation and sorting of bioplastics, so that they can be treated appropriately. In South Africa, SANS 1728, published in 2019 by the South African Bureau of Standards, requires that biodegradable, compostable, and oxo-biodegradable plastics, which fall under material identification code 7 (**Figure 4**), comply with the following international standards:

- Biodegradable: DIN 38412:30 or ISO 14855-1.
- Compostable: ISO 17088, EN 13432, or ASTM D6400.
- Oxo-biodegradable: ASTM D6954-04.

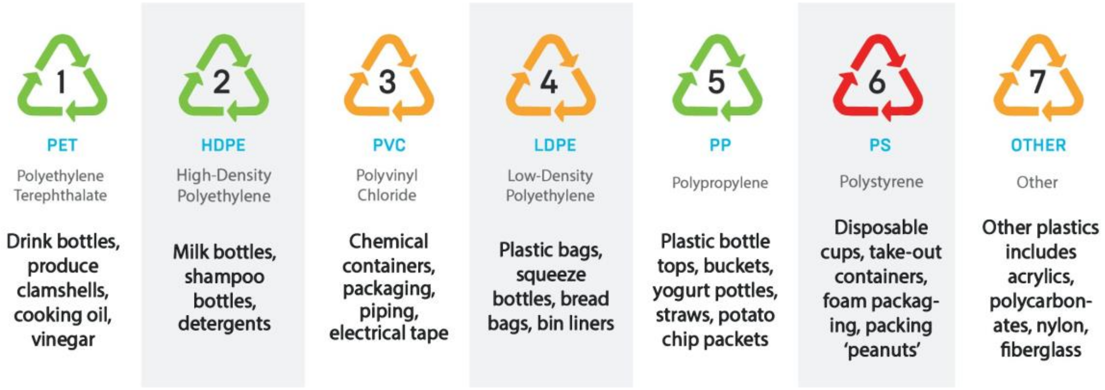


Figure 4: Plastic resin identification codes

There are local and international initiatives to create a unique material identification code for biodegradable bioplastics so they can be effectively separated and composted (ORASA pers. comm., and Moss group, 2020). COPCO (**CO**mpostable **P**ackaging **CO**uncil) – soon to be registered as a PRO which represents compostable packaging in South Africa - also recommends a labelling scheme and certification for compostable packaging; and to date has developed a logo (trademarked) for home compostable packaging only, while they are also busy working on developing a logo for industrial compostable packaging (personal communications).

3 METHODS

3.1 LCA and LCSA

Life Cycle Assessment (LCA), also known as environmental LCA (E-LCA), is a framework and standardised methodology for assessing the environmental impacts across the full life cycle of a product, i.e., "*from raw material acquisition through production, use, end of life treatment, recycling and final disposal (i.e., cradle-to-grave)*" (ISO 2006a). Application of LCA is guided by ISO standards 14040 (ISO 2006a) and 14044 (ISO 2006b) of 2006, which aim to ensure consistency in the application of the methodology and comparability of results.

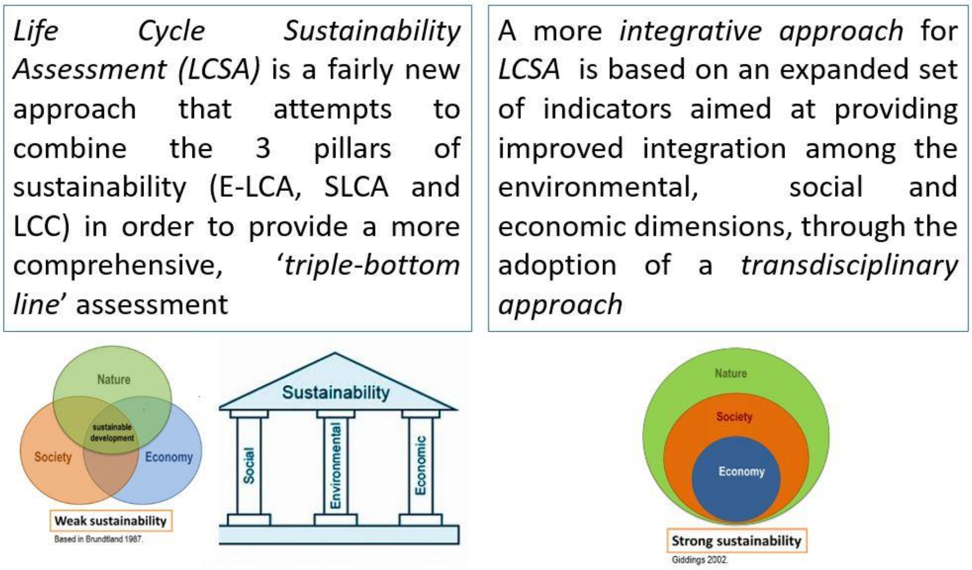
In line with the three 'pillars' of sustainability (environmental, social and economic); two additional approaches have also been developed, namely Social LCA (S-LCA), and Life Cycle Costing (LCC), aimed at assessing the social and economic impacts (respectively) of products across their life cycles. Life Cycle Sustainability Assessment (LCSA) is a fairly new approach which "*refers to the evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle*" (UNEP, 2011). LCSA attempts to combine E-LCA, S-LCA and LCC, to provide a more comprehensive assessment of products in terms of the three pillars of sustainability.

The benefits of conducting a LCSA include, among others (UNEP, 2011):

- Enables practitioners to organize complex environmental, economic and social information and data in a structured form;
- Helps clarifying the trade-offs between the three sustainability pillars, life cycle stages and impacts, products and generations by providing a more comprehensive picture of the positive and negative impacts along the product life cycle (thus emphasising hidden hotspots);
- Promotes awareness in value chain actors on sustainability issues and supports enterprises and value chain actors in identifying weaknesses and enabling further improvements of a product life cycle;
- Helps decision-makers choose sustainable technologies and products, as well as resources;
- Has the potential to inform labelling initiatives and provides guiding principles to achieve sustainable consumption and production (SCP).

In much of the early literature on LCSA (Kloepffer 2008; UNEP 2011), it was understood that conducting an LCSA required performing each type of assessment (E-LCA, S-LCA and LCC) in full; and synthesising the results. However, this type of approach fails to consider the interactions and inter-dependencies between the three dimensions of sustainability (Gbededo *et al*., 2018); while also making it difficult to interpret the results for decision making (particularly when trade-offs exist between the economic, social and environmental dimensions). As such, a second, more integrative approach to conducting LCSA has emerged; in which a single, unified assessment is conducted, but based on an expanded set of indicators, encompassing environmental, social and economic impacts (Guinee *et al*., 2011; Gloria *et al*., 2017). The aim is to provide improved integration among the environmental, social and economic dimensions, through the adoption of a transdisciplinary approach.

This study aims to apply the second of these LCSA approaches (**Figure 5**), in that we incorporate additional environmental and socio-economic indicators in order to achieve sustainable development objectives (see Section 4.6).



Life Cycle Sustainability Assessment (LCSA) is a fairly new approach that attempts to combine the 3 pillars of sustainability (E-LCA, SLCA and LCC) in order to provide a more comprehensive, '*triple-bottom line*' assessment

A more *integrative approach* for *LCSA* is based on an expanded set of indicators aimed at providing improved integration among the environmental, social and economic dimensions, through the adoption of a *transdisciplinary approach*

Figure 5: Life Cycle Sustainability Assessment Approaches: Triple-bottom line (left), Transdisciplinary Framework (right)

3.2 Goal of the Study

As per ISO 14044:2006 (ISO 2006b), the goal of an LCA study is defined through a consideration of the intended application, the reason for carrying out the study, and the intended audience. In the case of this study:

- **The intended application** is to identity material substitution opportunities for polystyrene take-out containers. The material alternatives should maintain product functionality and ensure that alternatives provide the best social, economic and environmental solution. In addition, internally within the broader UNIDO project, the recommendations of preferred alternative material options from the LCSA informed project activity 1.4, which aimed at demonstrating and testing the technologies for final treatment of the material alternatives identified.
- **The reason for carrying out the study** is to understand – and quantify - the life cycle environmental and socio-economic impacts of alternative material options to polystyrene take-out containers in South Africa. Thus, the reason for the study is to evaluate and suggest alternative materials that provide the best social, economic, and environmental solution compared to traditional plastic.
- **The intended audience** is primarily internal to the Project, since the LCSA results were intended to inform another activity of the Project. However, the funder (UNIDO) recognises the importance the study's results might be of interest to a wider audience, hence the study included an external peer review (conducted by Dr P. Notten (TGH), Dr. M. Sagisaka (UNIDO) and Dr. M. Yamamoto (University of Tokyo)) to ensure that the results are unbiased and conform with appropriate standards (ISO 14040, 2006a; ISO 14044, 2006b; UNEP 2011).

In short, **the goal of the study is to assess the environmental and socio-economic impacts of polystyrene take-out containers and various alternatives, throughout the products' life cycle**. This will enable a comparison of the life cycle environmental and socio-economic impacts of the various material types (as per **Table 2**) by considering the whole life cycle of a product – from raw material to use and disposal. It can also aid in the identification of the "hotspots" in a product's life cycle that contribute to a substantial part of the overall impacts.

3.3 Scope, boundary, and functional unit of the study

The scope of an LCA study covers decisions relating to the detail and accuracy of the study and related methodological decisions, including the choice of functional unit, system boundaries and data requirements. Scoping decisions may need to be revisited as the study progresses as more becomes known about the systems, and especially as more becomes known about their data availability.

In studies comparing single-use disposable food containers, there have been various functional units employed. When comparing a range of single-use cups, plates and clamshells, Franklin Associates (2011) compared products on a one-to-one basis. A similar approach was taken by van der Harst, Potting & Kroeze (2014) in a comparative LCA of disposable cups. A one-to-one comparison was possible as the products under consideration could fulfil the same function with regards to capacity for food or beverages. In other studies, a seemingly arbitrary number of uses is selected as a functional basis. For example, Madival *et al*. (2009) and Suwanmanee *et al*. (2013) selected a functional unit of 10 000 uses, whilst Häkkinen & Vares (2010) employed 100 000 uses. In this study, the products to be studied include both take-out food containers and beverage cups, made of the materials listed in **Table 2**.

The Meal-kits under consideration must have equivalent functionality. More specifically, the meal-kits have similar dimensions in terms of size and carrying capacity and would be suited in the carrying of hot meals or beverages. All Meal-kits considered in this study are single-use. The design should ensure adequate insulation from hot meals and beverages; with insulation in cups being particularly important. Therefore, aside from the Polystyrene and Bio-EPS cups, all cups are modelled as having a double wall in order to ensure that they are functionally equivalent. **Figure 3** and **Figure 6** provide examples of some take-out containers and cups investigated in this study.

The **functional unit (FU)** for this study is based on the number of take-away meal-kits used by one person in one year, i.e., $meal\text{-}kit \times capita^{-1} \times annum^{-1}$. Total national take-out container consumption is estimated from the fact that: "*South Africans spend close to R2 billion a month on fast food, which represents more than 10% of total discretionary spend*" (Business Tech, 2017). South Africa's population in 2017 was 57 million; therefore, suggesting that, on average, R 35 is spent on take-away meals per person per month. A burger and chips in 2017 cost R 36.48[2] on average. As such, it can be assumed that, on average, each person purchases 1 take-away meal per month. **Therefore, the average per person take-out meal-kit consumption is estimated at approximately one per month, or 12 meal-kits per person per year.**

The reference meal-kit is the polystyrene take-out container and cup, which is used as the reference product for the study. Information from major local producers determined that the most common dimensions and shape for the polystyrene food containers only (rectangular, 1400ml carrying capacity) and cups (250 ml carrying capacity) should be used as a reference.

An "Equivalent Function" of 1 was therefore assigned to the carrying capacity of the PS reference meal-kit. Mass, volumetric capacity and thickness of the other commercially available options were gathered using a precision scale and a micrometer, whereas the mass of the non-commercially available alternative materials and prototypes was inferred using the reference meal-kit dimensions and the specific material density. Reference flows for the functional unit (i.e., 12 meal-kits per person per year) were then calculated as follows: first the volumetric adjustment (relative to the reference product) was done to ensure equivalency, then for all the options the number of meal-kits per person per year were multiplied by the individual weights of each meal kit.

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[2] https://inflationcalc.co.za/?date1=1991-01-01&date2=2017-01-01&amount=6.60

Figure 6: Meal-kit alternative material.
Top left: paper/cardboard container; Top right: clear PET container; Bottom left: Bagasse container; Bottom right: PE-coated paper/cardboard cup

Table 2 summarises the meal-kit options already available, including their carrying capacity and functional equivalence with respect to the polystyrene meal-kit. Individual weights and carrying capacity have been measured, whenever possible (EPS, PET, Bagasse and Paper); and other material weights have been calculated using material density and functional equivalence in terms of volume. The last column provides the Reference flow, i.e., the amount of material used for each type of meal-kit to fulfil the functional unit (*grams of material per meal-kit*×*capita*$^{-1}$×*year*$^{-1}$). All materials are assumed to be 100% virgin; thus, no recycled content has been included. However, it is noted that thermoformed packaging is a significant user of rPET in South Africa, at least in fruit and vegetable punnets. Future iterations of the study may also consider the inclusion of meal-kits made of recycled content.

Table 2: Meal-kits mass, Functional Units and Reference Flows

		Material	**Container Type**	**Equivalent Function in terms of Volume* (ml)**	**Individual weights (g)**	**Reference Flow of 12 meal-kits (g)**
Conventional materials	Reference Product	**Polystyrene (XPS/EPS)**	Clamshell	1	10.47	125.64
			Cup	1	2.08	36
	Commercially Available Products	**Bagasse**	Clamshell	1.12	36	483.84
			Cup	1	19.12	229.39
		Paper	Clamshell	1.12	31	416.64
			Cup	1	14	168
		PET	Clamshell	0.80	33	316.80
			Cup	1	9.42	113.06
Alternative materials	Commercially Available Alternative Materials	**PP**	Clamshell	0.80	19.22	184.51
			Cup	1	9.42	113.04
		PLA	Clamshell	0.80	26	248.7
			Cup	1	12.6	151.2
		PBS	Clamshell	0.80	26.11	250.66
			Cup	1	17.06	204.72
		Mater-bi® (PBAT+PSM)	Clamshell	0.80	25.28	242.67
			Cup	1	16.52	198.24
		Bio-foam (expanded PLA)	Clamshell	1	11.51	138.12
			Cup	1	4.5	54
	Prototype	**PHB (used as proxy for the other materials: PHA, PHBV, PHBH)**	Clamshell	0.80	25.69 (25.07 – 26.11)	246.68 (240.67 – 250.7)
			Cup*	1	16.78 (16.38 – 17.06)	201.48 (196.56 – 204.72)

PS take-out containers and cups were chosen as a reference against which the volumes of the other containers and cups are compared. The volumes of the PS containers and cups used as the reference product are 1400 ml and 250 ml, respectively.

The life cycle system is made up of all the life cycle stages (unit processes) making up the product system, enclosed by the system boundary. In this study, the system boundary for each of the material options investigated ends at the end-of-life of the products, including either recycling (as a future treatment option) or disposal, consistent with the goal of a cradle-to-grave investigation.

Cradle-to-grave life cycle assessments were conducted for each of the meal-kit types. This included raw material extraction, product manufacturing and disposal. The life cycle assessments took both formal and informal disposal as options at end-of-life, including leakage into the natural environment. In South Africa, formally managed domestic waste is either recycled or landfilled (DEA, 2018). Waste that is not collected (i.e. informally managed) may be disposed in personal or communal dumps or burned (self-help disposal). Waste that is not properly managed also has the potential to enter the environment, and we have developed persistence and materials pollution indicators to address these impacts, which are not incorporated within standard E-LCA indicators (ReCiPe, 2016).

3.4 Meal-kit materials value chain

Polystyrene cups and take-out containers are made by expanding/extruding polystyrene pellets and then thermoforming them into the desired shape: cups are made from expanded polystyrene, EPS, and containers from extruded polystyrene, XPS. Polystyrene pellets are imported from Singapore, Taiwan, and Brazil [3], after which the manufacturing of the cups and containers is done locally. The major polystyrene manufacturers are in Gauteng, KwaZulu-Natal and Western Cape Provinces. The end-of-life options for polystyrene cups and take-out containers include landfill, open dumps and burning and the environment (**Figure 7, Figure 8**). Future scenarios include also some mechanical recycling using the EPR Regulation (2021) targets, however while recycling of PS items is happening is South Africa, recycling of XPS/EPS single-use items is hindered by its light weight and low value (see paper cups). When developing future scenarios, which included recycling; mechanical recycling for single-use packaging, using the EPR Regulation (2021) targets, were applied.

PET cups and take-out containers are made by thermoforming of PET resin[4]. PET is locally produced using imported terephthalic acid and locally produced ethylene (a combination of FT-synthesis and traditional oil refinery). There is 1 producer of PET in South Africa (Safripol (Pty) LTD, 3 PET manufacturers and 5 wholesalers, located around major cities in South Africa (Cape Town, Durban and Johannesburg)[5]. The end-of-life options for PET cups and take-out containers include landfill, open dumps and burning and the environment (**Figure 7, Figure 8**). Future scenarios include also some mechanical recycling using the EPR Regulation (DFFE, 2021) targets for or single-use packaging.

Polypropylene cups and take-out containers are made by thermoforming of PP resin both locally produced and imported. This study modelled the cups and take-out manufactured from locally manufactured polypropylene, due to lack of information regarding the amount of imported resin and the associated production sources. In South Africa, propylene is produced using coal as a feedstock via the CtL (i.e., Fischer-Tropsch synthesis) in Mpumalanga province (SASOL n.d.). The propylene is then polymerised into polypropylene resin by Safripol (Gauteng province) which is sold locally. The end-of-life options for PP cups and take-out containers include landfill, open dumps and burning, the environment (to model leaking and littering).(**Figure 7, Figure 8**). Future scenarios include also increased mechanical recycling using the EPR Regulation (DFFE, 2021) targets for single-use packaging.

Bagasse cups and take-out containers are currently imported from Southeast Asia (China, Taiwan, India)[6]. Bagasse is the sugarcane fibre waste left after juice extraction in the sugar industry, meaning the raw material for packaging is a waste product of another industry. Once the juice is extracted, the stalk is ground up and made into paper pulp, namely the bagasse. The processing mill extract the remaining moisture and press the dried bagasse into fibreboard sheets, which are then moulded into the desired shape (forming, hot pressing, drying). Often, a hydrophobic coating (PLA) is added to the container which increases their durability when in contact with wet food. The major distributors are based in Gauteng and Western Cape provinces[7]. The end-of-life options for bagasse cups and take-out containers include landfill, open dumps and burning and the environment. Future scenarios also include some organic recycling via industrial composting using the EPR Regulation (2021) targets for single-use compostable products (**Figure 7**).

Paper cups and take-out containers are mainly produced locally, with some imports occurring. For take-out containers food grade unbleached solid board is used[8], while for cups a combination of food grade unbleached (exterior wall) and bleached (interior wall) solid board is used. Often, a hydrophobic coating (PE or PLA) is added to the container and cup which increases their durability when in contact with beverages. The double walling design is to ensure insulation from heat. A grease-proof coating barrier is added to the take-out food containers. For paper cups the solid bleached board is imported from overseas (Stora Enso, North EU), and it comes in rolls already laminated (PE)[9]. The solid

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[3] Personal communication with Valeska Cloete (Mpact).

[4] Personal communication with Cheri Scholtz (PETCO).

[5] Personal communication with Cheri Scholtz (PETCO).

[6] Personal communication with John Fox (EnviroMall).

[7] Personal communication with John Fox (EnviroMall).

[8] Personal communication with Calvin de Souza (CPT Cartons & Labels).

[9] Personal communication with Carla Breytenbach (Detpak).

unbleached board for the take-out container and cups' outer layer is made of paper locally produced in South Africa. The end-of-life options for paper/cardboard cups and take-out containers include landfill, open dumps and burning and the environment (**Figure 7**).

Recycling of cups and take-out container could be done using the so-called liquid process recycling also used for liquid board carton. Thus, future scenarios may include some recycling using the EPR Regulation (DFFE, 2021) targets for liquid board packaging and/or single-use packaging. However, it is worth noting that recycling of paper cups is hindered mainly by two factors. The first is getting enough waste streams (as being an on-the-go item it is often disposed of on the go, thus difficult to separate from general waste, unless it is done in a controlled environment – e.g., malls, airports. Also, to consider that recycling is done by waste pickers and fueled by price; Thus, if there is no price associated with cups/container, or if the price is too low, pickers don't collect.[10]

PLA or *Polylactide* is a starch-based polymer made from maize. PLA take-out containers are manufactured by the extrusion and thermoforming of PLA granulate into take-out with the required thickness; an edge trimming (optional) step cut them to the desired shape. There are currently no local manufacturers of PLA, thus the majority of take-out container are imported from China. The PLA is manufactured according to the NatureWorks^{TM} production process (Vink & Davies, 2015). Major PLA container distributors are based in the Western Cape and Gauteng. Although PLA is biodegradable under industrial composting conditions, as BAU scenario it was assumed that it will not be composted due to the limited availability of industrial composting facilities which accept PLA in South Africa. Thus, PLA meal-kits were assumed to have the same fate at end-of-life as conventional single-use disposable items (disposed in landfill or open dumps) (**Figure 7, Figure 8**). Future scenarios also include some organic recycling via industrial composting using the EPR Regulation (DFFE, 2021) targets for single-use biodegradable products.

Polymer Starch Materials (PSM), also known as thermoplastic starch, is obtained by processing raw starch by chemical, physical and mechanical methods with the addition of plasticisers such as sorbitol, glycerol, and water. Blending it with other polymers (bio- and synthetic-based), fillers (clay), and natural fibres can improve the properties of PSM significantly. One of the most widely used commercially available thermoplastic starch is Mater-Bi® which mainly consists of corn starch blended with bioplastics (e.g., polybutylene adipate terephthalate or PBAT) and other compounds including natural plasticizers. A description of possible Mater-Bi® compositions have been described in **Global producers and potential of local production of alternatives** report for task 1.4. As BAU scenario it was assumed that PSM cup and container will not be composted due to the limited availability of industrial composting facilities. Thus, PSM meal-kit were assumed to have the same fate at end-of-life as conventional single-use disposable items (disposed in landfill or open dumps) (**Figure 7, Figure 8**). However, PSM is biodegradable and compostable, thus future scenarios include some organic recycling via industrial composting using the EPR Regulation (DFFE, 2021) targets for single-use compostable products.

Polybutylene succinate (PBS) is a biodegradable polyester and is currently mostly fossil-based but can be 100% bio-based (e.g., from residues from the sugar industry). PBS is produced from 1,4-butane diol (BDO), succinic acid and often in combination with a third monomer. PBS can replace low- and high- density PE and PP in current packaging applications and PBS can be converted into finished products using conventional plastic processing techniques, including blown film extrusion, twin-screw extrusion, thermoforming, injection- and compression moulding. As BAU scenario it was assumed that PBS cup and container will not be composted due to the limited availability of industrial composting facilities. Thus, PBS meal-kit were assumed to have the same fate at end-of-life as conventional single-use disposable items (disposed in landfill or open dumps) (**Figure 7, Figure 8**). However, PBS is biodegradable and compostable, thus future scenarios include some organic recycling via industrial composting using the EPR Regulation (DFFE, 2021) targets for single-use compostable products.

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[10] Personal communication with Carla Breytenbach (Detpak).

PHB or Polyhydroxybutyrate, is a polyhydroxyalkanoate (PHA), a polymer belonging to the polyesters class that are of interest as bio-derived and biodegradable plastics. There are mainly three types of PHA's that are commercially available: poly-3-hydroxybutyrate (PHB), poly-3-hydroxybutyrate-co-4-hydroxybutyrate [P(3-HB-co-4-HB), poly-3-hydroxybutyrate-co-valerate (PHBV) and polyhydroxybutyrate-co-hexanoate (PHBH). PHA's exhibit thermoplastic properties, which make them suitable for biomedical and packaging applications, and they are certified to be biodegradable in marine conditions. Major producers are in China and Europe (Italy). As BAU scenario it was assumed that PHB cup and container will not be composted due to the limited availability of industrial composting facilities. Thus, PHB meal-kit were assumed to have the same fate at end-of-life as conventional single-use disposable items (disposed in landfill or open dumps) (**Figure 7, Figure 8**). Future scenarios include some organic recycling via industrial composting using the EPR Regulation (DFFE, 2021) targets for single-use compostable products.

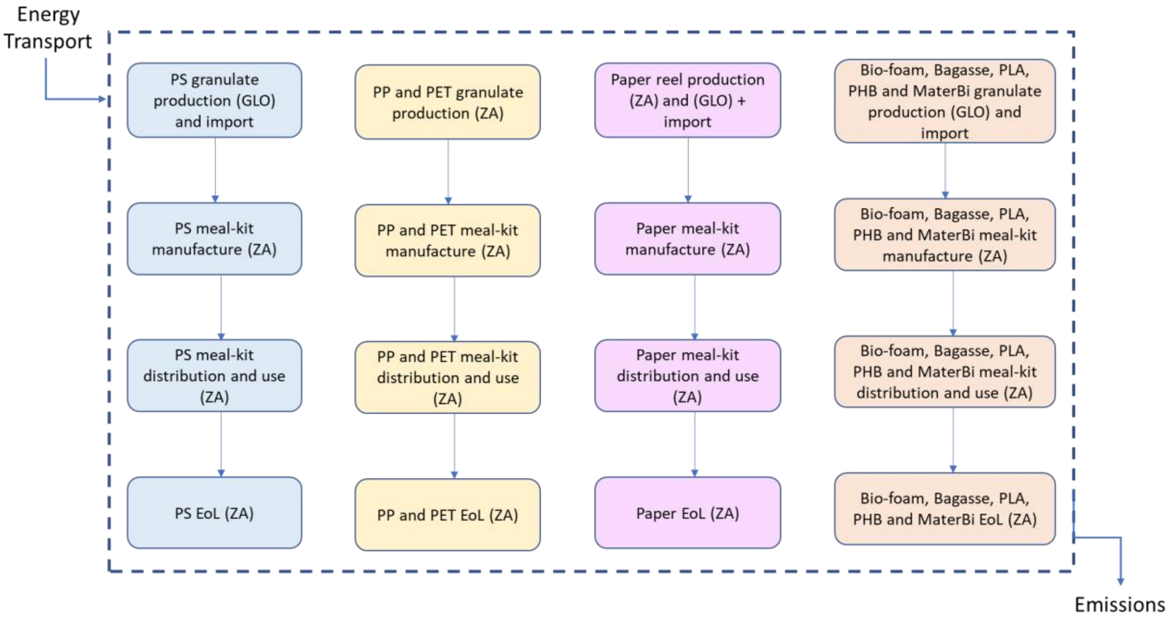

Figure 7: Meal-kit life cycle stages and system boundary

3.5 Life Cycle Inventory

This section provides an overview of the main data sources, modelling approach, allocation procedures, etc.; as well as assumptions and modelling choices relating to the life cycle stages of each meal-kit option (material production, manufacture, transport, end of life etc.).

The product life cycle stages, including relevant process descriptions, were informed by a combination of literature reviews, as well as data sourcing via relevant stakeholders along the value chain. Stakeholders were consulted in order to determine where the different life cycle stages took place, as well as the associated manufacturing methods, recycling rates for the different materials (where relevant), as well as the proportions going to each disposal option, since this information is not readily available for South Africa in existing Life Cycle Inventory (LCI) databases.

A combination of primary and secondary data sourcing was used to inform the inventory foreground data. Primary data to inform the product life cycles was provided by local manufacturers and distributors. Secondary data was sourced from literature and the ecoinvent v3.7 Database (ecoinvent, n.d.), while background data was based on datasets available in the ecoinvent v3.7 Database. The life cycles of the meal-kit options investigated were modelled using the SimaPro LCA Software 9.1.

Furthermore, wherever possible, background datasets from ecoinvent v3.7 were adapted to the South African context by replacing the electricity and water input to match the South African energy mix and geography, as well as relevant sub-processes. **Table 21** to **Table 24** (in Appendix C) detail the datasets used and or modelled in this study.

3.5.1 Allocation

The attributional framework, which aims at assessing the share of the global environmental burdens associated with a product, was chosen. This implies that the modelling of the end-of-life stage, namely the recycling process, as avoided processes, do not play a role in open-loop recycling in attributional LCAs. Within the attributional framework, the cut-off system model of the ecoinnvet Databases was selected, because it presents a high degree of transparency, and results are easier to reproduce (Ekvall, 2019). Also, no other process is included beyond the product life cycle, thus the product carries only the environmental impacts of the processes within its life cycle. This aligns with both the definition of the attributional LCA, and with ISO 14044 (International Organisation for Standardisation, 2006), where the approach is referred to as ‘process subdivision’.

3.5.2 Data sources

Specific datasets were used, either adapted from existing datasets or modelled as foreground datasets, for production of the raw materials (polymers) associated with each type of meal-kit option; and modelling the status quo of the respective value chain as described in Section 3.4. Specifically:

- **Polystyrene** pellets production occurs overseas and the granulate is imported from Singapore, Taiwan and Brazil, thus imports of PS pellets were modelled accordingly. Manufacture of PS meal-kit is done locally as expanded and extruded polystyrene (EPS and XPS respectively) with localised energy and water inputs (Appendix C, **Table 21, Table 22** and **Table 23**).
- **Paper** products are mainly manufactured locally from imported virgin bleached paper/solid board and locally produced unbleached paper/solid board, with some import of finished products occurring. Imports of PE laminated virgin reels from North Europe were modelled accordingly. However, since is no dataset representing South African forestry production in the ecoinvent Database, nor dataset representing any paper product manufacturing, the production of unbleached solid boards is based on background datasets, with localised energy and water inputs (Appendix C, **Table 21, Table 22** and **Table 23**).
- **PET bottle grade** production was modelled as produced in South Africa using imported terephthalic acid and locally produced ethylene (a combination of Sasol production and imported oil). Manufacture of PET meal-kit is done locally via thermoforming of PET into the desired form, with localised energy and water inputs (Appendix C, **Table 21, Table 22** and **Table 23**).
- **Polypropylene** production was modelled as produced in South Africa using locally produced propylene. Manufacture of PP meal-kit is done locally via thermoforming of PP into the desired form, with localised energy and water inputs (Appendix C, **Table 21, Table 22** and **Table 23**).
- **Bagasse** from sugarcane production is provided as a background dataset in the ecoinvent v3.6 and bagasse products are all imported from Southeast Asia (China, Taiwan, India). The processing mill extracted the remaining moisture from the bagasse pulp and pressed the dried bagasse into fibreboard sheets, which are then moulded into the desired shape (forming, hot pressing, drying). Thus, imports of finished products manufactured in Asia were modelled. An assembly was created using background datasets for bagasse production RoW, the

corresponding manufacturing process (injection moulding) and adapting the energy source to reflect the grid mix of the production region(s) (Appendix C, **Table 21, Table 22** and **Table 23**).

- **Polylactide** production is provided as a background dataset in the ecoinvent v3.6 and PLA products are all imported from Southeast Asia (China, Taiwan, India); thus production of PLA resin, manufacturing and imports of finished products were modelled accordingly. For PLA modelling both available datasets (Polylactide, granulate production {GLO} and Polylactide biopolymer resin, at plant/kg/RNA) are based on data from the world larges PLA plant (NatureWorks in Nebraska). For consistency with the other datasets used within the project, the ecoinvent dataset was chosen and used either as it is when PLA granulate or finished products are imported, or adapted to local context at per **Table 21** in Appendix C.
- **PBS** material is modelled under the assumption that the PBS components are fossil-based, rather than bio-based. When the polymer is locally produced (via the CtL process), material (coal), energy and water inputs were added accordingly (Appendix C, **Table 21, Table 22** and **Table 23**).
- **Mater-Bi® (PBAT+PSM)** material production is provided as a background dataset in the ecoinvent v3.7 and PSM products are all imported from Europe and Asia (China), thus production of PSM resin, manufacturing and imports of finished products were modelled accordingly. When localizing the production of PBAT, it was modelled under the assumption that the PBAT components are fossil-based, rather that bio-based (Appendix C, **Table 21, Table 22** and **Table 23**).
- **PHB** material production was modelled using Harding *et al.* (2008) LCI, thus using the production of sugar from sugarcane as substrate. PHB products are all imported from Europe and Asia (China), thus production of PHB resin, manufacturing and imports of finished products were modelled accordingly (Appendix C, **Table 21, Table 22** and **Table 23**).

Supporting datasets were modelled for meal-kit manufacturing, as relevant to each type of container; namely: expanded and extruded polystyrene (EPS and XPS respectively); extrusion of plastic sheet and thermoforming, inline; paper pulping, molding, etc. (Appendix C, **Table 21, Table 22** and **Table 23**). All scenarios of manufacturing occurring in South Africa and overseas were considered, with energy and water inputs adapted to the South African and/or global context as applicable.

Assembly datasets were modelled to represent meal-kit manufacturing. For each meal-kit type, a manufacturing step with specific energy and material requirements to make a single meal-kit, as well as transport, was modelled. A life cycle stage for each meal-kit was also modelled, inclusive of transport and distribution to retailers, and the disposal scenario (see Section 3.5.3).

3.5.3 End-of-Life

The disposal stage for each meal-kit was modelled to account for the different shares of disposed material that end up in recycling (when relevant), littering, sanitary and unsanitary landfill, open dumping, and open burning. Since existing LCI databases do not have a category for plastic leakage to the environment; leakage is modelled as disposal to an open dump as the closest approximation; to account for at least some of the associated environmental impacts. In parallel, we have modelled the end-of-life of materials in South Africa in order to develop an indicator for persistence and Materials Pollution into the environment, where it impacts terrestrial, freshwater and marine ecosystems.

The end-of-life flows were modelled using software for substance and material flow analysis, (subSTance flow Analysis, STAN[11], based on data from plastic flows from the Materials Flow Analysis (MFA) compiled by von Blottnitz *et al*. (2017) (**Figure 8**). Based on the MFA, and contrary to perceptions, less than 1% of total plastic reaching end of life enters the environment directly through

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[11] Home (stan2web.net)

littering. The vast majority enters some form of formal or informal waste management system, although there is in turn significant leakage from such systems to the environment.

Only 65% of the population have regular waste collection services; thus, 35% of the population rely on self-help disposal (StatsSA 2018), i.e. open dumping. To assess the impacts, self-help disposal can further be categorised as ‘burnt’ or ‘not burnt’. We assume that all open dumps are burnt annually as a measure to reduce waste volume, but only 60% of the waste actually burns (IPCC, 2006).

In terms of waste going to dedicated, official landfill sites, only a portion of such sites are fully compliant with legislative requirements, while the others can be described as non-compliant or ‘deficient’. The MFA data suggests that, of the plastic entering these various disposal options, 32% goes to self-help disposal, 38% to non-compliant landfill, and 30% to compliant landfill. In turn, leakage rates were estimated as 80% from self-help disposal (open dumping), 30% from non-compliant landfills, and 1% from compliant landfills (Von Blottnitz, 2019). Together with direct litter of 1%, there is a total of 275 Kilotonnes (Kt) of plastic leaking into the environment per annum – approximately 18% of the plastic that reaches end of life (see **Figure 8**).

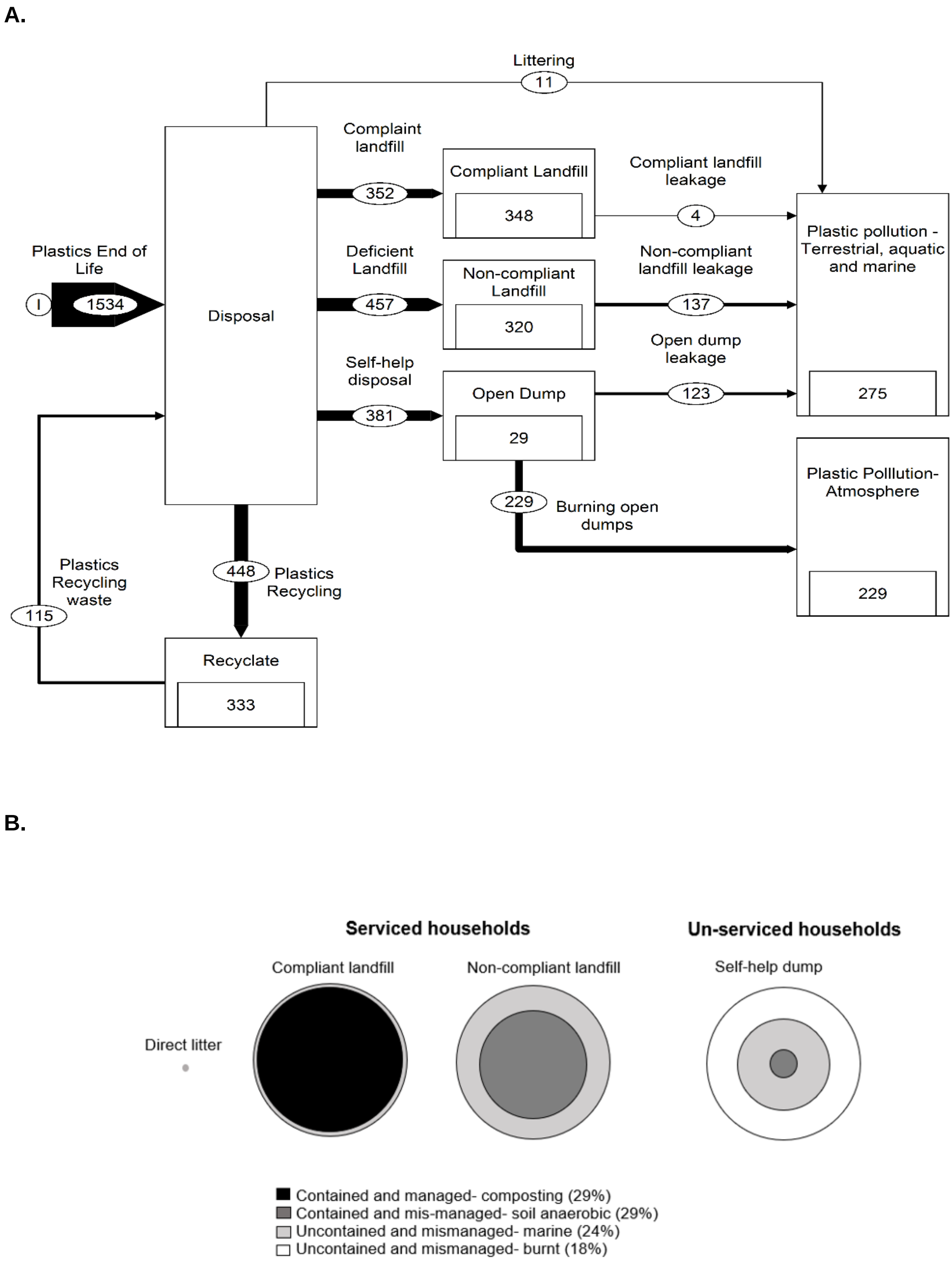

Figure 8: **A**: End-of-life model for municipal solid waste in South Africa. Materials flow was carried out using STAN, based on data from plastic flows from von Blottnitz et al 2017. The values shown are in Kilotonnes (Kt). **B**: The End-of-life fate of materials because of waste (mis)-management and leakage into the environment. The waste disposed to various waste management systems in South Africa with the fate in the receiving environments was captured as the end-of-life model in order to estimate biodegradation rates and determine material persistence indicator. Only where waste is from serviced households are collected and is disposed to compliant landfills, that effectively contained waste *in situ* as well as treat organic material appropriately through composting, is there no leakage into the environment. The key shows the amount of material in the receiving environment (% of total waste disposed).

Recycling: For each meal-kit type, recycling rates were obtained or estimated from publicly available sources (DFFE, 2021; Plastics SA 2019; PAMSA 2018, Polystyrene Association of SA), as well as personal communications with experts (Pretorius 2020; Spangenberg 2021). The end-of-life recycling rates applied to each meal-kit type are presented in **Table 3**, as per the targets in the EPR legislation pertaining to the Single Use Packaging category; and distinguishing between the different types of material: conventional plastics, compostable plastic products (bagasse, PBS and Mater-bi® meal-kits), and biodegradable plastic products (PLA, bio-foam and PHBH meal-kit).

In modelling the end of life for each type of container, the relevant recycling rates are applied, and the fraction disposed to direct littering (before entering the waste management system) is accounted for. Thereafter, the waste enters either one of the above-mentioned disposal and waste management solutions; from which the associated leakage rates are then estimated (see **Figure 8**).

Recycling can be viewed as a multi-functional process, thus end-of-life modelling is required to correctly allocate the benefits and burdens associated with the recycling process. Since the Cut-off system model was selected, this implies that recyclable materials are cut off from the producing system, i.e. they are removed from the producing activity, with no benefits or burdens allocated to them. Secondary materials are therefore modelled to only bear the burden of the recycling process and are free from the burdens associated with the primary production of the material (Wernet et al., 2016). The BAU scenario did not include any recycling activity, nor recycled content for the options investigated, since this is the status quo of take-out food containers. Recycling (in the form of open loop recycling, thus no recyclate was included in the manufacturing of take out- food containers), was modelled when exploring the sensitivity of the results, by using the EPR recycling targets as per **Table 3.**

Table 3: Targets recycling rate as per EPR Regulations (DFFE, 2021) which refers to Single Use Packaging recycling rates (mechanical recycling) and biodegradable/compostable packaging (Industrial composting)

			EPR scheme targets for material recovery: MR – mechanical recycling; IC – industrial composting					
	Material container type	Reference year (2021) Rec %	Y1	Y2	Y3	Y4	Y5	
Commercially available products (BAU)	PS	0%	30%	35%	40%	45%	50%	MR
	PET	0%	30%	35%	40%	45%	50%	MR
	Paper	0%	30%	35%	40%	45%	50%	MR
	Bagasse	0%	15%	25%	50%	65%	80%	IC - composable
Commercially available alternative materials	PP	0%	30%	35%	40%	45%	50%	MR
	PLA	0%	5%	15%	40%	55%	70%	IC - biodegradable
	PBS	0%	15%	25%	50%	65%	80%	IC - composable
	Mater-bi® (PBAT+PSM)	0%	15%	25%	50%	65%	80%	IC - composable
	Bio-foam (expanded PLA)	0%	5%	15%	40%	55%	70%	IC - composable
Prototypes	PHB	0%	5%	15%	40%	55%	70%	IC - biodegradable

3.5.4 Transport

This study considered transport from the raw material to the polymer producer; from the polymer producer to the meal-kit manufacturer; from the meal-kit manufacturer to the distributor; and at end of life, for modelling waste collection and transport to disposal sites (**Table 24**).

Transport to distributors/retailers is modelled in the Life Cycle datasets for each meal-kit, according to the actual mass transported. No transport during the use phase was considered, to avoid allocating burdens associated with transporting the meal from place of purchase to consumption and disposal; as these burdens are not attributable to the specific type of container and, are unlikely to differ between the different container options. Imports from overseas were modelled accordingly when exploring local production vs import of finished goods for all options investigated.

3.5.5 Assumption and limitations

Table 21 to **Table 24** in Appendix C detail the datasets used and/or modelled in this study. These include a combination of background datasets from the ecoinvent database (v. 3.6 and 3.7), as well as foreground datasets.

Background datasets were used “as is” when representing an imported polymer/product from the global supply chain or were adapted to the local context when needed; as part of the sensitivity analysis exploring local production, vs local manufacturing using imported polymers, vs. importing finished products.

Foreground datasets were modelled mainly for emerging materials based on proxies/extrapolation from datasets on similar materials (e.g., PBS), or from secondary data from literature (Harding et. al, 2008) (e.g., PHBH). These datasets included only the main material feedstocks and energy requirements, without including the infrastructure (e.g., chemical factory organics).

The nature of the product under investigation, single use food take-out containers and cups, make them prone to be disposed of as general waste, following either the route of landfilling or open dumping, or being directly littered. Data for material-specific end-of-life flows were unlikely to be found, thus the end-of-life flows were based on the MFA (von Blottnitz et al. 2017), which offered a fair representation of the general state of the waste management system in South Africa, although focused on plastics. There is no reason why food take-out containers made of bioplastic, paper or bagasse would not suffer the same fate as plastic ones. Possible material or nutrient recovery through mechanical recycling or industrial composting have been explored using the corresponding EPR targets for the single use product categories.

Open dumping and open burning are new datasets in the ecoinvent v3.6 database, which allowed for these options to be explicitly modelled. Material-specific datasets for sanitary and unsanitary landfilling, as well as open burning and open dumping, were used for PET, PS, PP and Paper. The latter was also used to model the bagasse meal-kit disposal in the different receiving environments. Plastic waste mixture, treatment of plastic mixture (open burning, open dumping and unsanitary landfills) and waste bioplastics, and treatment of plastic mixture (sanitary landfills) datasets have been used as proxies for materials like PLA, Mater-Bi®, PBS and PHBH.

3.6 Impact assessment methods

3.6.1 Standard environmental LCA indicators

The ISO standards do not recommend specific Life Cycle Impact Assessment (LCIA) methods but require the chosen method to be an internationally accepted one for comparative purposes. For this study, the widely accepted ReCiPe method, which includes a range of mid-point and end-point indicators, was chosen, as this method enables a wide spectrum of environmental impacts to be considered, to avoid burden-shifting. This method was therefore used for the environmental impact assessment at mid-point and end-point level, (ReCiPe, 2016; Huijbregts et al., 2017; Goedkoop et al., 2009) while a Single Score was also calculated, as shown in **Figure 9** and **Table 4.**

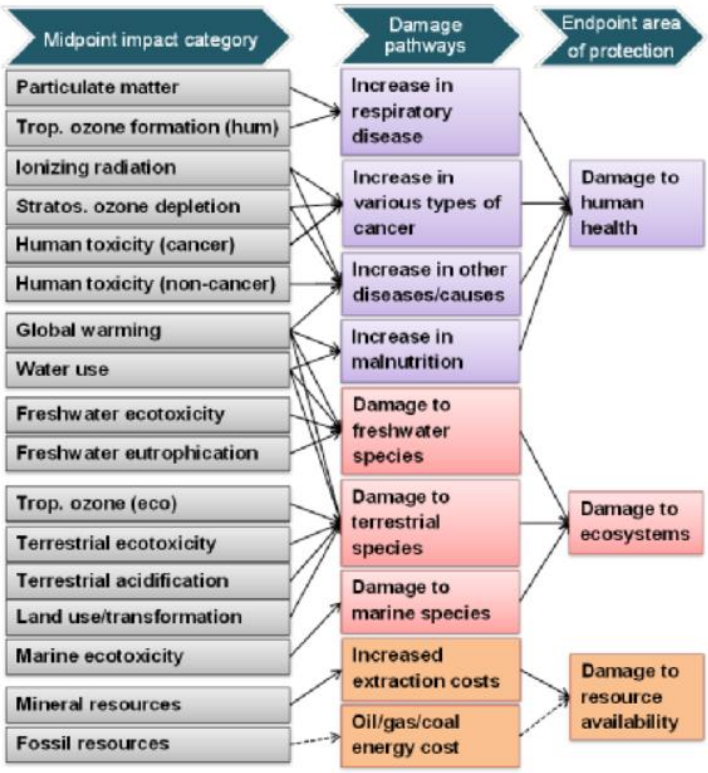

Figure 9: Overview of the impact categories that are covered in the ReCiPe 2016 methodology and their relation to the areas of protection (Source: Huijbregts et al., 2016).

Table 4: ReCiPe 2016 Mid-point, End-point and Single Score Indicators

Indicator		Unit	
GW	Global Warming	Kg CO2-eq	Kg of Carbon Dioxide equivalent
SOD	Stratospheric Ozone Depletion	Kg CFC11-eq	Kg of CFC-11 equivalent
IR	Ionizing Radiation	Kg Co-60-eq	Kg of Cobalt-60 equivalent
OF,HH	Ozone Formation, Human Health	Kg NOx-eq	Kg of Nitrogen Oxide equivalent
FPM	Fine Particulate Matter Formation	Kg PM2.5-eq	Kg of Particulate Matter <2.5µm
OF,TE	Ozone Formation, Terrestrial Ecosystem	Kg NOx-eq	Kg of Nitrogen Oxide equivalent
TA	Terrestrial Acidification	Kg SO2-eq	Kg of Sulphur Dioxide equivalent
FWE	Freshwater Eutrophication	Kg P-eq	Kg of Phosphorous equivalent
MarE	Marine Eutrophication	Kg N-eq	Kg of Nitrogen equivalent
TEcotox	Terrestrial Ecotoxicity	Kg 1,4-DCB-eq	Kg of 1,4- dichlorobenzene equivalent
FWEcotox	Freshwater Ecotoxicity	Kg 1,4-DCB-eq	Kg of 1,4- dichlorobenzene equivalent
MarEcotox	Marine Ecotoxicity	Kg 1,4-DCB-eq	Kg of 1,4- dichlorobenzene equivalent
HCTox	Human Carcinogenic Toxicity	Kg 1,4-DCB-eq	Kg of 1,4- dichlorobenzene equivalent
HNCTox	Human Non-Carcinogenic Toxicity	Kg 1,4-DCB-eq	Kg of 1,4- dichlorobenzene equivalent
LU	Land use	m^2/a crop-eq	Square metre per year crop equivalent
MRS	Mineral Resources Scarcity	Kg Cu-eq	Kg of Copper equivalent
FRS	Fossil Resource Scarcity	Kg oil-eq	Kg of oil equivalent
WU	Water Consumption	m^3	Cubic metre
HH	Human Health	DALY	Disability-Adjusted Life Years. One DALY represents the loss of the equivalent of one year of full health
Ecosys	Ecosystems	Species*yr	Actual species lost per year, based on species density and PDF (Potential Disappeared Fraction of species)
RES	Resources	USD2013	
SS	Single Score	Pt	Points

3.6.1.1 Normalisation and Weighting

As per **Table 4**, a total of 18 mid-point indicators are calculated in the ReCiPe 2016 method. Reporting and interpreting results across 18 indicators can be challenging, hence, normalisation and weighting were therefore applied to reduce the number of indicators on which to report. LCIA methods available within SimaPro already provide normalised scores for the E-LCA impact categories; and ReCiPe 2016 offers the possibility to calculate end point damage categories and a Single Score metric by aggregating and weighting normalised mid-point scores. ReCiPe 2016 includes global normalisation factors (Huijbregts et al., 2017) for a reference year (2010), as well as weighting factors from its previous version ReCiPe 2008 (Goedkoop et al., 2009). Regionalisation of impacts is applied only for water consumption since other impact categories do not have regionalised inventories.

Results are presented for the ReCiPe 2016 Endpoint (H) Single Score. **Table 5** reports the global normalisation factors for the endpoint damage categories for reference year 2010, as well as the weighting set (from ReCiPe 2008). The Single Score expressed in points (**Table 5**) is the total environmental load expressed as a single score, and is calculated by summing together the results of the damage categories (HH, ES, and RES), which are first multiplied by the corresponding weighting factors.

- There are different social perspectives and corresponding weighting approaches available in ReCiPe 2016. Specifically:
- 3 different social perspectives:
  - *Individualist* perspective (I), which is based on short-term interest, impact types that are undisputed, and technological optimism as regards human adaptation;
  - *Hierarchist* perspective (H), which is based on the most common policy principles with regards to time-frame and other issues; and
  - *Egalitarian* perspective (E), which is the most precautionary perspective, that takes into account the longest time-frame and impact types that are not yet fully established, but for which some indication is available.
- 2 different sets of weightings for each of the perspective (e.g. ReCiPe H/H (hierarchist) and ReCiPe H/A (hierarchist, average weighting)): these weighting factors are based on a panel weighting process performed at the damage category (Endpoint) level. A specific weighting set is available for each of the three perspectives referred to above. Additionally, there is an average (H/A or E/A or I/A) weighting set, which covers the average result for all three perspectives.

The hierarchist (H/A) version of ReCiPe with average weighting is chosen as the default. In general, value choices made in the hierarchist version are scientifically and politically accepted.

Sensitivity analysis has been done for both Single Score, mid- and end-point indicators. In the appendices, the mid-point and end-point results are presented.

Table 5: Recipe End Point (H), Normalisation and Weighting values (World 2010) H/A

Damage Category	Normalisation	Weighting
Human Health (HH)	42.1	400
Ecosystems (ES)	1396	400
Resources (RES)	0.0000357	200

When including additional indicators (see Section 3.6.2) in light of extending the environmental LCA by integrating other aspects of sustainability (see Section 4.6), ReCiPe 2016 mid-point indicators were used. This is due to the fact that the additional indicators developed are at mid-point along he cause-impact pathway (direct link to the environmental flows); and not yet integrated at the level of end-points; as this requires additional knowledge and data on pathways, exposure and damage.

3.6.2 Extending the environmental LCA

In addition to the standard environmental indicators used in the ReCiPe 2016 method, we developed additional indicators to assess other environmental and socio-economic impacts, namely:

- Two indicators relating to plastic pollution (see background in Section 3.6.3); namely:
  - The Persistence of leaked material; and
  - the Material Pollution Indicator.

- Two socio-economic indicators, namely:

- Cost (of the alternative material) to the manufacturer (see background and results in Section 4.3); and
- Jobs, in terms of the net job losses or gains in the transition from conventional plastics to biodegradable alternatives (background and results in Section 4.4).

When incorporating these additional indicators with the environmental indicators of the ReCiPe 2016 method, this was done at mid-point level. Each indicator was scaled using the *Min_Max scaling approach* (Section 4.6.1) so as to have relative scores. No specific weighting was initially applied; thus, each indicator was essentially given an equal weighting. For all aggregated scores, the sum of relative scores was used to compare the different options with one another, taking the environmental, social, and economic dimensions into account. The approach followed was based on the approach adopted by Russo et al. (2020) in the CSIR's LCSA study on South African grocery carrier bags. However, in Section 4.6.2, sensitivity analysis with different sets of weightings other than equal weighting was applied, specifically to understand the extent to which the application of equal weighting underestimates the significance of the MPI indicator.

3.6.3 Indicators for Material Pollution

A notable omission from all current impact assessment methods, including ReCiPe 2016, is an indicator to account for plastic pollution, specifically for the impacts of plastics and other materials leaking into the environment on biodiversity and ecosystems.

Plastic pollution, or more generally material pollution, is perceived as *'littering of the environment',* but this can occur directly (direct littering) or indirectly (leakage from waste-management systems). The material pollution of the environment is influenced by:

- The amount of material in terms of the products' surface area, since many of the impacts to ecosystems and biodiversity relate to the area lost as a result of habitat degradation;
- The probability of a product being abandoned and released into the environment, which is a function of the product's value or material price;
- Dispersion of the items in the environment by wind and water, which is a function of the product's mass or density;
- Rate of biodegradation, and hence the persistence of the product in the environment.

A model to incorporate the influence of these variables and derive an indicator of material pollution or 'littering of the environment' is shown in **Figure 10**.

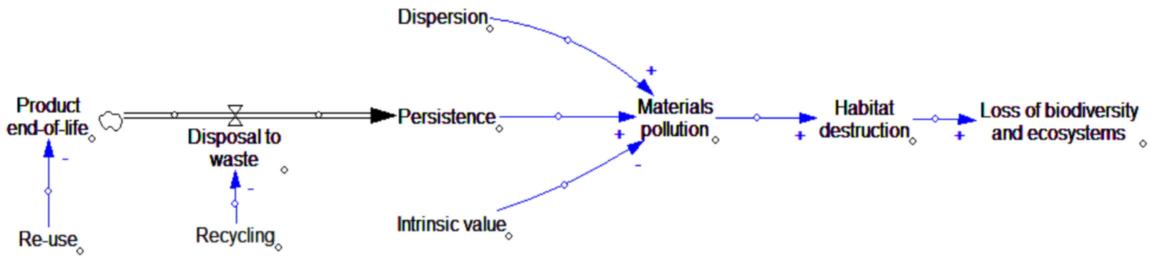

Figure 10: A model for an indicator of materials pollution or 'littering of the environment'. Model with the key variables and causality with arrows having reinforcing (+) or balancing (-) influence (Vensim PLE 8.2.1). Note that the Materials Pollution Indicator is a mid-point indicator for habitat destruction and the subsequent loss of biodiversity and ecosystems.

3.6.3.1 Persistence of leaked material

Based on the material flows and end-of-life waste management in South Africa, we calculated the amount of plastic or bioplastic material from the use and disposal of each product type, which enters South Africa's waste management systems, and then leaks into the environment (see Section 3.5.3. This midpoint indicator, Persistence$_{\_LM}$ (Persistence of leaked material), reflects the amount of material leaking into the environment, and its average lifetime (Stafford et al., 2022).

The biodegradation data was sourced from simulated laboratory tests for compost at 58 °C (industrial composting); seawater at 30°C (marine environment); and anaerobic sludge at 37°C (landfill). The specific standards under which the tests were carried out were ASTM D5630 for landfill, D5338 for compost, and ASTM D7081 and ASTM D6691 for the marine environment; with the evolution of carbon dioxide used to determine the amount of carbon lost from the sample from biodegradation (Greene, 2018; Muniyasamy *et al*. 2017). The apparent biodegradation rate constant (k') for each material type in the receiving environment (marine environment, landfill, and industrial composting) was calculated by assuming first order kinetics of exponential decay (Abu Qdais *et al*., 2016; Chem. Libretexts, 2019); as follows:

$$\frac{\partial N}{\partial t} = -k't$$

Where *N* is the amount of product material at time *t*, and *k'* is the apparent biodegradation rate constant.

If N_0 is the amount of product material at time 0, then integrating yields the following:

$$N = N_0 e^{-k\prime t}$$

Or, in a logarithmic form:

$$\ln\left(\frac{N}{N_0}\right) = -k't$$

Therefore, the apparent biodegradation rate constant is:

$$k' = -\frac{\ln\left(\frac{N}{N_0}\right)}{t}$$

The half-life, $T_{\frac{1}{2}}$ is the time taken for the material to biodegrade to half its original value:

$$T_{\frac{1}{2}} = \frac{\ln 2}{k'}$$

And the mean lifetime or average product material lifetime, τ, is:

$$\tau = \frac{1}{k'}$$

The weighted mean lifetime, τ_w, of a given amount (mass) of product material biodegrading in various receiving environments (m_1, m_2, m_3…) can be calculated as:

$$\tau_w = \tau_1 \frac{m_1}{m_1 + m_2 + m_3} + \tau_2 \frac{m_2}{m_1 + m_2 + m_3} + \tau_2 \frac{m_3}{m_1 + m_2 + m_3}$$

The amount of material persisting in the environment over time is defined by the amount of material disposed of, and its rate of biodegradation in the environment. The Persistence$_{LM}$ (Persistence of leaked material) indicator, P, is the product of *total amount* of material disposed of into the receiving environment(s), and the *weighted mean lifetime* of the material in the environment(s) (Stafford et al., 2022). The Persistence$_{LM}$ indicator has units with the product of mass and time; namely kilogram-years (kg.yr) or gram-seconds (g.s):

$$P = m_T \tau_w$$

Where m_T is the *total amount* of material disposed of into the receiving environment(s), $m_T = m_1 + m_2 + m_3 \ldots$

Aside from the Persistence of leaked material in the receiving environments, there are a number of other factors influencing the likelihood that a material will pollute the environment. Two of these are described in the following sub-sections.

3.6.3.2 Intrinsic value

The intrinsic value refers to the value of material in a product and the probability of an item being collected or being abandoned in the environment. It reflects the opportunity cost of material recovery, since a product made from a material with high value is likely to be collected or recovered for re-use and re-cycling. However, it is not the same as the current market value of recyclate which is affected by many other factors, including the market demand and the collection, sorting, and recycling costs. The intrinsic value, I, is the price of the material when recovered for recycling. Where a product is recycled in a closed-loop without loss of quality of the material, to produce recyclate for manufacturing of the same product, the intrinsic value is equal to the polymer material price. However, where there is loss of material quality in recycling, a factor for loss of quality can be included. Therefore, Intrinsic value can be described as follows:

$$I = R^q$$

Where:

I - Intrinsic value ($)

R - Price of polymer or raw material in the product ($)

q - Quality loss during recycling. For no loss in quality, $q=1$ and where there is a quality loss, $q<1$

3.6.3.3 Environmental dispersion

The environmental dispersion of a product refers to the likelihood of escaping waste management systems because of being easily wind-blown or buoyant in water. The mass of the product is a key aspect, since heavy products are less likely to be dispersed. However, given that many products fragment into smaller pieces upon disposal, the density of the material from which the product is made is a more relevant parameter; and is being applied to assess the impacts of marine plastics. Therefore, Dispersion, D, can be described as the reciprocal of density, ρ :

$$D = \frac{1}{\rho}$$

3.6.3.4 Material Pollution Indicator

A litter indicator has been developed previously to relate littering or polluting the environment with the product biodegradability, surface area and the price (Civancik-Uslu *et al.,* 2019). The Litter Potential Indicator, LPI, is calculated as follows:

$$\mathrm{LPI} = \frac{\mathrm{p1}}{\mathrm{p2.\,p3.\,p4}}$$

Where:

p1- The material surface area of the product (m2)

p2- The price of the product ($/kg or R/kg)

p3- The mass of the product (kg)

p4- the rate of biodegradation (day^{-1})

A similar composite indicator, the Material Pollution Indicator, MPI, was developed by the CSIR project team as a mid-point indicator **describing the potential impact of materials on biodiversity and ecosystems**. It incorporates **persistence** of materials in the environment (P), the **intrinsic value of the material that determines the likelihood of recovery and recycling,** (I) and likelihood of **dispersion to the environment** due to the density of the material(D). The MPI is defined as:

$$MPI = \frac{P.D}{I}$$

Where: P- persistence (kg.yr), D- dispersion (m^3/kg) and I- Intrinsic value ($).

Since the Dispersion, D, is determined by the material's density, ρ (kg/m^3),

$$D = \frac{1}{\rho}$$

and the Intrinsic value, I, is:

$$I = R^q$$

Then the Material Pollution Indicator:

$$MPI = \frac{P}{\rho.R^q}$$

The MPI therefore incorporates both the likelihood of the product material in the environment (considering its ease of dispersion, and the likelihood of recovery and recycling as a result of its material value). It captures the potential for materials causing damage once in the environment; based on the volume occupied by the material (m^3) in the environment, and its persistence in the environment (yr)). The units of MPI are $\frac{m^3}{\$}.yr$.

4 RESULTS

This section presents results for the Environmental LCA (E-LCA) in terms of the ReCiPe 2016 Single Score; as well as for the additional indicators developed by the project team, namely the impacts of material pollution on the environment (represented by the Persistence and Material Pollution indicators); affordability for the manufacturers in terms of costs of the raw material and jobs to quantify losses or gains in the transition from conventional plastics to biodegradable alternatives.

Section 4.5 will present the results for some of the alternative scenarios investigated, whereas Section 4.6 will illustrate an attempt to combine E-LCA results with the additional indicators for material pollution cost and jobs.

4.1 LCIA results

The results in Sections 4.1 to 4.4 were modelled for the **Business as Usual (BAU) scenario,** which depicts the following value chains:

- *Polystyrene*: polymer produced and imported from overseas, manufacturing in South Africa, EoL in South Africa.
- *PET & PP*: polymer production and manufacturing in ZA, EoL in South Africa*.*
- *Paper*: clamshell – both reels production and manufacturing in South Africa; cup – reels produced and imported from overseas, manufacturing in ZA; for clamshell and cup EoL in South Africa.
- *Bagasse, PLA, PBS, PBAT, PSM, Bio-foam, PHB*: finished product imported in ZA, EoL in South Africa.

A dedicated section (4.5) illustrates the Sensitivity Analysis on the following scenarios investigated:

- Local production vs imports of finished products (where production datasets representing the material inputs have been adapted to the corresponding geography, when necessary);
- Future scenarios with increased recycling rates; and
- impacts of different coating agents.

This section (4.1) focuses on the E-LCA results under the BAU scenario. **Figure 11** shows the E-LCA results for the various material options based on the ReCiPe 2016 Single Score (which aggregates across 18 standard environmental indicators); as well as a Contribution Analysis, which indicates how each stage in the value chain of each product contributes to its overall environmental impact.

From an environmental point of view, using the standard E-LCA indicators, the PS take-out containers performed the best when compared with all the other options; in large part by virtue of being extremely lightweight (3-fold lighter on average compared to the other alternatives). The Raw Material Extraction and Polymer Production stage of the value chain (green bars in **Figure 11)** accounts for the bulk of the environmental burden (71.2% on average) across all the meal-kit alternatives. The Manufacturing stage accounts for 14.5% (on average) of the environmental burden; followed by the Disposal (9.9%) and Transport (5.7%) stages. Recycling, when present (not all the alternatives in the BAU scenario have material recycling) accounts for -1.7% on average, meaning that it contributes to improving the overall performance of the applicable products by reducing the enviromental burdens associated with virgin material production.

Two of the bioplastic options, PLA and PHB, showed the highest overall environmental impacts. This is due to the bio-based nature of the polymer: PLA can be derived from various biomass residues (e.g., corn, sugar or beet) by a bacterial fermentation process; whereas the PHA family, which PHB belongs to, is produced via bacterial fermentation of carbon substrates derived from renewable feedstocks. The ReCiPe 2016 Mid-point results (see Appendix A, **Figure 22** to **Figure 39**) show the specific mid-point impact categories in which PLA and PHB based meal-kits scored higher among the bioplastics, but still lower compared to conventional plastics. Specifically, PHB derived from sugarcane shows the highest environmental impacts in 15 out of 18 impact categories; while PLA derived from maize scored as the second highest in 6 out of 18 impact categories. Impact categories in which all the bio-based meal-kit options (PLA, PHB, PSM and Bio-foam) performed worse than those made of other materials (conventional plastics, bagasse, and paper) include Land Use, Water Use and Marine Eutrophication. Appendix A presents the details regarding the LCIA Results Comparison for the ReCiPe 2016 End- and Mid-point Indicators for all the meal-kit alternatives.

To understand the effect of recycling on all the material alternatives investigated, a scenario analysis was performed using the EPR regulation targets (DFFE 2021) for each material. Section 4.5.2 and Appendix B show the ReCiPe 2016 Single Score and End- and Mid-point LCIA results for this scenario respectively.

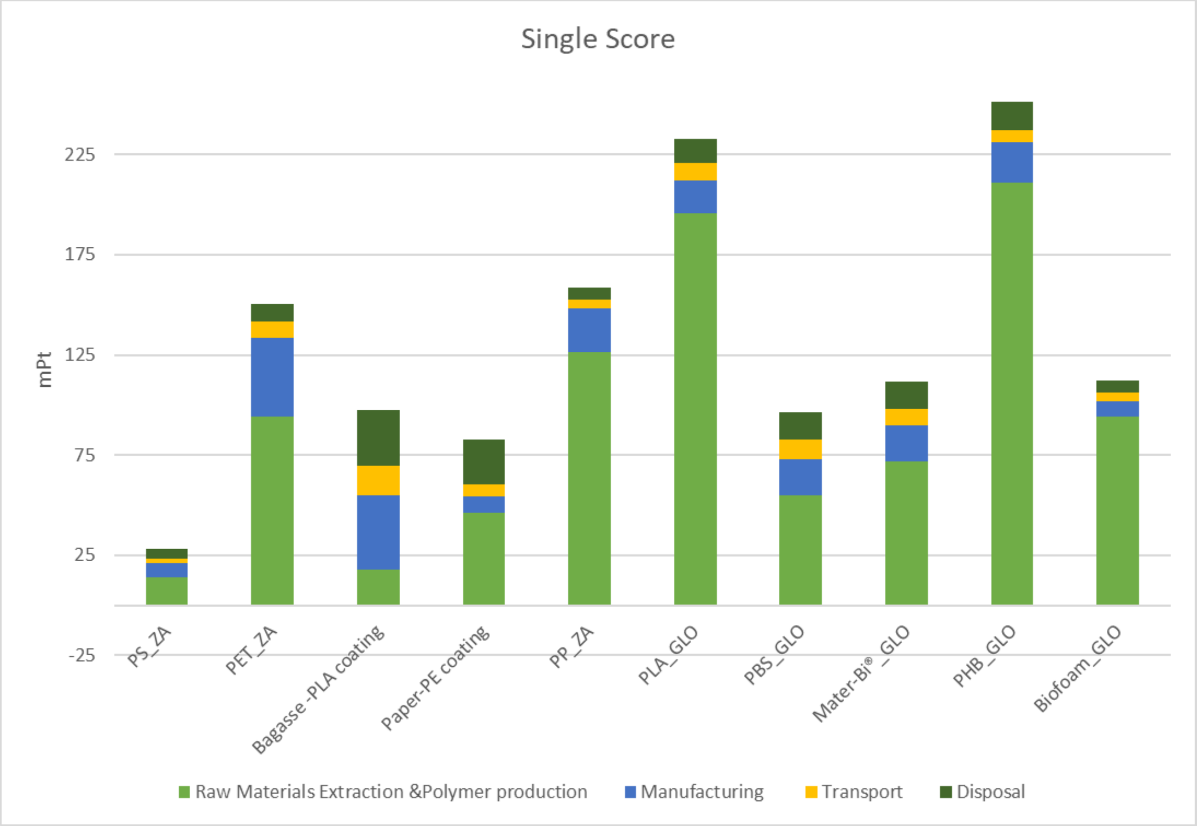

Figure 11: ReCiPe 2016 LCIA Result Comparison (Single Score) and Contribution Analysis for the 10 meal-kit alternatives considered in the study

4.2 Persistence$_{LM}$ and Material Pollution Indicator

The previous section showed that, based on standard E-LCA indicators, the PS options outperform any of the alternatives. However, in terms of the end-of-life impacts of material leaking into the environment, based purely on persistence in the environment and material pollution as additional indicators, the results are significantly different.

This section presents the results related to the impact of waste leaking into the environment. To account for this; both Persistence and Material Pollution indicators were derived. **Table 6** reports all the calculation details, whereas **Figure 13** and **Figure 14** show the resulting impacts of all the meal-kit alternatives in terms of material persisting in the environment and in terms of the Material Pollution Indicator, respectively.

In terms of the findings, **Figure 12** shows how conventional plastics are very persistent in the environment when compared to biodegradable paper, bioplastics or bagasse. **Figure 14** shows how the best option from an E-LCA point of view (PS) performs at least 400 times worse in terms of material pollution when compared to paper/cardboard alternatives. These results clearly indicate that the environmental benefits associated with plastics are dependent on proper end-of-life management of these materials.

The results show that PS has a lower persistence compared to other conventional plastics (PET, PP) due to the low density of XPS/EPS and mass of polymer in the product. Overall, however, the persistence of PS and other plastics (PET, PP) is substantially greater than that of all alternatives, including paper, PLA, PBS, Mater-Bi®, and PHB. Furthermore, the low density of some plastics, particularly PS, results in a Materials Pollution Indicator for polystyrene that is 1284 times and 2456 times higher than that of the paper cup and clamshell, respectively.

These results do not include the various moisture-barrier coatings that are used on the cups and containers. Some of the alternatives to polystyrene, namely bagasse and paper, require a coating to reduce moisture permeability of the cups and clamshells so that they can adequately perform the required function. The most common coating is the conventional petroleum derived polymer, Polyethylene, that persists in the environment long after the paper component has degraded. The photo in **Figure 12** shows a polyethylene coated cup 4-6 years after disposal to a home composting system, with the thin polyethylene plastic coating being the only visible remaining component.

Figure 12: PE coated cup 4-6 years after disposal to a home composting system

The standard polyethylene (PE) coating amounts to 3%w/w of the cup or container, but various bioplastics can also be used. PLA is increasingly being used (at 5% w/w), and other bioplastics (PHB, PBS) could also serve the same purpose. The relatively small proportion of plastic/bio-plastic coating may have a significant influence on biodegradation and hence persistence and material pollution. Specifically, the coating (3% PE or 5% PLA/PBAT/PBS) will influence the persistence and Material Pollution Indicator of the paper and bagasse products.

We therefore conducted a more detailed assessment of the impacts of various coatings in terms of persistence and material pollution (**Table 7**). The results show that non-biodegradable coatings, such as PE, have a significant influence and can increase the persistence and MPI of paper/bagasse containers by more than 580%. In contrast, use of all biodegradable coatings had a minimal effect (<10%) on the persistence and MPI of the cups/containers; with the biodegradable materials (PBS, PBAT, PHA) increasing the Material Pollution Indicator (relative to the case of the paper/bagasse product with no coating) by less than 6%, or 9% in the case of PLA.

Table 6: PersistenceLM and Material Pollution Indicators' Results

Material type	Container Type	Reference Flow (g)	Mean material lifetime (yr)			Amount in receiving environment (g)			Weighted material lifetime (yr)	Persistence$_{LM}$ (kg.yr)	Material price ($/kg)	Price of polymer in material reference flow ($)	Density (kg/m^3)	MPI, Material Pollution Indicator (m^3/$).yr
			Contained or Composted*	Marine	Landfill	Contained or Composted	Marine	Landfill						
XPS/EPS	Clamshell	125.64	24.41	246.33	172.18	36.07	29.01	36.69	140.94	17.708	1.20	0.15	20	**5.87254**
	Cup	36	24.41	246.33	172.18	10.34	8.31	10.51	140.94	5.074	1.20	0.04	30	**3.91503**
Bagasse	Clamshell	483.84	0.20	1.28	0.81	138.91	111.72	141.28	0.73	0.352	0.80	0.39	1200	**0.00076**
	Cup	229.39	0.20	1.28	0.81	65.86	52.97	66.98	0.73	0.167	0.80	0.18	1200	**0.00076**
Paper	Clamshell	461.64	0.20	1.28	0.81	132.54	106.59	134.80	0.73	0.336	0.80	0.37	1400	**0.00065**
	Cup	168	0.20	1.28	0.81	48.23	38.79	49.06	0.73	0.122	0.80	0.13	1400	**0.00065**
PET	Clamshell	316.8	24.41	246.33	172.18	90.95	73.15	92.51	140.94	44.650	1.00	0.32	1380	**0.10213**
	Cup	113.06	24.41	246.33	172.18	32.46	26.11	33.01	140.94	15.935	1.00	0.11	1380	**0.10213**
PP	Clamshell	184.51	24.41	246.33	172.18	52.97	42.60	53.88	140.94	26.005	1.50	0.28	920	**0.10213**
	Cup	113.04	24.41	246.33	172.18	32.45	26.10	33.01	140.94	15.932	1.50	0.17	920	**0.10213**
PLA	Clamshell	248.7	0.20	9.61	7.97	71.40	57.42	72.62	5.68	1.413	4.40	1.09	1240	**0.00104**
	Cup	151.2	0.20	9.61	7.97	43.41	34.91	44.15	5.68	0.859	4.40	0.67	1240	**0.00104**
PBS	Clamshell	250.66	0.20	0.82	0.48	71.96	57.88	73.19	0.48	0.120	5.50	1.38	1250	**0.00007**
	Cup	204.72	0.20	0.82	0.48	58.78	47.27	59.78	0.48	0.098	5.50	1.13	1250	**0.00007**
Mater-Bi ®	Clamshell	242.67	0.21	0.82	0.48	69.67	56.03	70.86	0.48	0.117	4.20	1.02	1210	**0.00009**
	Cup	99.13	0.21	0.82	0.48	28.46	22.89	28.95	0.48	0.048	4.20	0.42	1210	**0.00009**
Bio-foam (expanded PLA)	Clamshell	138.12	0.20	9.61	7.97	39.65	31.89	40.33	5.68	0.785	4.40	0.61	80	**0.01615**
	Cup	54	0.20	9.61	7.97	15.50	12.47	15.77	5.68	0.307	4.40	0.24	80	**0.01615**
PHB	Clamshell	246.68	0.18	0.88	0.16	70.82	56.96	72.03	0.37	0.092	16.00	3.95	1200	**0.00002**
	Cup	201.48	0.18	0.88	0.16	57.84	46.52	58.83	0.37	0.075	16.00	3.22	1200	**0.00002**

* Compost refers to industrial composting

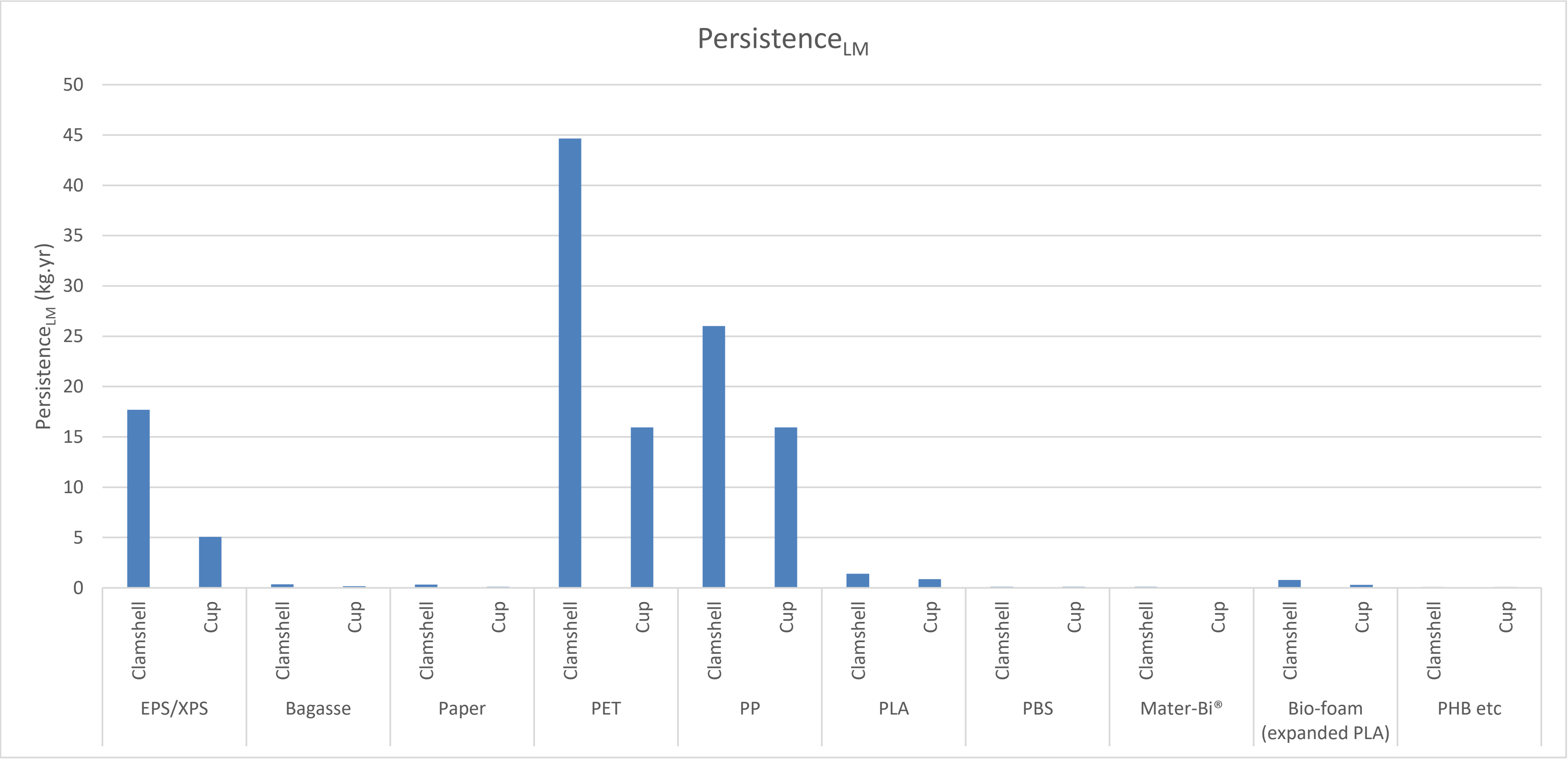

Figure 13: Persistence$_{LM}$ Indicator Results

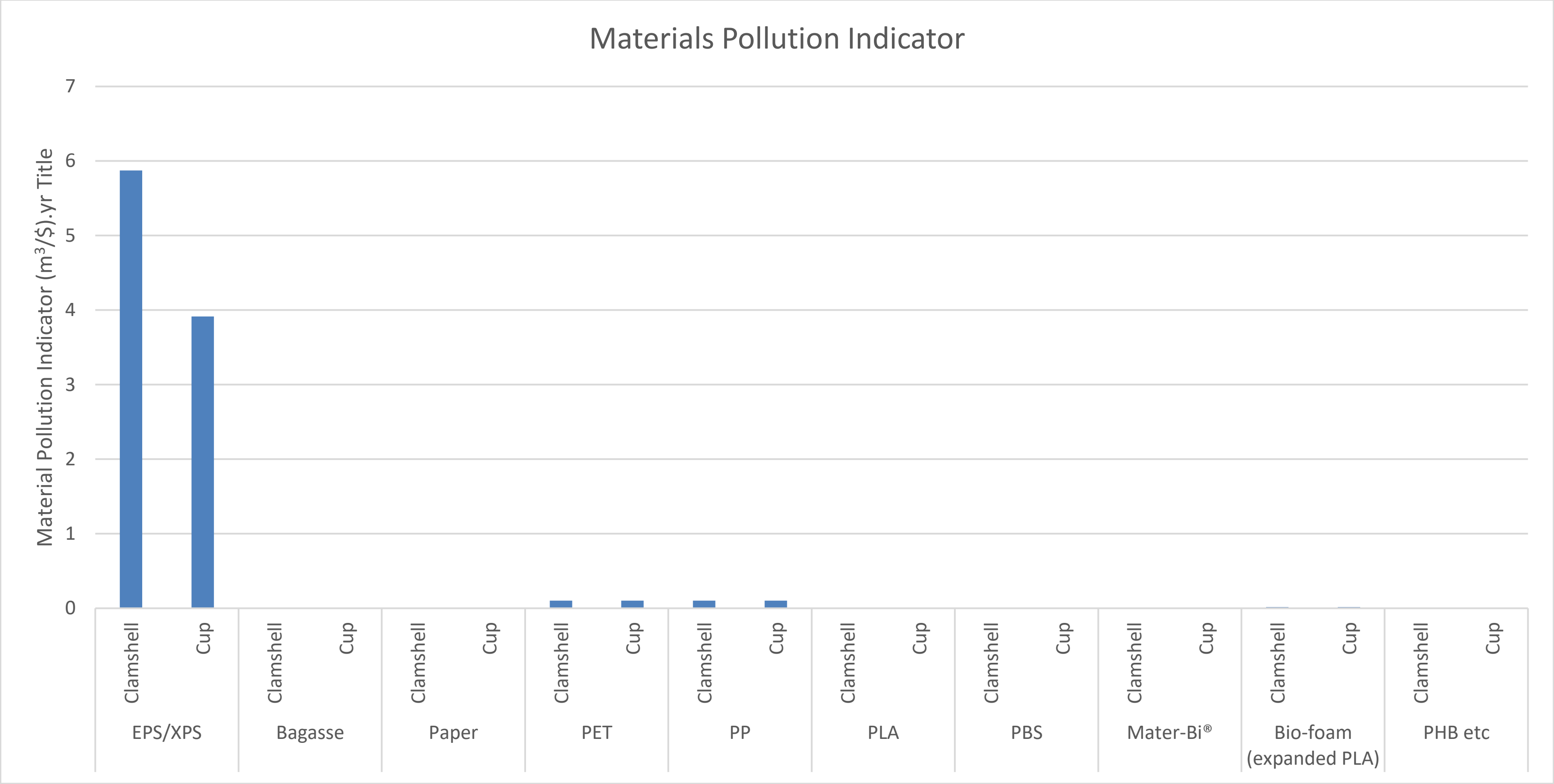

Figure 14: Material Pollution Indicator Results

Table 7: PersistenceLM and Material Pollution Indicator, different material coating comparison

					Persistence$_{LM}$ $(m^3/\$)$.yr	**Material price $/kg**	**Price of polymer or raw material in product/reference flow ($)**	**Density kg/m3**	**MPI, Material Pollution Indicator with coatings**
Material	**Container Type & Coating**	**Functional Unit in terms of Volume**	**Individual weights (gr)**	**Reference Flow (g)**					
Bagasse	Clamshell	1.12	36.00	483.84	0.35	0.80	0.39	1200	**0.001**
	_3%PE	1.12	1.08	14.5152	2.05	0.90	0.01	950	**0.165**
	_5%PLA	1.12	1.80	24.192	0.14	4.40	0.11	1240	**0.001**
	_5%PBS	1.12	1.80	24.192	0.01	5.50	0.13	1250	**0.000**
	_5%PBAT	1.12	1.80	24.192	0.01	4.20	0.10	1210	**0.000**
	_5%PHB	1.12	1.80	24.192	0.01	16.00	0.39	1200	**0.000**
	Cup	1	19.12	229.44	0.17	0.80	0.18	1200	**0.001**
	_3%PE	1	0.57	6.8832	0.97	0.90	0.01	950	**0.165**
	_5%PLA	1	0.96	11.472	0.07	4.40	0.05	1240	**0.001**
	_5%PBS	1	0.96	11.472	0.01	5.50	0.06	1250	**0.000**
	_5%PBAT	1	0.96	11.472	0.01	4.20	0.05	1210	**0.000**
	_5%PHB	1	0.96	11.472	0.00	16.00	0.18	1200	**0.000**
Paper	Clamshell	1.12	31.00	416.64	0.30	0.80	0.33	1400	**0.001**
	_3%PE	1.12	0.93	12.4992	1.76	0.90	0.01	950	**0.165**
	_5%PLA	1.12	1.55	20.832	0.12	4.40	0.09	1240	**0.001**
	_5%PBS	1.12	1.55	20.832	0.01	5.50	0.11	1250	**0.000**
	_5%PBAT	1.12	1.55	20.832	0.01	4.20	0.09	1210	**0.000**
	_5%PHB	1.12	1.55	20.832	0.01	16.00	0.33	1200	**0.000**
	Cup	1	14.00	168	0.12	0.80	0.13	1400	**0.001**
	_3%PE	1	0.42	5.04	0.71	0.90	0.00	950	**0.165**

_3%PLA	1	0.70	8.4	0.05	4.40	0.04	1240	**0.001**
_5%PBS	1	0.70	8.4	0.00	5.50	0.05	1250	**0.000**
_5%PBAT	1	0.70	8.4	0.00	4.20	0.04	1210	**0.000**
_5%PHB	1	0.70	8.4	0.00	16.00	0.13	1200	**0.000**

4.3 Cost

Here results regarding the cost to manufacturers is presented. Cost in the case of the alternative materials assumes that the materials can be applied as drop-in replacements, thus using the same technologies to produce the meal-kit options.

The cost of packaging containers is largely a function of material price; and therefore, the price of each material (FOB materials market price, $/tonne, Plastics today 2021) was used to estimate the cost of materials used in each meal kit (cup and take-out container), for both polystyrene and the various alternatives. This captures the price of plastic/bioplastic/paper/bagasse material that is used for the manufacturing of the product (cups and clamshells); however, it does not include the cost of manufacturing. It therefore captures the cost of material to the manufacturer, but the transition to alternatives may require additional investment in manufacturing infrastructure. It is therefore preferable that alternatives are “drop-in” replacements, requiring little additional infrastructure and associated manufacturing costs.

Polystyrene (XPS/EPS) material in the cup or clamshell has a very low material price, with the alternatives such as paper (as well as bagasse and bioplastics) being at least twice as costly (**Figure 15**). Bioplastics such as PLA, PBAT and PBS material cost about five times more than polystyrene, while PHA / PHBH is about forty times the cost of polystyrene. Polystyrene (XPS/EPS) clamshells and cups are clearly more affordable, and this is also partly attributable to the low material weight of expanded polystyrene products (>95% air).

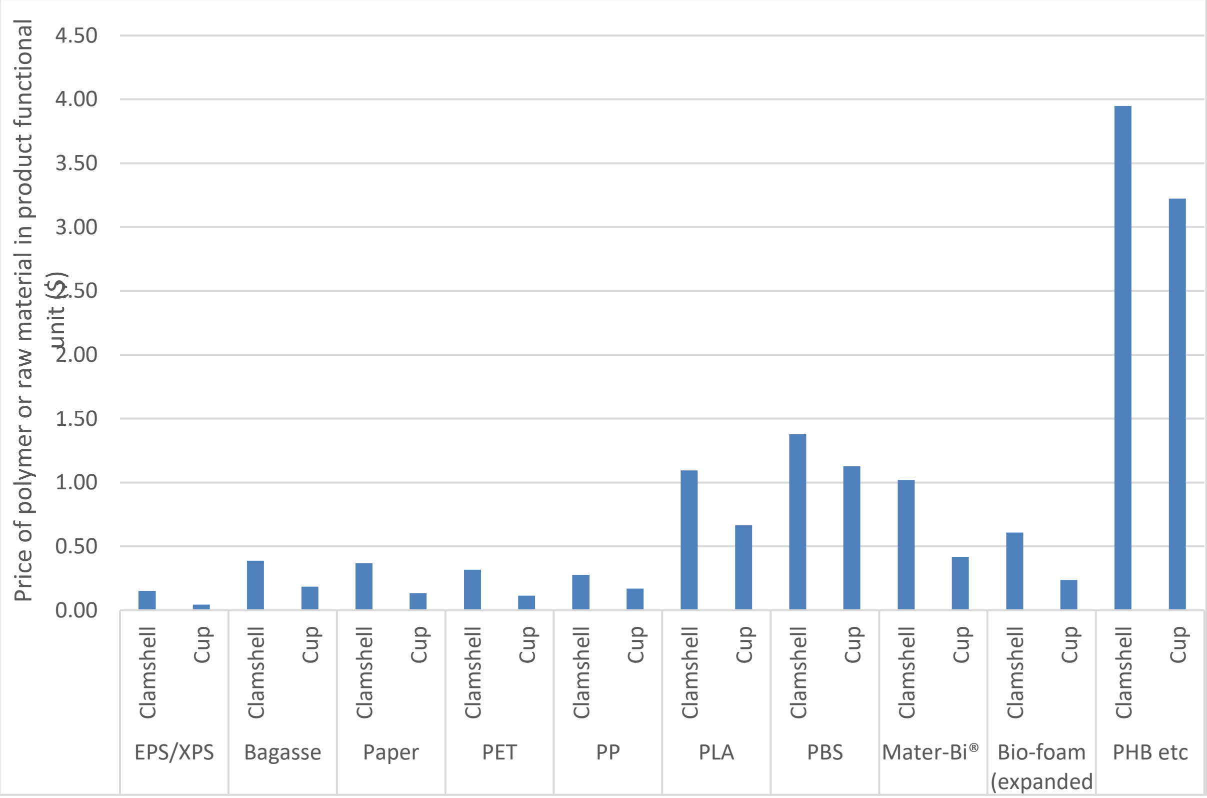

Figure 15: Cost of raw material for meal-kits made from different materials

4.4 Jobs in plastic food take-out containers and alternatives

The conventional plastics industry has been a major employer worldwide, but job losses in the manufacturing, recycling, and waste management sectors are expected as demand decreases (Talberth et al., 2020). The Ellen MacArthur Foundation (2017) predicts that by 2050, the plastics industry will consume 20% of total oil production, down from 5% today, leading to significant job reductions in petroleum-based plastic production. However, job gains are expected in manufacturing alternative materials such as PLA, PHA, and cellulose-based plastics (Philp et al., 2013), and in the waste management, recycling, and composting sectors (EPRS, 2017; (Philp et al., 2013). Additionally, the shift to a circular economy model has the potential for job growth in waste management, recycling, and composting (EPRS, 2017). For example, in the EU, the European Environmental Bureau (2018) estimates that this transition could create 850,000 new jobs by 2030.

Quantifying the exact net job losses or gains in the transition from conventional plastics to biodegradable alternatives is challenging due to the numerous factors influencing the job market, including regional variations, policy changes, and technological advancements.

In terms of the transition from current plastics to alternatives, our analysis suggests that **a greater number of jobs (employment) will result from the transition from current plastics to alternative materials** (see **Table 8**). This is a result of: (i) more material (mass) in the paper and compostable products, resulting in (ii) a greater number of jobs in the life cycle of paper and compostable products; mainly from the raw materials production stage (biomass feedstock). The reference flows in **Table 9** refers to 1 meal in a take-out container, per person per month (different containers were adjusted to volumetric equivalency).

Table 8: Jobs for each cup and clamshell material type

	Material	Container Type	Reference Flow (g) per person	Reference flow for SA population* (kt)	Jobs per reference flow for SA population**, **
Commercially Available	**Polystyrene (XPS/EPS)**	Clamshell	125.64	7.45	191
		Cup	36	2.13	55
	Bagasse	Clamshell	483.84	28.69	75
		Cup	229.39	13.60	66
	Paper	Clamshell	416.64	24.71	1092
		Cup	168	9.96	440
	PET	Clamshell	316.80	18.79	465
		Cup	113.06	6.70	166
Commercially Available Alternative Materials	**PP**	Clamshell	184.51	10.94	271
		Cup	113.04	6.70	166
	PLA	Clamshell	248.7	14.75	924
		Cup	151.2	8.97	562
	PBS	Clamshell	250.66	14.86	931
		Cup	204.72	12.14	760
	PBAT or PSM (Mater-bi)	Clamshell	242.67	14.39	901
		Cup	198.24	11.76	737
	Bio-foam (expanded PLA)	Clamshell	138.12	3.20	201
		Cup	54	7.45	191
Prototypes	**PHB (used as proxy for the other materials: PHA, PHBV, PHBH)**	Clamshell	246.68 (240.67 – 250.7)	14.63	917
		Cup*	201.48 (196.56 – 204.72)	8.19	513

*59.3 million population in South Africa

** Total life cycle jobs per kilo-tonne (kt) product in Table 10. The Jobs per reference flow meal-kit for SA population *excludes* the jobs in recycling/composting/material recovery, since the BAU scenario assumes 0% recycling of all meal-kit options.

In addition, for polystyrene, currently the polymer is imported into South Africa; there are no South African jobs in the raw materials production part of the product life cycle. As a result, there are less jobs (from a South African perspective) associated with polystyrene as compared to other plastics (South African jobs in plastics overall is estimated at 68 per kt product, while polystyrene is 64 per kt product). The result is that there are a greater number of jobs in bio-based materials as compared to polystyrene, and this can largely be attributed to the raw materials production stage (biomass feedstock production, such as sugar-cane) (**Table 8** and **Table 9**).

Table 9: Jobs per value chain stage for meal-kits made from different materials

	Jobs per kilo-tonne (kt) product			
	Plastics	Polystyrene	Paper	Bioplastics and bio-composite
Raw materials	1	0	10	35
Polymer production	3	0	3	3
Manufacturing	20	20	31	25
recycling/recovery	30	30	24	24
Total	54	50	68	87

Using this data, polystyrene can be compared to the alternatives, by estimating the total product life cycle jobs for the South Africa population using take-away containers (cups and clamshells) made from various materials (**Figure 16**).

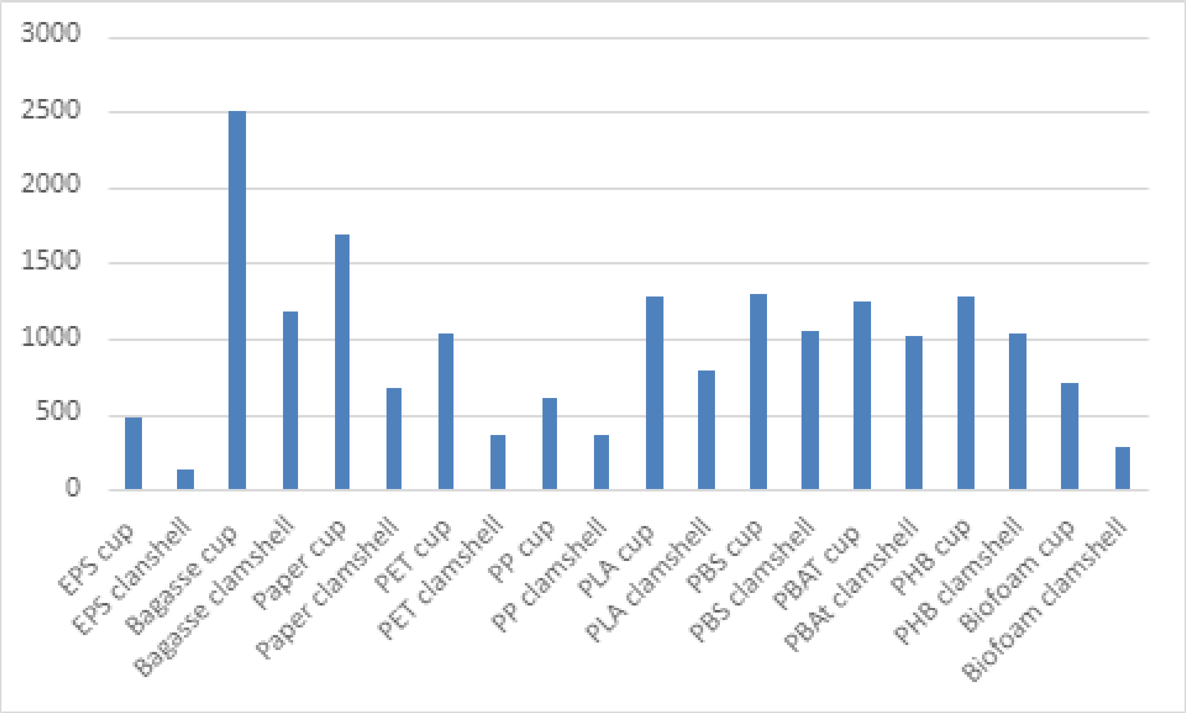

Figure 16: Estimated Jobs for South Africa population using take-away containers (cups and clamshells) made from various materials (CSIR unpublished data, 2023)

Understanding job transitions associated with the shift from conventional plastics to biodegradable alternatives is crucial for developing informed policies that support the transition from converntional materials to more environmentally sustainable alternatives. While there may be job losses in moving away from conventional materials, there are jobs gains from new value =chains and the move to a bioeconomy. However, to facilitate this transition, governments and industry stakeholders should invest in workforce re-skilling, education, and vocational training programs. Policies promoting innovation and investment in the bio-economy, such as the bio-based and biodegradable materials sector will facilitate the shift towards a sustainable economy (Talberth et al., 2020). Key aspects for a just transition from conventional materials to alternatives were identified[12] as:

- Policy development: Establish clear policies and regulations promoting alternative materials adoption, with incentives for research and development, industry standards for biodegradable materials, and waste management guidelines.
- Public-private collaboration: Encourage cooperation between the public sector, private industries, and research institutions to drive innovation, develop new technologies, and leverage financial resources for alternative materials adoption.
- Education and capacity building: Implement education and training programs to develop necessary skills for workers transitioning from conventional plastics to alternative materials industries, including vocational training, university courses, and on-the-job training.
- Infrastructure development: Invest in infrastructure for production, distribution, and recycling or composting of alternative materials, including manufacturing facilities, transportation networks, and waste management systems supporting a bio-economy.
- Financial support: Provide financial incentives, such as tax breaks, grants, or low-interest loans, encouraging businesses and entrepreneurs to invest in alternative materials and related technologies.
- Social protection measures: Implement social protection measures for workers who may lose their jobs during the transition, including unemployment benefits, job placement services, and retraining programs.
- Community engagement: Foster community engagement and raise awareness about alternative materials benefits through public campaigns, educational programs, and local initiatives.
- Environmental conservation: Implement measures to mitigate environmental impacts of conventional plastics, including plastic pollution reduction initiatives, clean-up efforts, and habitat restoration.
- Monitoring and evaluation: Establish a monitoring and evaluation framework to track the transition progress and make data-driven decisions for continuous improvement.
- Regional and international cooperation: Collaborate with regional and international partners to share best practices, knowledge, and resources, and develop harmonized standards and policies.

By addressing these aspects, South Africa can facilitate a just transition to alternative materials, benefiting the environment, economy, and society.

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[12] CSIR team requirements for switching to alternatives" ECD/SEW SWOT analysis REF to market study report.

4.5 Sensitivity/Scenario Analysis

Some Scenarios were investigated to understand how the results were influenced by the following parameters with respect to the BAU base case:

1. Local production VS Imports of finished goods;
2. Increasing recycling rates;
3. Different coating materials.

The results presented here refer to the ReCiPe 2016 Single Score indicator only. *Appendix B - Mid- and End-point LCA Results for the Scenario Analysis* presents the results for all ReCiPe 2016 end- and mid-point Indicators.

4.5.1 Local production VS Imports of finished goods

The BAU Scenario included a mix of both locally produced meal-kits, imports of finished products, as well as alternatives where raw materials were produced elsewhere, and manufacturing occurred locally. In this section, we investigated all possible production routes for each of the meal-kit options (i.e., three different scenarios for each meal-kit).

Table 10 shows the comparison of the business as usual (BAU) scenario (highlighted in RED in **Table 10**) - which differs for the different material alternatives - with alternative scenarios regarding the location of production:

- ZA production: Both the raw materials and the finished products are produced in South Africa
- ZA manufacturing only: Raw materials are produced elsewhere and imported; with the final product manufactured in South Africa (; and
- GLO production: Both the raw materials and the finished products are produced elsewhere, and then imported.

It is evident that local production impacts negatively on the overall environmental performance of the investigated options. This is due to South Africa's reliance on coal-fired electricity; as well as the CtL production process for monomers, which impacts not only conventional plastic, but also the fossil-based alternative material options (PBS and PBAT).

Alternative options to consider when thinking of material replacement, which show a relatively moderate increase in environmental burdens associated with fully localised production as compared to global production (i.e. an increase in the Single Score of ~20%, highlighted in GREEN in **Table 10**); are Paper, Bagasse and PBS, which also show potential to be organically recycled (industrial composting). Localising the manufacturing stage only translates in an increase in environmental burdens of 9.5% on average for Bagasse and all the biodegradable plastics relative to the case of fully global production, due to the South African electricity grid mix heavily relying on coal-fired production. Such a scenario may also preserve the manufacturing industry since the bioplastics can be dropped into existing plastic manufacturing processes.

4.5.2 Increasing recycling rates

Using the targets for increasing recycling rates for different materials and single-use products under the EPR regulations (DFFE, 2021) (**Table 3**); the following future scenarios were explored versus the BAU:

- Improved mechanical recycling for the conventional plastic and Paper meal-kits:
  - Recycling rates for Single Use Packaging were applied to PS, PET, PP and Paper;

- Industrial composting (as organic recycling) for the bioplastic and Bagasse meal-kits:
    - Recycling rates for biodegradable and compostable Single Use Packaging were applied, respectively.

Table 11 and **Figure 17** present the results (based on the ReCiPe Single Score) for future recycling rate scenarios (based on the targets under the EPR regulations) (**Table 3**) for the different material alternatives, relative to the BAU scenario. Potential benefits for recycling (i.e. producing recyclate through the recycling process) are displayed separately, i.e. as potential improvements in the overall performances of the investigated options, should these be able to avoid the production of virgin material (a virgin material substitution ratio of 1:0.8 (Lazarevic, 2010) was applied, when modelling recycling production, which means recyclate is able to substitute virgin material partially) when the waste streams are recycled. The results show that increasing recycling rates, either as mechanical recycling or composting, will improve the overall environmental performances of the investigated options. Specifically, environmental performance improves by up to ~40% for both conventional plastic (PP and PET respectively when material type recycling rate targets or targets for single use packaging are applied); as well as for biodegradable/compostable alternative materials over a 5-years period based on the targets for both mechanical recycling and industrial composting in the EPR Regulations.

However, the overall ranking of the different material alternatives remains unchanged as compared to the BAU case. It is important to note that while several bioplastics (PHB, PBS, Mater-Bi®) are readily biodegradable and fully compostable under both home and industrial conditions, PLA is only compostable under industrial composting conditions, where temperature, heat and moisture can be regulated and optimised (Song *et al.* 2009). In addition, the coating (comprising ca. 5% of product mass) to improve the moisture resistance of the paper/cardboard and bagasse products also influences their compostability. The conventional coatings applied are polyethylene (PE) for paper meal-kits, which is not biodegradable and cannot be composted; but can potentially be substituted for compostable bioplastic alternatives (see Section 4.5.3) and PLA for bagasse meal-kits. As mentioned, these bioplastics can be certified according to their composability in home and industrial composting systems (European Environment Agency, 2020).

4.5.3 Different coating materials

Two of the meal-kit alternatives require coating materials as waterproof/grease barriers, namely the Bagasse and Paper options. In the BAU case, the Bagasse meal-kit comes with a PLA coating, whereas the Paper meal-kit come with a PE (polyethylene) coating. The coating accounts for 3-5% by mass of the total weight of the meal-kit (clamshell food container and cup).

The impact on the overall environmental performance of switching to alternative coating materials; both in terms of the coating production as well as the implications for disposal; were assessed by means of scenario analysis. **Table 12** illustrates the results comparison for the ReCiPe 2016 Single Score indicator only and excludes Persistence$_{LM}$ and MPI indicators. The effect of different coating material at EoL are presented in **Table 7.**

The bagasse meal-kit shows overall environmental improvements when other materials are used for coating the inner surface. Except for the PE option, the other coating alternatives (various bioplastics) can be organically recycled (via industrial and home composting). As such, the bagasse meal-kit's environmental performance can be improved by both increasing recycling rates and by using less resource intensive and bio-degradable coating materials.

In the case of the paper meal-kit, the BAU scenario with a PE coating agent for the paper meal-kit and PLA coating for the bagasse meal-kit, has lower environmental impacts as compared to alternative types of materials based on ReCiPe 2016 Single Score only. Biodegradable options which may be considered as alternative materials and which show only a relatively minor increase in environmental burdens (<5%) are PBS, PSM (Mater-Bi®) and PBAT.

Table 10: ReCiPe 2016 Single Score LCIA results comparing Local production VS Imports of finished products

	Unit	**PS**	**PET**	**Bagasse**	**Paper**	**PP**	**PLA**	**PBS**	**Mater-Bi®**	**Bio-foam (expanded PLA)**	**PHB**
ZA Production	mPt	41.5	**150**	119	**82.7**	**158**	380	114	183	182	342
	%*	+48.7%		**+22.3%**			+63.1%	**+18%**	+61.9%	+62.5%	+36.3%
ZA Manufacturing Only	mPt	**27.9**	110	118	82.7	50.2	246	111	127	118	267
	%		-26.7%	+21.3%	0%	-68.2%	+5.9%	+14.9%	+12.4%	+5.4%	+6.4%
GLO Production	mPt	24.4	92.8	**97.3**	75.1	40.5	**233**	**96.6**	**113**	**112**	**251**
	%	-12.5%	-38.1%		-9.2%	-74.4%					

* This refers to % change from the BAU.

Table 11: ReCiPe 2016 Single Score LCIA results comparing impacts of Increasing recycling rates

Meal-kit Material type		**PS**	**PET**	**Bagasse**	**Paper**	**PP**	**PLA**	**PBS**	**MaterBi®**	**Bio-foam (expanded PLA)**	**PHB**
BAU (Single Score mPt)		**27.9**	**150**	**97.3**	**82.7**	**158**	**233**	**96.6**	**113**	**112**	**251**
MC - Single Use Packaging RRs	Y1	-14.7%	-19.3%		-9.2%	-23.4%					
	Y2	-17.2%	-22.7%		-10.6%	-27.2%					
	Y3	-19.7%	-26.0%		-12.2%	-31%					
	Y4	-21.9%	-29.3%		-13.8%	-34.8%					
	Y5	-24.4%	-32.7%		-15.4%	**-38.9%**					
Organic Recycling (Industrial Composting)	Y1			-7.2%			-0.4%	-1.6%	-1.8%	-0.9%	-0.4%
	Y2			-12%			-1.7%	-4.5%	-3.5%	-1.8%	-1.6%
	Y3			-24%			-4.3%	-11.6%	-9.7%	-4.5%	-4.4%
	Y4			-31.1%			-6.5%	-15.9%	-13.5%	-6.3%	-5.9%
	Y5			**-38.5%**			-7.3%	-20.2%	-17%	-7.1%	-7.6%

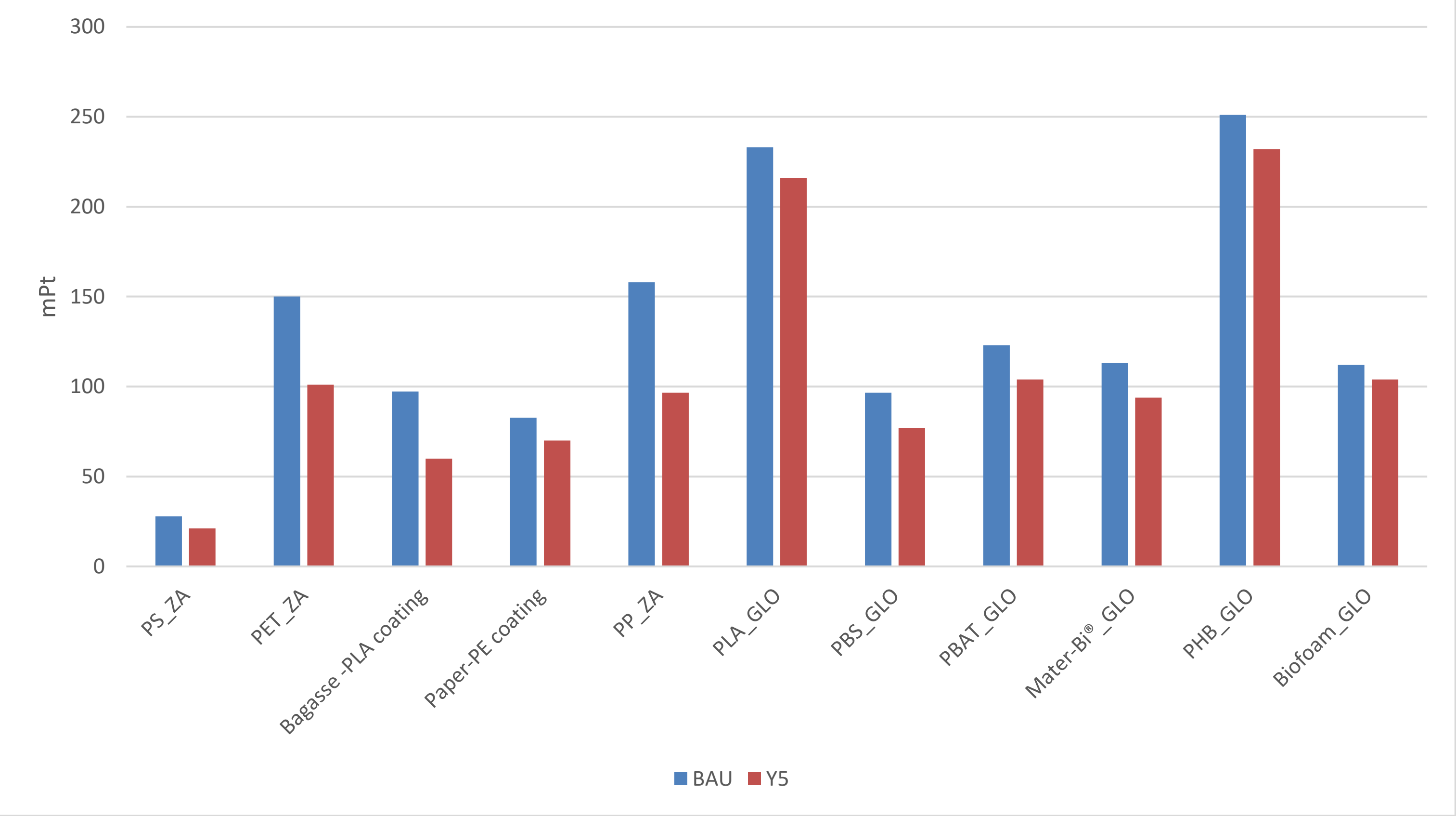


Figure 17: ReCiPe 2016 Single Score LCIA results comparing impacts of Increasing recycling rates (BAU vs Y5)

Table 12: ReCiPe 2016 Single Score results comparing the impact of different coating materials on overall LC and on coating production and meal-kit disposal

Meal-kit material type	**Coating type (5% by mass)**	**Single Score**					
		Overall LC		**Coating Production**		**Disposal**	
		mPt	%	mPt	%	mPt	%
Bagasse	**PLA (BAU)**	**97.3**		**17.3**		**27.8**	
	PE (3% by mass)	81.6	-16.1%	2.8	-83.9%	27.8	
	PBAT	86.7	-10.9%	6.7	-61.3%	27.8	
	PBS	84.3	-13.4%	4.3	-75.3%	27.8	
	PHB	96.8	-0.5%	16.8	-2.9%	27.8	
	Mater-Bi®	86	-11.6%	6.0	-65.3%	27.8	
Paper	PLA	94.6	14.4%	14.2	1265%	22.4	-0.44%
	PE (BAU; 3% by mass)	**82.7**		**1.04**		**22.5**	
	PBAT	85.9	3.9%	5.48	427%	22.4	-0.44%
	PBS	83.9	1.5%	3.51	238%	22.4	-0.44%
	PHB	94.2	13.9%	13.8	1227%	22.4	-0.44%
	Mater-Bi®	85.3	3.1%	4.93	374%	22.4	-0.44%

4.6 A tentative approach to aggregation of indicators in LCSA

Although there is no consolidated framework, LCSA has emerged as a useful tool to combine different aspects of sustainability within the context of a products' life cycle (UNEP,2011). Specifically, it aims to assess all environmental, social, and economic impacts with the aim of improving decision-making for sustainability.

While the application of many individual indicators can provide valuable insight into environmental performance and product sustainability; communicating a multitude of complex, multi-dimensional indicators in a comprehensive way can become complicated and confusing. For ease of communication and to inform decision making, it is often necessary to aggregate the multiple indicators into a much smaller set of indicators, or even a single metric. Many of the LCIA methods available within LCA tools already provide normalised scores for the conventional E-LCA impact categories. ReCiPe 2016 calculates three end point damage categories and a single score metric by aggregating and weighting across the 18 normalised mid-point scores (Huijbregts et al., 2017; Goedkoop et al., 2009). However, in the case of an LCSA study, when "new indicators" are applied (such as Persistence$_{\text{LM}}$, MPI, Cost and jobs), there is no standardised methodology of combining the E-LCA results with those for the additional indicators.

Composite indicators are easier to comprehend as compared to a large number of individual indicators. Data on different indicators can be aggregated without being scaled if all the variables are measured with the same unit. However, in many cases the variables to be aggregated have different intrinsic units of measure, and different measurement techniques. The various indicators therefore have to be rendered comparable, by normalizing them to the same scale. Therefore, scaling (or normalisation) is required to compare indicators in various scales and units on a common basis, by converting the measurements to a standard scale (e.g., 0-1 or 0-100), so that they can be mathematically aggregated.

4.6.1 Scaling and Aggregation – Min-Max normalisation

The Min-Max Normalisation method rescales data into different intervals based on minimum and maximum values, such that all indicators have an identical range. In min-max normalisation, which is the technique used by well-known sustainability indices such as the Human Development Index (HDI), Sustainable Society Index (SSI) and Environmental Performance Index (EPI), indicators are normalised to have an identical range (0-1 by default; but easily converted to any pre-determined scale), by applying one of the following formulae (depending on the direction of the indicator's effect) (Saisana and Philippas, 2012):

Where higher raw values are desirable: $x_i' = \frac{x_i - \min(x)}{\max(x) - \min(x)}$

Where lower raw values are desirable: $x_i{}' = \frac{\max(x) - x_i}{\max(x) - \min(x)}$

Where *xi'* is the normalised score, x_i is the raw indicator score, and *min(x)* and *max(x)* are the minimum and maximum indicator values respectively. Importantly, the minimum and maximum values used in the calculation can either be the minimum and maximum as observed in the data itself; or they can be imposed (fixed) thresholds. If observed minima and maxima are used, the resulting scores can become distorted by the presence of extreme values or outliers (Organisation for Economic Cooperation and Development, 2008), while comparability of scores over time is also compromised (as the observed minima and maxima will change over time, affecting the resulting scores) (Nahman et al., 2016).

By converting all indicator scores to a common scale, the min-max normalisation approach also allows for results to be graphically illustrated using "spider" or "radar" diagrams. These diagrams are a powerful tool to visually present different indicators, which allow for multiple indicator scores to be seen at a glance. This enables a visual comparison of products' overall performance, with the good and poor performing options easily identified by looking at the number of indicators on which they perform well as compared to poorly.

4.6.2 LCSA Results

Mid-point scores from the conventional LCA, as well as scores for the additional indicators, are converted to a common scale (0-1) by using the Min-Max method, which favours higher values. Furthermore, in working towards an aggregated single metric, we calculated an *Overall (dimensionless) Score* by summing and weighting all the scaled scores (**Table 13**). The approach followed that of Russo et al. (2020) in the CSIR's LCSA study on South African grocery carrier bags, which was extended by exploring several weighting options:

- Equal weighting – all midpoint indicators are weighted the same (e.g., global warming potential receives the same weight as ozone formation), as per Russo et al. (2020). However, in the case of plastic packaging and other single use plastic products, it could be argued that the new indicators developed by the project team to account for plastic pollution (such as the MPI) should receive a higher weighting as it is the plastic pollution issue that is of particular concern. Therefore, we also provide results based on:
- Incrementally increasing the weighting of the Material Pollution Indicator (MPI). This was done both to test the robustness of the results, and to understand when a shift in the ranking would occur (and in favour of which type of meal-kit alternative). Specifically, since it is found that the conventional PS meal-kit still comes out as the preferred option even when the new $\text{Persistence}_{\text{LM}}$ and MPI indicators are added, but with equal weighting applied (see **Table 13**); and since the aim of this study is to identify feasible alternatives based on concerns relating to plastic pollution, we incrementally increased the weighting for the MPI until the next best alternative was identified.

With the addition of the new indicators, and under an assumption of equal weighting, the PS meal-kit still comes out as the best performing option overall; followed by the Bio-foam option; thus, confirming that material light-weighting plays a significant role. The coated paper and bagasse meal-kits score third and fourth; followed by the bioplastics. The conventional plastic alternatives (PP and PET) occupy the last two positions.

Figure 18 shows the comparison of the radar diagrams for the conventional PS take-out container alongside all the alternatives investigated in this study. In each diagram, the blue-shaded offers a visual representation of the relative overall score for that specific meal-kit option across all indicators (with equal weighting applied). It can easily be seen from the diagrams that the PS option has the smallest area, and therefore performs best overall, although it performs very poorly specifically on the MPI.

Indeed, the Polystyrene option has the lowest overall score, followed by Bio-foam (PLA), and then by coated paper and coated bagasse (**Table 13**, **Figure 18**). When comparing the different meal-kit options using the radar diagrams in **Figure 18**, possible alternatives which show some trade-off start to emerge. In Section 5, these results are discussed in terms of the best trade-offs among the different perspectives, when including additional indicators to the conventional-E-LCA results.

However, given the current global interest in the impacts of plastic pollution in the environment, and the mounting evidence regarding the significance of the ecological and ecosystem impacts; it could be argued that the application of equal weighting underestimates the significance of the MPI indicator.

We therefore explored several scenarios with a higher weighting applied to the MPI indicator relative to the other indicators. Interestingly, even when applying a weighting as high as 50% to the MPI indicator alone (and with the remaining 50% weighting apportioned equally across all the other indicators), the overall rankings do not change – polystyrene still comes out as the top ranked option.

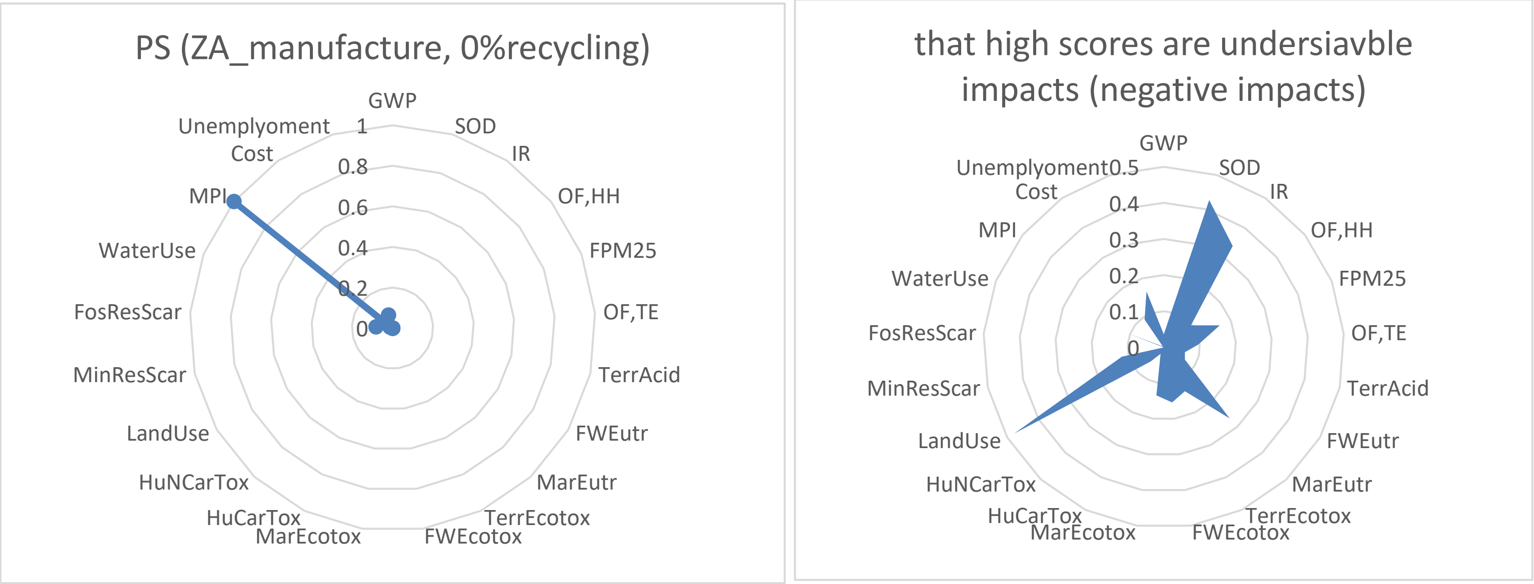
Only when 75% of the weighting is assigned to MPI, and 25% of the weighting to all other indicators combined, does the ranking order begin to change, with the Bio-foam meal-kit becoming the preferred option over the PS take-out container, which scores second. As expected, increasing the weighting of the MPI results in all the biodegradable options moving up the rankings.

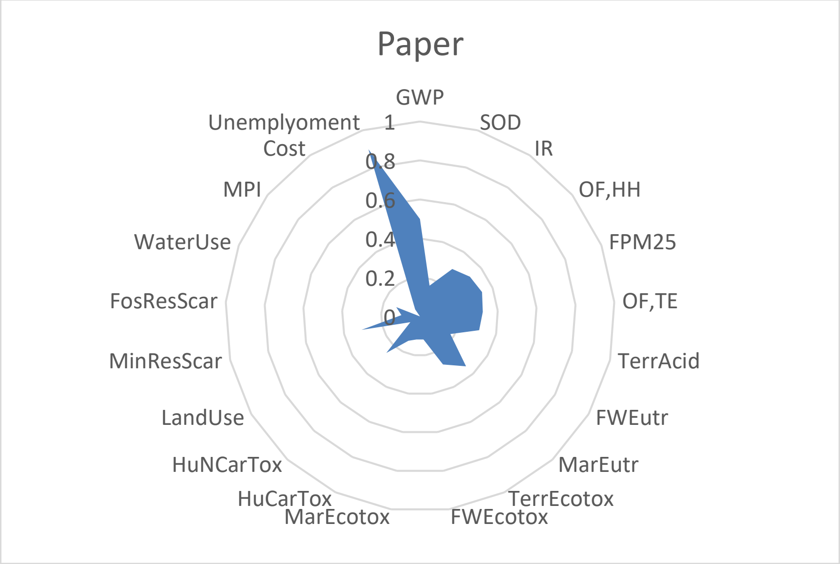
Since weighting is subject to judgement based on the perspectives of different stakeholders, more research (and expert/stakeholder involvement) is envisaged in determining an appropriate set of weightings (relevant for the South African context) for results aggregation. As part of our ongoing work in the development of the LCSA methodology, it is proposed that a broader expert/stakeholder consultation process be conducted to develop such a set of weightings. The results presented in this section are therefore a first attempt and would be needed to be refined further.

Table 13: Overall Score based on the Min-Max normalisation method and alternative approaches to weighting

Meal-kit type	Overall score (equal weighting)	Meal-kit type	50% weighting to MPI	Meal-kit type	75% weighting to MPI
PS (ZA_manufacture, 0%recycling)	1.03	PS (ZA_manufacture, 0%recycling)	0.51	Bio-foam - expanded PLA (GLO_ZA_imported)	0.67
Bio-foam - expanded PLA (GLO_ZA_imported)	2.70	Bio-foam - expanded PLA (GLO_ZA_imported)	1.35	PS (ZA_manufacture, 0%recycling)	0.76
Paper - PE coating	3.43	Paper - PE coating	1.72	Paper - PE coating	0.86
Bagasse -PLA coating (GLO-ZA_imported)	4.65	Bagasse -PLA coating (GLO-ZA_imported)	2.33	Bagasse -PLA coating (GLO-ZA_imported)	1.16
PSM-Mater-Bi (GLO_ZA_imported)	5.29	PSM-Mater-Bi (GLO_ZA_imported)	2.65	PSM-Mater-Bi (GLO_ZA_imported)	1.32
PBS (GLO_ZA_imported)	6.88	PBS (GLO_ZA_imported)	3.44	PBS (GLO_ZA_imported)	1.72
PLA (GLO_ZA_imported)	7.79	PLA (GLO_ZA_imported)	3.90	PLA (GLO_ZA_imported)	1095
PHB (GLO_ZA_imported)	11.96	PHB (GLO_ZA_imported)	5.98	PHB (GLO_ZA_imported)	
PP (ZA_produced, 0% recycling)	1297	PP (ZA_produced, 0% recycling)	6.49	PP (ZA_produced, 0% recycling)	.2.99
PET (ZA_produced, 0% recycling)	13.29	PET (ZA_produced, 0% recycling)	6.65	PET (ZA_produced, 0% recycling)	3.33

Figure 18: Radar diagrams obtained with the Min-Max normalisation method. For consistency with the other normalised midpoint indicators, where a higher score indicates poor performance, Jobs are reported as “Unemployment”, so that high scores of all indicators are undesirable (negative impacts).

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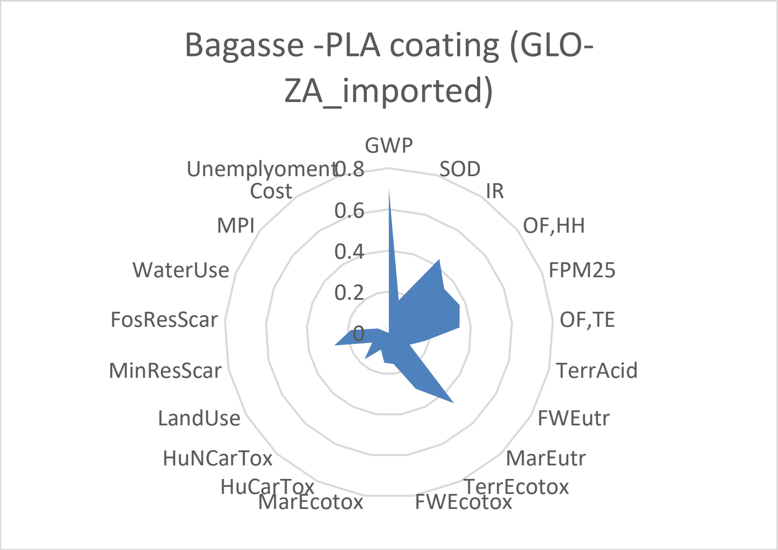
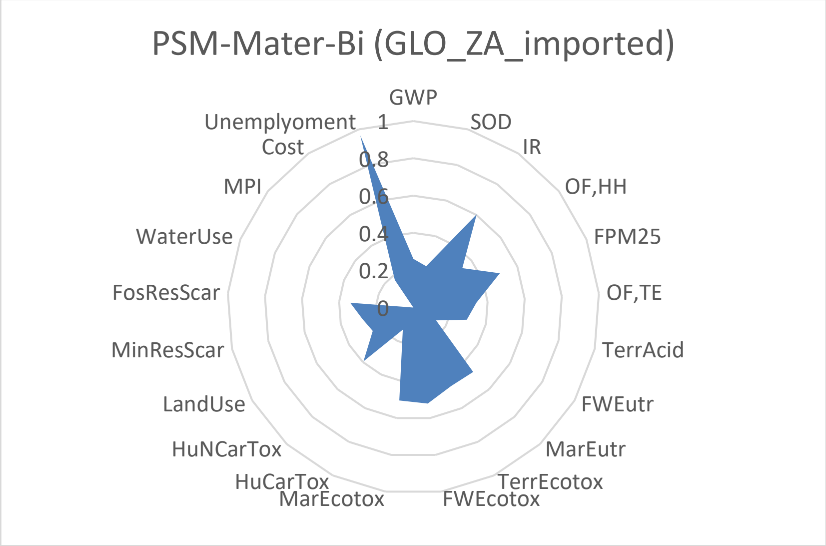

Bagasse -PLA coating (GLO-ZA_imported)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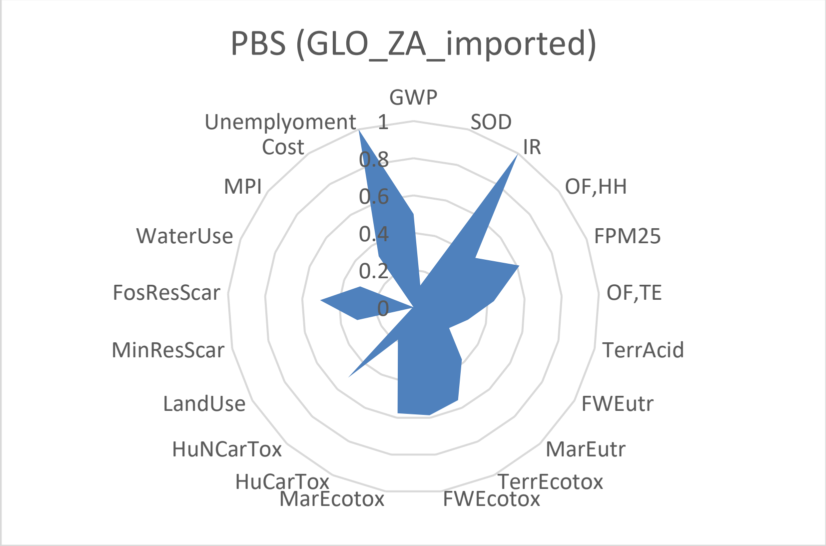
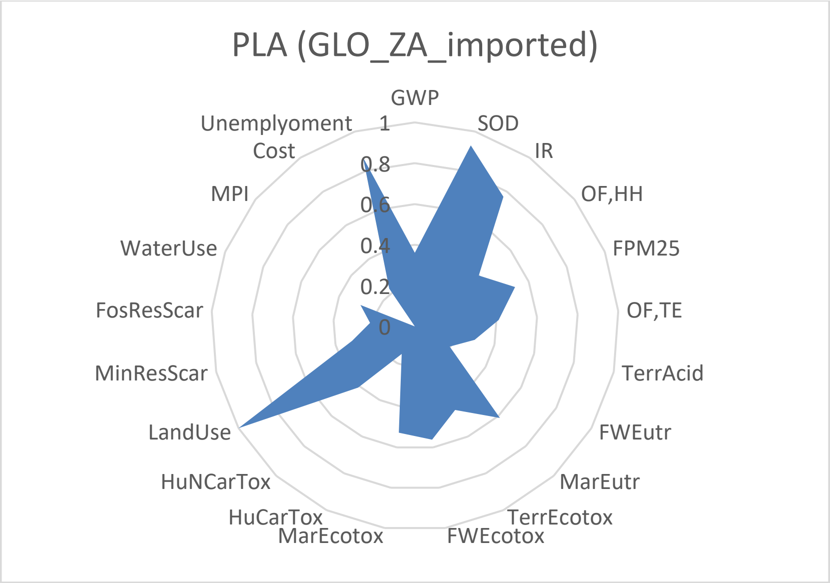
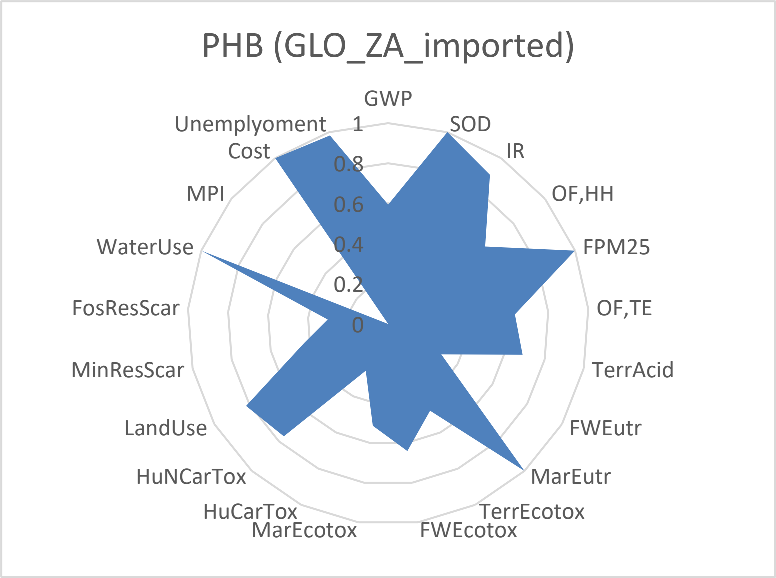
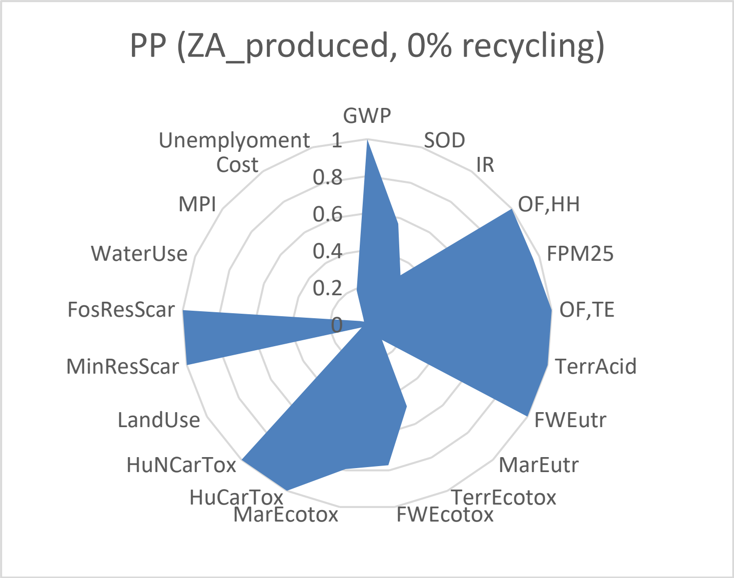
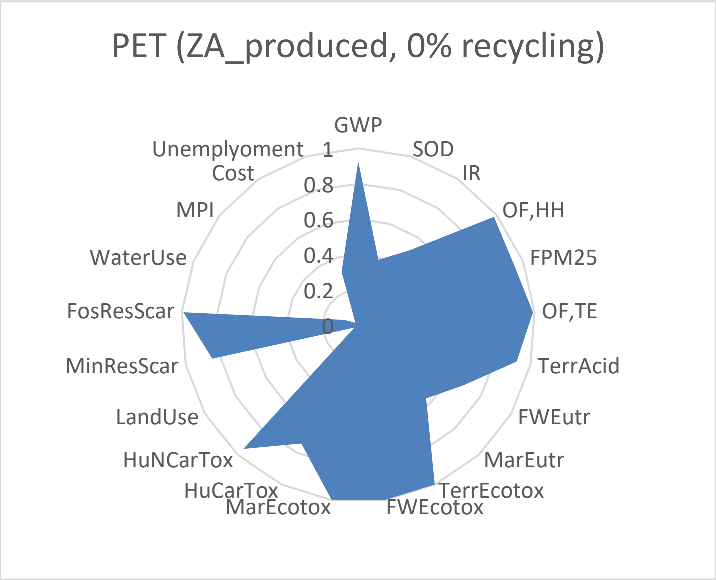

PBS (GLO_ZA_imported)


PLA (GLO_ZA_imported)


PHB (GLO_ZA_imported)


PP (ZA_produced, 0% recycling)


PET (ZA_produced, 0% recycling)

5 DISCUSSION AND FUTURE IMPROVEMENT

The results of the BAU scenario (which included only landfilled and mis-managed end-of-life flows) showed that among all the meal-kit options (including the materials currently in use, commercially available alternatives, and possible prototypes); the raw material extraction and polymer production stages of the value chain are responsible for the bulk of the environmental impact associated with meal-kit use in South Africa. This highlights the need for product re-use and material recycling and recovery to transition toward a more circular economy.

Solely from an E-LCA point of view, Polystyrene had the lowest overall environmental impacts (due to its being extremely lightweight – 3-fold lighter on average compared to the other options), followed by coated Paper/Cardboard and Bagasse, PBS, and Bio-foam PLA.

A combination of background datasets from the ecoinvent database (v. 3.6 and 3.7) and foreground datasets were used to model the systems under study. Specifically, background datasets were used “as is” when representing an imported polymer/product from the global supply chain or were adapted to the local context when needed. Foreground datasets were modelled mainly for emerging materials based on extrapolation from datasets on similar materials (e.g., PBS), or from secondary data from literature (Harding et. Al, 2008) (e.g., PHBH). These datasets included only the main material feedstocks and energy requirements, without including the infrastructure (e.g., chemical factory organics). The results showed that these material alternatives scored rather poorly when compared to other material alternatives – PHBH being the least preferable of all of them. When including the required infrastructure in the dataset modelling, the LCIA results have would been even worse.

Looking specifically at the new indicators developed by the project team aimed at reflecting the impacts associated with plastic pollution; namely persistence and the material pollution indicator; the bioplastics (PLA, PBA, PHB, Mater-Bi®), bagasse and paper perform substantially better than polystyrene and other conventional plastics. Polystyrene is at least four hundred times worse in terms of material pollution than paper; due to its low rate of biodegradation and hence its high persistence, as well as its low density and low intrinsic value; which hinders its collection/recovery for re-use and recycling and makes it prone to disperse in the environment.

However, given the legacy of wide-spread polystyrene use, and the considerable costs in collection and sorting, additional solutions upstream of waste management are clearly needed to avoid the problems with material pollution and move to a more circular economy. Switching to material alternatives that have a lower persistence and material pollution is an appropriate intervention to reduce the material pollution of the environment, but these alternatives may result in the shifting of the environmental burden to other impact categories, resulting in overall impacts greater than that of polystyrene.

In this study, polystyrene has the lowest overall impacts, even with the inclusion of the material pollution indicator. However, to works towards a total score (including the new indicators), we scaled the indicators 0-1 and then aggregated (summed) the indicators with equal weighting. This is not recommended by ISO14044, as the aggregation of mid-point indicators that describe an environmental pollutant does not consider the characterisation and impact assessment from the amounts measured by these indicators and is therefore inherently problematic and biased. In other words, while we have included climate change and material pollution indicators (amongst several others) in this LCA assessment, we have not gained a sufficient understanding of these indicators to enable an integrated assessment of impacts to human health, ecosystems and natural resources.

Other than the already commercialised options of Bagasse and Paper, which may be preferable (depending on the availability of recycling and composting infrastructure); another potential commercially available material alternative is Bio-foam (expanded PLA), as well as PBS, which have relatively low overall environmental impacts (both in terms of material pollution and the ReCiPe E-LCA indicators). This agrees with the findings of a UNEP study, which stated that “If there is a need for single-use options only, the least environmentally problematic choice would be to use paper cups (PLA lining), which would be recycled, rather than landfilled" (UNEP, 2021b). If the mechanical recycling route is followed – which is unlikely for the South African context, since paper cups are most likely to end up being dispose of with general waste, and thus landfilled; unless they are collected separately. Paper cups with PE lining could be recycled using the process for recycling liquid board packaging (LBP), but this is practiced to a very limited extend in South Africa due to cost and the economies of scale needed for LBP recycling plants. As such, this study explored the effect of different lining options; concluding that a biodegradable lining would improve the Paper/Bagasse meal-kit environmental performance whether it is recycled (composted) or if it eventually ends up in the environment.

Among the bioplastics, Bio-foam (expanded PLA) was the material with the lowest environmental impacts; but PLA requires industrial composting, unlike materials such as PBS, PBAT and starch (Mater-Bi®) and PHB, which are compostable in both home and industrial systems. Industrial composting (according to EN 13432) requires >90% biodegradation at 58°C in 180 days, while home composting (Vincotte certification) requires >90% biodegradation at 20–30°C in 365 days (Song *et al.* 2009). Therefore, PBS and Mater-Bi®-like materials may be a preferred choice since they do not require dedicated industrial composting systems to be in place. When landfilled, their relative contribution to the disposal stage is around 10% for sanitary landfills, and around 16-17% for unsanitary landfills and open dumping. Industrial composting requires dedicated infrastructure to control moisture and temperature. When considering localising PBS production with local fossil-based raw materials (coal in the case of South Africa), PBS still shows one of the lowest environmental impacts among all the material alternatives considered. In addition, there is the potential to produce low-density PBS foam, with properties like Bio-foam PLA. The report on Task 1.3 of this project, which focused on the potential for local production of alternatives, found that "*PBS can replace low- and high-density PE and PP in current packaging applications as films and as injection and blow-moulded containers. There are also reports on the potential of PBS to replace polystyrene, particularly as foam, as property profiles are improved".*

Furthermore, PBS could easily replace the conventional PE coating barrier in both the Paper and Bagasse alternatives, which could further increase their performance on both the Persistence and Material Pollution indicators; where they currently score poorly compared to the other biodegradable options, due to the PE/PLA coating barriers, which do not degrade in the environment (PE) or come with a higher environmental burden (PLA).

Two bio-based meal-kits, namely those made of PLA and PHB, stand out among all bioplastic options as having the greatest impacts, mainly due to the feedstock used (maize and sugarcane, respectively), and specifically related to the agricultural practices to produce the substrate for the fermentation process. To improve the environmental performance of these products, it would be good to explore whether sugar-rich bio-waste could be used instead of maize and sugarcane.

Further development of the current study, and of the adopted approach to LCSA more broadly, is aimed at improving the integration of the results into a single metric, which will aggregate both the E-LCA and the newly developed indicators to account for material pollution in the environment, as well as additional socio-economic indicators (i.e., jobs and cost). However, to date, there is no consolidated methodology to achieve this. We are exploring some normalisation approaches such as the Min-Max Normalisation method, which is a technique used by well-known sustainability indices such as the HDI, SSI and EPI. Indicators are normalised to have an identical range (0-1 by default; but easily converted to any pre-determined scale), which then allows indicators to be compared and aggregated. However, to report on end-point indictors such as impacts to human health and ecosystems, considerable knowledge needs to be gained in understanding the impacts of plastic pollution and integrating the impact assessment. In addition, we propose that an expert/stakeholder consultation process be carried out to determine an appropriate set of weightings relevant to the South African context.

Furthermore, the newly developed indicators (particularly the material pollution indicator) will be further developed), while other relevant socio-economic indicators for inclusion in LCSA studies in the South African context may also be identified.

Lastly, under Task 1.5 of this project, on *Demonstration of identified technologies/material,* two possible bioplastics made of PBS and PHBH, with different percentages of bagasse fiber content, are currently under testing. A dedicated E-LCA could be carried out to further explore the environmental impacts of these options. Considering the potential of PBS to replace polystyrene, particularly as foam (i.e., Bio-foam), a further prototype made of expanded PBS could be investigated from an LCA point of view.

6 CONCLUSIONS

This study highlights the importance of considering a range of impacts in carrying out Life Cycle Assessment (LCA) studies and introduces additional environmental and socio-economic indicators which are currently missing from existing life cycle impact assessment methods (persistence, material pollution, cost and jobs). In doing so, this study increases the scope and depth of environmental life cycle assessment (E-LCA), towards a broader Life Cycle Sustainability Assessment (LCSA) approach.

Polystyrene take-out containers and cups serve a valuable purpose in containing and insulating hot meals and drinks for take-out. However, they contribute to the problem of marine litter and material pollution. Assessing the life cycle impacts of polystyrene and alternative materials using a standard E-LCA, it was found that the raw material extraction and polymer production stages have the most significant environmental impacts. Locally sourced materials and conversion processes have higher impacts due to South Africa's reliance on coal-based electricity and the CtL process.

Comparing polystyrene to alternative materials, the E-LCA showed that polystyrene has the lowest overall impacts, but this assessment did not consider the newly developed material pollution and persistence indicators. However, even when these new indicators are included in the assessment, and when additional socio-economic indicators (jobs and cost) are also included, the conventional polystyrene container is still the best performer, unless an extremely high (75%) weighting is applied to the material pollution indicator alone.

Nevertheless, the slow degradation and increased material pollution potential of polystyrene suggests that alternative materials could be considered; but bearing in mind that doing so may lead to a shifting of environmental burdens to other areas of concern. Bio-foam from expanded PLA was identified as the most favourable option among the alternatives (second best option following polystyrene); but requires industrial composting infrastructure. Other alternatives such as coated paper, bagasse, and certain bioplastics demonstrated lower material pollution and persistence, compared to Polystyrene Home compostable paper and bioplastics have the benefit of a higher degree of degradability as compared to the conventional plastics. Although paper and bagasse can be composted, their common polyethylene coating hinders biodegradation. Bioplastics requiring industrial composting are less suitable, due to the current lack of industrial composting infrastructure in South Africa. Furthermore, to improve composting of compostable bioplastics, there needs to be effective separation at source, which can be enhanced with distinct product codes and labelling. Legislation could be used to ensure that the effective treatment of biodegradable compostable plastics is accommodated, alongside the recycling of conventional plastics.

Polystyrene cups and clamshells were found to be more affordable than alternatives. At the same time, the low price of polystyrene is one of the factors leading to its high rate of leakage into the environment and material pollution since there is little value in recovery of the material and the low-density of polystyrene makes it likely to disperse.

Finally, compared to polystyrene, there are a greater number of jobs in the bio-plastics value chain, and a switch from plastic to compostable alternatives such as paper, bagasse and bioplastics would therefore be expected to increase jobs and reduce unemployment, by an estimated 20%.

In conclusion, transitioning from polystyrene to compostable alternatives can significantly reduce plastic pollution and the associated impacts. However, doing so will lead to a shifting of environmental burdens to other areas of concern, and a higher overall environmental impact.

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Appendix A – Mid- and End-point LCIA Results

This section presents the ReciPe 2016 LCIA results comparison regarding the Contribution Analysis, for all the mid- and end-point indicators of the RecCiPe2016 LCIA method as described in **Table 4.**

End-point Indicators LCIA Results

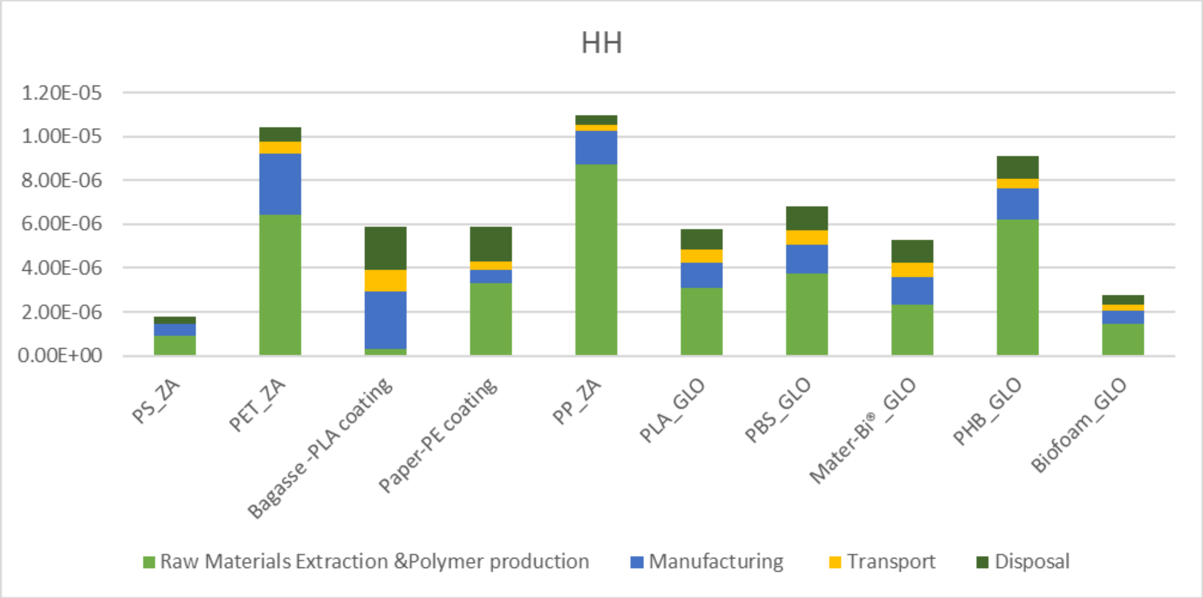

Figure 19: Human Health LCIA results comparison

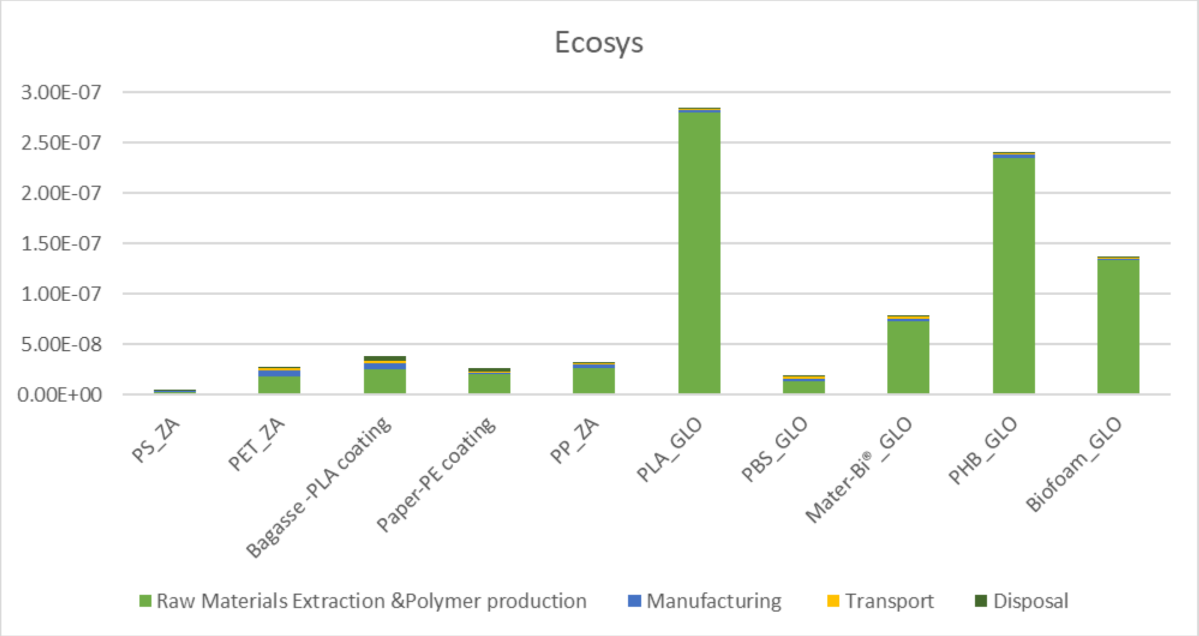

Figure 20: Ecosystems LCIA results comparison

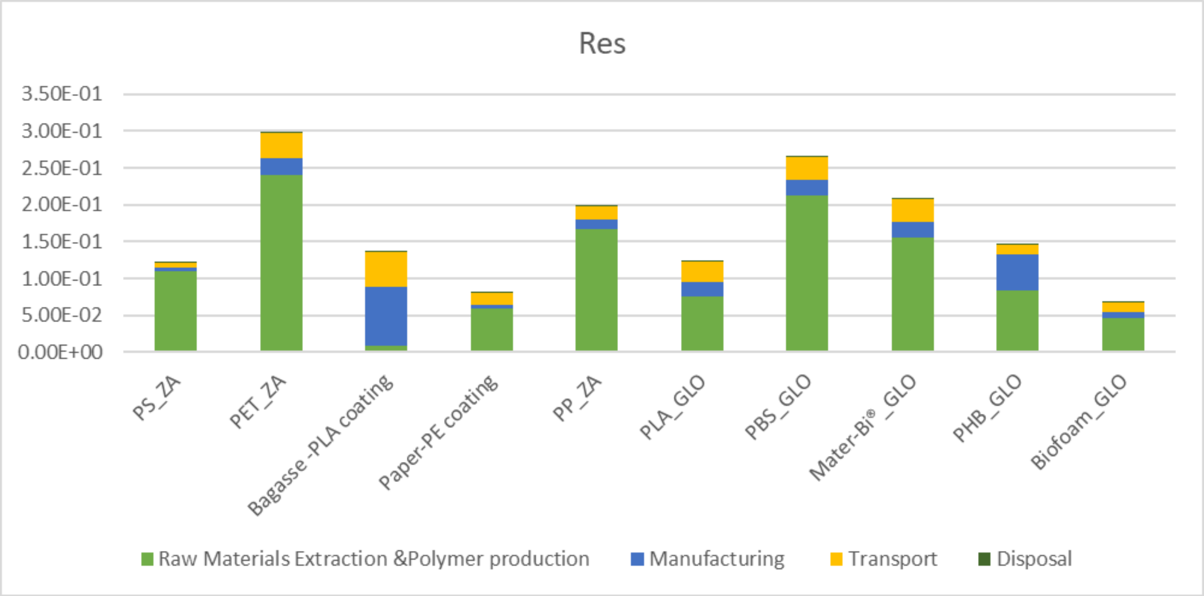

Figure 21: Resources LCIA results comparison

Mid-point Indicators LCIA Results

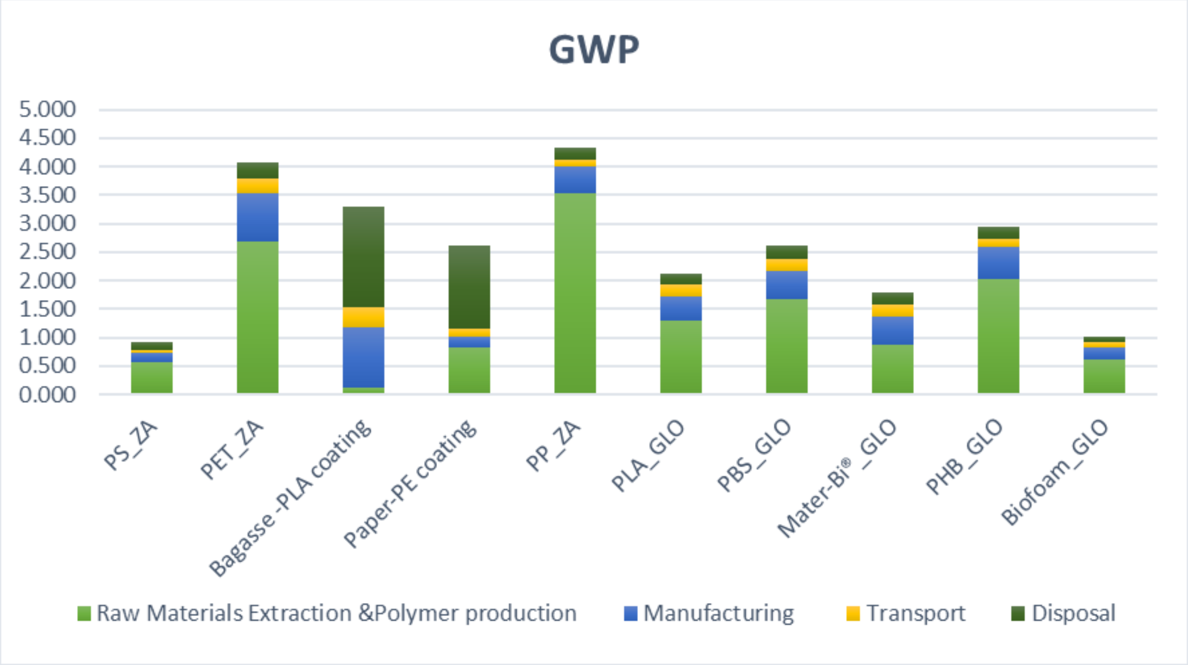

Figure 22: Global Warming Potential LCIA results comparison

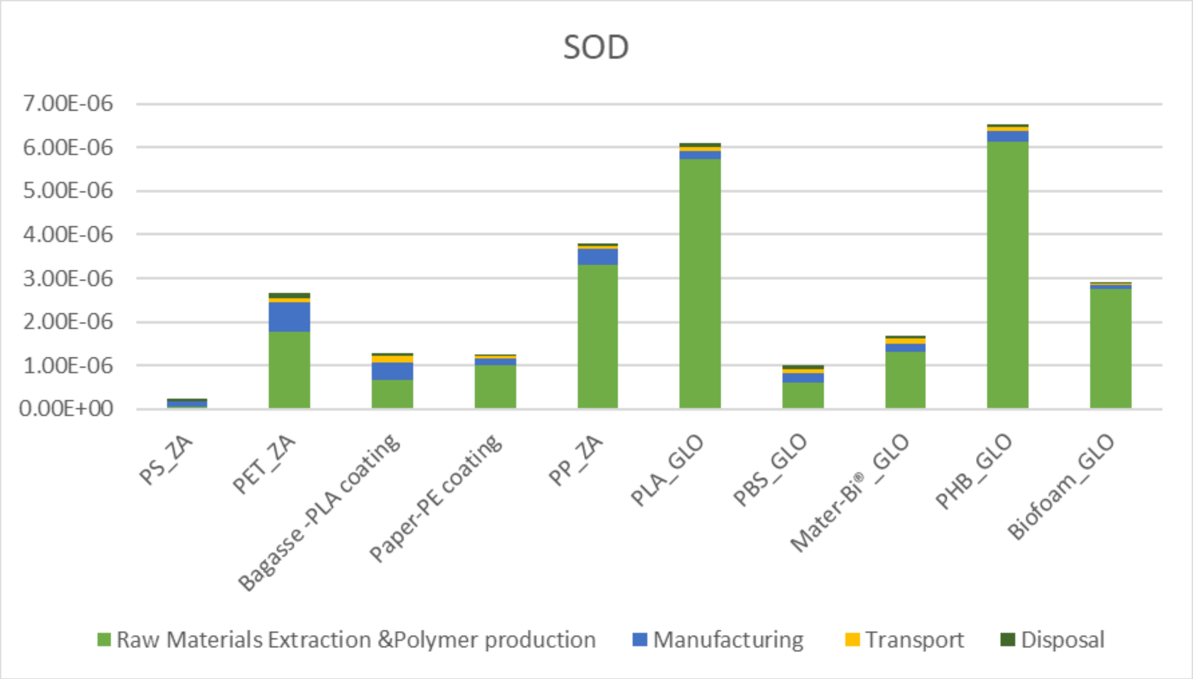

Figure 23: Stratospheric Ozone Depletion LCIA results comparison

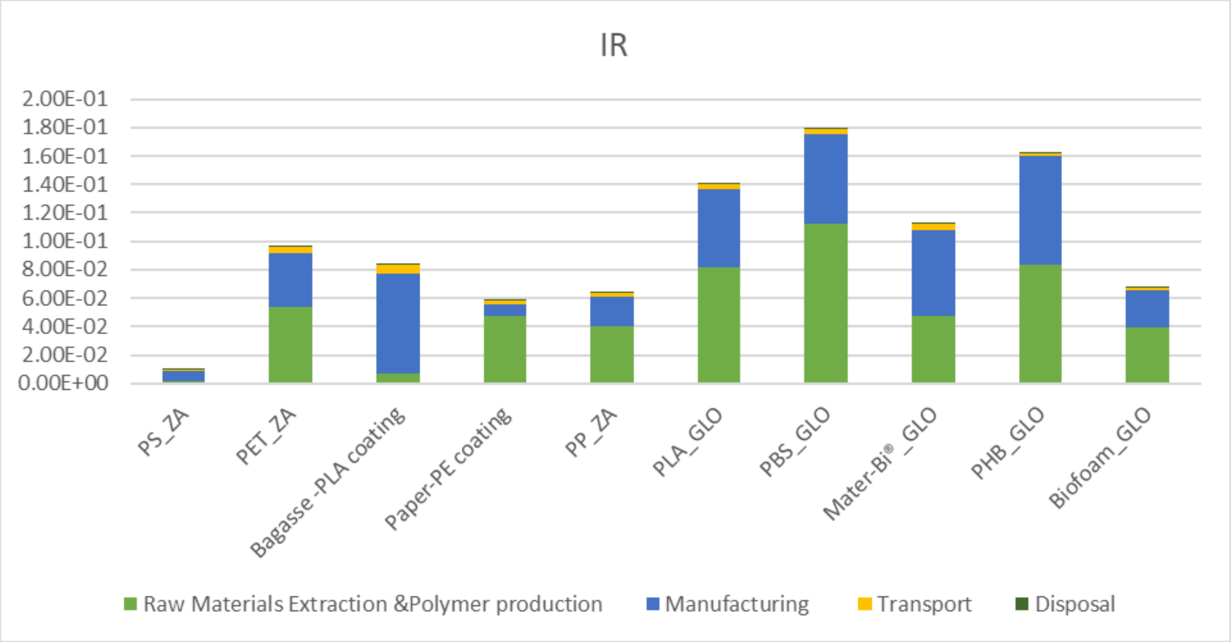

Figure 24: Ionizing Radiation LCIA results comparison

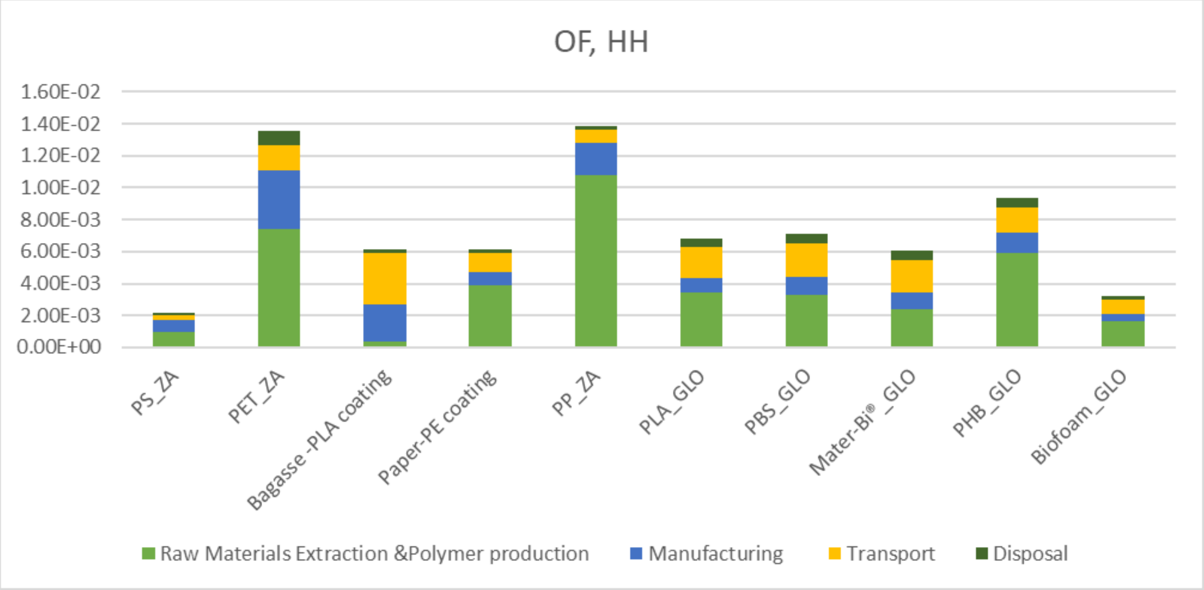

Figure 25: Ozone Formation, Human Health LCIA results comparison

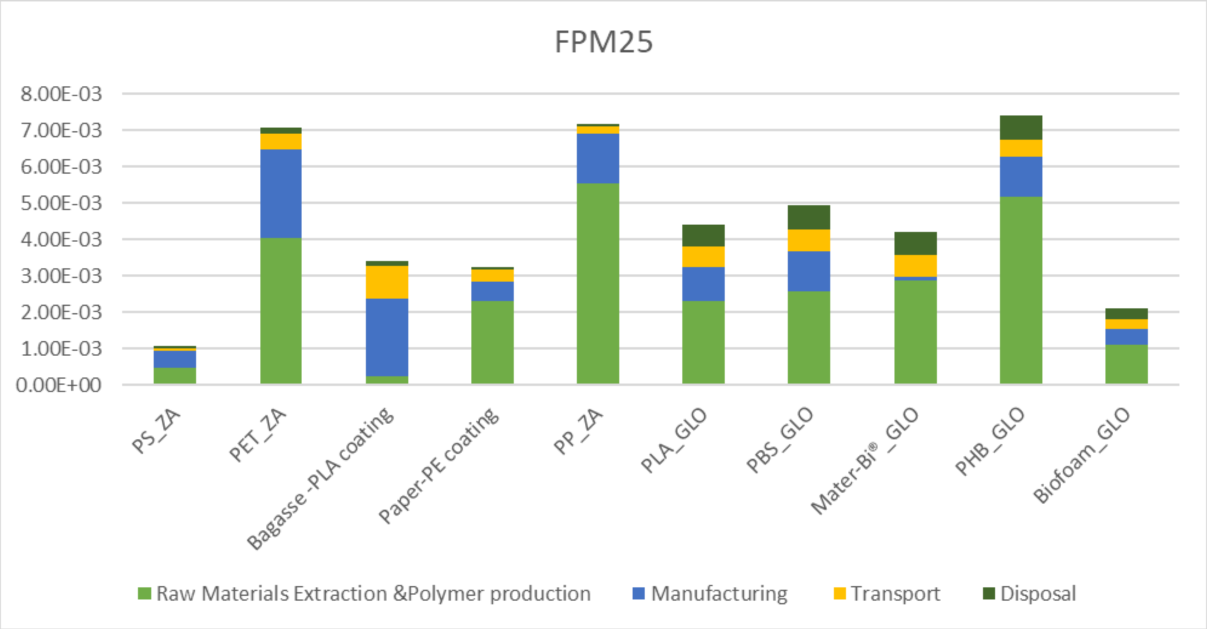

Figure 26: Fine Particulate Matter LCIA results comparison

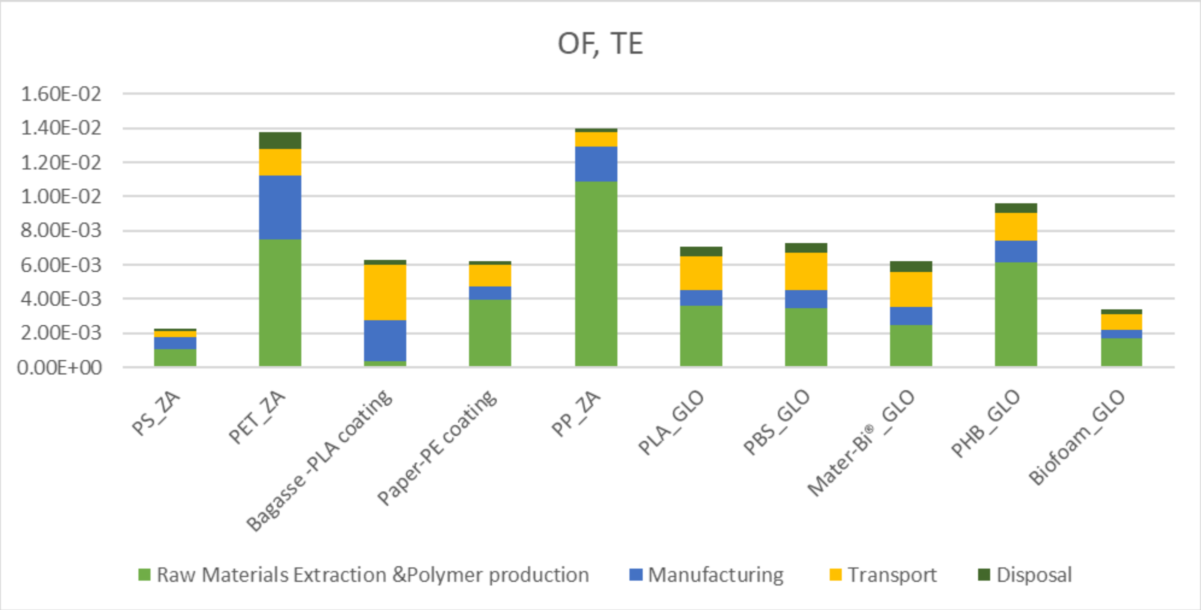

Figure 27: Ozone Formation, Terrestrial Ecosystem LCIA results comparison

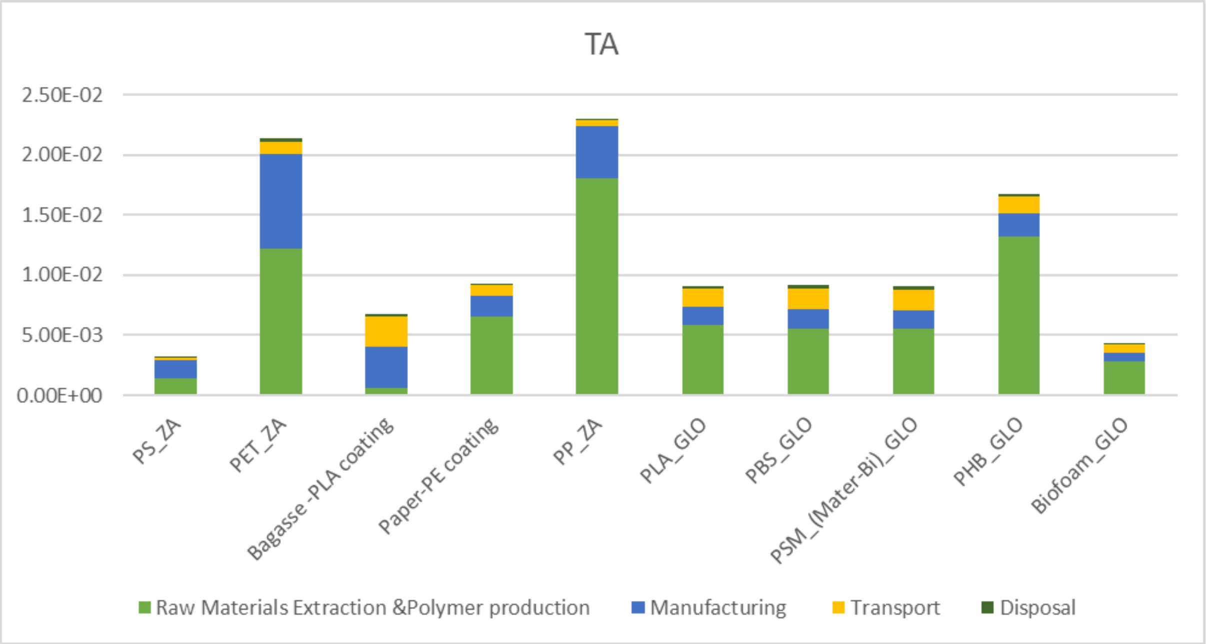

Figure 28: Terrestrial Acidification LCIA results comparison

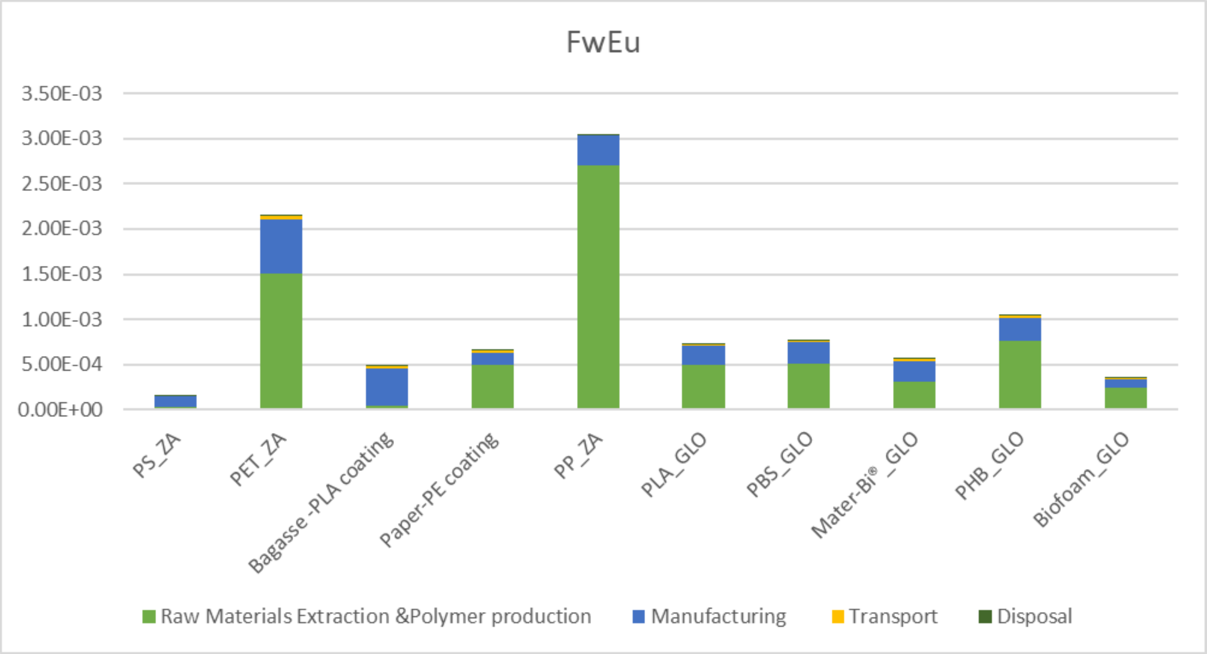

Figure 29: Freshwater Eutrophication LCIA results comparison

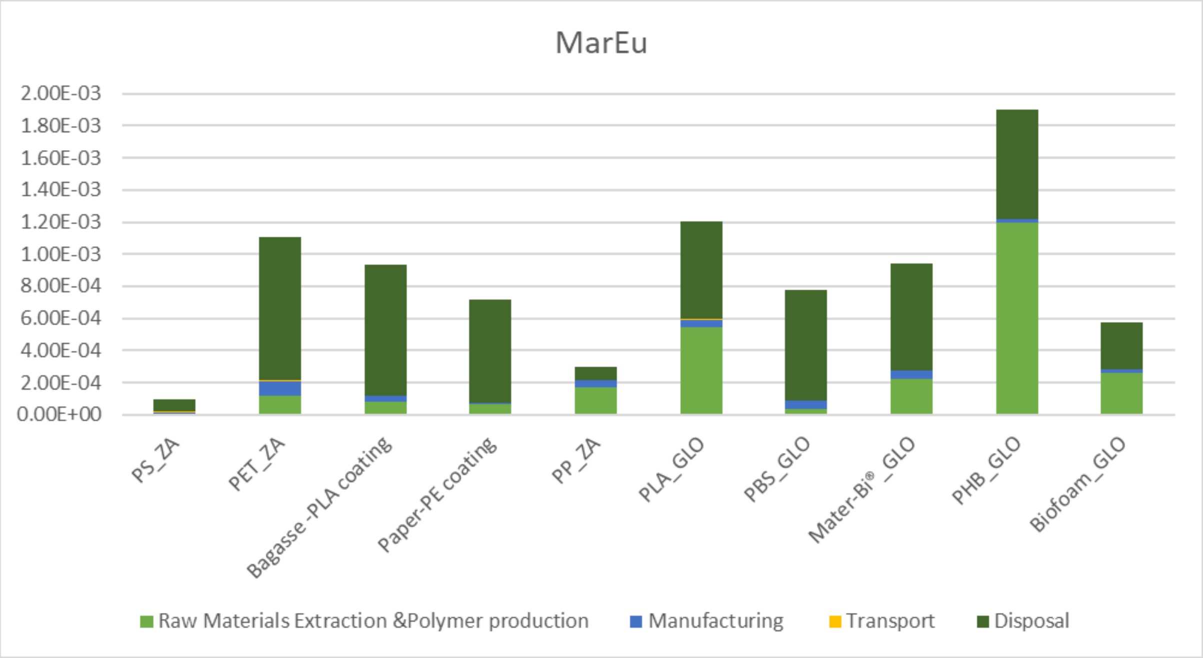

Figure 30: Marine Eutrophication LCIA results comparison

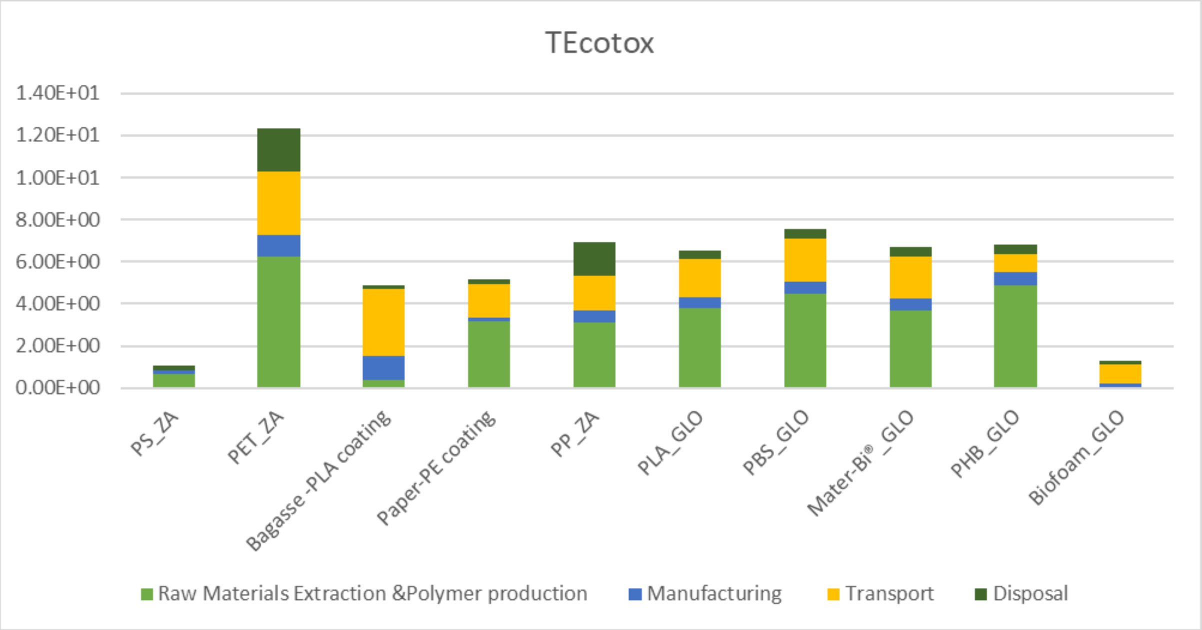

Figure 31: Terrestrial Ecotoxicity LCIA results comparison

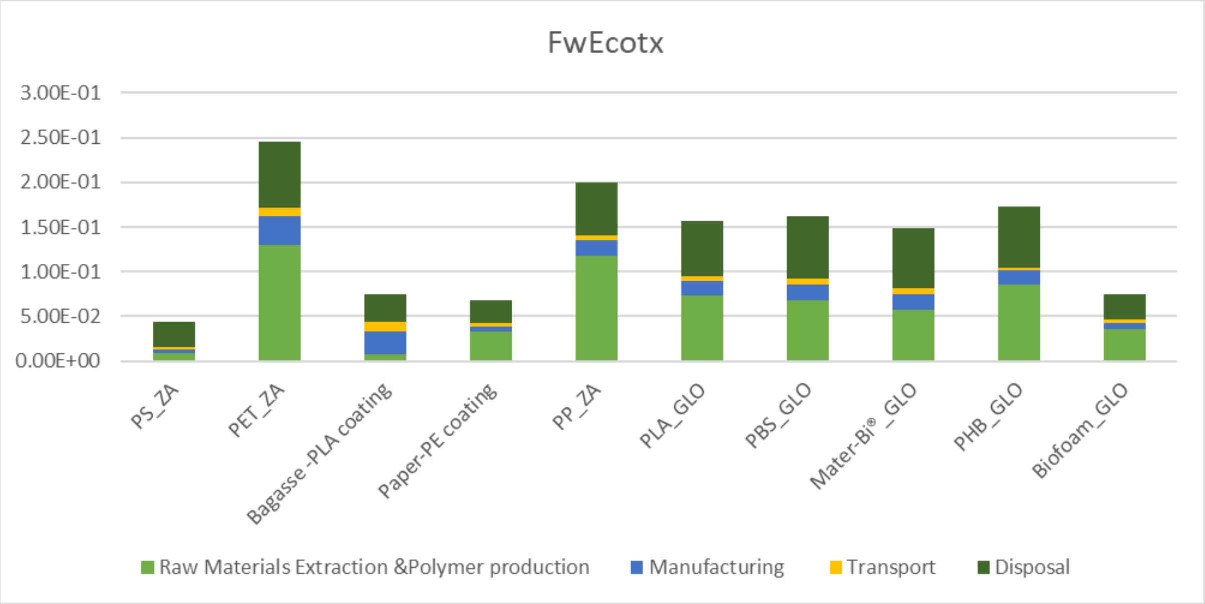

Figure 32: Freshwater Ecotoxicity LCIA results comparison

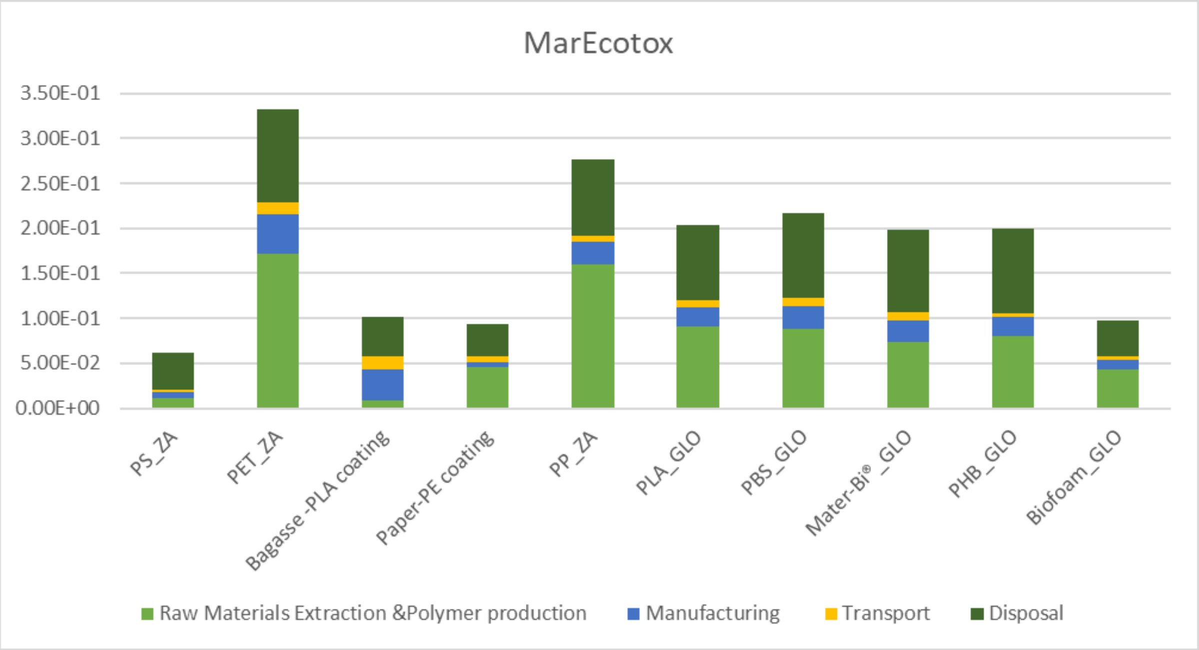

Figure 33:Marine Ecotoxicity LCIA results comparison

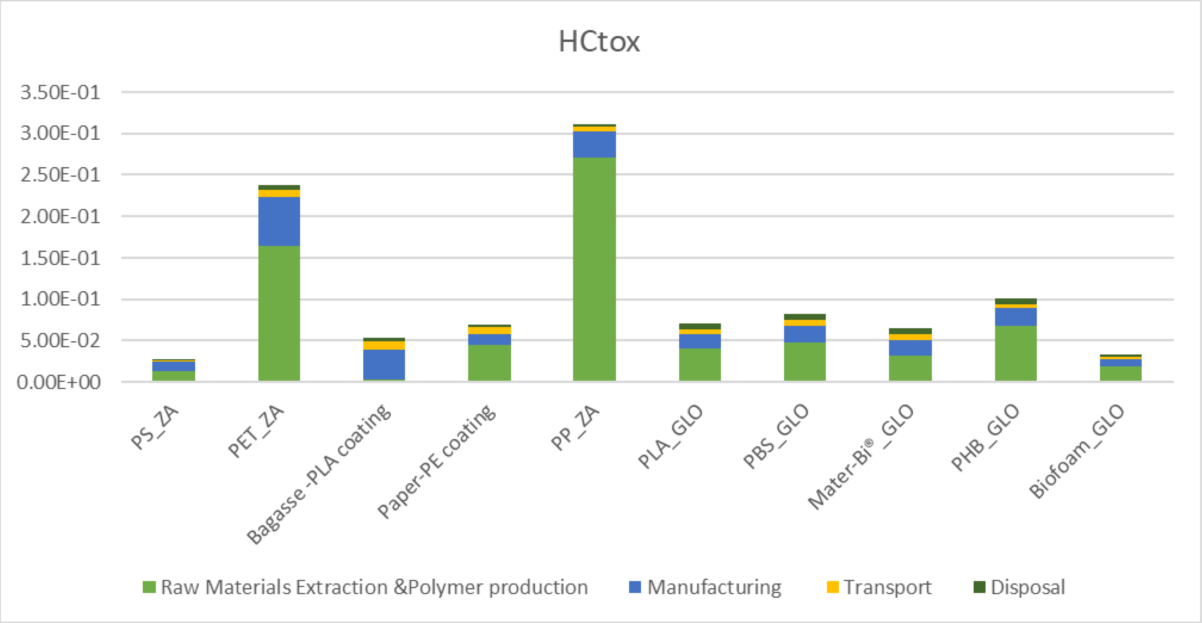

Figure 34: Human Carcinogenic Toxicity LCIA results comparison

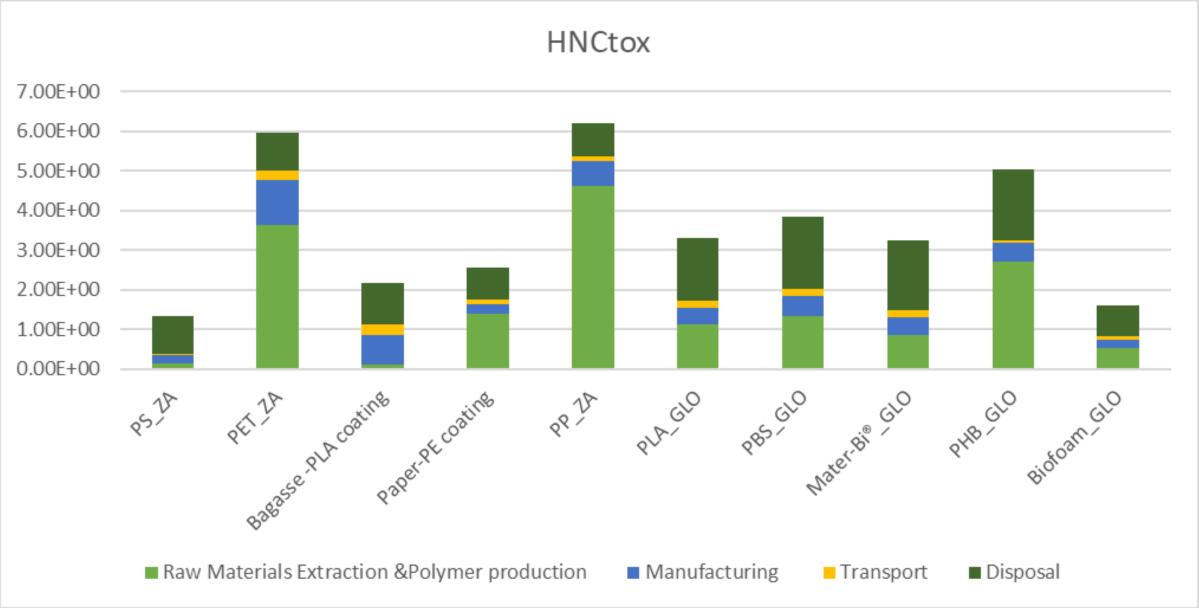

Figure 35: Human Non-Carcinogenic Toxicity LCIA results comparison

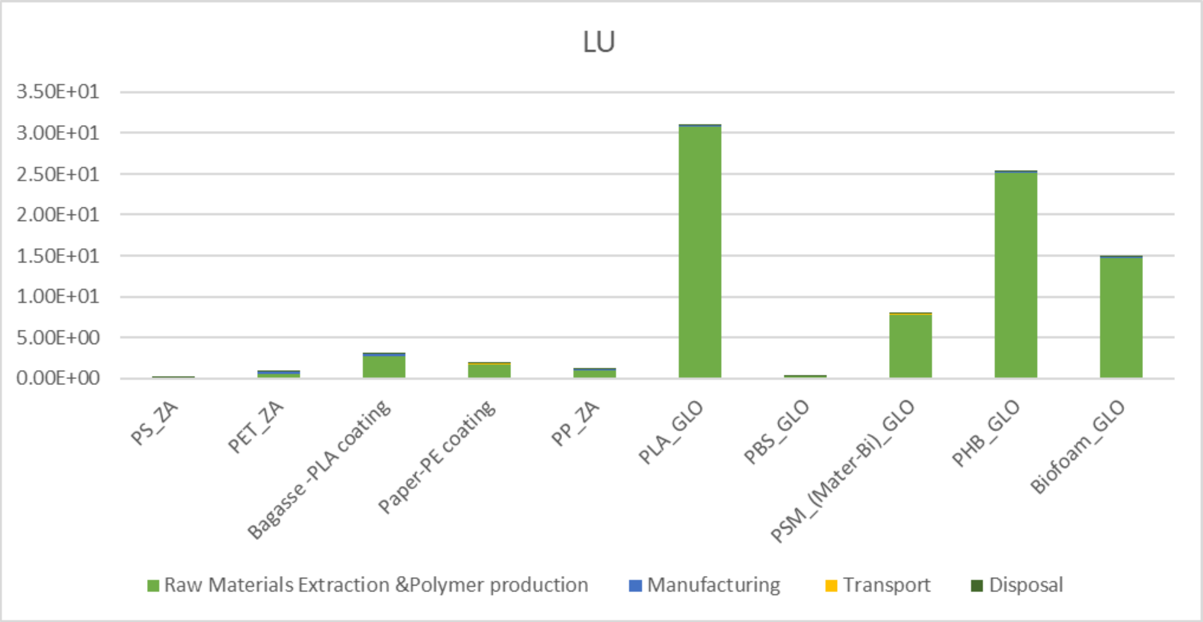

Figure 36: Land Use LCIA results comparison

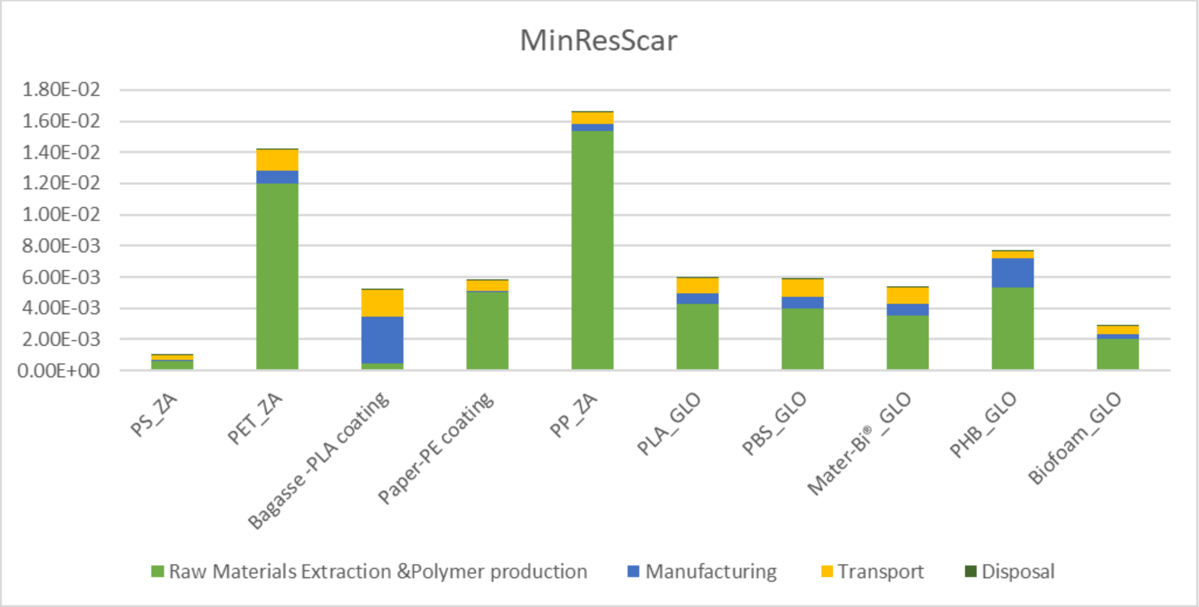

Figure 37: Mineral Resource Scarcity LCIA results comparison

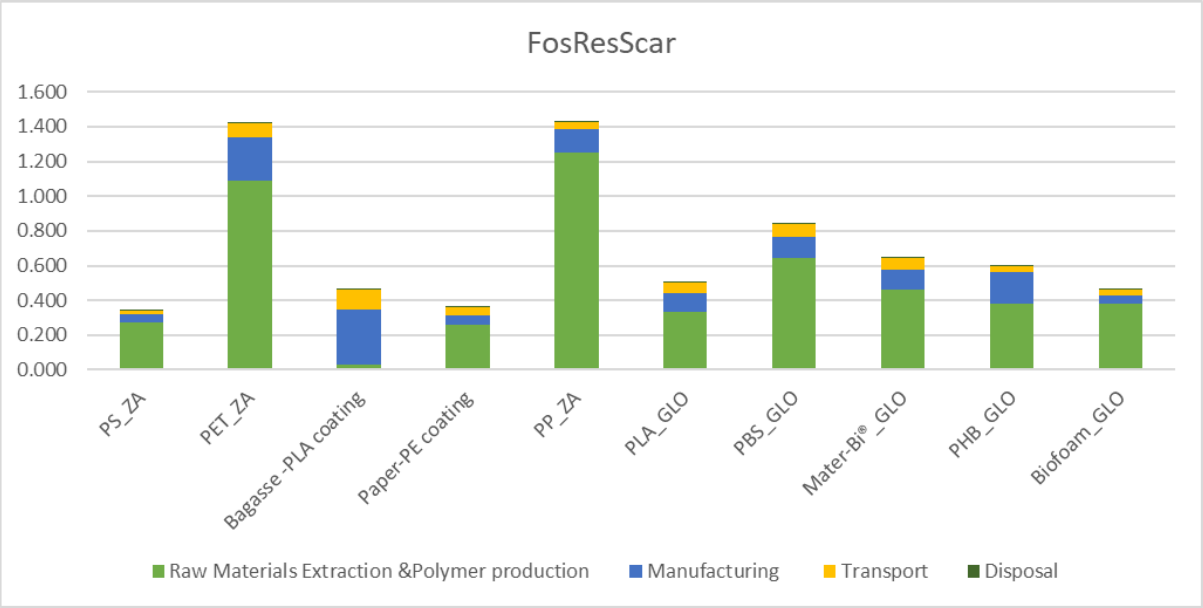

Figure 38: Fossil Resource Scarcity LCIA results comparison

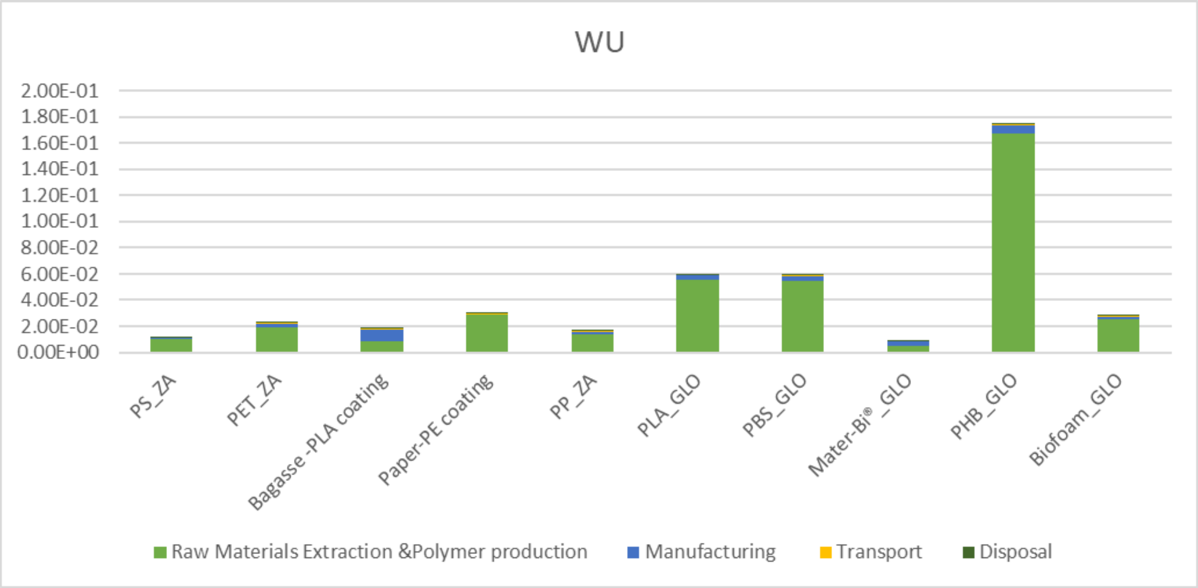

Figure 39: Water Use LCIA results comparison

Appendix B - Mid- and End-point LCA Results for the Scenario Analysis

This section presents the details of the Scenario Analysis at Mid- and End-point level obtained with the ReCiPe 2016 LCIA method.

End-Point LCIA Results

Table 14: ReCiPe 2016 End-point LCIA results comparing Local production VS Imports of finished goods

	Unit	**PS**	**PET**	**Bagasse**	**Paper**	**PP**	**PLA**	**PBS**	**Mater-Bi®**	**Bio-foam (expanded PLA)**	**PHB**
ZA Production	DALY	**2.9e-06**	1.1e-05	6.9e-06	5.3e-06	1.1e-05	6.7e-06	8e-06	7e-06	3.8e-06	1.1e-05
	%	+49.5%		+17.3%			32.9%	+17.7%	+32.5%	35.7%	+19.5%
	Species*yr	**7e-09**	2.7e-08	5.5e-08	2.7e-08	3.1e-08	5.1e-07	1.8e-08	1.7e-07	2.4e-07	2.8e-07
	%	+61.9%		+42.3%			+78.5%	+29.3%	+122.6%	+77.9%	+17.1%
	USD 2013	0.123	0.33	0.12	0.08	0.198	0.13	0.25	0.12	**0.06**	0.13
	%	+0.82%		-13.1%			-9.1%	-4.5%	-3.9%	-9.2%	-14.3%
ZA Manufacturing Only	DALY	**1.9e-06**	7.6e-06	7.4e-06	5.3e-06	3.4e-06	6.7e-06	7.8e-06	6.3e-06	3.2e-06	1.03e-05
	%		-26.7%	+24.6%	0.6%	-68.7%	+15.8%	+15.2%	+18.7%	+15.5%	+12.9%
	Species*yr	**4.3e-09**	1.8e-08	4.3e-08	2.6e-08	8.2e-09	2.9e-07	1.7e-08	8.1e-08	1.4e-08	2.4e-07
	%		-34.1%	+13.3%	-4.4%	-73.7%	+1.1%	+23.6%	+4.1%	+1.5%	+1.7%
	USD 2013	0.122	0.38	0.13	0.10	0.195	0.14	0.26	0.21	**0.07**	0.15

	%		+15.4%	-4.4%	+26.8%	-1.5%	-2.1%	-0.8%	-0.9%	-1.6%	-1.4%
GLO Production	DALY	**1.7e-06**	6.4e-06	5.8e-06	4.8e-06	2.8e-06	5.8e-06	6.8e-06	5.3e-06	2.8e-06	9.1e-06
	%	-12.5%	-38.5%		-9.3%	-74.8%					
	Species*yr	**3.6e-09**	1.4e-08	3.9e-08	2.5e-08	6.1e-09	2.8e-07	1.4e-08	7.8e-08	1.4e-07	2.4e-07
	%	-18.0%	-48.4%		-9.9%	-80.5%					
	USD 2013	0.112	0.38	0.14	0.09	0.197	0.14	0.27	0.21	**0.07**	0.15
	%	-8.2%	+16.3%		+15.5%	-0.51%					

Table 15: ReCiPe 2016 End-point LCIA results comparing impact of increasing recycling rates

		PS			PET			Bagasse			Paper			PP			PLA			PBS			PSM (Mater-Bi®)			Bio-foam (expanded PLA)			PHB		
BAU	***Indicator (Units*)***	***HH***	***ES***	***RES***	***HH***	***ES***	***RES***	***HH***	***ES***	***RES***	***HH***	***ES***	***RES***	***HH***	***ES***	***RES***	***HH***	***ES***	***RES***	***HH***	***ES***	***RES***	***HH***	***ES***	***RES***	***HH***	***ES***	***RES***	***HH***	***ES***	***RES***
	Value	**1.9e-06**	**4.3e-09**	**0.12**	**1.0e-05**	**2.7e-08**	**0.33**	**5.9e-06**	**3.8e-08**	**0.14**	**5.3e-06**	**2.7e-08**	**0.08**	**1.1e-05**	**3.1e-08**	**0.19**	**5.8e-06**	**2.8e-07**	**0.14**	**6.9e-06**	**1.4e-08**	**0.27**	**5.3e-06**	**7.8e-08**	**0.21**	**2.8e-06**	**1.4e-07**	**0.07**	**9.1e-06**	**2.4e-07**	**0.15**
Mechanical Recycling	***Y1***	-14.6%	-12.2%	-27.0%	-19.3%	-20.1%	-27.6%				-8.9%	-11.0%	-2.8%	-23.4%	-24.0%	-24.7%															
	Y2	-16.7%	-14.1%	-31.6%	-22.6%	-23.4%	-32.2%				-10.4%	-12.9%	-3.2%	-27.3%	-28.1%	-28.8%															
	Y3	-19.3%	-16.2%	-36.1%	-25.8%	-26.7%	-36.8%				-11.7%	-14.7%	-3.7%	-31.1%	-31.9%	-32.8%															
	Y4	-21.9%	-18.2%	-40.7%	-29.0%	-30.0%	-41.4%				-13.3%	-16.5%	-4.2%	-35.0%	-36.1%	-36.9%															
	Y5	-24.0%	-20.3%	-45.3%	-32.2%	-33.7%	-46.0%				-14.8%	-18.4%	-4.6%	-38.9%	-39.9%	-40.9%															
Organic Recycling (Industrial Composting)	***Y1***							-5.3%	-15.1%	-0.7%							-0.9%	-0.4%	-0.7%	-0.9%	-8.6%	0.0%	-1.1%	-1.4%	0.0%	-1.1%	0.0%	-0.1%	-0.5%	-0.4%	0.0%
	Y2							-8.6%	-25.1%	-0.7%							-2.6%	-1.1%	-0.7%	-2.6%	-25.0%	0.0%	-3.2%	-4.2%	0.0%	-2.9%	-0.7%	-0.3%	-1.9%	-1.2%	-0.7%
	Y3							-17.1%	-49.9%	-1.5%							-7.1%	-2.8%	-0.7%	-6.9%	-66.4%	-0.4%	-8.7%	-11.5%	-0.5%	-7.2%	-2.9%	-0.7%	-5.0%	-3.8%	-0.7%
	Y4							-22.2%	-65.0%	-2.2%							-9.7%	-3.9%	-1.4%	-9.6%	-91.4%	-0.4%	-11.9%	-15.9%	-0.5%	-9.7%	-3.7%	-0.9%	-6.9%	-5.0%	-1.4%
	Y5							-27.5%	-79.9%	-2.2%							-12.5%	-4.9%	-1.4%	-12.1%	-116.4%	-0.8%	-14.9%	-20.1%	-1.0%	-12.6%	-5.1%	-1.2%	-8.8%	-6.7%	-1.4%

*** HH (Human Health): DALY, ES (Ecosystems): species*yr; RES (Resources): USD2013**

Table 16: ReCiPe 2016 End-point LCIA results comparing the impact of different coating materials on overall LC and on coating production and meal-kit disposal

Meal-kit material type	**Coating type (3-5% by mass)**	**Human Health (DALY)**						**Ecosystems (species*yr)**						**Resources (USD 2013)**					
		Overall LC		Coating Production		Disposal		Overall LC		Coating Production		Disposal		Overall LC		Coating Production		Disposal	
		DALY	%	DALY	%	DALY	%	species*yr	%	species*yr	%	species*yr	%	UDS 2013	%	UDS 2013	%	UDS 2013	%
Bagasse	**PLA (BAU)**	5.9E-06		2.7E-07		1.98E-06		3.8E-08		2.5E-08		5.09E-09	-3.2%	1.4E-01		8.1E-03		1.24E-03	
	PE (3% by mass)	5.7E-06	-2.9%	1.1E-07	-59.2%	1.97E-06	-0.5%	1.4E-08	-64.0%	2.7E-10	-98.9%	5.18E-09	1.8%	1.4E-01	3.6%	1.4E-02	73.5%	1.24E-03	
	PBAT	6.1E-06	3.2%	4.6E-07	73.0%	1.98E-06		1.5E-08	-61.9%	1.2E-09	-95.3%	5.09E-09	0.0%	1.5E-01	7.3%	1.9E-02	130.5%	1.24E-03	
	PBS	5.9E-06	0.3%	2.9E-07	9.7%	1.98E-06		1.4E-08	-63.2%	7.1E-10	-97.1%	5.09E-09	0.0%	1.5E-01	5.8%	1.7E-02	105.7%	1.24E-03	
	PHB	6.1E-06	3.9%	5.0E-07	85.4%	1.98E-06		3.2E-08	-16.2%	1.9E-08	-24.9%	5.09E-09	0.0%	1.4E-01	-1.5%	6.7E-03	-17.2%	1.24E-03	
	Mater-Bi®	5.8E-06	-1.2%	2.0E-07	-24.0%	1.98E-06		1.9E-08	-49.6%	6.0E-09	-76.1%	5.09E-09	0.0%	1.4E-01	2.9%	1.2E-02	49.9%	1.24E-03	
Paper	PLA	5.4E-06	1.5%	2.2E-07	236.9%	1.6E-06	-0.6%	4.7E-08	72.1%	2.0E-08	11491%	4.1E-09	-2.4%	7.2E-02	-7.4%	6.6E-03	-40.5%	9.9E-04	-0.4%
	PE (BAU - 3% by mass)	5.3E-06		6.5E-08		1.6E-06		2.7E-08		1.8E-10		4.2E-09		7.8E-02		1.1E-02		1.0E-03	
	PBAT	5.5E-06	4.5%	3.8E-07	483.1%	1.6E-06	-0.6%	2.7E-08	0.4%	9.6E-10	444%	4.1E-09	-2.4%	8.1E-02	3.6%	1.5E-02	36.9%	9.9E-04	-0.4%
	PBS	5.4E-06	2.1%	2.4E-07	270.8%	1.6E-06	-0.6%	2.7E-08	0.7%	5.8E-10	231%	4.1E-09	-2.4%	7.9E-02	1.5%	1.4E-02	22.5%	9.9E-04	-0.4%
	PHB	5.6E-06	5.1%	4.1E-07	524.6%	1.6E-06	-0.6%	4.2E-08	53.3%	1.5E-08	8593%	4.1E-09	-2.4%	7.1E-02	-8.8%	5.5E-03	-50.6%	9.9E-04	-0.4%
	Mater-Bi®	5.3E-06	0.6%	1.7E-07	155.4%	1.6E-06	-0.6%	3.1E-08	14.7%	4.9E-09	2667%	4.1E-09	-2.4%	7.6E-02	-3.2%	9.9E-03	-10.9%	9.9E-04	-0.4%

Mid-Point LCIA Results

Table 17 presents the ReciPe 2016 LCIA Mid-point results when comparing locally produced meal-kit (including of raw material production), with manufacturing of products in South Africa from imports of raw materials, with imports of finished goods. BAU Scenario Results for each meal-kit material option are in **BOLD RED font**. **BAU scenarios** are those whom the percentages compare with.

Table 17: ReCiPe 2016 Mid-Point Results Comparison for Local production Vs Manufacturing VS Imports of finished goods

ZA Production																																				
	GWP		SPD		IR		OF, HH		FPM25		OF, TE,		TA		FwEu		MarEu		TEcotox		FwEcotoc		MarEcotox		HCTox		HNCTox		LU		MRS		FRS		WU	
	Kg CO_2 eq	%	Kg CFC11 eq	%	Kg Co60 eq	%	Kg NOx eq	%	Kg PM2.5 eq	%	Kg NOx eq	%	Kg SO_2 eq	%	Kg P eq	%	Kg N eq	%	Kg 1,4DCB eq	%	Kg 1,4DCB eq	%	Kg 1,4DCB eq	%	Kg 1,4DCB eq	%	Kg 1,4DCB eq	%	m2a crop eq	%	Kg Cu eq	%	Kg oil eq	%	m^3	%
PS	1.25	39.4%	5/0E-07	117.0%	2.5E-02	156.4%	4.3E-03	100.9%	2.0E-03	94.3%	4.8E-03	113.7%	6.4E-03	100.6%	4.0E-04	161.6%	1.2E-04	33.3%	2.12	25.4%	5.7E-02	28.1%	7.8E-02	27.5%	5.2E-02	84.6%	1.78	33.8%	0.148	147.5%	1.3E-03	28.8%	4.5E-01	32.6%	1.2E-02	10.8%
PET	**4.07**		**2.7E-06**		**9.7E-02**		**1.4E-02**		**7.1E-03**		**1.4E-02**		**2.1E-02**		**2.1E-03**		**1.1E-03**		**12.3**		**2.5E-01**		**3.3E-01**		**2.4E-01**		**5.97**		**0.84**		**1.4E-02**		**1.4E+00**		**2.3E-02**	
Bagasse	3.57	8.2%	1.7E-06	29.9%	6.5E-02	-22.2%	7.7E-03	24.6%	4.2E-03	22.9%	7.8E-03	23.7%	1.3E-02	95.8%	9.5E-04	92.9%	8.6E-04	-8.4%	5.01	2.7%	8.3E-02	10.8%	1.1E-01	12.9%	1.0E-01	88.4%	2.8	28.4%	4.49	52.2%	5.1E-03	-3.4%	5.7E-01	23.3%	3.1E-03	-82.9%
Paper	**2.61**		**1.3E-06**		**6.0E-02**		**6.0E-03**		**3.2E-03**		**6.0E-03**		**9.4E-03**		**6.8E-04**		**7.2E-04**		**4.59**		**6.8E-02**		**9.3E-02**		**6.7E-02**		**2.57**		**1.81**		**5.8E-03**		**3.6E-01**		**3.0E-02**	
PP	**4.32**		**3.8E-06**		**6.4E-02**		**1.4E-02**		**7.2E-03**		**1.4E-02**		**2.3E-02**		**3.1E-03**		**3.0E-04**		**6.92**		**2.0E-01**		**2.8E-01**		**3.1E-01**		**6.2**		**1.13**		**1.7E-02**		**1.4E+00**		**1.6E-02**	
PLA	2.56	20.2%	8.5E-06	39.8%	8.3E-02	-41.1%	1.0E-02	46.4%	6.0E-03	36.8%	1.0E-02	44.7%	1.8E-02	100.4%	1.3E-03	77.9%	1.1E-03	-8.3%	6.9	6.0%	1.8E-01	15.3%	2.4E-01	15.7%	1.3E-01	87.5%	4.56	37.3%	55.4	79.3%	8.7E-03	45.6%	6.7E-01	31.6%	2.1E-02	-62.1%
PBS	2.91	11.5%	1.4E-06	42.0%	1.1E-01	-37.4%	8.8E-03	23.9%	6.1E-03	23.7%	9.0E-03	23.2%	1.5E-02	61.9%	1.1E-03	38.2%	8.1E-04	3.1%	7.63	0.9%	1.7E-01	-71.9%	2.3E-01	7.4%	1.2E-01	45.6%	4.45	15.9%	0.423	56.7%	5.6E-03	-4.8%	9.4E-01	12.2%	5.6E-02	-5.9%
Mater-Bi ®	2.21	23.5%	3.4E-06	103.0%	6.5E-02	-42.3%	9.2E-03	51.4%	5.7E-03	36.0%	9.3E-03	50.2%	1.6E-02	77.2%	9.8E-04	74.6%	8.5E-04	-9.6%	6.51	-2.4%	1.7E-01	10.7%	2.2E-01	11.1%	1.1E-01	66.7%	4.28	31.7%	17.4	121.4%	6.1E-03	13.4%	7.7E-01	19.2%	1.0E-02	17.4%
Bio-foam (expanded PLA)	1.23	20.6%	4.1E-06	39.7%	4.0E-02	-41.2%	4.8E-03	46.2%	2.9E-03	37.0%	4.9E-03	45.0%	8.8E-03	100.5%	6.2E-04	77.6%	5.3E-04	-8.5%	3.31	6.1%	8.7E-02	15.2%	1.1E-01	15.7%	6.3E-02	88.1%	2.18	37.1%	26.5	79.1%	4.2E-03	45.6%	3.2E-01	31.3%	1.0E-02	-62.1%
PHB	3.42	16.7%	6.9E-06	6.3%	8.7E-02	-46.0%	1.2E-02	31.6%	8.9E-03	20.7%	1.3E-02	29.7%	2.6E-02	53.6%	1.6E-03	56.7%	1.8E-03	-4.7%	6.65	-2.1%	2.0E-01	13.3%	2.3E-01	12.5%	1.6E-01	61.4%	6.15	21.8%	29.4	16.2%	7.6E-03	-1.6%	7.6E-01	26.1%	1.9E-01	10.3%
ZA Manufacturing Only																																				
	GWP		SPD		IR		OF, HH		FPM25		OF, TE,		TA		FwEu		MarEu		TEcotox		FwEcotoc		MarEcotox		HCTox		HNCTox		LU		MRS		FRS		WU	
	Kg CO_2 eq	%	Kg CFC11 eq	%	Kg Co60 eq	%	Kg NOx eq	%	Kg PM2.5 eq	%	Kg NOx eq	%	Kg SO_2 eq	%	Kg P eq	%	Kg N eq	%	Kg 1,4DCB eq	%	Kg 1,4DCB eq	%	Kg 1,4DCB eq	%	Kg 1,4DCB eq	%	Kg 1,4DCB eq	%	m2a crop eq	%	Kg Cu eq	%	Kg oil eq	%	m^3	%
PS	**0.897**		**2.3E-07**		**9.8E-03**		**2.1E-03**		**1.1E-03**		**2.3E-03**		**3.2E-03**		**1.5E-04**		**8.9E-05**		**1.69**		**4.4E-02**		**6.1E-02**		**2.8E-02**		**1.33**		**0.0598**		**9.9E-04**		**3.4E-01**		**1.1E-02**	
PET	3.04	-25.3%	1.3E-06	-52.1%	1.0E-01	7.8%	1.1E-02	-22.1%	5.4E-03	-23.7%	1.1E-02	-21.0%	1.5E-02	-30.4%	1.0E-03	-53.4%	1.0E-03	-6.3%	12.1	-1.6%	2.1E-01	-14.7%	2.8E-01	-15.1%	1.3E-01	-46.4%	4.18	-30.0%	0.417	-50.4%	8.9E-03	-37.2%	1.2E+00	-17.6%	2.2E-02	-2.2%
Bagasse	3.66	10.9%	1.8E-06	44.9%	6.9E-02	-17.4%	9.2E-03	49.4%	4.7E-03	38.5%	9.3E-03	48.4%	1.5E-02	118.1%	9.3E-04	89.6%	9.4E-04	0.7%	5.33	9.2%	8.5E-02	13.1%	1.2E-01	13.9%	1.0E-01	86.6%	2.81	28.9%	3.15	6.8%	5.2E-03	-0.8%	5.9E-01	27.0%	1.7E-02	-5.5%
Paper	2.64	1.1%	1.1E-06	-13.4%	5.4E-02	-9.2%	6.6E-03	11.3%	3.3E-03	3.7%	6.7E-03	11.5%	7.8E-03	-16.8%	4.9E-04	-27.5%	7.1E-04	-1.3%	5.43	18.3%	6.4E-02	-5.4%	8.3E-02	-10.7%	5.0E-02	-25.5%	2.32	-9.7%	1.72	-5.0%	6.3E-03	9.3%	3.5E-01	-2.0%	3.1E-02	0.3%
PP	1.52	-64.8%	6.3E-07	-83.5%	3.8E-02	-40.3%	5.0E-03	-63.8%	2.5E-03	-64.6%	5.1E-03	-63.1%	7.4E-03	-67.8%	4.7E-04	-84.7%	1.4E-04	-52.0%	4.81	-30.5%	1.0E-01	-48.7%	1.4E-01	-48.6%	5.8E-02	-81.2%	1.94	-68.7%	0.186	-83.5%	3.0E-03	-82.2%	6.9E-01	-51.6%	8.0E-03	-50.1%
PLA	2.33	9.4%	6.4E-06	5.1%	1.1E-01	-19.3%	8.6E-03	26.6%	5.3E-03	19.5%	8.9E-03	25.5%	1.4E-02	49.0%	9.6E-04	32.6%	1.2E-03	1.7%	6.75	3.7%	1.7E-01	5.1%	2.2E-01	5.4%	9.7E-02	37.2%	3.73	12.3%	31	0.3%	5.9E-03	-0.7%	5.8E-01	15.2%	5.5E-02	-2.0%
PBS	2.83	8.4%	1.4E-06	35.0%	1.5E-01	-17.3%	9.2E-03	28.9%	5.9E-03	19.8%	9.4E-03	28.1%	1.4E-02	55.4%	1.0E-03	30.7%	8.0E-04	2.7%	7.84	3.7%	1.7E-01	-72.3%	2.3E-01	6.0%	1.1E-01	35.9%	4.31	12.2%	0.392	45.2%	5.8E-03	-0.7%	9.3E-01	10.3%	5.7E-02	-3.9%
Mater-Bi ®	2.01	12.3%	2.0E-06	20.1%	8.2E-02	-26.6%	8.1E-03	32.8%	5.2E-03	22.3%	8.2E-03	31.8%	1.4E-02	53.9%	8.2E-04	46.4%	9.7E-04	2.1%	6.94	4.0%	1.6E-01	6.0%	2.1E-01	6.6%	9.4E-02	44.0%	3.7	13.8%	7.98	1.5%	5.3E-03	-0.7%	7.3E-01	13.0%	7.6E-03	-14.1%
Bio-foam (expanded PLA)	1.12	9.8%	3.1E-06	4.8%	5.4E-02	-19.3%	4.1E-03	26.3%	2.5E-03	19.4%	4.2E-03	25.4%	6.5E-03	48.4%	4.6E-04	32.5%	5.9E-04	1.6%	3.24	3.8%	7.9E-02	5.2%	1.0E-01	5.4%	4.6E-02	37.4%	1.79	12.6%	14.9	0.7%	2.8E-03	-0.7%	2.8E-01	14.8%	2.6E-02	-1.9%
PHB	3.19	8.9%	6.9E-06	5.8%	1.2E-01	-25.9%	1.2E-02	23.0%	8.5E-03	15.0%	1.2E-02	22.4%	2.2E-02	31.0%	1.3E-03	25.0%	1.9E-03	1.1%	7.12	4.9%	1.8E-01	5.2%	2.1E-01	6.0%	1.3E-01	29.7%	5.52	9.3%	25.4	0.4%	7.7E-03	0.1%	6.9E-01	15.5%	1.7E-01	-0.6%
Global Production (and Import of finished goods)																																				
	GWP		SPD		IR		OF, HH		FPM25		OF, TE,		TA		FwEu		MarEu		TEcotox		FwEcotoc		MarEcotox		HCTox		HNCTox		LU		MRS		FRS		WU	
	Kg CO_2 eq	%	Kg CFC11 eq	%	Kg Co60 eq	%	Kg NOx eq	%	Kg PM2.5 eq	%	Kg NOx eq	%	Kg SO_2 eq	%	Kg P eq	%	Kg N eq	%	Kg 1,4DCB eq	%	Kg 1,4DCB eq	%	Kg 1,4DCB eq	%	Kg 1,4DCB eq	%	Kg 1,4DCB eq	%	m2a crop eq	%	Kg Cu eq	%	Kg oil eq	%	m^3	%
PS	0.871	-2.9%	1.6E-07	-31.3%	1.2E-02	23.1%	2.0E-03	-6.1%	9.6E-04	-8.9%	2.1E-03	-5.8%	2.4E-03	-26.0%	8.9E-05	-41.1%	8.6-05	-3.6%	1.66	-1.8%	4.2E-02	-4.1%	5.9E-02	-4.3%	2.2E-02	-22.9%	1.23	-7.5%	0.0324	-45.8%	1.0E-03	4.4%	3.0E-01	-4.5%	1.0E-02	2.1%
PET	2.77	-31.9%	8.6E-07	-67.7%	1.4E-01	46.1%	8.2E-03	-39.8%	4.2E-03	-40.1%	8.6E-03	-37.4%	8.9E-03	-58.5%	6.8E-04	-68.3%	1.0E-03	-8.1%	11.8	-4.1%	2.0E-01	-19.2%	2.7E-01	-19.6%	9.1E-02	-61.5%	3.62	-39.4%	0.271	-67.7%	9.0E-03	-36.8%	1.1E+00	-24.6%	2.4E-02	4.9%
Bagasse	**3.3**		**1.3E-06**		**8.3E-02**		**6.2E-03**		**3.4E-03**		**6.3E-03**		**6.7E-03**		**4.9E-04**		**9.3E-04**		**4.88**		**7.5E-02**		**1.0E-01**		**5.4E-02**		**2.18**		**2.95**		**5.2E-03**		**4.6E-01**		**1.8E-02**	
Paper	2.5	-4.2%	9.7E-07	-24.0%	6.0E-02	0.5%	5.2E-03	-13.1%	2.8E-03	-12.1%	5.2E-03	-13.0%	5.7E-03	-39.1%	4.1E-04	-39.9%	7.1E-04	-1.9%	4.47	-2.6%	6.1E-02	-10.1%	8.3E-02	-10.7%	3.9E-02	-40.9%	2.15	-16.3%	1.67	-7.7%	6.1E-03	4.7%	3.0E-01	-15.4%	3.1E-02	0.7%
PP	1.37	-68.3%	4.0E-07	-89.4%	5.8E-02	-8.9%	3.7E-03	-73.6%	1.9E-03	-73.5%	3.8E-03	-72.7%	4.1E-03	-82.1%	2.9E-04	-90.4%	1.3E-04	-56.7%	4.63	-33.1%	9.6E-02	-51.7%	1.3E-01	-51.8%	3.9E-02	-87.5%	1.63	-73.7%	0.106	-90.6%	3.0E-03	-82.0%	6.4E-01	-55.6%	8.9E-03	-44.8%
PLA	**2.13**		**6.1E-06**		**1.4E-01**		**6.8E-03**		**4.4E-03**		**7.1E-03**		**9.1E-03**		**7.3E-04**		**1.2E-03**		**6.51**		**1.6E-01**		**2.0E-01**		**7.0E-02**		**3.32**		**30.9**		**5.9E-03**		**5.1E-01**		**5.6E-02**	
PBS	**2.61**		**1.0E-06**		**1.8E-01**		**7.1E-03**		**4.9E-03**		**7.3E-03**		**9.1E-03**		**8.0E-04**		**7.8E-04**		**7.56**		**6.2E-01**		**2.2E-01**		**8.2E-02**		**3.84**		**0.27**		**5.8E-03**		**8.4E-01**		**6.0E-02**	
Mater-Bi ®	**1.79**		**1.7E-06**		**1.1E-01**		**6.1E-03**		**4.2E-03**		**6.2E-03**		**9.0E-03**		**5.6E-04**		**9.5E-04**		**6.67**		**1.5E-01**		**2.0E-01**		**6.5E-02**		**3.25**		**7.86**		**5.4E-03**		**6.5E-01**		**8.9E-03**	
Bio-foam (expanded PLA)	**1.02**		**2.9E-06**		**6.7E-02**		**3.3E-03**		**2.1E-03**		**3.4E-03**		**4.4E-03**		**3.5E-04**		**5.8E-04**		**3.12**		**7.5E-02**		**9.8E-02**		**3.4E-02**		**1.59**		**14.8**		**2.9E-03**		**2.4E-01**		**2.7E-02**	
PHB	**2.93**		**6.5E-06**		**1.6E-01**		**9.4E-03**		**7.4E-03**		**9.6E-03**		**1.7E-02**		**1.0E-03**		**1.9E-03**		**6.79**		**1.7E-01**		**2.0E-01**		**1.0E-01**		**5.05**		**25.3**		**7.7E-03**		**6.0E-01**		**1.7E-01**	

Table 18: ReCiPe 2016 Mid-point LCIA results comparing the impact of different coating materials on overall LC and on coating production and meal-kit disposal

			Meal-kit Type	**Bagasse**						**Paper**					
			Coating type (3-5% by mass)	**PLA (BAU)**	PE (3% by mass)	PBAT	PBS	PHB	PSM (Mater-Bi®)	PLA	**PE (BAU; 3% by mass)**	PBAT	PBS	PHB	PSM (MaterBi®)
Impact Category	Value Chain stage	Units													
Global Warming Potential	Overall	Kg CO$_2$ eq		**3.3**	3.27	3.45	3.31	3.34	3.26	2.61	**2.61**	2.73	2.62	2.65	2.58
		%			-0.91%	4.55%	0.30%	1.21%	-1.21%			4.60%	0.38%	1.53%	-1.15%
	Coating Production	Kg CO$_2$ eq		**0.113**	0.0549	0.266	0.13	0.16	0.0763	0.0924	**0.0359**	0.218	0.107	0.101	0.0625
		%			-51.42%	135.40%	15.04%	41.59%	-32.48%	157.38%		507.24%	198.05%	181.34%	74.09%
	Disposal	Kg CO$_2$ eq		**1.77**	1.81	1.77	1.77	1.77	1.77	1.43	**1.46**	1.43	1.43	1.43	1.43
		%			2.26%					-2.05%		-2.05%	-2.05%	-2.05%	-2.05%
Stratospheric Ozone Depletion	Overall	Kg CFC11 eq		**1.27E-06**	7.72E-07	5.16E-06	8.05E-07	1.25E-06	8.61E-07	1.65E-06	**1.27E-06**	4.84E-06	1.28E-06	1.64E-06	1.32E-06
		%			-39.21%	306.30%	-36.61%	-1.57%	-32.20%	29.92%		281.10%	0.79%	29.13%	3.94%
	Coating Production	Kg CFC11 eq		**5.09E-07**	1.17E-08	4.4E-06	4.75E-08	4.88E-07	1.04E-07	4.17E-07	**5.34E-09**	3.61E-06	3.89E-08	3.92E-07	8.49E-08
		%			-97.70%	764.44%	-90.67%	-4.13%	-79.57%	7708.99%		67503.00%	628.46%	7240.82%	1489.89%
	Disposal	Kg CFC11 eq		**4.09E-08**	4.02E-08	4.09E-08	4.09E-08	4.09E-08	4.09E-08	3.28E-08	**3.24E-08**	3.28E-08	3.28E-08	3.28E-08	3.28E-08
		%			-1.71%					1.23%		1.23%	1.23%	1.23%	1.23%
Ionizing Radiation	Overall	Kg Co-60 eq		**0.0834**	0.0784	0.0806	0.085	0.0829	0.0789	0.0605	**0.0597**	0.0582	0.0618	0.06	0.0568
		%			-6.00%	-3.36%	1.92%	-0.60%	-5.40%	1.34%		-2.51%	3.52%	0.50%	-4.86%
	Coating Production	Kg Co-60 eq		**0.00718**	0.00216	0.00432	0.00879	0.00662	0.0027	0.00588	**0.0038**	0.00354	0.00721	0.00532	0.00221
		%			-69.92%	-39.83%	22.42%	-7.80%	-62.40%	54.74%		-6.84%	89.74%	40.00%	-41.84%
	Disposal	Kg Co-60 eq		**0.000188**	0.000187	0.000188	0.000188	0.000188	0.000188	0.000151	**0.000151**	0.000151	0.000151	0.000151	0.000151
		%			-0.53%										
Ozone Formation, Human Health	Overall	Kg NOx eq		**0.00615**	0.00597	0.00621	0.00612	0.00634	0.00606	0.0603	**0.00595**	0.00608	0.00601	0.00618	0.00595
		%			-2.93%	0.98%	-0.49%	3.09%	-1.46%	913.45%		2.18%	1.01%	3.87%	
	Coating Production	Kg NOx eq		**0.00269**	0.00013	0.000348	0.00026	0.000471	0.000192	0.000233	**0.00517**	0.000285	0.000213	0.000357	0.000157
		%			-95.17%	-87.06%	-90.33%	-82.49%	-92.86%	-95.49%		-94.49%	-95.88%	-93.09%	-96.96%

	Disposal	Kg NOx eq		**0.000269**	0.000239	0.000269	0.000269	0.000269	0.000269	0.000216	**0.000193**	0.000216	0.000216	0.000216	0.000216
		%			-11.15%					11.92%		11.92%	11.92%	11.92%	11.92%
Particulate Matter 2.5 Formation	Overall	Kg PM2.5 eq		**0.0034**	0.00322	0.00346	0.0034	0.00361	0.00337	0.00333	**0.00322**	0.00338	0.00333	0.00351	0.00331
		%			-5.29%	1.76%	0.00%	6.18%	-0.88%	3.42%		4.97%	3.42%	9.01%	2.80%
	Coating Production	Kg PM2.5 eq		**0.000199**	6.85E-05	0.000258	0.000202	0.000412	0.00017	0.000163	**3.35E-05**	0.000211	0.000165	0.000296	0.00014
		%			-65.58%	29.65%	1.51%	107.04%	-14.57%	386.57%		529.85%	392.54%	783.58%	317.91%
	Disposal	Kg PM2.5 eq		**0.000127**	8.01E-05	0.000127	0.000127	0.000127	0.000127	0.000102	**6.47E-05**	0.000102	0.000102	0.000102	0.000102
		%			-36.93%					57.65%		57.65%	57.65%	57.65%	57.65%
Ozone Formation, Terrestrial Ecosystem	Overall	Kg NOx eq		**0.00628**	0.00609	0.00634	0.00625	0.000646	0.00617	0.0061	**0.00602**	0.00615	0.00607	0.00625	0.00602
		%			-3.03%	0.96%	-0.48%	-89.71%	-1.75%	1.33%		2.16%	0.83%	3.82%	
	Coating Production	Kg NOx eq		**0.000301**	0.000143	0.000366	0.000271	0.000488	0.000199	0.000247	**8.54E-05**	0.0003	0.000222	0.00037	0.000164
		%			-52.49%	21.59%	-9.97%	62.13%	-33.89%	189.23%		251.29%	159.95%	333.26%	92.04%
	Disposal	Kg NOx eq		**0.000276**	0.000246	0.000276	0.000276	0.000276	0.000276	0.000222	**0.000198**	0.000222	0.000222	0.000222	0.000222
		%			-10.87%					12.12%		12.12%	12.12%	12.12%	12.12%
Terrestrial Acidification	Overall	Kg SO_2 eq		**0.00674**	0.00637	0.00681	0.00666	0.00728	0.0067	0.00953	**0.00936**	0.00959	0.00946	0.00997	0.00949
		%			-5.49%	1.04%	-1.19%	8.01%	-0.59%	1.82%		2.46%	1.07%	6.52%	1.39%
	Coating Production	Kg SO_2 eq		**0.000512**	0.000156	0.000588	0.000434	0.00105	0.000472	0.00042	**9.28E-05**	0.000482	0.000356	0.000746	0.000387
		%			-69.53%	14.84%	-15.23%	105.08%	-7.81%	352.59%		419.40%	283.62%	703.88%	317.03%
	Disposal	Kg SO_2 eq		**0.00016**	0.000148	0.00016	0.00016	0.00016	0.00016	0.000128	**0.000119**	0.000128	0.000128	0.000128	0.000128
		%			-7.50%					7.56%		7.56%	7.56%	7.56%	7.56%
Freshwater Eutrophication	Overall	Kg P eq		**0.000492**	0.000461	0.000489	0.000488	0.000508	0.000473	6.91E-05	**0.000676**	0.000688	0.000687	0.000704	0.000675
		%			-6.30%	-0.61%	-0.81%	3.25%	-3.86%	-89.78%		1.78%	1.63%	4.14%	-0.15%
	Coating Production	Kg P eq		**4.41E-05**	1.28E-05	4.14E-05	4.01E-05	0.0000602	2.56E-06	3.61E-05	**8.91E-06**	0.000034	3.29E-05	3.95E-05	0.000021
		%			-70.98%	-6.12%	-9.07%	36.51%	-94.20%	305.16%		281.59%	269.25%	343.32%	135.69%
	Disposal	Kg P eq		**8.79E-06**	8.93E-06	8.79E-06	8.79E-06	8.79E-06	8.79E-06	7.09E-06	**7.24E-06**	7.09E-06	7.09E-06	7.09E-06	7.09E-06
		%			1.59%					-2.07%		-2.07%	-2.07%	-2.07%	-2.07%
Marine Eutrophication	Overall	Kg N eq		**0.000934**	0.000862	0.000888	0.000888	0.000981	0.000904	0.000774	**0.00072**	0.000736	0.000736	0.000812	0.000749
		%			-7.71%	-4.93%	-4.93%	5.03%	-3.21%	7.50%		2.22%	2.22%	12.78%	4.03%
	Coating Production	Kg N eq		**4.86E-05**	1.25E-06	2.95E-06	2.82E-06	0.0000955	1.81E-05	3.98E-05	**9.1E-07**	2.41E-06	2.31E-06	7.77E-05	1.49E-05
		%			-97.43%	-93.93%	-94.20%	96.50%	-62.76%	4273.63%		164.84%	153.85%	8438.46%	1537.36%
	Disposal	Kg N eq		**0.000817**	0.000792	0.000802	0.000802	0.000802	0.000802	0.00066	**0.000644**	0.00066	0.00066	0.00066	0.00066

		%			-3.06%					2.48%		2.48%	2.48%	2.48%	2.48%
Terrestrial Ecotoxicity	Overall	Kg CO_2 eq		**4.88**	4.79	4.94	4.94	4.97	4.83	4.61	**4.59**	4.66	4.66	4.68	4.57
		%			-1.84%	1.23%	1.23%	1.84%	-1.02%	0.44%		1.53%	1.53%	1.96%	-0.44%
	Coating Production	Kg 1,4 DCB eq		**0.296**	0.101	0.354	0.353	0.386	0.248	0.243	**0.0558**	0.291	0.289	0.288	0.203
		%			-65.88%	19.59%	19.26%	30.41%	-16.22%	335.48%		421.51%	417.92%	416.13%	263.80%
	Disposal	Kg 1,4 DCB eq		**0.156**	0.26	0.156	0.156	0.156	0.156	0.126	**0.211**	0.126	0.126	0.126	0.126
		%			66.67%					-40.28%		-40.28%	-40.28%	-40.28%	-40.28%
Freshwater Ecotoxicity	Overall	Kg 1,4 DCB eq		**0.075**	0.0702	0.074	0.0738	0.0753	0.0731	0.071	**0.068**	0.0702	0.0701	0.0713	0.0695
		%			-6.40%	-1.33%	-1.60%	0.40%	-2.53%	4.41%		3.24%	3.09%	4.85%	2.21%
	Coating Production	Kg 1,4 DCB eq		**0.00647**	0.00166	0.00549	0.00528	0.00679	0.00458	0.0053	**0.00124**	0.0045	0.00433	0.00516	0.00376
		%			-74.34%	-15.15%	-18.39%	4.95%	-29.21%	327.42%		262.90%	249.19%	316.13%	203.23%
	Disposal	Kg 1,4 DCB eq		**0.0318**	0.318	0.0318	0.0318	0.0318	0.0318	0.0257	**0.0259**	0.0257	0.0257	0.0257	0.0257
		%			900.00%					-0.77%		-0.77%	-0.77%	-0.77%	-0.77%
Marine Ecotoxicity	Overall	Kg 1,4 DCB eq		**0.101**	0.096	0.101	0.1	0.1	0.0994	0.0965	**0.0933**	0.0959	0.0957	0.0953	0.0948
		%			-4.95%	0.00%	-0.99%	-0.99%	-1.58%	3.43%		2.79%	2.57%	2.14%	1.61%
	Coating Production	Kg 1,4 DCB eq		**0.00794**	0.00217	0.00719	0.00691	0.00643	0.00585	0.00651	**0.00161**	0.0059	0.00567	0.0047	0.0048
		%			-72.67%	-9.45%	-12.97%	-19.02%	-26.32%	304.35%		266.46%	252.17%	191.93%	198.14%
	Disposal	Kg 1,4 DCB eq		**0.0432**	0.0435	0.0432	0.0432	0.0432	0.0432	0.0349	**0.0354**	0.0349	0.0349	0.0349	0.0349
		%			0.69%					-1.41%		-1.41%	-1.41%	-1.41%	-1.41%
Human Carcinogenic Toxicity	Overall	Kg 1,4 DCB eq		**0.0536**	0.0514	0.0543	0.0539	0.0556	0.0527	0.0676	**0.0667**	0.0682	0.0678	0.0692	0.0669
		%			-4.10%	1.31%	0.56%	3.73%	-1.68%	1.35%		2.25%	1.65%	3.75%	0.30%
	Coating Production	Kg 1,4 DCB eq		**0.00345**	0.00157	0.00416	0.00375	0.00541	0.00257	0.00283	**0.000974**	0.00341	0.00307	0.00372	0.00211
		%			-54.49%	20.58%	8.70%	56.81%	-25.51%	190.55%		250.10%	215.20%	281.93%	116.63%
	Disposal	Kg 1,4 DCB eq		**0.00392**	0.00359	0.00392	0.00392	0.00392	0.00392	0.00316	**0.0029**	0.00316	0.00316	0.00316	0.00316
		%			-8.42%					8.97%		8.97%	8.97%	8.97%	8.97%
Human Non-Carcinogenic Toxicity	Overall	Kg 1,4 DCB eq		**2.18**	2.07	2.2	2.19	2.3	2.15	2.63	**2.57**	2.65	2.63	2.72	2.6
		%			-5.05%	0.92%	0.46%	5.50%	-1.38%	2.33%		3.11%	2.33%	5.84%	1.17%
	Coating Production	Kg 1,4 DCB eq		**0.0983**	0.0336	0.121	0.106	0.217	0.0697	0.0805	**0.0224**	0.0996	0.0866	0.157	0.0571
		%			-65.82%	23.09%	7.83%	120.75%	-29.09%	259.38%		344.64%	286.61%	600.89%	154.91%
	Disposal	Kg 1,4 DCB eq		**1.05**	1	1.05	1.05	1.05		0.85	**0.813**	0.85	0.85	0.85	0.85
		%			-4.76%					4.55%		4.55%	4.55%	4.55%	4.55%

Land Use	Overall	m2a crop eq		**2.95**	0.215	0.228	0.225	2.22	0.839	4.01	**1.81**	1.78	1.77	3.41	2.28
		%			-92.71%	-92.27%	-92.37%	-24.75%	-71.56%	121.55%		-1.66%	-2.21%	88.40%	25.97%
	Coating Production	m2a crop eq		**2.74**	0.00451	0.0183	0.0145	2.01	0.629	2.25	**0.00268**	0.015	0.0119	1.64	0.515
		%			-99.84%	-99.33%	-99.47%	-26.64%	-77.04%	83855%		459.70%	344.03%	61094%	19116%
	Disposal	m2a crop eq		**0.00287**	0.00286	0.00287	0.00287	0.00287	0.00287	0.00231	**0.00232**	0.00231	0.00229	0.00229	0.00229
		%			-0.35%					-0.43%		-0.43%	-1.29%	-1.29%	-1.29%
Mineral Resource Scarcity	Overall	Kg Cu eq		**0.00524**	0.00499	0.00524	0.00519	0.0053	0.00514	0.0059	**0.0058**	0.00589	0.00585	0.00594	0.00582
		%			-4.77%	0.00%	-0.95%	1.15%	-1.91%	1.72%		1.55%	0.86%	2.41%	0.34%
	Coating Production	Kg Cu eq		**0.000369**	0.000111	0.000363	0.00031	0.000425	0.000268	0.000302	**7.38E-05**	0.000297	0.000254	0.000338	0.00022
		%			-69.92%	-1.63%	-15.99%	15.18%	-27.37%	309.21%		302.44%	244.17%	357.99%	198.10%
	Disposal	Kg Cu eq		**3.59E-05**	3.59E-05	3.59E-05	3.59E-05	0.0000359	3.59E-05	2.88E-05	**2.89E-05**	2.88E-05	2.88E-05	2.88E-05	2.88E-05
		%								-0.35%		-0.35%	-0.35%	-0.35%	-0.35%
Fossil Resource Scarcity	Overall	Kg oil eq		**0.463**	0.471	0.494	0.485	0.464	0.471	0.347	**0.357**	0.372	0.364	0.0348	0.353
		%			1.73%	6.70%	4.75%	0.22%	1.73%	-2.80%		4.20%	1.96%	-90.25%	-1.12%
	Coating Production	Kg oil eq		**0.0289**	0.0365	0.0598	0.0507	0.0301	0.037	0.0237	**0.0277**	0.049	0.0415	0.0192	0.0303
		%			26.30%	106.92%	75.43%	4.15%	28.03%	-14.44%		76.90%	49.82%	-30.69%	9.39%
	Disposal	Kg oil eq		**0.00326**	0.00325	0.00326	0.00326	0.00326	0.00326	0.00261	**0.00262**	0.00261	0.00261	0.00261	0.00261
		%			-0.31%					-0.38%		-0.38%	-0.38%	-0.38%	-0.38%
Water Use	Overall	m^3		**0.0183**	0.0144	0.0178	0.0179	0.027	0.014	0.0329	**0.0304**	0.0324	0.0325	0.04	0.0293
		%			-21.31%	-2.73%	-2.19%	47.54%	-23.50%	8.22%		6.58%	6.91%	31.58%	-3.62%
	Coating Production	m^3		**0.00467**	0.000695	0.00412	0.00428	0.0133	0.000331	0.00383	**0.000605**	0.00338	0.00351	0.0109	0.000271
		%			-85.12%	-11.78%	-8.35%	184.80%	-92.91%	533.06%		458.68%	480.17%	1701.65%	-55.21%
	Disposal	m^3		**2.89E-05**	2.81E-05	2.89E-05	2.89E-05	0.0000289	2.89E-05	2.32E-05	**2.27E-05**	2.32E-05	2.32E-05	2.32E-05	2.32E-05
		%			-.2.77%					2.20%		2.20%	2.20%	2.20%	2.20%

Table 19: ReCiPe 2016 Mid-point LCIA results comparing impact of increasing recycling rates (Mechanical Recycling)

			GWP	**SOD**	**IR**	**OF, HH**	**FPM25**	**OF, TE**	**TA**	**Fw Eutr**	**Mar Eutr**	**Terr Ecotox**	**Fw Ecotox**	**Mar Ecotox**	**HC Tox**	**HNC Tox**	**LU**	**MinRes Scar**	**FosRes Scar**	**WU**
Meal-kit type		**Units**	Kg CO_2 eq	Kg CFC11 eq	Kg Co-60 eq	Kg NOx eq	Kg PM25 eq	Kg NOx eq	Kg SO_2 eq	Kg N eq	Kg P eq	Kg 1,4-DCB eq	Kg 1,4-DCB eq	Kg 1,4-DCB eq	Kg 1,4-DCB eq	Kg 1,4-DCB eq	Kg CO_2 eq	Kg Cu eq	Kg oil eq	m^3 eq
PS	**BAU**		**0.897**	**2.3E-07**	**0.0096**	**0.00214**	**0.00105**	**2.3E-03**	**0.00319**	**0.000151**	**8.9E-05**	**1.69**	**0.0442**	**0.0611**	**0.028**	**1.33**	**0.0598**	**0.000994**	**0.34**	**0.0111**
	Y1	**%**	-19.6%	3.5%	12.8%	-7.9%	-5.1%	-8.8%	-4.4%	10.6%	-25.8%	-5.3%	-19.7%	-19.8%	-6.4%	-19.5%	11.9%	-1.7%	-22.4%	-25.3%
	Y2	**%**	-23.0%	4.3%	14.9%	-9.3%	-6.1%	-10.2%	-5.0%	12.6%	-30.1%	-6.5%	-22.9%	-23.2%	-7.5%	-23.3%	13.9%	-1.9%	-26.2%	-29.5%
	Y3	**%**	-26.2%	4.8%	16.9%	-10.3%	-7.0%	-11.5%	-5.6%	13.9%	-34.4%	-7.1%	-26.2%	-26.5%	-8.6%	-26.6%	15.9%	-2.2%	-30.0%	-33.9%
	Y4	**%**	-29.5%	5.7%	20.0%	-11.7%	-7.9%	-13.3%	-6.6%	15.9%	-38.7%	-8.3%	-29.4%	-29.8%	-9.6%	-29.9%	17.9%	-2.5%	-33.5%	-38.1%
	Y5	**%**	-32.8%	6.1%	22.1%	-13.1%	-8.9%	-14.6%	-7.2%	17.2%	-43.0%	-9.5%	-32.8%	-33.1%	-10.7%	-33.3%	19.9%	-2.8%	-37.4%	-42.3%
PET	**BAU**		**4.07**	**2.7E-06**	**0.0965**	**0.0136**	**0.00705**	**0.0138**	**0.0214**	**0.00214**	**0.00111**	**12.3**	**0.245**	**0.332**	**0.237**	**5.97**	**0.84**	**0.0142**	**1.42**	**0.0226**
	Y1	**%**	-21.9%	-7.9%	-4.5%	-16.2%	-6.8%	-16.7%	-5.1%	-0.9%	-18.7%	-35.0%	-33.1%	-34.3%	-5.1%	-19.4%	-3.7%	-8.5%	-4.9%	-2.2%
	Y2	**%**	-25.6%	-24.7%	-16.1%	-19.9%	-18.3%	-20.3%	-17.3%	-23.8%	-32.1%	-24.8%	-29.8%	-29.5%	-24.9%	-27.0%	-24.0%	-33.5%	-28.2%	-32.3%
	Y3	**%**	-29.2%	-28.1%	-18.3%	-22.8%	-20.9%	-23.2%	-20.1%	-27.1%	-36.7%	-28.3%	-33.9%	-33.7%	-28.3%	-30.8%	-27.4%	-38.3%	-32.1%	-36.7%
	Y4	**%**	-32.7%	-31.5%	-20.6%	-25.7%	-23.4%	-26.1%	-22.4%	-30.8%	-41.2%	-31.9%	-38.4%	-38.0%	-32.1%	-34.7%	-30.8%	-43.1%	-36.2%	-41.6%
	Y5	**%**	-36.4%	-35.2%	-23.0%	-28.7%	-26.1%	-28.9%	-24.8%	-34.1%	-45.8%	-35.4%	-42.4%	-42.2%	-35.4%	-38.5%	-34.3%	-48.0%	-40.3%	-46.0%
Paper	**BAU**		**2.61**	**1.3E-06**	**0.0597**	**0.00595**	**0.00322**	**0.00602**	**0.00936**	**0.000676**	**0.00072**	**4.59**	**0.068**	**0.0933**	**0.0667**	**2.57**	**1.81**	**0.0058**	**0.357**	**0.0304**
	Y1	**%**	-14.6%	-1.6%	-3.4%	-3.9%	-2.5%	-4.0%	-1.6%	-1.2%	-21.9%	-3.7%	-9.4%	-9.4%	-2.8%	-8.2%	-11.0%	-1.9%	-1.7%	-8.9%
	Y2	**%**	-16.9%	-1.6%	-3.9%	-4.5%	-3.1%	-4.7%	-1.9%	-1.5%	-25.6%	-4.1%	-11.0%	-10.9%	-3.3%	-9.7%	-12.7%	-2.2%	-2.0%	-10.2%
	Y3	**%**	-19.5%	-2.4%	-4.5%	-5.2%	-3.4%	-5.1%	-2.2%	-1.6%	-29.3%	-4.8%	-12.6%	-12.5%	-3.9%	-10.9%	-14.9%	-2.6%	-2.2%	-11.8%
	Y4	**%**	-21.8%	-2.4%	-5.0%	-5.9%	-4.0%	-5.8%	-2.5%	-1.9%	-32.9%	-5.4%	-14.1%	-14.0%	-4.3%	-12.5%	-16.6%	-2.9%	-2.5%	-13.2%
	Y5	**%**	-24.5%	-2.4%	-5.7%	-6.4%	-4.3%	-6.5%	-2.8%	-2.1%	-36.5%	-6.1%	-15.7%	-15.6%	-4.8%	-13.6%	-18.8%	-3.3%	-2.8%	-14.5%
PP	**BAU**		**4.32**	**3.2E-06**	**0.064**	**0.0138**	**0.00717**	**0.0139**	**0.023**	**0.00306**	**0.0003**	**6.92**	**0.199**	**0.276**	**0.31**	**6.19**	**1.13**	**0.0166**	**1.43**	**0.0161**
	Y1	**%**	-24.5%	-32.2%	-14.8%	-21.7%	-21.2%	-21.6%	-21.3%	-25.2%	-24.0%	-19.7%	-25.6%	-25.7%	-25.2%	-25.2%	-25.1%	-38.6%	-25.2%	-25.5%
	Y2	**%**	-28.5%	-29.9%	-17.3%	-25.4%	-24.7%	-25.2%	-24.8%	-29.4%	-28.0%	-22.8%	-30.2%	-30.1%	-29.4%	-29.4%	-29.3%	-32.5%	-29.4%	-29.8%
	Y3	**%**	-32.6%	-34.1%	-19.8%	-29.1%	-28.3%	-29.1%	-28.3%	-33.7%	-32.3%	-26.2%	-34.2%	-34.4%	-33.5%	-33.6%	-33.5%	-36.7%	-33.6%	-33.5%
	Y4	**%**	-36.6%	-38.3%	-22.3%	-32.8%	-31.8%	-32.7%	-32.2%	-37.9%	-36.3%	-29.3%	-38.7%	-38.8%	-37.7%	-37.8%	-37.6%	-41.6%	-37.8%	-38.1%
	Y5	**%**	-40.7%	-42.5%	-24.8%	-36.4%	-35.3%	-36.5%	-35.7%	-42.2%	-40.3%	-32.7%	-42.7%	-43.1%	-41.9%	-42.0%	-41.8%	-46.1%	-42.0%	-42.3%

Table 20: ReCiPe 2016 Mid-point LCIA results comparing impact of increasing recycling rates (Organic Recycling - Industrial Composting)

			GWP	**SOD**	**IR**	**OF, HH**	**FPM25**	**OF, TE**	**TA**	**Fw Eutr**	**Mar Eutr**	**Terr Ecotox**	**Fw Ecotox**	**Mar Ecotox**	**HC Tox**	**HNC Tox**	**LU**	**MinRes Scar**	**FosRes Scar**	**WU**
Meal-kit type		**Units**	Kg CO_2 eq	Kg CFC11 eq	Kg Co-60 eq	Kg NOx eq	Kg P eq	Kg NOx eq	Kg SO_2 eq	Kg N eq	Kg P eq	Kg 1,4-DCB eq	Kg 1,4-DCB eq	Kg 1,4-DCB eq	Kg 1,4-DCB eq	Kg 1,4-DCB eq	Kg CO_2 eq	Kg Cu eq	Kg oil eq	m^3 eq
Bagasse	**BAU**		**3.3**	**1.3E-06**	**0.0834**	**0.00615**	**0.0034**	**0.00628**	**0.00674**	**0.000492**	**0.000934**	**4.88**	**0.075**	**0.101**	**0.0536**	**2.18**	**2.95**	**0.00524**	**0.463**	**0.0183**
	Y1	**%**	-7.88%	-5.51%	-2.40%	-0.98%	-0.88%	-1.11%	-1.34%	-0.81%	-14.03%	-1.02%	-6.80%	-6.24%	-1.49%	-7.80%	-18.6%	-6.11%	-0.22%	-6.56%
	Y2	**%**	-13.1%	-8.66%	-3.96%	-1.63%	-1.76%	-1.75%	-2.37%	-1.22%	-23.34%	-98.1%	-68.2%	-67.9%	-2.43%	-12.8%	-31.5%	-10.31%	-0.43%	-11.5%
	Y3	**%**	-26.4%	-16.5%	-7.91%	-3.25%	-3.24%	-3.34%	-4.60%	-1.63%	-46.68%	-3.28%	-22.5%	-21.9%	-5.04%	-25.7%	-63.1%	-20.42%	-1.08%	-22.9%
	Y4	**%**	-33.9%	-21.4%	-10.3%	-4.23%	-4.41%	-4.30%	-6.08%	-3.25%	-60.71%	-4.30%	-29.3%	-28.6%	-6.53%	-33.1%	-82.0%	-26.72%	-1.51%	-29.5%
	Y5	**%**	-41.8%	-26.3%	-12.7%	-5.20%	-5.29%	-5.25%	-7.42%	-4.07%	-74.73%	-5.33%	-36.0%	-35.4%	-8.02%	-40.8%	-99.1%	-32.82%	-1.73%	-36.6%
PLA	**BAU**		**2.13**	**6.1E-06**	**1.4E-01**	**6.8E-03**	**4.4E-03**	**7.1E-03**	**9.1E-03**	**7.3E-04**	**1.2E-03**	**6.51**	**1.6E-01**	**2.1E-01**	**7.1E-02**	**3.32**	**3.1E+01**	**5.9E-03**	**5.1E-01**	**5.6E-02**
	Y1	**%**	-0.47%	-0.16%	0.00%	-0.44%	-0.91%	-0.57%	-0.22%	-0.14%	-2.50%	-0.31%	-1.91%	-1.96%	-0.57%	-2.41%	-0.32%	-1.18%	0.00%	-0.36%
	Y2	**%**	-1.41%	-0.66%	-0.71%	-1.32%	-2.27%	-1.42%	-0.77%	-0.28%	-8.33%	-1.08%	-6.37%	-6.37%	-1.70%	-7.53%	-0.97%	-3.20%	-0.20%	-1.25%
	Y3	**%**	-4.23%	-1.97%	-2.14%	-3.52%	-6.14%	-3.55%	-2.19%	-0.55%	-22.00%	-3.07%	-15.9%	-16.7%	-4.55%	-20.2%	-2.91%	-8.59%	-0.40%	-3.56%
	Y4	**%**	-5.63%	-2.63%	-2.86%	-31.28%	-8.41%	-4.96%	-3.07%	-0.83%	-93.03%	-4.15%	-22.3%	-23.1%	-6.11%	-27.7%	-3.88%	-11.95%	-0.59%	-4.80%
	Y5	**%**	-7.04%	-3.45%	-3.57%	-6.31%	-10.45%	-6.24%	-3.94%	-0.97%	-38.58%	-5.38%	-28.1%	-29.4%	-7.81%	-35.2%	-4.85%	-15.15%	-0.79%	-6.23%
PBS	**BAU**		**2.61**	**1E-06**	**0.179**	**0.0071**	**0.00494**	**0.0073**	**0.00914**	**0.000796**	**0.000781**	**7.56**	**0.162**	**0.217**	**0.0824**	**3.84**	**0.27**	**0.00584**	**0.841**	**5.9E-02**
	Y1	**%**	11.88%	-1.60%	0.00%	-0.56%	-0.61%	-0.55%	-0.33%	-3.52%	-4.87%	-0.26%	-1.85%	-2.30%	-0.49%	-2.60%	-46.7%	-1.20%	0.00%	-2.18%
	Y2	**%**	-1.53%	-4.90%	-0.56%	-1.55%	-2.23%	-1.51%	-0.98%	-3.64%	-14.60%	-1.06%	-6.79%	-6.91%	-1.58%	-7.55%	-139%	-3.60%	-0.12%	-3.02%
	Y3	**%**	-3.83%	-13.4%	-2.23%	-3.94%	-6.07%	-3.97%	-2.63%	-4.02%	-38.67%	-2.91%	-17.9%	-17.9%	-4.25%	-19.8%	-371%	-9.93%	-0.36%	-5.36%
	Y4	**%**	-5.36%	-18.5%	-2.79%	-5.35%	-8.30%	-5.34%	-3.50%	-4.27%	-53.14%	-4.10%	-24.1%	-24.9%	-5.95%	-27.3%	-511%	-13.53%	-0.48%	-6.87%
	Y5	**%**	-6.90%	-23.5%	-3.35%	-6.90%	-10.53%	-6.85%	-4.49%	-4.52%	-67.73%	-5.16%	-30.9%	-31.3%	-7.52%	-34.6%	-648%	-17.29%	-0.59%	-8.21%
Mater-Bi ®	**BAU**		**1.79**	**1.7E-06**	**0.112**	**0.00607**	**0.00422**	**0.00622**	**0.00903**	**0.00056**	**0.000945**	**6.67**	**0.149**	**0.198**	**0.0654**	**3.25**	**7.86**	**0.00536**	**0.647**	**8.9E-03**
	Y1	**%**	-0.56%	-1.18%	0.00%	-0.49%	-0.95%	-0.64%	-0.33%	-0.18%	-3.92%	-0.45%	-2.01%	-2.02%	-0.61%	-2.77%	-1.53%	-1.31%	-0.15%	-3.05%
	Y2	**%**	-1.68%	-2.96%	-0.89%	-1.65%	-2.61%	-1.61%	-0.89%	-0.36%	-11.64%	-1.20%	-6.71%	-7.07%	-1.99%	-8.62%	-4.58%	-3.92%	-0.15%	-9.26%
	Y3	**%**	-5.03%	-7.69%	-2.68%	-4.45%	-6.87%	-4.50%	-2.55%	-0.89%	-31.01%	-3.30%	-18.8%	-18.7%	-5.35%	-22.8%	-12.3%	-10.45%	-0.46%	-24.6%
	Y4	**%**	-7.26%	-10.7%	-4.46%	-6.10%	-9.48%	-6.11%	-3.43%	-1.07%	-42.54%	-4.50%	-25.5%	-25.8%	-7.34%	-31.1%	-16.9%	-14.37%	-0.62%	-33.8%
	Y5	**%**	-9.50%	-13.6%	-5.36%	-7.74%	-12.09%	-7.72%	-4.32%	-1.43%	-54.18%	-5.70%	-32.9%	-32.8%	-9.33%	-39.7%	-21.6%	-18.28%	-0.77%	-43.0%
Bio-foam (expanded PLA)	**BAU**		**1.02**	**2.9E-06**	**0.0672**	**0.00327**	**0.00211**	**0.00338**	**0.00438**	**0.000348**	**0.000576**	**3.12**	**0.0752**	**0.0977**	**0.0337**	**1.59**	**14.8**	**0.00285**	**0.243**	**0.0269**
	Y1	**%**	0.00%	-0.34%	-0.30%	-0.61%	-0.95%	-0.59%	-0.23%	-0.29%	-2.78%	-0.32%	-1.99%	-2.05%	-0.30%	-2.52%	0.00%	-1.05%	-0.41%	-0.37%
	Y2	**%**	-0.98%	-1.03%	-0.74%	-1.53%	-2.37%	-1.48%	-0.91%	-0.29%	-8.33%	-0.96%	-5.98%	-6.24%	-4.45%	-7.55%	-0.68%	-3.51%	-0.41%	-1.12%
	Y3	**%**	-4.02%	-2.05%	-2.23%	-3.67%	-6.16%	-3.55%	-2.28%	-0.86%	-22.05%	-2.88%	-16.1%	-16.8%	-4.45%	-20.1%	-2.70%	-8.77%	-0.82%	-3.35%

	Y4	**%**	-5.59%	-2.74%	-3.12%	-5.20%	-8.53%	-5.03%	-3.20%	-0.86%	-30.38%	-4.17%	-22.2%	-23.1%	-5.93%	-27.7%	-4.05%	-11.93%	-0.82%	-4.83%
	Y5	**%**	-7.16%	-3.42%	-3.87%	-6.42%	-10.43%	-6.21%	-3.88%	-1.15%	-38.72%	-5.45%	-28.3%	-29.4%	-7.72%	-35.2%	-4.73%	-15.09%	-0.82%	-5.95%
PHB	**BAU**		**2.93**	**6.5E-06**	**0.162**	**0.00935**	**0.0074**	**0.00964**	**0.0168**	**0.00104**	**0.00190**	**6.79**	**0.173**	**0.20**	**0.101**	**5.05**	**25.3**	**0.00768**	**0.601**	**0.174**
	Y1	**%**	-0.34%	-0.15%	0.00%	-0.32%	-0.54%	-0.41%	0.00%	0.00%	-1.58%	-0.44%	-2.31%	-2.50%	-0.99%	-1.78%	-0.79%	-0.91%	0.00%	0.00%
	Y2	**%**	-1.02%	-0.77%	-0.62%	-1.07%	-1.49%	-1.14%	-0.60%	0.00%	-5.79%	-1.33%	-6.36%	-7.50%	-1.39%	-5.54%	-1.58%	-2.86%	-0.17%	0.00%
	Y3	**%**	-3.07%	-1.99%	-1.85%	-2.89%	-3.92%	-2.90%	-1.19%	0.00%	-15.26%	-3.24%	-16.2%	-19.5%	-3.56%	-14.7%	-3.95%	-7.42%	-0.50%	-1.15%
	Y4	**%**	-4.44%	-2.76%	-3.09%	-3.96%	-5.54%	-4.05%	-1.79%	-0.96%	-21.05%	-4.57%	-22.6%	-26.5%	-4.85%	-20.2%	-5.53%	-10.29%	-0.67%	-1.72%
	Y5	**%**	-5.80%	-3.52%	-3.70%	-5.88%	-7.03%	-5.08%	-2.38%	-0.96%	-27.37%	-5.74%	-28.9%	-33.5%	-6.24%	-25.9%	-6.72%	-13.02%	-2.50%	-1.72%

Appendix C - Dataset modelling and data quality

Table 21 to **Table 24** details the datasets used and or modelled in this study. They are a combination of background dataset from the ecoivent database (v. 3.6 and 3.7) and foreground datasets.

Background datasets were used "as is" when representing a imported polymer/product from the global supply chain, or were adapted to the local context when needed: i.e. sensitivity analysis exploring the local production, vs local manufacturing using imported polymers, vs. importing finished products.

Foreground datasets were modelled mainly for emerging materials based on proxies/extrapolation from dataset on similar materials (e.g. PBS), or from secondary data from literature (Harding et. al, 2008) (e.g. PHBH). These datasets included only the main material feedstocks and energy requirements, without including the infrastructure (e.g. chemical factory organics). Results showed that these material alternatives scored rather poor when compared to other material alternatives – PHB being the least preferable of all of them. When including the infrastructure in the dataset modelling, LCIA results would be even worse, thus, excluding it from the modelling had no effect on the overall environmental performance.

Table 21: Data source and adaptations for production/supporting processes

Polymer / Material	Unit Process	Adaptation for ZA context
EPS/XPS	Polystyrene extruded {RoW}	***Inputs:*** Water, cooling, unspecified natural origin {ZA} Electricity, medium voltage {ZA} Polystyrene, expandable {RoW_ZA Adapted} ***Emissions/Waste:*** *Water {ZA}* Waste polystyrene, market for {ZA_Adapted}
	Polystyrene expandable {RoW}	***Inputs:*** Electricity, medium voltage {ZA} Water, cooling, unspecified natural origin {ZA} Water, river {ZA} Water, unspecified natural origin {ZA} Water, well {ZA}

		Emissions/Waste: *Water {ZA}*
Bagasse	Bagasse, from sugarcane {RoW}, sugarcane processing, traditional annexed plant	***Inputs:*** Chemical, organic, synthetic fuel production from coal {ZA} Concrete, normal {ZA} Sugarcane production {RoW-ZA_adapted} Water, well {ZA}
Paper	Solid bleached board production {RoW}	***Inputs:*** Hard coal {ZA} Heavy fuel oil {ZA} Electricity, medium voltage {ZA} Water, unspecified natural origin {ZA} ***Emissions/Waste:*** *Water {ZA}*
	Solid unbleached board production {RoW}	***Inputs:*** Hard coal {ZA} Heavy fuel oil {ZA} Electricity, medium voltage {ZA} Water, cooling, unspecified natural origin {ZA} Water, unspecified natural origin {ZA} ***Emissions/Waste:*** *Water {ZA}*
PET	Polyethylene terephthalate, granulate production, bottle grade {RoW}	***Inputs:*** Average ethylene production mix {ZA} Chemical, organic, synthetic fuel production from coal {ZA} Electricity mix, medium voltage {ZA} Ethylene glycol production {RoW-ZA_adapted} Water, unspecified natural origin {ZA} Water, lake {ZA} Water, river {ZA} Water, well {ZA}

		Emissions/Waste: Waste plastic, mixture {ZA}
PP	Polypropylene resin, at plant/RNA_ZA_adapted_production	***Inputs:*** Electricity, low voltage {ZA} Ethylene, average, market for {ZA} Propylene, market for {ZA} ***Emissions/Waste:*** Waste polypropylene, market for waste polypropylene {ZA} Water, unspecified natural origin {ZA}
PLA and Bio-foam (expanded PLA)	Polylactide, granulate production {GLO-ZA_produced}	***Inputs:*** Maize starch {RoW_ZA Adapted} Naptha {ZA} Electricity, low voltage {ZA} ***Emissions/Waste:*** Wastewater from maize starch production {GLO-ZA Adapted} Waste bioplastic {ZA-Adapted}, market for waste plastic, mixture
PBS	Foreground dataset to represent either GLO and South African production (with adaptation)	Succinic acid production {GLO-ZA_Adapted} Butane-1,4-diol production {RoW-ZA_adapted}
Mater-bi® (PBAT+PSM)	Polyester-complexed starch biopolymer production {RoW-ZA_adapted}	***Inputs:*** Maize starch {RoW_ZA Adapted} Naptha {ZA} Electricity, low voltage {ZA}
PHB (used as proxy for the other materials: PHA, PHBV, PHBH)	Foreground dataset to represent either GLO and South African production (with adaptation)	***Inputs:*** Water, cooling, unspecified natural origin {ZA} Water, unspecified natural origin {ZA} Sugar, from sugarcane processing {RoW-ZA Adapted} Electricity, medium voltage {ZA}
Polymer / Material	**Unit Process**	**Adaptation for ZA context**
Maize Starch	Maize starch production {RoW-ZA_adapted}	***Inputs:*** Maize grain {ZA} Tap water {ZA}

		Electricity, medium voltage {ZA}
Ethylene glycol	Ethylene glycol {RoW}	***Inputs:*** Average ethylene production mix {ZA} Electricity, medium voltage {ZA} Water, unspecified natural origin {ZA}
Sugarcane	Sugarcane production {RoW-ZA_adapted}	***Inputs:*** Fertilising by broadcaster {ZA} Harvesting, sugarcane {RoW_ZA Adapted} using Diesel {ZA} Irrigation, market for {ZA} Tillage, ploughing {ZA} ***Emissions/Waste:*** Water {ZA} in surface (river) and groundwater
Succinic acid	Succinic acid production {GLO_ZA_Adapted}	***Inputs:*** Tap water {ZA} Electricity, medium voltage {ZA} Water, unspecified natural origin {ZA} Water, river {ZA} Water, well {ZA} ***Emissions/Waste:*** Water {ZA} in surface (river) and groundwater
Butane-1,4-diol	Butane-1,4-diol production {RoW_ZA_adapted}	***Inputs:*** Chemical, organic, synthetic fuel production from coal {ZA} Electricity, medium voltage {ZA} Water, cooling, unspecified natural origin {ZA} ***Emissions/Waste:*** Water {ZA} in surface (river) and groundwater

Table 22: Data source and adaptations for conversion/supporting processes

Process / Technology	Unit Process	Adaptation for ZA context
Injection moulding	Injection moulding {RoW-ZA_adapted}	***Inputs:*** Chemical, organic, synthetic fuel production from coal {ZA} Electricity, medium voltage {ZA} Polyethylene, low density, granulate {RoW_ZA Adapted} Polypropylene, granulate production {RoW_ZA Adapted} Water, cooling, unspecified natural origin {ZA} ***Emissions/Waste:*** Water {ZA} to water Waste plastic, mixture (RoW_ZA Adapted}
Extrusion	Extrusion of plastic sheets and thermoforming, inline {RoW-ZA_Adapted}	***Inputs:*** Chemical, organic, synthetic fuel production from coal {ZA} Electricity mix, medium voltage {ZA} Polypropylene, granulate production {RoW_ZA Adapted} Tap water {ZA} ***Emissions/Waste:*** Waste plastic, mixture {RoW_ZA Adapted}
Polymer foaming	Polymer foaming {RoW-ZA_adapted}	***Inputs:*** Water, unspecified natural origin {ZA} Electricity mix, medium voltage {ZA} ***Emissions/Waste:*** Water {ZA} to water
Process-specific burdens	Process-specific burdens, residual material landfill {RoW_ZA Adapted}	***Inputs:*** Electricity mix, low voltage {ZA}
	Process-specific burdens, sanitary landfill {RoW_ZA Adapted}	***Inputs:*** Electricity mix, low voltage {ZA} Electricity mix, medium voltage {ZA}
	Process-specific burdens, slag landfill {RoW_ZA Adapted}	***Inputs:*** Electricity mix, low voltage {ZA}

Table 23: Data source and adaptations for end-of-life processes

Process / Technology	Unit Process	Adaptation for ZA context
Sanitary landfills	Waste (PS / PET / PP / PE / plastic mixture), treatment of waste (PS / PET / PP / PE / plastic mixture), sanitary landfill {RoW_ZA Adapted}	Cement, unspecified {ZA} Electricity mix, low voltage {ZA} Electricity mix, high voltage {ZA} Process-specific burdens, residual material landfill {RoW_ZA Adapted} Process-specific burdens, sanitary landfill {RoW_ZA Adapted} Process-specific burdens, slag landfill {RoW_ZA Adapted}
Unsanitary landfills	Waste (*PS / PET / PP / PE / plastic mixture / packaging paper*), treatment of waste (*PS / PET / PP / PE / plastic mixture / packaging paper*), unsanitary landfill, dry infiltration class (100 mm) {GLO}	n.a.
Open dump	Waste (*PS / PET / PP / PE / plastic mixture / packaging paper*), treatment of waste ((*PS / PET / PP / PE / plastic mixture / packaging paper*), open dump, dry infiltration class (100 mm) {GLO}	n.a.
Open burning	Waste (*PS / PET / PP / PE / plastic mixture / packaging paper*), treatment of waste (*PS / PET / PP / PE / plastic mixture / packaging paper*), open burning {GLO}	n.a.
Recycling	*(PS / PET / PP)* recycling of *(PS / PET / PP)* {GLO_ZA Adapted}	Electricity mix, medium voltage {ZA}
Composting (industrial)	Compost {RoW-ZA_Adapted}| treatment of biowaste, industrial composting	***Inputs:*** Cement, unspecified {ZA} Clinker {ZA} Concrete 35MPa / normal {ZA} Electricity mix, low, medium and high voltage {ZA} Diesel {ZA} Hard coal {ZA} Heavy fuel oil {ZA} Light fuel oil {ZA} Liquified petroleum gas {ZA} Petrol, unleaded {ZA} Transport, freight, train {ZA} Transport, freight, light commercial vehicle {ZA},

		Transport freight, lorry 16-32 metric ton {ZA} Transport freight, lorry, unspecified {ZA} Water, cooling, unspecified natural origin {ZA} Water, lake {ZA} Water, river {ZA} Water, unspecified natura origin {ZA} Water, well {ZA}

Table 24: Data source and adaptations for transport processes

Transportation stage	Unit Process	Assumptions
Pellets from producers to meal-kit manufactures (CT, Durban or JHB)	Transport, freight, lorry >32 metric ton, EURO2 {ZA}	1300, 650 and 84km for CT, Durban and JHB; average 680km from Safripol to either Berri Astrapack, Mpact Versapck and Zibo Containers
Manufacture containers to distributors	Transport, freight, lorry 3.5-7.5 metric ton, EURO2 {ZA}	700 km on average from major producer to distributor/retailers/users
PS pellets from overseas	Transport, freight, sea, container ship {GLO}	5600 nm* on average from Singapore, Taiwan, India, Europe and Brazil
PP from overseas	Transport, freight, sea, container ship {GLO}	India and South Korea, 6200 nm on average (11500 km)
Bagasse container from overseas	Transport, freight, sea, container ship {GLO}	China, Taiwan, India 6100 nm on average (11300 km)
PLA container from overseas	Transport, freight, sea, container ship {GLO}	China 7000 nm on average (13000 km)
PLA resin from oversea	Transport, freight, sea, container ship {GLO}	China and US 7000 nm on average (13000 km)
PSM (e.g MaterBi) and PBAT resin from oversea	Transport, freight, sea, container ship {GLO}	Europe and China 6800 nm on average (12600 km)

PBS resin from oversea	Transport, freight, sea, container ship {GLO}	Thailand and China 6550 nm on average (12200 km)
PHA's resin from oversea	Transport, freight, sea, container ship {GLO}	US, Europe and China 7150 nm on average (13200 km)
Home/collection point to landfill/dump	Transport, freight, lorry, unspecified {ZA}	For most serviced households the distance to landfill is 20 km, while self-help dump is within 2 km. Weighted average 6 km
From recycling plant (MRF) to manufacturer	Transport, freight, lorry 3.5-7.5 metric ton, EURO2 {ZA}	50 km, 3-7 t truck
Solid bleached paper reels (already laminated) for cup from North Europe	Transport, freight, sea, container ship {GLO}	15700 km * on average

*converted from nautical miles; 1 nm equates to 1.852 km; sea distances retrieved from SEA-DISTANCES.ORG - Distances