Comparing Grocery Carrier Bags in South Africa from an Environmental and Socio-Economic Perspective

Evidence from a Life Cycle Sustainability Assessment

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PREFACE AND ACKNOWLEDGEMENTS

This study was commissioned by the Department of Science and Innovation (DSI); through the Waste Research, Development and Innovation (RDI) Roadmap; with co-funding through the Council for Scientific and Industrial Research (CSIR) Parliamentary Grant.

The study was conducted by the CSIR's Sustainability, Economics and Waste Research Group within the Smart Places Cluster. The main contributing authors to the report were Dr Valentina Russo (Systems Engineer specialising in Life Cycle Assessment and Systems Thinking), who led the LCA modelling; Prof William Stafford (Principal Scientist specialising in Industrial Ecology and Industrial Engineering), who assessed the carrier bags in terms of material persistence, employment and affordability; and Anton Nahman (Principal Scientist specialising in Environmental Economics and Waste Management), who coordinated the study and compiled the report.

Other CSIR team members who contributed to the study include Willem de Lange and Lorren Haywood (assistance with data collection and analysis relating to the persistence and employment indicators); as well as Sudhakar Muniyasamy (laboratory testing of the thickness, mass and volumetric capacity of each carrier bag).

The study has been conducted following the LCA approach as per ISO 14040 and 14044 (2006). In accordance with these standards, an expert review panel was consulted to provide oversight throughout the course of the project, and to provide a critical review of the report. The panel consisted of:

- Prof. Harro von Blottnitz, University of Cape Town, South Africa;
- Dr. Philippa Notten, The Green House, South Africa.
- Lorren de Kock, WWF-SA, South Africa

The panel members have been involved throughout the study; providing guidance and feedback in terms of the goal and scope definition, critical assumptions, modelling choices, etc. They also conducted a thorough review of two earlier drafts of the final report. They are gratefully acknowledged for their insights and contributions to the study.

The following are also acknowledged for their support and input to the study: Linda Godfrey, Douglas Trotter and Lee-Hendor Ruiters (CSIR), Henry Roman (DSI), Mamogala Musekene and Dumisani Buthelezi (Department of Environment, Forestry and Fisheries), Anton Hanekom, Douw Steyn and Jacques Lightfoot (PlasticsSA), Annabé Pretorius (Plastix 911), Cheri Scholtz (PETCO), Mandy Naudé (PolyCo), Sanjeev Raghubir (Shoprite Checkers), Ralph Jewson (Woolworths) and Andre Nel (Pick 'n Pay).

STATEMENT BY THE REVIEW PANEL

"This LCA is, in our professional opinion, competently executed and presented according to accepted formats, following the norms laid down in the ISO standards 14040 and 14044. It is well-informed by the findings of plastic bag LCAs done in other countries, and uses the latest available South African data to produce locally relevant knowledge. The range of bags studied is impressive and valuable, and the inclusion of realistic end-of-life fates given lacking waste management service provision to a third of the population is a very important feature of this study. The attempt to define a persistence indicator as an addition to the environmental impact assessment indicators produced by standard methods is commendable, and adds valuable new insights. Likewise, the attempt to include locally relevant data on costs of bags and employment numbers is commendable and adds important evidence. These three additional indicators are not fully integrated into the life cycle impact assessment, but provide decision-makers with useful and locally relevant information. The methods used to rank alternatives studied are explained and here we point out that the aggregation into a single score is not provided for in the ISO standards. It needs to borne in mind that other choices could have been made, resulting in somewhat different final rankings of alternatives. A suggestion for future work would thus be to take the results into a multi-criteria decision support process with government and other relevant stakeholders to determine a weighting set for the impact indicators. This would advance the current ranking approach, that applies equal weighting regardless of magnitude or significance of the impact in the South African context. Nonetheless, the results obtained are robust, as evidenced by the sensitivity analyses done.

The peer reviewers would like to point out that, in comparing across the indicators studied, policy-makers and decision-makers should bear in mind that how we design, manage, regulate and use plastic shopping bags does have a very significant bearing on the persistence of plastic in our environment, but (at the national scale) it has much less of a bearing on most other environmental impacts studied, on consumer expenditure and on the absolute number of jobs that could be created or destroyed"

- Prof H von Blottnitz (University of Cape Town), Dr P Notten (The Green House), L de Kock, (WWF-SA)

EXECUTIVE SUMMARY

Introduction

In this study, we conduct a Life Cycle Sustainability Assessment of alternative options for grocery carrier bags in South Africa. The goal of the study was as follows:

> **"To compare different types of carrier bags that are (or could be) offered by South African retailers, in terms of environmental and socio-economic performance across the product life cycle."**

We include bags that are already available in retail stores in South Africa, as well as a number of bags that are not yet commercially available. The intention is to provide evidence to inform current discussions among policymakers, retailers and the general public around single-use plastic carrier bags and their alternatives (including reusable bags, biodegradable/compostable bags, and paper bags). In short, the study aims to answer the question of which type of bag is "best" in the South African context. Sixteen types of carrier bags were assessed in the study; made from a range of different materials; varying in terms of their recycled content; and with varying degrees of reusability, recyclability and biodegradability (Table i).

Table i: Carrier bags assessed in the LCSA study

Single-use / reusable	Type of material	Name	Description	Modelled % of recycled content
Single-use	Fossil-based plastic	HDPE_24_100	HDPE; with thickness of 24 microns (24 µm)	100%
		HDPE_24_75	HDPE 24 µm	75%
		HDPE_24_50	HDPE 24 µm	50%
		HDPE_24_25	HDPE 24 µm	25%
		HDPE_24_0	HDPE 24 µm	0%
		LDPE	Low density polyethylene	0%
	Fossil-based with bio-additive	HDPE_ECM	HDPE bags with ECM additive	0%
	Biodegradable plastic	PBS+PBAT_ZA	PBS+PBAT, using locally produced PBS and PBAT	0%
		PBS+PBAT_IMP	PBS+PBAT, using imported PBS and PBAT	0%
		PBAT+Starch_ZA	PBAT+Starch, using locally produced PBAT and locally grown maize	0%
		PBAT+Starch_IMP	PBAT+Starch, using imported PBAT+Starch	0%
	Paper	Paper	Brown (Kraft) paper bags	54.8%
Reusable	Fossil-based plastic	HDPE_70	HDPE bags with a thickness of 70 µm	100%
		PP	Polypropylene bags	0%
		Polyester_W	Woven fabric polyester	100% (rPET)
		Polyester_NW	Non-woven (spun-bond and stitched) polyester	85% (rPET)

Methodology

The different types of carrier bags were assessed and compared against a broad range of environmental indicators, as well as two key socio-economic indicators.

Environmental indicators were based primarily on the ReCiPe 2016 impact assessment methodology; which comprises 18 impact categories (indicators) at midpoint level, three damage categories (endpoints), as well as an aggregated single score index (see Table ii). Endpoints (damage to human health, damage to ecosystems, and damage to resource availability) are calculated by aggregating and weighting normalised midpoint scores. In turn, the single score is calculated by aggregating and weighting across the three damage categories.

However, existing impact assessment methodologies (including ReCiPe 2016) do not currently include indicators relating to the impacts associated with plastic pollution. As such, given the current global prominence of this issue, we develop a new indicator, namely persistence of plastic material in the environment, which is used as a proxy for impacts associated with plastic pollution.

We also add two key socio-economic indicators that are particularly relevant in the South African context; namely impacts on employment, and affordability to consumers. All of the indicators used in the assessment, including the three new indicators (persistence, employment and affordability), are listed in Table ii.

Table ii: Indicators used in the LCSA assessment

Methodology	Level	Indicator	Unit
ReCiPe 2016	Midpoint impact categories	Global Warming	Kg CO_2-eq
		Stratospheric Ozone Depletion	Kg CFC11-eq
		Ionizing Radiation	Kg Co-60 eq
		Ozone Formation, Human Health	Kg NOx eq
		Fine Particulate Matter Formation	Kg PM2.5 eq
		Ozone Formation, Terrestrial Ecosystem	Kg NOx eq
		Terrestrial Acidification	Kg SO_2 eq
		Freshwater Eutrophication	Kg P eq
		Marine Eutrophication	Kg N eq
		Terrestrial Ecotoxicity	Kg 1,4-DCB eq
		Freshwater Ecotoxicity	Kg 1,4-DCB eq
		Marine Ecotoxicity	Kg 1,4-DCB eq
		Human Carcinogenic Toxicity	Kg 1,4-DCB eq
		Human Non-Carcinogenic Toxicity	Kg 1,4-DCB eq
		Land use	m2a crop eq
		Mineral Resources Scarcity	Kg Cu eq
		Fossil Resource Scarcity	Kg oil eq
		Water Consumption	m3
	Endpoint damage categories	Human Health	DALYs
		Ecosystems	Species/yr
		Resources	USD2013
	Single score (aggregation of the above)		milli Point (mPt)
New indicators	Midpoint impact categories	Persistence	Kg of material
		Employment	No. of jobs
		Affordability	ZAR

Functional unit and key assumptions

In comparative LCA studies, a common 'functional unit' needs to be defined, which allows all bags to be compared on an equal basis. The **functional unit** for this study was:

> **"Carrying one person's annual groceries (870.48 litres) from the supermarket to the home in South Africa".**

The number of each type of bag required to fulfil this functional unit was determined on the basis of the volumetric capacity of each bag, as well as the extent to which each type of bag would be reused. Specifically, we assume that:

- bags that are intended for single use will only be used once each; such that a new bag is purchased for each shopping trip
- bags intended for reuse will be reused continuously over the course of the entire year (i.e., 52 times, assuming a weekly shopping trip)

The resulting number of each type of bag needed to fulfil the functional unit is provided in Table iii.

Table iii: Assumed number of times each type of bag is used, and number of bags needed to fulfil the functional unit

Single-use / reusable	Bag type	Capacity (litres)	Number of times each bag is used	Number of bags needed per year to fulfil the functional unit (870.48 litres)
Single-use	HDPE_24_100	16.74	1	52.00
	HDPE_24_75	16.74	1	52.00
	HDPE_24_50	16.74	1	52.00
	HDPE_24_25	16.74	1	52.00
	HDPE_24_0	16.74	1	52.00
	LDPE	24.00	1	36.27
	HDPE_ECM	13.00	1	66.96
	PBS+PBAT_ZA	14.73	1	59.10
	PBS+PBAT_IMP	14.73	1	59.10
	PBAT+Starch_ZA	19.00	1	45.81
	PBAT+Starch_IMP	19.00	1	45.81
	Paper	19.97	1	43.59
Reusable	HDPE_70	23.23	52	0.72
	PP	18.98	52	0.88
	Polyester_W	13.69	52	1.22
	Polyester_NW	26.75	52	0.62

Results

Based on the above-mentioned assumptions, the environmental impact associated with each type of bag is illustrated in Figure i. These results take into account the number of bags required over the course of the year to fulfil annual grocery shopping requirements, as per Table iii. Note that the results in Figure i are based on the ReCiPe 2016 aggregated single score (excluding the new indicators developed in this study). The results indicate that the reusable, fossil-based plastic bags have a far lower environmental impact as compared to the single-use options (fossil-based or biodegradable).

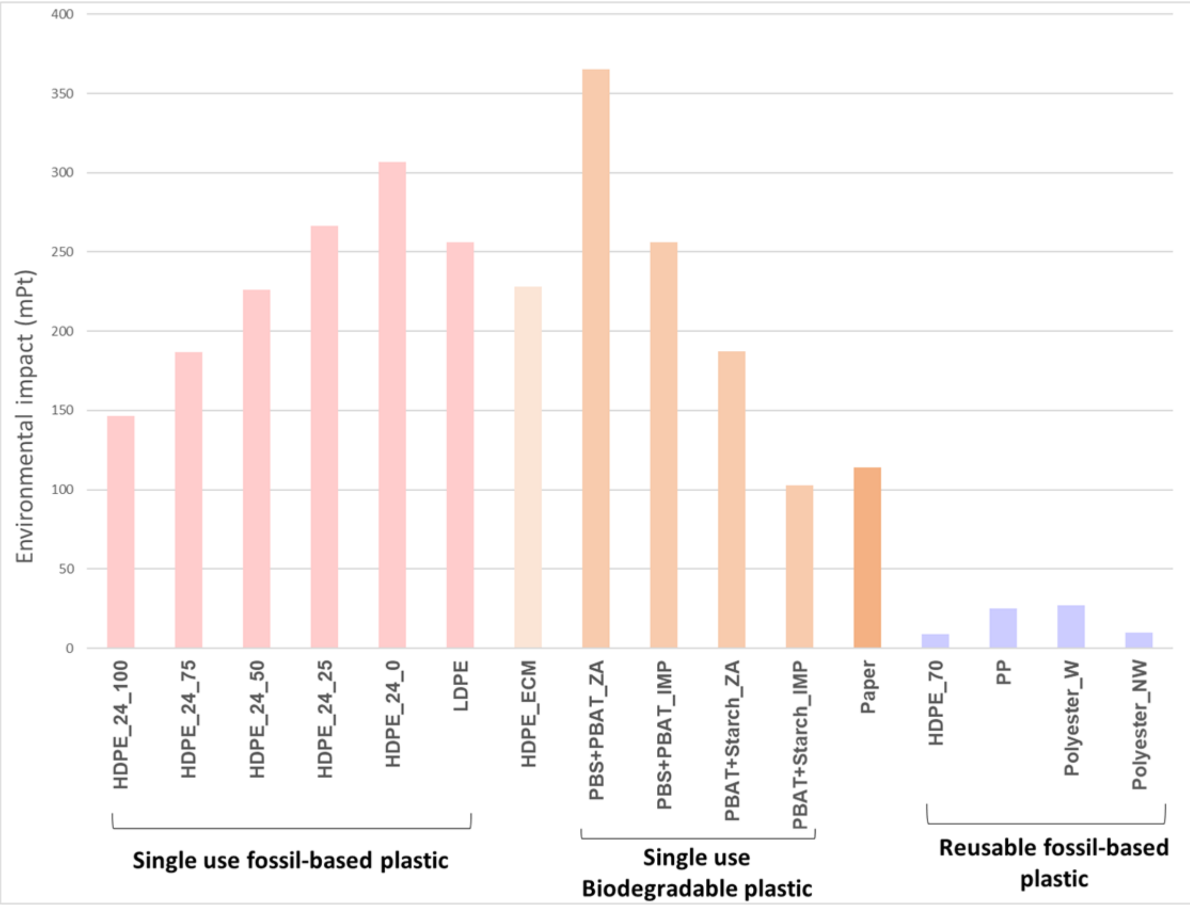

Figure i: Environmental impact per bag type, based on ReCiPe 2016 single score (excluding persistence, employment and affordability). Based on assumption that single-use bags are used once each, and that reusable bags are used continuously over the course of the year to fulfil annual grocery shopping requirements.

The overall ranking of bags (across all environmental and socio-economic indicators) is as per Table iv. These rankings take into account both the ReCiPe 2016 indicators, as well as our new indicators (persistence, employment and affordability); and are based on an equal weighting across all indicators.

Table iv: Overall ranking of bags across all environmental and socio-economic indicators (assuming that single-use bags are only used once each; and that reusable bags are reused continuously to fulfil annual grocery shopping requirements). Overall ranking calculated based on equal weighting across indicators.

Rank	Bag type	Type of material	Single-use / reusable
1	HDPE_70	Fossil-based plastic	Reusable
2	Polyester_NW	Fossil-based plastic	Reusable
3	PP	Fossil-based plastic	Reusable
4	Polyester_W	Fossil-based plastic	Reusable
5	HDPE_24_100	Fossil-based plastic	Single-use
6	HDPE_24_75	Fossil-based plastic	Single-use
7	PBAT+Starch_IMP	Biodegradable plastic	Single-use
8	HDPE_24_50	Fossil-based plastic	Single-use
9	LDPE	Fossil-based plastic	Single-use
10	HDPE_ECM	Fossil-based with bio-additive	Single-use
11	HDPE_24_25	Fossil-based plastic	Single-use
12	PBAT+Starch_ZA	Biodegradable plastic	Single-use
13	HDPE_24_0	Fossil-based plastic	Single-use
14	Paper	Paper	Single-use
15	PBS+PBAT_IMP	Biodegradable plastic	Single-use
16	PBS+PBAT_ZA	Biodegradable plastic	Single-use

From Table iv it can be seen that, over the course of a year, based on our assumptions regarding the number of times each bag is reused (i.e., how many of each bag needs to be purchased over the course of the year), the best performing bag overall is the reusable HDPE 70 µm bag (HDPE_70), closely followed by the reusable non-woven polyester bag (Polyester_NW). Indeed, the four reusable bags (HDPE_70, Polyester_NW, PP and Polyester_W) occupy the top four positions in the rankings. The worst performing among the reusable bags (although still better than any of the single-use bags) is the woven polyester bag (Polyester_W).

Interestingly, the best performing among the single-use bags is the HDPE 24 µm bag with 100% recycled content (HDPE_24_100), which is currently the most common bag found in formal sector grocery stores in South Africa. It can also be seen that the higher the recycled content of the bags, the better the overall performance. The HDPE 24 µm bag with 100% recycled content (HDPE_24_100) achieves the highest ranking from among the HDPE 24 µm bags, while the HDPE bags with lower recycled content rank progressively worse.

It is also evident that the worst performing bag overall over the course of a year (based on our assumptions regarding the number of bags required to fulfil annual shopping requirements) is the biodegradable PBS+PBAT bag made using locally produced PBS and PBAT (PBS+PBAT_ZA).

Finally, it is notable that the top six bags are all made from conventional fossil-based plastics (HDPE, polyester and polypropylene). Of the seven worst performing bags, five are made from alternative types of materials (paper, biodegradable plastics, and the HDPE bag made with an ECM additive intended to aid biodegradation).

It should be borne in mind that the overall rankings in Table iv are calculated assuming an equal weighting across all indicators. In principle, differential weighting could be applied to emphasise specific midpoint categories of relevance to a particular decision making context (e.g. employment); or to highlight impact categories where carrier bags make a disproportionately high contribution to the overall problem (e.g. persistence). It is therefore suggested that a set of weightings appropriate to the South African context be developed, through a multi-criteria decision analysis approach, incorporating government and other relevant stakeholders.

It is also important to note that these results are based on our assumption that single-use bags will only be used once each, and that reusable bags will be reused continuously over the course of a year to fulfil annual grocery shopping requirements. In reality, the reusable PP and polyester bags are likely to be able to last beyond one year; while it is also possible that, in their current design, the reusable HDPE_70 bags may not last for an entire year's worth of grocery shopping; with the handles noted as a potential weak point. Furthermore, bags that are intended for single use can in fact be reused to a certain extent.

As such, we conduct sensitivity analysis on these assumptions, as follows:

- Assuming that the HDPE_70 bag will only last for 6 months, or 3 months (as opposed to the baseline of one year)
- Assuming that the PP and Polyester bags will last for 2 years, or 4 years (as opposed to the baseline of one year)
- Assuming that the single-use bags will be used twice, or 4 times (as opposed to the baseline of once).

The results of the sensitivity analysis show that the overall ranking of bags is robust to changes in these assumptions. Across all of these scenarios, the HDPE_70 and Polyester_NW bags retain the top two positions in the rankings. However, if we assume that the HDPE_70 bag will not last for an entire year, *or* that the Polyester_NW bag will last for beyond one year; then these two bags trade places; with Polyester_NW becoming the top-ranked bag, and HDPE_70 falling to second.

The only time that these two bags fall out of the top two is if we assume that they will only be used a very small number of times; or that single-use bags will be used many times over. Ignoring for now our assumptions from Table iii regarding how many times each type of bag is reused, Table v provides an indication of the break-even point for each reusable bag, that is, the number of times that each reusable bag needs to be used in order to outperform the standard single-use HDPE 24 µm bag with 100% recycled content. Note that the break-even points in Table v are based on the ReCiPe 2016 single score, which aggregates across the various environmental indicators in the ReCiPe 2016 impact assessment methodology (i.e., the new indicators developed in this study; namely persistence, employment and affordability; are excluded).

Table v: Number of uses required for reusable bags to break even with the reference bag (single-use HDPE 24 µm bag with 100% recycled content); based on environmental impacts (ReCiPe 2016 single score; excluding persistence, employment and affordability)

Bag type	Number of uses required to break even with the reference bag (HDPE_24_100)
HDPE_70	3
Polyester_NW	4
PP	9
Polyester_W	10

Finally, Table vi presents the rankings for some specific indicators of interest; namely global warming, land use, water consumption, persistence (as a proxy for impacts associated with plastic pollution), employment, and affordability. Again, these results are based on the assumption that single-use bags will only be used once, and that reusable bags will be reused throughout the year to fulfil the functional unit.

Table vi: Ranking of bags on specific midpoint impact categories of interest (listed from best to worst); based on assumed number of reuse times in fulfilling annual shopping requirements

Rank	Global warming	Land use	Water use	Persistence (plastic pollution)	Employment	Affordability
1	HDPE_70	Polyester_NW	HDPE_70	PBAT+Starch_IMP	Paper	HDPE_70
2	Polyester_NW	HDPE_70	Polyester_NW	PBAT+Starch_ZA	HDPE_24_100	Polyester_NW
3	PP	Polyester_W	Polyester_W	PBS+PBAT_IMP	HDPE_24_75	PP
4	Polyester_W	PP	PP	PBS+PBAT_ZA	HDPE_24_50	LDPE
5	Paper	PBAT+Starch_IMP	HDPE_ 24_100	Paper	PBS+PBAT_ZA	HDPE_24_100
6	PBAT+Starch_IMP	PBAT+Starch_ZA	HDPE_ECM	HDPE_70	PBS+PBAT_IMP	HDPE_24_75
7	HDPE_ 24_100	HDPE_24_100	HDPE_ 24_75	Polyester _W	HDPE_24_25	HDPE_24_50
8	HDPE_ 24_75	HDPE_24_75	LDPE	Polyester _NW	HDPE_24_0	HDPE_24_25
9	HDPE_ 24_50	HDPE_ECM	HDPE_24_50	PP	LDPE	HDPE_24_0
10	HDPE_ECM	LDPE	HDPE_24_25	HDPE_ECM	PBAT+Starch_ZA	Polyester_W
11	PBAT+Starch_ZA	HDPE_24_50	HDPE_24_0	LDPE	HDPE_ECM	PBAT+Starch_ZA
12	LDPE	HDPE_24_25	Paper	HDPE_24_100	PBAT+Starch_IMP	PBAT+Starch_IMP
13	HDPE_24_25	HDPE_24_0	PBAT+Starch_IMP	HDPE_24_75	Polyester_NW	Paper
14	PBS+PBAT_IMP	PBS+PBAT_IMP	PBAT+Starch_ZA	HDPE_24_50	Polyester_W	PBS+PBAT_ZA
15	HDPE_24_0	PBS+PBAT_ZA	PBS+PBAT_ZA	HDPE_24_25	HDPE_70	PBS+PBAT_IMP
16	PBS+ PBAT_ ZA	Paper	PBS+PBAT_IMP	HDPE_24_0	PP	HDPE_ECM

The rankings for most environmental indicators (e.g. global warming, land use and water use in Table vi) are similar to the overall rankings presented in Table iv; with the four fossil-based plastic reusable bags occupying the top four positions. Single-use Paper bags perform particularly poorly in terms of land use, while the biodegradable plastic bags perform poorly in terms of water use.

By contrast, in terms of persistence (a proxy for the impacts associated with plastic pollution), the biodegradable bags occupy the top five positions, as expected. In particular, the biodegradable plastic bags (made from PBAT+Starch and PBS+PBAT) are the best performers, followed by Paper.

These are followed by the reusable bags, which fare relatively well on this indicator under the assumption that they are reused many times throughout the year; which implies that only a relatively small amount of material is disposed of each year. However, it should be noted that, given the larger amount of material embedded in reusable bags (per bag), they would perform very poorly in terms of persistence if they are instead used only a small number of times before being discarded.

Interestingly, the HDPE_ECM bag, which is marketed as being biodegradable, fares relatively poorly on the persistence indicator (i.e., it does not biodegrade to the extent that is expected). This finding is consistent with the contested nature of its claimed biodegradability. Finally, as expected, the single-use fossil-based plastic bags perform worst in terms of persistence. However, the results show that even biodegradable materials can persist in the environment when the rate of biodegradation is less than the rate of accumulation from continued disposal. This suggests that reduced consumption of bags through an emphasis on reuse should be a focus of intervention to reduce plastic pollution.

Turning to the socio-economic indicators, it is worth noting that the rankings for employment are the opposite of what is found for most of the environmental indicators. Based on our assumptions regarding the number of times each type of bag is used; the single-use bags are preferable from an employment perspective. This is because significantly fewer reusable bags would need to be produced per annum to fulfil annual grocery shopping requirements as compared to single-use bags; resulting in fewer jobs as compared to single-use bags, for which more bags would need to be produced. In other words, if there was a switch away from producing single-use bags towards producing only reusable bags, a decrease in employment could be expected.

In particular, single-use Paper bags perform best from an employment perspective, with significantly more jobs involved in producing the number of Paper bags that would be required to fulfil annual shopping needs as compared to any of the plastic options. Interestingly, the second best bag from an employment perspective is the standard single-use HDPE 24 µm bag, specifically the variant with 100% recycled content; followed by the versions with 75% and 50% recycled content, respectively. This suggests that the current status quo bag does indeed perform relatively well from an employment point of view. It also indicates that the higher the recycled content, the better the performance in terms of employment, owing to the labour intensive nature of the recycling industry (collection, sorting etc.) in South Africa.

Finally, it is interesting to note that, contrary to what may have been expected, the ranking in terms of affordability is similar to the rankings on the environmental indicators; with the reusable bags generally performing better than the single-use bags. Although reusable bags have higher upfront costs as compared to single-use bags (i.e., higher cost per bag), they begin to pay off the more often they are reused. Over the course of a year, assuming that single-use bags are only used once, and that reusable bags are reused continuously to fulfil annual grocery shopping requirements, the reusable bags are more cost-effective. While the upfront cost of the polyester and PP reusable bags may be prohibitive for very low income consumers, the HDPE_70 reusable bag has a far lower upfront cost, comparable to that of the single-use bags.

Conclusions and recommendations

Based on overall performance across all environmental and socio-economic indicators, and on our assumptions regarding the number of times each type of bag is reused; the best performing bags are the four fossil-based, reusable bags (HDPE_70, Polyester_NW, PP and Polyester_W). In fact, the top six bags are all made from conventional fossil-based plastics (HDPE, polyester and polypropylene). Of the seven worst performing bags, five are made from alternative types of materials (paper, biodegradable plastics, and the HDPE bag made with an ECM additive intended to aid biodegradation). A sensitivity analysis indicates that these rankings are robust to changes in key assumptions.

In terms of the results for specific indicators; the rankings on most environmental indicators are similar to the overall ranking; with the four fossil-based plastic reusable bags generally occupying the top four positions. Single-use Paper bags perform particularly poorly in terms of land use, while the biodegradable plastic bags perform poorly in terms of water use. In terms of persistence, the biodegradable plastic bags (made from PBAT+Starch and PBS+PBAT) are the best performers, followed by Paper. The HDPE_ECM bag, which is marketed as being biodegradable, fares relatively poorly, as do the single-use fossil-based plastic bags.

In terms of socio-economic indicators, the ranking in terms of affordability is similar to the rankings on the environmental indicators; with the reusable bags generally performing better than the single-use bags, over the course of a year. Although reusable bags have higher upfront costs than single-use bags, they begin to pay off the more often they are reused.

Finally, the rankings for employment are the opposite of what is found for most of the environmental indicators. Specifically, based on annual shopping requirements, single-use bags are preferable to reusable bags from an employment perspective; as more bags need to be produced, resulting in more jobs. In particular, single-use Paper bags perform best from an employment perspective; followed by the standard single-use HDPE 24µm bags, particularly those with higher proportions of recycled content.

Returning to the overall rankings across all indicators (Table iv); assuming that single-use bags are only used once, and that reusable bags are reused continuously over the course of a year to fulfil annual grocery shopping requirements, the reusable HDPE 70 µm bag (HDPE_70) is the top-performing bag overall; closely followed by the reusable non-woven (spun-bond and stitched) polyester bag (Polyester_NW). Specific findings and recommendations regarding these two bags are as follows:

- The HDPE 70 µm bag (HDPE_70) is the top-performing bag overall, assuming an equivalent lifespan as the second best performing bag (Polyester_NW). However, in its current design (this type of bag is currently only available from one retail group), the HDPE_70 bag does not appear to be as durable as the other reusable bags (Polyester or Polypropylene). In particular, the handles are noted as a weak point, which could potentially limit the number of times this type of bag can be reused. Nevertheless, this limitation could potentially be overcome through improved design. In addition, the break-even analysis finds that the

HDPE_70 bag only needs to be used three (or more) times to surpass the environmental performance of the single-use reference bag.

- The non-woven (spun-bond and stitched) polyester bag (Polyester_NW) is the second best performing bag overall, assuming an equivalent lifespan with the HDPE_70 bag; while assuming a longer lifespan as compared to HDPE_70, the Polyester_NW bag overtakes HDPE_70 as the top-ranked bag. Discussions with experts suggest that polyester bags are not currently recycled in South Africa; they were therefore modelled with a 0% recycling rate in this study. However, polyester can in principle be recycled through reheating and conversion back into polymer fibres for further reuse. The feasibility of this technology should therefore be investigated for South Africa; as recycling of these bags would further improve their performance (although not to the extent that it would overtake the HDPE_70 bag).

In general, the analysis shows that for all types of bags, the more times a bag is reused, the better its performance; particularly from an environmental (and affordability) perspective. The number of times a bag is reused is the single largest contributing factor to its environmental performance, across all types of bags. Doubling the amount of times a bag is used (e.g. using a bag twice instead of just once) results in a halving of its environmental impact.

As such, the general recommendation is that all bags be reused for their primary purpose (to carry groceries) as many times as possible. Even bags intended for 'single-use' should be reused as many times as possible. On the other hand, using a reusable bag only once is the worst possible outcome; since these bags have a higher material content as compared to single-use bags; and therefore a higher environmental impact (per bag) if they are only used once. As such, approaches to behavioural change to encourage reuse of bags (such as economic incentives, behavioural 'nudges', etc.) should be considered.

Only when primary reuse (as a carrier bag) is no longer possible, should bags be reused for a secondary purpose, e.g. as a bin liner (Danish EPA, 2018).

Finally, only when all options for primary and secondary reuse have been exhausted, should bags be recycled or composted (as appropriate). The analysis shows that increasing recycling rates does lead to some improvement in environmental performance; although not to the same extent as an increase in the number of times bags are reused. For example, an increase in recycling rates from current rates to 60% leads to a 4% reduction in environmental impact, on average. In terms of recycled content, the HDPE 24 µm bag with 100% recycled content performs 52% better as compared to the virgin HDPE bag. However, increasing the number of times bags are reused remains the single most effective way of improving their environmental performance.

LIST OF ACRONYMS

Acronym	Definition
APOS	Allocation at the Point Of Substitution
CTL	Coal To Liquid
DALY(s)	Disability-Adjusted Life Year(s), quantifying the burden of disease from mortality and morbidity (unit for the Human Health damage category). One DALY can be thought of as one lost year of "healthy" life.
E-LCA	Environmental Life Cycle Assessment
Ecosys	Ecosystems
EOL	End of life
FosResScar	Fossil Resource Scarcity
FPM	Fine Particulate Matter Formation
FWEcotox	Freshwater Ecotoxicity
FWEutr	Freshwater Eutrophication
GW	Global Warming
HDPE	High Density Polyethylene
HH	Human Health
HuCarTox	Human Carcinogenic Toxicity
HuNCarTox	Human Non-Carcinogenic Toxicity
IR	Ionizing Radiation
Kg 1,4-DCB eq	Kg of 1,4- dichlorobenzene equivalent
Kg CFC11-eq	Kg of Trichlorofluoromethane equivalent (a chlorofluorocarbon)
Kg CO2-eq	Kg of Carbon Dioxide equivalent
Kg Co-60 eq	Kg of Cobalt-60 equivalent
Kg Cu eq	Kg of Copper equivalent
Kg N eq	Kg of Nitrogen equivalent
Kg NOx eq	Kg of Nitrogen Oxide equivalent
Kg oil eq	Kg of oil equivalent
Kg P eq	Kg of Phosphorous equivalent
Kg PM2.5 eq	Kg of Particulate Matter <2.5µm
Kg SO2 eq	Kg of Sulphur Dioxide equivalent
LandUse	Land Use
LC	Life Cycle
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LDPE	Low Density Polyethylene
m2a crop eq	Square metre per year crop equivalent
m3	Cubic metre
MarEcotox	Marine Ecotoxicity

Acronym	Definition
MarEutr	Marine Eutrophication
µm / micron	Micrometre
MinResScar	Mineral Resources Scarcity
mPt	milli Point; the unit used in LCIA for the aggregated single score, which is a composite index across all environmental indicators
OF, HH	Ozone Formation, Human Health
OF, TE	Ozone Formation, Terrestrial Ecosystem
PBAT	Polybutylene Adipate Terephthalate
PBS	Polybutylene Succinate
PET	Polyethylene Terephthalate
PP	Polypropylene
Res	Resources
rPET	Recycled PET
S-LCA	Social Life Cycle Assessment
SOD	Stratospheric Ozone Depletion
Species/yr	Species per year; measures the potential extinction rate (unit for the Ecosystems damage category)
TerrAcid	Terrestrial Acidification
TerrEcotox	Terrestrial Ecotoxicity
USD	United States Dollar
USD2013	US dollar in 2013 (unit for the Resources damage category)
WaterUse	Water Consumption
ZA	South Africa
ZAR	South African Rand

TABLE OF CONTENTS

1 Introduction

1.1 Need for this study

In recent years, the issue of plastic waste has received significant attention from both policy makers and the general public. Plastic waste often enters the environment (either directly as litter, or through leakage from waste management systems); where it degrades only over very long periods, typically breaking down physically into microplastics (plastic fragments smaller than 5mm in length); and potentially polluting terrestrial, aquatic and marine ecosystems, and endangering living organisms.

In response to these impacts, and increasing public pressure, a number of countries have implemented stringent measures to regulate or even ban certain single-use plastic products, including plastic carrier bags. At the same time, there has been an increase in the development of alternatives to conventional fossil-based plastics, including so called 'bioplastics'.

In South Africa, the Department of Environment, Forestry and Fisheries (DEFF) is currently considering stricter regulations (including potential bans) on a number of single-use plastic products, including single-use plastic carrier bags. However, the Department acknowledges that the implications of banning certain products need to be carefully considered. From an environmental perspective, it is critical to assess whether the alternatives to single-use plastic carrier bags are in fact any better; particularly taking into account the entire life cycle of the product in question (resource extraction, manufacturing, transport, use, and disposal).

To date, no assessments have been conducted to compare the broad range of alternative carrier bag options from a life cycle perspective in the South African context. An earlier study (Sevitz et al. 2003) conducted a Life Cycle Assessment (LCA) of plastic and paper carrier bags in South Africa; but the broader range of carrier bag options that have since become available, are yet to be assessed in the local context.

More recent international studies, such as in Denmark (Danish EPA 2018) and the UK (UK Environment Agency 2011) have looked at a broader range of alternatives, but these studies are not necessarily relevant to a developing country context. In particular, there are significant differences in the energy generation profile and waste management systems between Europe and South Africa, as well as in behavioural aspects relating to reuse, recycling and littering. These factors influence the overall environmental performance of the different types of bags, implying that the results from these studies cannot necessarily be applied to South Africa.

In addition, a notable deficiency in existing LCA studies is that the impacts of plastic pollution on the environment are not well understood, and as such are not yet incorporated in existing LCA models and databases. Given the current global focus on impacts associated with plastic leakage into the environment, particularly the marine environment, this is a notable gap.

Furthermore, the above-mentioned studies, as with most other LCA studies, only consider environmental impacts; rather than adopting a broader 'sustainability' perspective. Sustainability is often defined in terms of three 'pillars' or dimensions; namely environmental, social and economic. Therefore, from a sustainability perspective, environmental impacts should ideally be looked at alongside social and economic considerations; particularly in a developing country context.

For example, reusable bags tend to be more expensive, such that a ban on single-use plastic bags may have negative impacts on poor consumers. Impacts on employment and on the economy are also highly relevant in the South Africa context. In particular, it is critical to assess whether any reductions in employment as a result of a ban on particular products are outweighed by gains associated with the development of alternatives. Indeed; in response to industry's concerns over potential job losses associated with a ban on single-use plastics; the Minister of Environment, Forestry and Fisheries has acknowledged the need to understand the implications of such a ban for employment in South Africa, and for the informal sector.

In many cases, there may be trade-offs between environmental and socio-economic considerations – that is, some types of bags may be preferable from an environmental perspective, while others may be preferable from a socio-economic perspective.

In short, the economic, social and environmental impacts of single-use plastic carrier bags; as well as of all viable alternatives; should be assessed throughout their life cycles, in order to determine whether the benefits of banning single-use plastic bags actually justify the potential costs; and to identify 'which bag is best' from an overall sustainability perspective, in the South African context.

This study attempts to address these gaps; by conducting a comparative environmental and socio-economic life cycle assessment of different types of carrier bags in South Africa. The intention is to provide objective, evidence-based information to inform decision making regarding single-use plastic carrier bags in South Africa (see Section 2). The study goes beyond existing LCA studies of carrier bags by (1) incorporating the impacts associated with plastic leakage to the environment, and (2) incorporating key socio-economic impacts of relevance to the developing country context; namely impacts on employment, and impacts on affordability for consumers. The methodology to be employed is referred to as 'Life Cycle Sustainability Assessment' (see Section 1.2).

1.2 What is Life Cycle Sustainability Assessment?

Life Cycle Assessment (LCA), also known an environmental LCA (E-LCA), is an approach to 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 2006). Application of LCA is guided by ISO standards 14040 and 14044 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 that attempts to combine E-LCA, S-LCA and LCC, in order to provide a more comprehensive, 'triple-bottom line' assessment of products in terms of the three pillars of sustainability. In other words, the aim of LCSA is to inform decision making based on the overall environmental, social and economic performance of products across their life cycles (UNEP 2011).

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, it could be argued that this type of approach fails to take into account the interactions and inter-dependencies between the economic, social and environmental dimensions of sustainability (Gbededo et al. 2018); while also making it difficult to interpret 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 the literature; in which a single, unified assessment is conducted, but based on an expanded set of indicators, encompassing environmental, social and economic impacts (Gloria et al. 2017; Guinee et al. 2011). The aim is to provide improved integration among the environmental, social and economic dimensions, through the adoption of a transdisciplinary approach.

This study applies the second of these LCSA approaches, in that we expand the set of indicators beyond those associated with a conventional environmental LCA, to also incorporate key socio-economic indicators.

As a starting point, we conduct an environmental LCA using the ReCiPe 2016 impact assessment methodology (Huijbregts et al. 2016, 2017), which includes a broad range of environmental impact categories.

We then expand on the ReCiPe 2016 impact assessment in two important ways. Firstly, it is important to note that none of the established LCA impact assessment methodologies, ReCiPe 2016 included, contain impact categories relating to plastic leakage, or plastic pollution. This could be explained by the fact that plastic pollution has only recently become a prominent issue, and there is not yet sufficient quantitative data linking specific quantities of plastic leaking into the environment to specific impacts. As such, given the current global focus on impacts related to plastic pollution, particularly in the marine environment, we add an additional environmental indicator, to reflect the impacts associated with plastic pollution. Given the lack of scientific data quantifying the linkage between specific quantities of plastic entering the environment and specific environmental impacts, we use persistence in the environment as a proxy for impact. All else being equal, we assume that the longer a specific plastic item persists in the environment, the more likely it is to cause damage.

Secondly, in extending the assessment from a conventional environmental LCA to a Life Cycle Sustainability Assessment (LCSA); we add two socio-economic indicators which are seen as particularly pertinent in the South African context, namely impacts on employment, and impacts in terms of the affordability of bags to consumers. These are some of the key socio-economic issues currently entering the debate around carrier bags – there are questions both around the impacts on employment and on affordability (particularly for poor consumers) if single-use plastic bags were to be banned. As such, it is important to be able to assess trade-offs between environmental and socio-economic considerations across the different types of bags.

1.3 Structure of the report

In conducting this study, we follow the guidelines for conducting LCA studies as set out in ISO Standards 14040 and 14044.

The ISO standards recommend that LCA studies be conducted according to four phases, namely:

1. Goal and scope definition (Identify product(s) to be assessed; establish context, goal, scope, and system boundaries).
2. Life Cycle Inventory (Identify and quantify energy, water, and materials as inputs as well as environmental releases as outputs).
3. Life Cycle Impact assessment (Assess the potential human and ecological effects, quantify metrics)
4. Interpretation (Compare data from Inventory Analysis and Impact Assessment stages to select or recommend a preferred product, process, or technology)

This report is structured as follows: Sections 2 and 3 present the goal and scope respectively. Section 4 provides details on the Life Cycle Inventory (LCI). Section 5 describes the Life Cycle Impact Assessment (LCIA) methodology, including the ReCiPe 2016 methodology used for the standard E-LCA indicators; as well as the methodology used to develop and incorporate the three additional indicators used in the study – namely persistence, employment and affordability. The main set of LCIA results (for both the ReCiPe 2016 indicators as well as the three additional indicators) is provided in Section 6. Section 7 provides the results of sensitivity analysis on key parameters and assumptions. Section 8 concludes and provides recommendations arising from the study.

Note that the assumptions underlying the study are set out in Sections 3 and 4. Section 3 presents key assumptions regarding the number of times that each type of bag is reused, on which the main set of results provided in Section 6 is based. These assumptions are then varied in Section 7 (sensitivity analysis), in order to assess the extent to which the results are affected by a change in these assumptions. Sections 3 and 4 also set out the system boundaries (inclusions/exclusions), modelling choices, and assumptions regarding product life cycles and end of life (disposal to different categories of landfill, leakage rates, recycling rates, etc.).

2 Goal of the study

The goal of the study was as follows:

> **"To compare different types of carrier bags that are (or could be) offered by South African retailers, in terms of environmental and socio-economic performance across the product life cycle."**

While the focus is largely on the bags currently available in large grocery supermarket stores; we also include bags that are more commonly found in other types of retail stores (such as clothing stores and fast-food outlets). The intention is that the outcomes and recommendations of the study would be applicable not only to grocery stores, but to other types of retailers as well. We also include a number of other bags that are not yet commercially available, for the purposes of comparison with existing alternatives. In short, the intention was to evaluate the broadest possible range of potential carrier bags that could be relevant in the South African context, in order to provide recommendations regarding which bags should be promoted for current and future use in South Africa. Section 3 provides more detail on the scope of the study; i.e. the particular types of carrier bags and retailers that are included in the study.

The aim of this assessment is to inform government, producers, retailers and consumers as to the environmental and socio-economic impacts associated with a wide range of different types of carrier bags. The intention is to provide an objective, scientific assessment of the performance of various carrier bag options that are already available or could potentially be adopted in South Africa, across their respective life cycles.

In particular, the key objective of the study is to provide evidence to inform current policy discussions around the potential banning of single-use plastic carrier bags and other single-use plastic products; and to inform the broader discussion around which type of bag should be promoted for use in South Africa, from an environmental and socio-economic perspective.

As such, the intended target audience of the study includes the following:

- National government, and in particular the Department of Environment, Forestry and Fisheries (DEFF);
- Provincial environmental departments;
- The plastics industry, and in particular manufacturers of plastic bags, as well as relevant industry bodies, representatives and producer responsibility organisations;
- Civil society and NGOs, e.g. environmental lobby groups;
- Retailers; and
- Consumers and the general public

Many of these stakeholders have been consulted during the course of the study; including DEFF, various manufacturers, PlasticsSA, PETCO, PolyCo, and many of the large retailers.

3 Scope of the study

3.1 Types of carrier bags included in the assessment

The study compares a total of sixteen different types of carrier bags that are or could potentially be offered by South African retailers to consumers. This includes the bag types that are already available in large grocery supermarkets in South Africa (specifically in the formal sector); as well as bags that are more commonly found in other types of retail stores (such as clothing stores and fast-food outlets). Finally, we also include bags that are not yet commercially available in South Africa, for the purposes of comparison with existing alternatives. As mentioned above, the intention is to include the broadest possible range of potential bag types that could be relevant in the South African context, in order to provide recommendations regarding which type of bag should be promoted for current and future use in South Africa.

The bags vary in terms of the materials from which they are made, whether they are fossil-fuel based (i.e. 'conventional' plastics) or bio-based; whether or not they are recyclable; whether or not they are biodegradable; and whether they are intended for single use or to be reused (see Table 1). Within these categories, bags also differ in terms of their size, thickness, and the amount of recycled content from which they are produced.

In the formal sector, the most common bag currently found in all of South Africa's major grocery stores is made from High-Density Polyethylene (HDPE), with a thickness of 24 micrometres (24 µm, or 24 microns). HDPE is an example of a 'conventional' fossil-based or petro-based plastic. Fossil-based plastics are derived from a fossil-fuel source (such as coal, oil or natural gas); and are not typically biodegradable (or, they degrade only over extremely long time periods); although they are generally recyclable.

The 24 µm HDPE bags are intended for single use, although in practice they can be reused a number of times, either for additional shopping trips (primary reuse); or for other purposes, for example, as a bin-liner (secondary reuse). These bags can be made from varying proportions of recycled content, ranging from 0 – 100%. Currently, the most common carrier bag in South Africa (at least among regulated bags within the formal sector) are 24 µm HDPE bags made from 100% recycled content (this bag type is offered by South Africa's largest grocery supermarket group; and is increasingly offered by other retailers as well). A number of variations in terms of recycled content are included in the assessment, in order to assess the extent to which the degree of recycled content affects overall environmental and socio-economic performance.

By contrast, South African clothing retailers tend to offer bags made from Low-Density Polyethylene (LDPE), another fossil-based plastic, which are also intended for single use (although in practice they can also be reused). HDPE and LDPE are both forms of polyethylene (PE); although they have different properties. In many other countries, the common grocery bag is made from LDPE rather than HDPE; so it is worthwhile comparing how LDPE bags compare with HDPE bags in the South African context.

In addition to the 24 µm HDPE bag, South Africa's largest grocery retail group has also introduced a thicker, 70 µm HDPE bag, which is stronger and intended for reuse. Many grocery retailers also offer bags made from other types of fossil-based plastics, such as polypropylene (PP) and polyester; which are also stronger than the common 24 µm HDPE bag, and intended to be reused many times.

Furthermore, a number of alternatives to conventional fossil-based plastics are beginning to gain traction in the South African market. “Bioplastic” is a commonly used term to describe some of these alternatives; although this term can be confusing; as it can refer to plastics that are bio-based (that is, derived from biomass sources) but not biodegradable, or biodegradable but not bio-based; or both bio-based and biodegradable. For example, certain fossil-based plastics can be rendered degradable (e.g. through the introduction of an additive to facilitate degradation); while not all bio-based plastics are biodegradable. Figure 1 provides a useful framework for understanding the different categories of plastics.

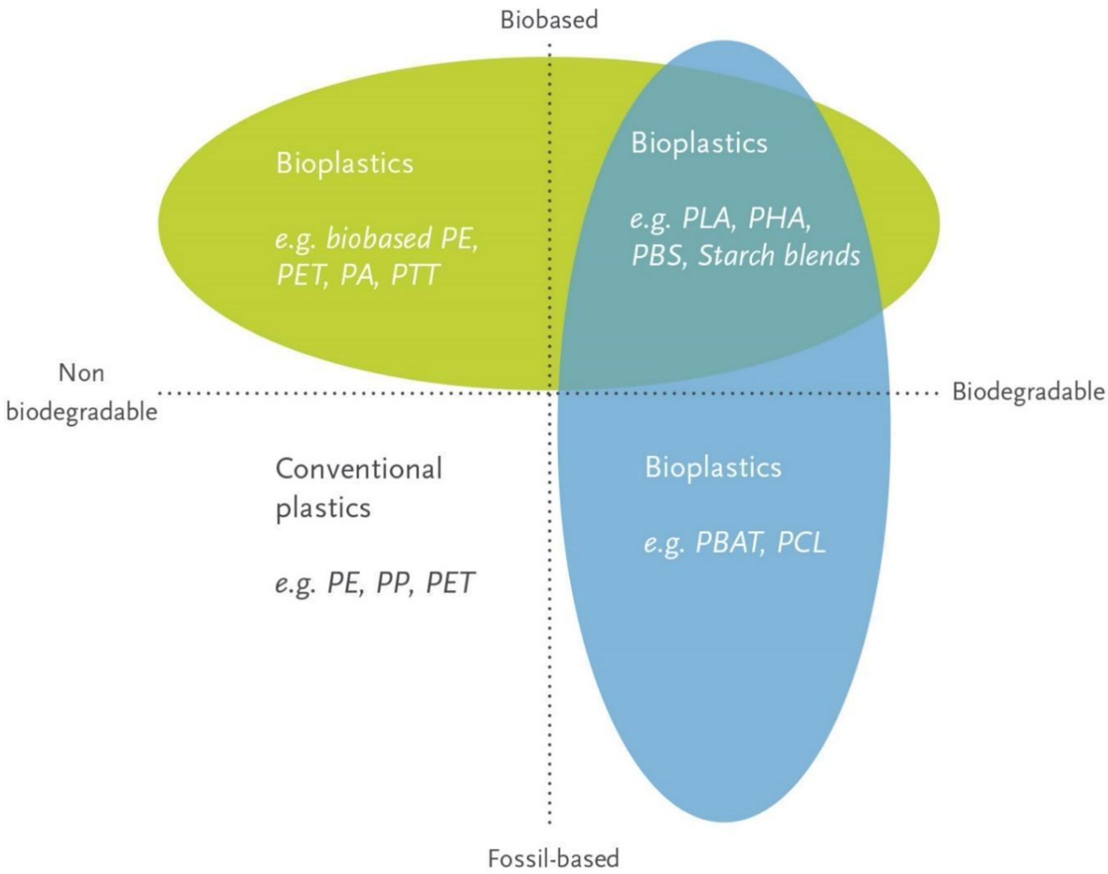

Figure 1: Categorizing plastics as fossil-based vs bio-based, and biodegradable vs non-biodegradable (Source: European Bioplastics 2019)

It is also important to distinguish between biodegradable, compostable and ‘oxo-degradable’ plastics. Biodegradation refers to the process whereby materials break down through the action of micro-organisms into carbon dioxide, water and biomass. Compostable plastics are materials that undergo degradation by biological processes during composting to yield carbon dioxide, water, inorganic compounds, and biomass at a rate consistent with other known compostable materials, and leave no visible distinguishable or toxic residue. As such, while the definition of biodegradation does not include either a specific time limit or specific conditions under which materials break down; compostable plastics are defined by the standard conditions and timeframe under which they will biodegrade. Finally, ‘oxo-degradable’ plastics are typically conventional plastics that are blended with an additive to mimic the biodegradation process; but that instead break down into smaller particles (microplastics), and are not truly biodegradable.

A number of single-use, biodegradable options were considered in this study; some of which are currently available in certain retail outlets, and some of which are not yet commercially available. These include bags derived from combinations of (1) Polybutylene Succinate (PBS) and Polybutylene Adipate Terephthalate (PBAT); and (2) PBAT and starch; as well as a fossil-based HDPE bag with an ECM additive intended to aid biodegradation. Finally, the study also includes brown (Kraft) paper bags, which are available in some South African grocery supermarkets.

Table 1 provides the full list of 16 bag types that are assessed in the study. For ease of reference, colour coding is used throughout the report to distinguish different categories of bags, as follows:

- Single-use: Yellow
  - Fossil-based plastic (single-use): Pink
  - Fossil-based plastic with bio-additive (single-use): Light orange
  - Biodegradable plastic (single-use): Medium orange
  - Paper (single-use): Dark orange

- Reusable, fossil-based plastic: Purple

Table 1: Bag types assessed in the LCSA study

Single-use / reusable	Type of material	Name	Description	Comments	Modelled % of recycled content
Single-use	Fossil-based plastic	HDPE_24_100	HDPE with thickness of 24 µm and 100% recycled content (reference bag)	High Density Polyethylene (HDPE) bags represent the current status quo in terms of being the standard bag type found in grocery supermarkets in the formal sector in South Africa, and is therefore used as the "reference bag" against which the alternatives are compared. These bags typically retail for approximately 60c (for the standard 'maxi' size labelled as having a 24 litre capacity). They are intended for single use but in principle could be reused a number of times. These bags vary in terms of the proportion of recycled plastic content. Specifically, the reference bag will be the HDPE_24 bag with 100% recycled content (HDPE_24_100); since this is the bag provided in stores owned by South Africa's largest grocery retail group (and is increasingly offered by other retailers as well); and can therefore be assumed to be the most common bag type in South Africa (at least among regulated carrier bags in the formal sector).	100%
		HDPE_24_75	HDPE 24 µm; 75% recycled content		75%
		HDPE_24_50	HDPE 24 µm; 50% recycled content		50%
		HDPE_24_25	HDPE 24 µm; 25% recycled content		25%
		HDPE_24_0	HDPE 24 µm; 0% recycled content		0%
		LDPE	Low density polyethylene (LDPE) bags	Low density polyethylene (LDPE) bags have similar qualities to HDPE, but in South Africa these are typically offered by clothing retailers and department stores, rather than grocery stores. Currently these bags tend to have 0% recycled content.	0%
	Fossil-based plastic with bio-additive	HDPE_ECM	HDPE bags with ECM additive	Fossil-based bags (made with HDPE) with an ECM additive, which is intended to aid biodegradation. Probiotic additive (ECM) at less than 1% creates microbial biofilm that promotes degradation. Early claims of complete biodegradation in landfill in less than 5 years seem to be unfounded. There is evidence of 49.28% biodegradation in 900 days under non-typical conditions (industrial composting needed). No evidence of further biodegradation (United States Court of Appeals, 2017). A company in South Africa is currently importing and marketing these bags for local use, while there is also interest in local production.	0%
Single-use	Bio-degradable plastic	PBS+PBAT_ZA	PBS+PBAT bags, using locally produced PBS and PBAT	Bags made from a combination of polybutylene succinate (PBS) and polybutylene adipate terephthalate (PBAT). The PBS and PBAT could be either locally produced or imported. These bags are biodegradable and compostable, under the right conditions. At the time of writing, the PBS+PBAT bags are still under development in South Africa and have been trialled by one of South Africa's major grocery retailers. Currently the succinate and 1,4 butane-diol for PBS are petro-based; as are the 1,4 butane-diol, adipic acid and terephthalic acid for PBAT; although there is a potential to switch to bio-based feedstocks.	0%
		PBS+PBAT_IMP	PBS+PBAT bags, using imported PBS and PBAT		0%

Single-use / reusable	Type of material	Name	Description	Comments	Modelled % of recycled content
		PBAT+Starch_ZA	PBAT+Starch bags, using locally produced PBAT and locally grown maize	Bags made from a combination of PBAT and starch. Both components could be either locally produced or imported. These bags are biodegradable and compostable, under the right conditions. Currently, the PBAT component, which makes up 85% of the total content, is petro-based; although there is potential to switch to bio-based 1,4 butane-diol, adipic acid and terephthalic acid for PBAT. The starch component, which makes up 15% of the total content, is bio-based. Next generation PBAT+Starch has a greater bio-based content (1,4 butane-diol. adipic acid and starch), and terephthalic acid certified as carbon neutral; and will be included in future studies.	0%
		PBAT+Starch_IMP	PBAT+Starch bags, using imported PBAT+Starch		0%
	Paper	Paper	Brown (Kraft) paper bags	Brown paper bags. Made from unbleached Kraft paper, these types of bags have largely fallen out of favour since the 1970s, as they are not as durable as plastic bags (particularly when carrying wet items) (Danish EPA, 2018). However, they seem to be regaining popularity among some consumers due to the perception that they are more environmentally friendly.	54.8%
Re-usable	**Fossil-based plastic**	HDPE_70	HDPE bags with a thickness of 70 µm.	A new bag type recently launched by one of South Africa's major grocery supermarket chains, which retails for R3 per bag. Customers receive a 50c discount on their grocery bill each time the bag is reused. Stronger and more durable than 24 µm bags; intended for reuse. They are currently produced with 100% recycled content.	100%
		PP	Polypropylene (PP) bags	Made by weaving PP fibres. Significantly stronger and more durable than conventional LDPE and HDPE carrier bags. Intended to be reused many times (Danish EPA, 2018).	0%
		Polyester_W	Woven fabric polyester bags	Woven polyester bags are made by spinning and weaving polyester fibres to form a fabric, that is then stitched to produce a bag. These bags are foldable to 'pocket-size' and typically come with a built-in storage pocket, and can be reused many times. The material is similar to that used in polyester clothing. For the bag assessed in this study, the polyester is from 100% recycled polyethylene terephthalate (rPET).	100% (rPET)
		Polyester_NW	Non-woven (spun-bond and stitched) polyester bags	Non-woven polyester bags are made by spinning and thermally bonding polyester fibres made from polyethylene terephthalate (PET). The spun-bond-material is then stitched to form a bag. The bag to be assessed in this study is made from 85% recycled PET (rPET) and 15% virgin PET. The polyester fibres are usually thinner and lighter than the original polymers, resulting in a very light and foldable bag that can be reused multiple times (Danish EPA, 2018).	85% (rPET)

3.2 Function

For comparison purposes, the different types of carrier bags are assessed in terms of their primary function; i.e. **to carry groceries (or other items) from the retailer to the home**.

3.3 Functional unit

In comparative LCA (or LCSA) studies, such as the current study, the products being compared differ in terms of performance characteristics in relation to fulfilling their primary function. For example, in fulfilling the function of carrying groceries from the retailer to the home, the different types of bags being assessed have different capacities with respect to the maximum volume or weight of groceries that they can carry in a single load.

The different bags also differ in terms of the amount of material they are made from (all else being equal, more material typically equates to a higher environmental impact, per bag), and the number of times they can be reused. Reusable bags tend to be thicker than single-use bags; and therefore comprise of more material. However, the more often the reusable bags are in fact reused, the better will be their environmental performance in comparison to single-use bags, as the burden associated with their life cycle is “spread out” over a higher number of uses. As such, the assessment can’t simply be conducted on a “per bag” basis. Instead, a common ‘functional unit’ needs to be defined, which will allow all bags to be compared on an equal basis.

In previous LCA studies of carrier bags conducted in other countries, two different approaches to defining the functional unit have been adopted. Typically, the functional unit is defined in terms of bags required to carry a defined quantity of groceries over a defined period of time (e.g. a year) (e.g. UK Environment Agency, 2011; Environment Australia, 2002). In the case of reusable bags, the overall impact of the bag is divided by the number of times it is reused, to ensure comparability with single-use bags.

More recently, the Danish EPA (2018) adopted a slightly different approach, defining the functional unit as “Carrying one time grocery shopping with an average volume of 22 litres and with an average weight of 12 kilograms from Danish supermarkets to homes in 2017 with a (newly purchased) carrier bag” (Danish EPA 2018: 32). Then, the number of reuse times required for the reusable bags to break even with the single-use bags is calculated.

Each of these approaches to defining the functional unit comes with advantages and disadvantages. In the first approach, the different bag types can be compared directly in terms of their impact per functional unit. However, assumptions must be made regarding the number of times each type of bag is reused. The second approach avoids the need to make such assumptions; however; in not defining the number of reuse times, it is more difficult to make comparative assertions – the emphasis is more on defining the number of times each type of bag *must* be reused for its impact to ‘break even’ with that of a reference bag.

There is certainly value in each of these approaches; since both allow for useful recommendations to be made. However, the primary objective of this study is to compare the environmental and socio-economic performance of different types of carrier bags, and to identify which type of carrier bag is 'best' from a sustainability perspective; rather than to identify the number of reuse times for each type of bag to break even with a reference bag. As such, the former approach (based on the number of bags required to carry a defined quantity of groceries over a defined period of time, taking into account an assumed number of times that each type of bag is reused); is considered more appropriate for the purposes of this study, and is therefore used to provide an overall ranking of the bag types. (In addition, however, we do also provide an assessment of the number of reuse times required for each type of bag to break even with the reference bag; based on the impacts associated with a single use of each bag type).

As such, the **functional unit** for the study is as follows:

> **"Carrying one person's annual groceries (870.48 litres) from the supermarket to the home in South Africa".**

The annual quantity of groceries purchased per person (870.48 litres) is an estimate, based on the current consumption and carrying capacity of the most common bag type in South African formal sector grocery stores, namely the single-use 24 µm HDPE 'maxi' size bag. This bag (specifically the variant with 100% recycled content) is used as the 'reference product', that is, the baseline bag against which all the alternatives are compared.

The current consumption of this bag type is calculated based on revenues from the plastic bag levy. In 2016-17, R232 million in levies was recovered. Based on a levy in that year of 8c per bag, 2.9 billion bags were purchased in South Africa (BusinessTech 2019). Although the consumption of bags was shown to decline in 2017-18, we use the 2016-17 estimates in order to be consistent with the Materials Flow Analysis data used in the end of life modelling (see Section 4.4). With a population of approximately 56 million in 2016-17 (Statistics South Africa 2016, 2017), 2.9 billion bags equates to 52 bags per person per year, or one bag per person per week (on average). Note that the consumption of unregulated bags (not covered by the government levy on plastic bags) is not included in this estimate; which can therefore be seen as conservative.

The carrying capacity of the reference bag was measured by taking the dimensions of the bag (excluding handles). Although the maxi-size bags are commonly understood to have a capacity of 24 litres, this was found to only be the case if the height is measured from the base of the bag all the way up to the top of the handles. In practice, however, it will not be easy to carry groceries when the bag is fully loaded to the top of the handles. A more realistic assessment of the capacity of a bag is obtained by measuring the height from the base of the bag to the point where the handles start (i.e., excluding the handles). Measured in this way, the capacity of the reference bag is 16.74 litres.

The annual consumption of groceries per person (used to define the functional unit) is therefore calculated as 52 * 16.74 = 870.48 litres.

Then, for comparison purposes, for each bag type, the number of bags required to fulfil the functional unit (that is, the number of bags that need to be purchased to fulfil annual grocery shopping requirements) is calculated based on two factors, namely, the volumetric capacity of each bag type, and the extent to which the bags are reusable (see Section 3.4).

Note of course that the actual volume of groceries carried per trip will differ from the carrying capacity of the bag; the carrying capacity is rather used as an estimate of the volume of groceries carried per trip. It is important to note that the volume of groceries specified in the functional unit (870.48 litres in this case) can be a fairly arbitrary decision; it does not affect the final results, since the number of each type of bag required to fulfil the functional unit is adjusted accordingly based on their respective carrying capacities and the number of times they are reused.

3.4 Reference flows

The different bag types under consideration vary in terms of both their dimensions (and therefore volumetric capacities), as well as in terms of the mass of material needed to produce a bag. This implies that the bags differ in terms of the quantity of material required to fulfil the functional unit.

In comparative LCA (or LCSA) studies, the different products being assessed are each assigned a reference flow value, which indicate the relative material requirements for each product to fulfil the functional unit, relative to the pre-defined reference product; and thereby to serve as a basis for comparing impacts across the different products, taking into account their differing volumetric capacities and material requirements. In this study, as mentioned above, the reference product is the standard South African HDPE 24 µm 'maxi' sized bag with 100% recycled content. The reference flows indicate the material requirements for each alternative type of bag relative to the reference bag, associated with the number of bags required to fulfil the functional unit (Table 2).

Since the different bag types have different volumetric capacities, the capacity of each bag relative to the reference bag was used to determine the number of bags required in each case to fulfil the functional unit. Thereafter, the associated material mass was used to define the reference flows for each bag type. Volumetric capacities and masses of each bag were assessed in a laboratory by the CSIR's Chemicals cluster; using stringent testing methods based on a sample of 20 of each bag type. The resulting data is provided in Table 2.

The number of each bag type required to fulfil the functional unit also needs to take into account the extent to which each type of bag is likely to be reused. Although bags that are intended for single-use can (and indeed should) be reused a number of times, and although bags intended for reuse will not necessarily be reused, it is necessary for the purposes of the study to make certain assumptions regarding the number of times each type of bag would, on average, be used. These assumptions are adjusted in sensitivity analyses (see Section 7).

As such, for the main set of results (presented in Section 6), we assume that the bags that are intended for single use will only be used once each; such that a new bag is purchased for each shopping trip. On the other hand, we assume that the bags intended for reuse will only be purchased once, and reused over the course of the entire year to fulfil the functional unit (i.e., 52 times, assuming a weekly shopping trip).

The resulting number of bags needed per year, and the reference flows, are provided in Table 2.

Note of course that, in reality, bags that are intended for single use may be used multiple times, whereas reusable bags may in theory only be used once, or a small number of times, with an additional bag being purchased frequently. As such, we also conduct sensitivity analysis on our assumptions regarding the number of times each bag type is reused, and the number of each type of bag needed to fulfil the functional unit, in order to analyse the extent to which the results change in response to changes in these assumptions (see Section 7).

It will also be noted that for most bag types, the number of bags required, as indicated in Table 2, is not a whole number. This is because these numbers are calculated based on the volumetric capacity of each bag type relative to the functional unit. Of course, for an individual consumer, a whole number of bags will be purchased (e.g., 1 PP bag will be purchased, rather than 0.88 bags). However, the indicated numbers of bag types required per individual should be seen as national averages.

Table 2: Number of each bag type required to fulfil the functional unit, and corresponding mass of material (reference flows)

Single-use / reusable	Bag type	Mass of bag when empty (grams)	Capacity (litres)	Number of times each bag is used	Number of bags needed per year to fulfil the functional unit	Reference flow (mass of material needed to fulfil the functional unit) (g per person per annum).
Single-use	HDPE_24_100	11.00	16.74	1	52.00	572.00
	HDPE_24_75	11.00	16.74	1	52.00	572.00
	HDPE_24_50	11.00	16.74	1	52.00	572.00
	HDPE_24_25	11.00	16.74	1	52.00	572.00
	HDPE_24_0	11.00	16.74	1	52.00	572.00
	LDPE	15.32	24.00	1	36.27	555.66
	HDPE_ECM	6.35	13.00	1	66.96	425.20
	PBS+PBAT_ZA	18.00	14.73	1	59.10	1 063.80
	PBS+PBAT_IMP	18.00	14.73	1	59.10	1 063.80
	PBAT+Starch_ZA	9.50	19.00	1	45.81	435.24
	PBAT+Starch_IMP	9.50	19.00	1	45.81	435.24
	Paper	38.42	19.97	1	43.59	1 674.70
Reusable	HDPE_70	48.41	23.23	52	0.72	34.89
	PP	66.47	18.98	52	0.88	58.63
	Polyester_W	28.00	13.69	52	1.22	34.24
	Polyester_NW	66.66	26.75	52	0.62	41.72

3.5 System boundaries

Each bag type was modelled based on the full life cycle, from cradle-to-grave (i.e. from resource extraction to end of life). Generally speaking, the life cycle of each type of bag includes the following stages (although the specific life cycle will differ in each case):

1. Extraction of raw materials. These include oil, natural gas and/or coal in the case of fossil-based plastics; or bio-based materials (e.g. wood fibres, maize) in the case of paper or bio-based plastics
2. Processing of raw materials into polymers or paper, which are the materials used for bag production
3. Bag production
4. Purchase and use by consumer
5. Reuse, where applicable
6. End-of life (e.g. litter, disposal at landfill, or recycling; as well as leakage to the environment)

In addition, the life cycle includes transport between the various facilities or locations at which each of the above stages occur (see Section 4.5).

Some of the bag types included in the study consist of more than one component material; e.g., a different type of material is used for the handles or for inserts/linings within the bags. For example, polypropylene bags tend to have nylon or polyester handles; while some paper bags have a non-paper, waterproof lining. For the purposes of this study; we focus only on the main component materials of the bags themselves; and not on other materials that may have been used for these other components; such as handles and stitching. Additives such as fillers, glues, water-proofing additives, inks and dyes are also excluded from the scope of the study.

Generally speaking, reuse options include "**primary reuse**", which refers to reuse for the same purpose as that for which the bag was originally designed (i.e., as a carrier bag for shopping); and "**secondary reuse**", which refers to reuse of the bag for another purpose; e.g. as a bin liner, for picking up dog faeces, as a carry bag for personal belongings, etc. This distinction is important; as it has a bearing on the number of times a bag can be reused, and also on the available end of life options. In principle, a bag can be reused multiple times as a carrier bag, after which it can then be recycled, reused for a secondary purpose, or disposed. On the other hand, once a bag has been used as a bin liner, or to pick up dog faeces, it can only be disposed (unless it is used in a recycling bin for dry recyclables, in which case it can potentially be reused multiple times, or recycled). In general, it is recommended that bags be reused for their primary purpose as many times as possible. Only when this is no longer possible, should bags be reused for a secondary purpose, or recycled (Danish EPA, 2018).

In this study, we model primary reuse (where applicable); but not secondary reuse. This is because of the multitude of possible secondary reuse options for the different types of bags; and the lack of data on the types and extent of secondary uses for each bag type that could be used to inform sensible assumptions. In addition, incorporating secondary reuse substantially increases the modelling complexity; as in many cases the secondary use will displace another product (e.g. a new bin liner). The life cycle of the displaced product would then also need to be included in the study, thereby expanding the boundaries of the study.

As such, it was not possible to include secondary reuse within the scope of this study; although this is not expected to significantly influence the overall rankings.

Recycling enters the life cycle in two ways; firstly; in the production stage, to the extent that bags are made from recycled content; and at end of life, where the bags themselves are recycled, thereby reducing both waste disposal impacts and the need for virgin raw materials.

In terms of geographical boundaries; we assume that the bags, as well as the primary materials, are mainly produced in South Africa; with the exception of the PBS+PBAT PBAT+Starch bags, for which import of polymers has been modelled as an additional scenario. End of life, disposal and recycling are modelled as taking place in the South African context.

For assumptions and modelling choices related to the product life cycles of the specific bag types (e.g. around material production, bag manufacture and end of life modelling), as well as around data sources and allocation, please refer to Section 4.

4 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 bag (material production, bag manufacture, transport, end of life etc.). For a comprehensive list of the datasets modelled and their main modelling features, see Appendix A.

4.1 Data Sources and modelling approach

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. In particular, stakeholders were consulted in order to determine recycling rates for the different materials, 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.

The life cycles were modelled using SimaPro LCA Software v 9.0. A combination of primary and secondary data sourcing was used to inform the inventory foreground data. Data related to product manufacturing were gathered from the ecoinvent v3.6 database (available online at https://v36.ecoquery.ecoinvent.org/) and Van der Velden et al (2014). Secondary data was sourced from literature and the ecoinvent v3.6 database. Background data was based on datasets available in the SimaPro Software v9.0 - i.e. the ecoinvent v3.5 database.

Furthermore, wherever possible, background datasets from ecoinvent v3.5 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.

4.2 Allocation

LCAs can be consequential or attributional in nature. In consequential LCA, the focus is on understanding how production and use of the product in question affects global environmental outcomes. In attributional LCA, by contrast, the focus is on understanding what portion of overall environmental impacts can be attributed to the specific product in question (Ekvall 2019). Since the goal of this study is to compare different carrier bag options in terms of the specific impacts associated with each, rather than to understand the impacts of carrier bags on global environmental outcomes; we applied attributional LCA.

In attributional LCA studies, allocation is the process of apportioning the input and/or output flows of a process to the specific product system under study. Typically, a single process (e.g. a manufacturing process) gives rise to multiple different outputs (including products and by-products). As such, it would not be fair to apportion all environmental burdens (impacts) associated with a process to the specific product being assessed. Instead, it is necessary to apportion the impacts arising from the process between the various different products that are produced (Weidema, 2018).

However, the ISO standards recommend avoiding allocation, if possible, by expanding the product system to include the additional functions related to the co-products (ISO 14040 and ISO 14044). As such, system expansion was performed in this study to maintain comparability of the product systems in terms of product outputs, through balancing a change in output volume (Weidema 2006), for the specific cases of HDPE and polyester bags. In the case of HDPE bags (made with varying degrees of recycled HDPE) and polyester bags (made from recycled PET, rPET); there is the combined production of bags using resin from both recyclate and virgin sources; and there are varying amounts of recyclate used in bag production which must be accounted for. Therefore, to avoid the issues associated with allocation of recyclate in the HDPE and polyester bag production, we expanded the system boundary to include the HDPE or PET bottle from which the recyclate was generated; and analysed the bags produced with varying percentages of recyclate, by incorporating a market for recyclate in the model. This decision is based on the grounds that this is a prospective and comparative LCSA study which is intended to inform product development and public policymaking, including potential future substitutions among alternative product systems (Weidema 2000).

Where allocation could not be avoided, we applied economic rather than mass-based allocation; as this ensures that burdens are allocated mainly to the primary product being produced, rather than disproportionately allocating burdens to lower value, high-volume by-products, as tends to be the case in the mass-based approach. As such, we apply the APOS (Allocation at the Point Of Substitution) system model within ecoinvent (ecoinvent 2020b), which attributes burdens to specific processes according to market values.

To be consistent with the economic nature of the APOS system model, economic allocation was also used to attribute the burdens to the recyclate content in the HDPE and polyester bags; based on the global market prices of virgin and recyclate materials); as well as at the end of life (EOL). In many studies, 'cut-off' allocation is applied to the recyclate, so that the recyclate is essentially 'free' of environmental burdens, aside from the required upgrading of the material (i.e. collection, washing, drying and chipping or pelletizing). Arguably, however, the model should reflect the environmental burden of the recyclate from its previous life cycle (e.g. as a bottle). Economic allocation at end of life ensures that the environmental burdens are shared between multiple products based on their market values, which is the driving force for industrial production. It also better reflects the need to value waste as a resource, and captures the current nature of the plastics industry and the fate of plastics at end of life. Currently, plastic waste is increasingly viewed as a resource; with recyclate able to substitute for virgin polymers in the market. Therefore, our modelling approach was to use economic allocation, where the recyclate carries environmental burdens according to its market value relative to virgin material. In other words, since HDPE and PET bottles are produced and used before a portion of the material reaching end of life is upgraded as recyclate, which is in turn used in the production of HDPE and polyester bags respectively; the life cycles of these two products are also included, to account for the environmental burdens carried by the recycled material. However, burdens associated with disposal and potential leakage of the bottles are excluded, since these are avoided through recycling.

The end of life of the bottles was modelled following the approach suggested by Nordelöf et al (2019), where waste collection and treatment as well as recycling and upgrading are explicitly modelled (see Section 4.4). Specifically, we applied APOS to the recyclate, using the prices of virgin and recycled HDPE and PET in the modelling, to account for the respective burden carried by the two materials.

The end of life modelling is described in Section 4.4. See Weidema (2000) for more discussion around avoiding allocation through system expansion, and Ponsioen (2015) for a discussion on allocation procedures related to recycling.

4.3 Material production and bag manufacture

Specific datasets were modelled for production of the raw materials (monomers and polymers) associated with each type of bag; including HDPE (both virgin and recycled, as well as for bag and bottle grade), LDPE, PET (amorphous and bottle grade, both virgin and recycled), PP, PBS, PBAT, and Paper (Kraft paper – unbleached).

Monomer production was modelled using the Sasol Coal-to-Liquids (CTL) process (which includes South African coal as an input), as well as imports of oil. In turn, Sasol precursors and monomers were used to model the synthesis of polymers. Reaction yields of 95% were assumed. Sasol infrastructure was included in background data (land occupation by industrial area and petrochemical facility). Pipelines for the inland transport of oil as well as Sasol monomers were also included; any additional built infrastructure was excluded.

In the case of HDPE and LDPE, we assume production of ethylene and polyethylene at the Sasolburg complex, with the feedstock consisting of 15% ethylene from oil imports (from the Middle East, arriving in Durban and transported by pipeline to Sasolburg).

For the HDPE 24 µm bags, the recyclate content was varied from 0% to 100% to illustrate how overall environmental and socio-economic performance differs depending on the proportion of recycled content in the bags. Different options for recycled content were illustrated by explicitly modelling five different HDPE 24 µm bag types, with recycled content of 0%, 25%, 50%, 75% and 100%, as follows: HDPE_24_0; HDPE_24_25; HDPE_24_50; HDPE_24_75 and HDPE_24_100, respectively (see Section 3.1)

Polypropylene (PP) was modelled as produced by SASOL, i.e. using coal as a main feedstock, plus 15% imported oil. PET was modelled as produced in South Africa using imported terephthalic acid and locally produced ethylene (a combination of Sasol production and imported oil).

The PBS+PBAT and PBAT+Starch bags are both modelled under the assumption that the PBS and PBAT components are fossil-based, rather than bio-based; as this better reflects the current situation (see Table 1); and under two different assumptions around whether the polymers are imported or locally produced (by SASOL). This was done to assess the variation in environmental and socio-economic performance when polymer production takes place in South Africa, as compared to when it takes place overseas and polymers are imported. This analysis is conducted by modelling the scenarios for local and imported polymers explicitly as separate bags: PBS+PBAT_ZA and PBS+PBAT_IMP respectively; and PBAT+Starch_ZA and PBAT+Starch_IMP respectively (see Section 3.1).

In all cases, bag manufacturing is modelled as occurring locally. The two different scenarios were modelled as follows:

- When polymers are produced in South Africa: modelled as Sasol production of polymers in South Africa; bag manufacture is done locally
- When polymers are imported: modelled as import from global market for polymers; bag manufacture is done locally.

For the PBAT+Starch_ZA bag, maize production for the starch component was modelled according to South African production, which is dominated by rain-fed agriculture; whereas in the case of PBAT+Starch_IMP, both components are imported.

Similarly, for the HDPE_ECM bag, South African maize starch is used to model the ECM additive.

Supporting datasets were modelled for plastic bag manufacturing, as relevant to each type of bag; namely stretch blow moulding, extrusion of plastic sheets, and textile production_non-woven_spun-bond.

Assembly datasets were modelled to represent bag manufacturing. For each bag type, a manufacturing step with specific energy and material requirements to make a single bag was modelled.

A life cycle stage for each bag was also modelled, inclusive of bag distribution to retailers, a disposal scenario for each bag, and the number of uses over the one-year time horizon.

Finally, a disposal scenario stage for each bag was modelled to account for the different shares of disposed material that end up in recycling, littering, sanitary and unsanitary landfill, open dumping and open burning (see Section 4.4).

Appendix A provides details on all the material and processing/assembly processes that were modelled in SimaPro for each bag type; including a description of how these have been modified to be consistent with the South African context.

4.4 End of Life

The end of life flows were modelled based on the Materials Flow Analysis (MFA) compiled by von Blottnitz et al. (2017) (see Figure 2).

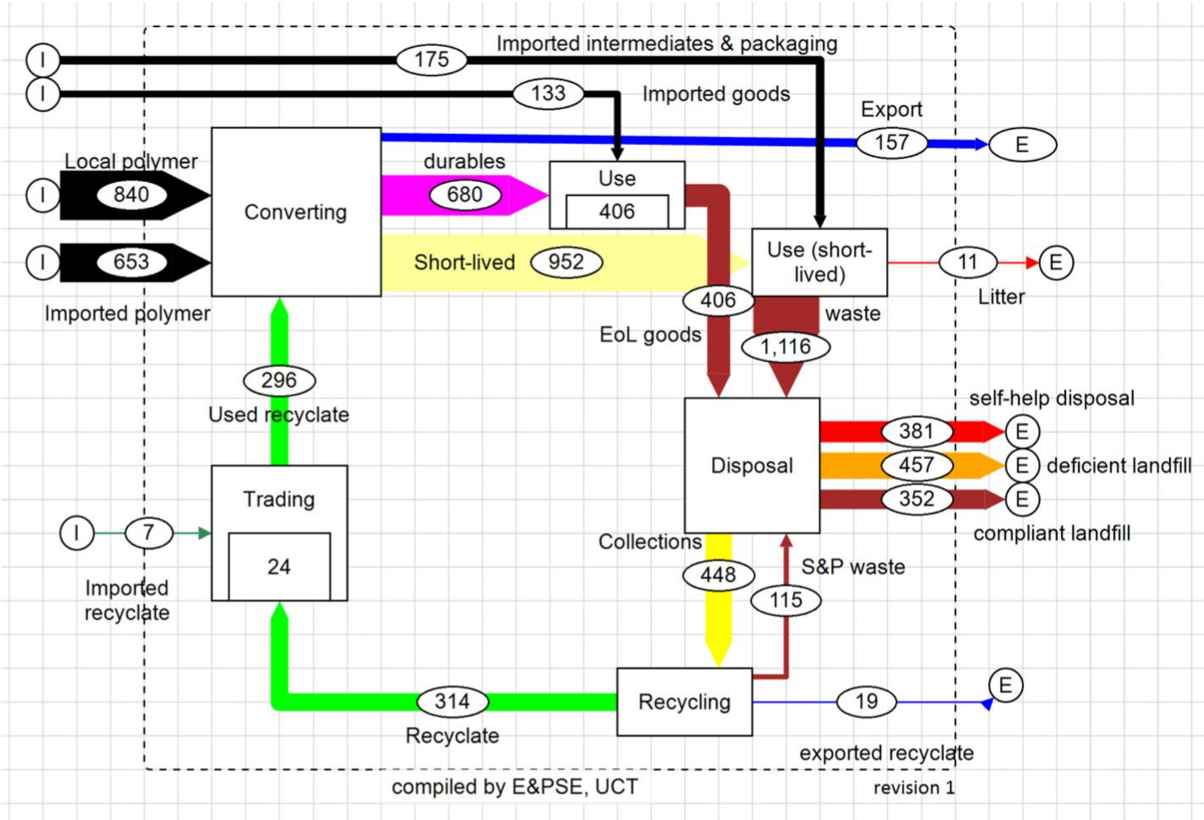

Figure 2: Material Flow Analysis of plastics in South Africa (Source: von Blottnitz et al. 2017).

Based on the MFA, and contrary to perceptions, less than 1% of total plastic reaching end of life enters the environment directly through littering. The vast majority enters some form of formal or informal waste management system (disposal or recycling); although there is in turn significant leakage from such systems to the environment.

Only 65% of the population have regular waste collection services; so 35% of the population rely on self-help disposal (StatsSA 2018), i.e. open dumping. Self-help disposal can further be categorised as 'burnt' or 'not burnt' We assume that all open dumps are burnt annually, but only 60% of the waste actually burns (IPCC, 2006). Open dumping and open burning are new datasets in the ecoinvent v3.5 database, which allowed for these options to be explicitly modelled. 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 3).

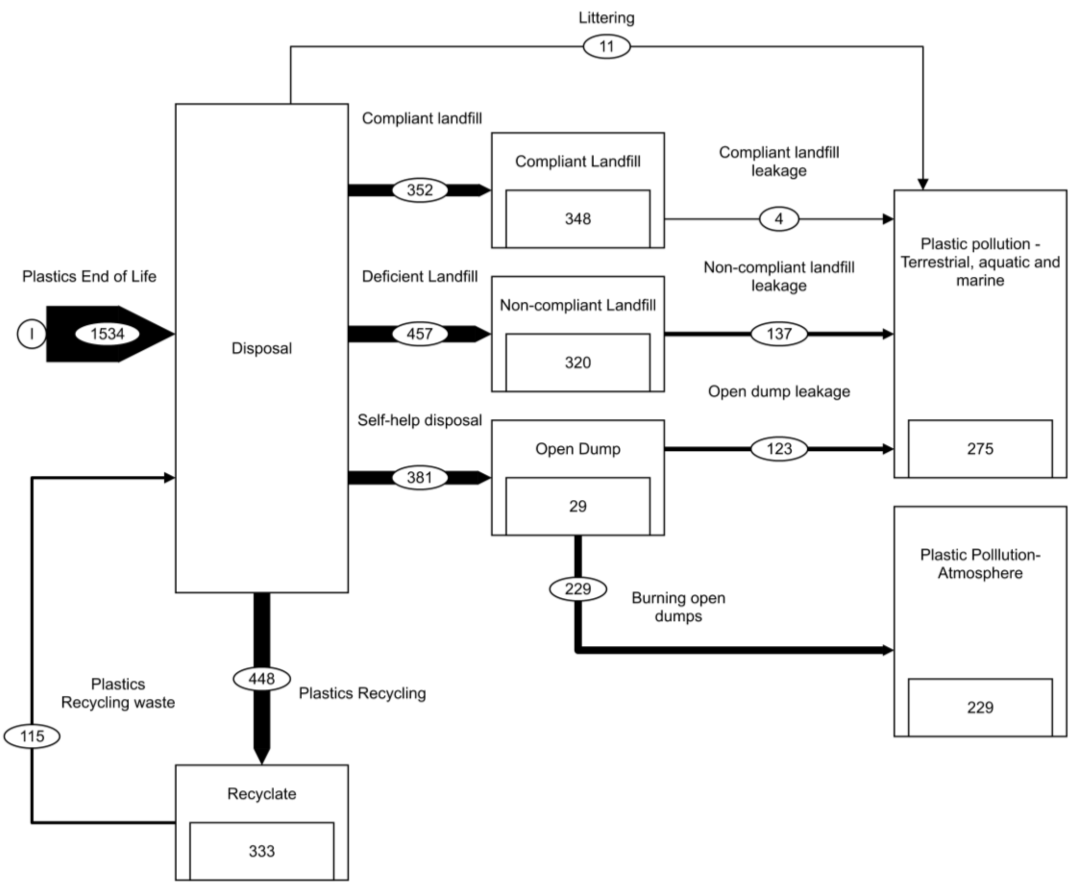

Figure 3: Plastics end of life in South Africa (based on data from von Blottnitz et al 2017). Values shown are in Kilotonnes (Kt).

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; in order to account for at least some of the associated environmental impact.

For each bag type, output recycling rates were obtained or estimated from publicly available sources (PlasticsSA 2019; PAMSA 2018), as well as personal communications with experts (Pretorius 2020; Scholtz 2020). The end of life recycling rates applied to each bag type are presented in Table 3 (although these are varied in a sensitivity analysis). In addition, in the case of HDPE and polyester bags, where system expansion is applied (refer to Section 4.2), recycling rates of 29.01% and 33.5% respectively are applied for HDPE and PET bottles.

Note that the recycling rates used in the modelling differ slightly from those published by PlasticsSA (2019) for the corresponding polymers. This is because PlasticsSA measures the recycling rate for these polymers as recycled tonnages as a % of the virgin market consumption. However, for purposes of end of life modelling, we need to know the end of life fate of each bag entering the market; irrespective of whether that bag was itself derived from virgin or recycled polymer. As such, for our purposes, the denominator should be adjusted to include not only the virgin market consumption for each polymer; but also that derived from recycled polymers. Note also that for the HDPE bags, the same rate is applied as for LDPE, since HDPE bags tend to be recycled within the LDPE stream (Pretorius 2020).

Table 3: Output recycling rates per bag type applied in the end of life modelling (derived based on PlasticsSA 2019, PAMSA 2018, Pretorius 2020)

Bag type	Output recycling rate applied in end of life modelling (%)
HDPE_24_100	28.80
HDPE_24_75	28.80
HDPE_24_50	28.80
HDPE_24_25	28.80
HDPE_24_0	28.80
LDPE	28.80
HDPE_ECM	0.00
PBS+PBAT_ZA	0.00
PBS+PBAT_IMP	0.00
PBAT+Starch_ZA	0.00
PBAT+Starch_IMP	0.00
Paper	54.80
HDPE_70	28.80
PP	19.67
Polyester_W	0.00
Polyester_NW	0.00

In modelling the end of life of the different types of bags, the bags were apportioned to the various waste management options according to the above-mentioned splits. First, the recycling rates for each type of bag are applied. Then, the fraction lost to direct littering (before entering the waste management system) is accounted for. Finally, the waste enters either one of the above-mentioned disposal options, in accordance with the above-mentioned splits; from which the associated leakage rates are then applied (see Figure 3).

The end of life modelling followed the EOL Recycling approach (Nordelöf et al, 2019; Weidema, 2000); where all the EOL steps, i.e. waste collection and sorting, recycling, as well as upgrading of the recycled material (i.e. recyclate production) are modelled explicitly (see Section 4.2). This means that credits should be awarded to production systems for providing waste streams containing materials that are recycled back to the same or other production systems as a secondary raw material. In the product system where those secondary materials are used as an input, the recycled material carries only the burdens caused by the recovery and upgrading processes.

However, in our study, there are two cases where system processes are interconnected at the level of exchanging recycled material (i.e. in the case of HDPE and polyester bags; with HDPE and PET bottles respectively). Since the aim is to develop a more comprehensive picture, while also capturing what the recyclate material was in its first 'life', we accounted for the burdens carried by the recyclate stemming not only from the upgrading process, but also from the life cycle of the original product. For example, in the case of recyclate derived from a bottle, we accounted for an allocated share of the material extraction and product manufacturing, distribution and use phase burdens associated with the bottle life cycle (see Section 4.2).

4.5 Transport

This study considered transport from the raw material producer (including imports of oil) to the polymer producer; from the polymer producer to the bag manufacturer; from the bag manufacturer to the distributor; and at end of life, for modelling waste collection and transport to disposal sites (see Appendix A for assumptions).

For example, the datasets for raw material production include transport of raw material constituents (e.g. oil and pipelines); while the dataset for coal production in South Africa includes the transport of coal with conveyor belts.

Transport to retailers is modelled in the Life Cycle datasets for each bag according to the actual mass transported.

Finally, transport during the use phase (from the retailer to the home, and multiple two-way trips in the case of reusable bags) was set to zero in the model, to avoid allocating burdens associated with grocery shopping to the bags. Consumers are assumed to travel to the retailer for the purpose of purchasing groceries, rather than specifically to purchase a bag. The bag is required for carrying the groceries, rather than for its own sake.

4.6 Sensitivity Analysis

Sensitivity Analysis was carried out to test the robustness of the model and to highlight how results differ when key parameters vary. In particular, the sensitivity analyses focused on the assumptions regarding reuse and recycling of the different bag types. Specifically, sensitivity analysis was conducted on four key parameters:

1. **Lifespan of the HDPE 70 µm reusable bag**: There is uncertainty regarding the lifespan of the HDPE 70 µm bag (i.e., the number of times the bag can be reused); specifically, whether it will be able to last for as long as the other reusable bag types. Recall from Table 2 that the reusable bags are all assumed to be used 52 times. As such, for the main set of results, we assume that the HDPE_70 bags will last for one year (52 uses); while in a sensitivity analysis, we model two shorter lifespans: One in which the lifespan is 50% of the baseline (26 uses); and one in which the lifespan is 25% of the baseline (13 uses). These variations were modelled and the results compared to the baseline scenario in the sensitivity analysis.

2. **Lifespan of the PP and Polyester reusable bags:** In contrast to the HDPE_70 bag, there is a wide perception that the other reusable bag types, namely the Polyester and PP bags, can last beyond the one-year time frame assumed for this study. As such, we look at two alternative scenarios in which the lifespan of these bags is extended to two and four years. These variations were modelled and the results compared to the baseline scenario in a sensitivity analysis.

3. **Re-using "single-use bags":** The bag types referred to in this report as being intended for "single use" (i.e. the HDPE 24 µm, LDPE, HDPE_ECM, PBS+PBAT, PBAT+Starch and Paper bag types) can, in fact, potentially be reused a number of times. As such, we conducted sensitivity analysis on two additional scenarios; one in which we assume that each single-use bag would be used twice, and another in which they would be used four times, in addition to the baseline scenario in which each bag would only be used once.

4. **End of life recycling rates** were varied in order to determine both the sensitivity of the model results to the recycling rates applied (since actual recycling rates for the various bag types are not well understood); and also to illustrate how the results would be affected by changes in recycling rates. In the base case, our best estimate of the 'actual' recycling rate for each bag type is applied, based on best available data and/or discussions with experts (see Section 4.4). In the sensitivity analysis, we applied a range of alternative recycling rates (0%, 60% and 100%) for each bag type. The 60% scenario was designed to show how improving the sector from the current status quo will impact the environmental performance of each bag type. A rate of 60% was selected to reflect an approximate doubling of the average recycling rate among those bag types that are currently recycled, and could be seen as a realistic best practice scenario. In addition, two extreme cases (0% and 100%) were assessed. While a 100% recycling rate is not necessarily realistic, the 0% and 100% scenarios were applied in order to assess the robustness of the results to extreme changes in recycling rates.

The main results of the study, based on the standard assumptions described in Sections 3 and 4, are presented in Section 6; while the results of the sensitivity analysis are presented in Section 7.

Note that changes to two other relevant parameters, namely the recycled content of the HDPE 24 µm bags, as well as the use of locally produced vs imported polymers for the biodegradable bags, were incorporated in the study through modelling these variations explicitly as separate bag types within the set of bag options (see Sections 3.1 and 4.3); rather than through sensitivity analysis.

5 Life Cycle Impact Assessment Methodology

The general approach to life cycle impact assessment (LCIA) is to assess material and energy flows through inventory analysis; to identify impacts associated with these inputs and outputs ('impact categories', or 'midpoint' impacts), and finally to identify the associated damages ('damage categories' or 'endpoints', that is, where a specific impact causes damage to human and/or environmental health or well-being). For example, the use of water (an input) in a production process contributes towards an increase in overall water consumption (midpoint impact), which in turn can lead to depletion of water resources (endpoint damage category). Similarly, emissions of greenhouse gases (an output) contribute towards global warming (midpoint), which in turn gives rise to climate change, causing damage to human and environmental health and well-being (endpoints).

In this study, the LCSA was carried out based on both environmental and socio-economic impacts.

The environmental LCA was carried out primarily using SimaPro software (v9.0) and current ecoinvent (v3.5 and v3.6) databases. The ReCiPe 2016 impact assessment method was used for impact assessment (Figure 4), with global normalisation (Huijbregts et al., 2016, 2017). The ReCiPe 2016 impact assessment method covers a wide range of environmental indicators, and is described in Section 5.1.

In addition, however, one of the aims of this study is to extend the analysis offered by existing impact assessment methods, by incorporating a number of additional indicators of relevance to the issue of single-use plastics, and to the South African context.

In particular, a notable omission from all current impact assessment methods (including ReCiPe 2016) is the absence of an indicator relating to the impacts of plastic leakage into the environment. As such, given the current global focus on impacts related to plastic pollution, particularly in the marine environment, we develop an additional environmental indicator to be used in the analysis, to reflect the impacts associated with plastic pollution. Given the lack of scientific data quantifying specific environmental impacts related to specific quantities of plastic entering the environment, we use persistence in the environment as a proxy for impact – all else being equal, we assume that the longer a specific plastic item persists in the environment, the more likely it is to cause damage. The methodology used in developing this indicator and assessing the bag types is provided in Section 5.2.1.

Furthermore, in extending the assessment from a conventional environmental LCA to a Life Cycle Sustainability Assessment (LCSA); we add two socio-economic indicators which are seen as being particularly pertinent in the South African context, namely, impacts on employment, and impacts in terms of the affordability of the bags to consumers. These are two of the key socio-economic issues currently entering the debate around carrier bags in South Africa. The methodology used in assessing each of the bag types on these indicators is provided in Sections 5.2.2 and 5.2.3 respectively.

Finally, in order to provide an overall ranking of the bags, it is necessary to integrate the results of the ReCiPe 2016 impact assessment with the results for the three new indicators (persistence, employment and affordability). In Section 5.3, we describe the approach used to integrate the indicators, and to develop an overall ranking based on all of the environmental and socio-economic indicators.

5.1 Conducting the environmental LCA using ReCiPe 2016

ReCiPe 2016 is a harmonized life cycle impact assessment method consisting of a wide range of environmental indicators (impact categories). It provides characterization factors for each indicator that are representative for the global scale, while maintaining the possibility for application of characterization factors at a country or continental scale (Huijbregts et al. 2016).

The methodology comprises of 18 impact categories at midpoint level, three damage categories (endpoints), as well as an aggregated single score index (see Figure 4 and Table 4). Endpoints (damage to human health, damage to ecosystems, and damage to resource availability) are calculated by aggregating and weighting normalised midpoint scores. In turn, the single score is calculated by aggregating and weighting across the three damage categories.

As will be seen in Sections 5.3 and 6.3, the overall results and rankings for this study are determined based on a novel approach to aggregating scores across all midpoint impact categories; including both the ReCiPe 2016 midpoint indicators, as well our three new indicators (persistence, employment, and affordability).

Nevertheless, for certain purposes (e.g. sensitivity analysis), this approach became unwieldy; and as such it was necessary to default back to the use of an established impact assessment method (ReCiPe 2016 in this case); and particularly to the use of a single score in the case of sensitivity analysis (in order to assess how changes in certain assumptions affect overall rankings in terms of environmental performance). In these circumstances, the ReCiPe 2016 single score was applied. However, it is important to note that the use of a single score within LCA studies is contentious, particularly given the subjectivity inherent in the weighting of indicators. The ReCiPe 2016 single score, for example, is based on weightings established in a European context, and its relevance to the South African context is therefore questionable. As such, any results provided in this study that are based on the ReCiPe 2016 single score should be treated with caution. Instead, as mentioned above, the main results for this study are instead based on our own aggregation approach across all of the environmental and socio-economic indicators (see Sections 5.3 and 6.3).

Within the ReCiPe 2016 method, in order to calculate endpoints and single scores on the basis of midpoint impact scores, three different options for weighting can be used: Individualist (I) (anthropocentric perspective), Hierarchist (H) (consensus model), and Egalitarian (E) (based on the precautionary principle) (Huijbregts et al. 2016). The Hierarchist (H) perspective, which is the default option, was chosen for this study in cases where endpoint and single scores are presented; as this approach is viewed as representing a balanced perspective.

Table 4 shows the ReCiPe 2016 impact categories applied in this study; as well as their units; while Figure 4 provides an overview of the relationships between the midpoint impact categories and the endpoint damage categories (areas of protection).

For more details on the ReCiPe 2016 method, including a more detailed description of each of the impact categories, as well as of the characterization factors, normalisation factors and weightings applied in aggregating from midpoint impact categories to endpoint damage categories and the overall single score, refer to Huijbregts et al. (2016 and 2017).

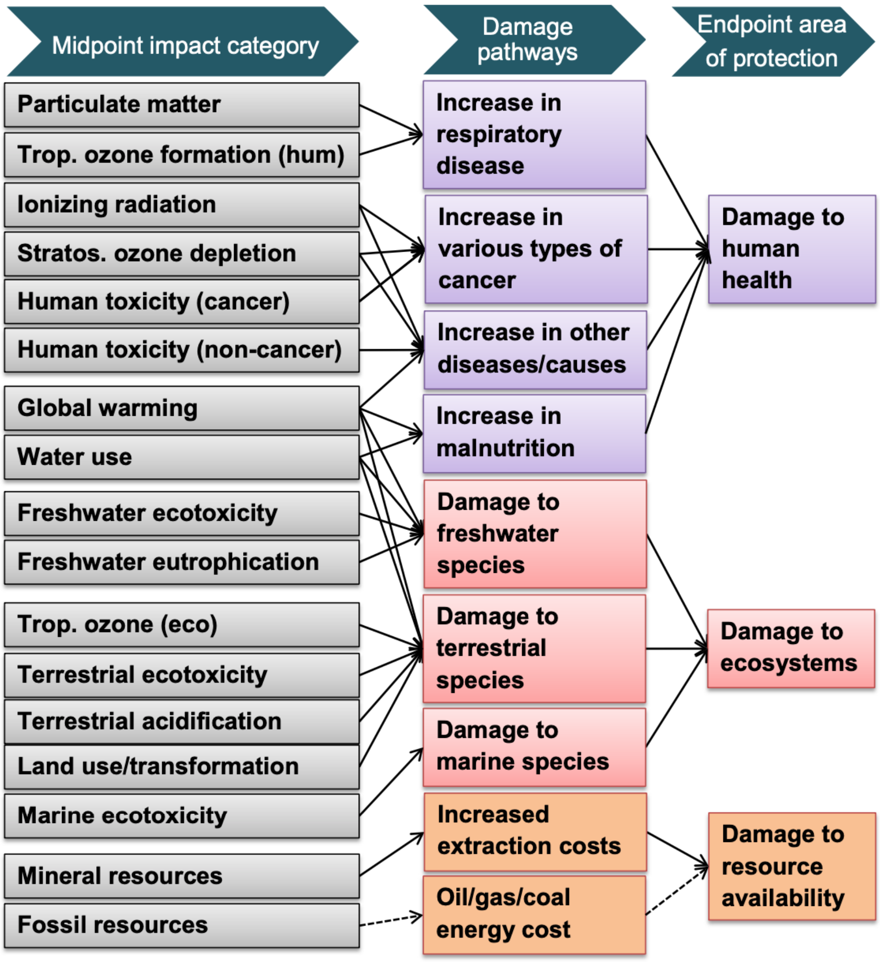

Figure 4: Overview of the impact categories that are covered in the ReCiPe 2016 methodology and their relation to the areas of protection (Source: Huijbregts et al., 2016).

Table 4: ReCiPe 2016 impact categories used in this study (see Section 5.2 for additional indicators applied)

Level	Indicator		Unit	
Midpoint impact categories	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
	TerrAcid	Terrestrial Acidification	Kg SO2 eq	Kg of Sulphur Dioxide equivalent
	FWEutr	Freshwater Eutrophication	Kg P eq	Kg of Phosphorous equivalent
	MarEutr	Marine Eutrophication	Kg N eq	Kg of Nitrogen equivalent
	TerrEcotox	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
	HuCarTox	Human Carcinogenic Toxicity	Kg 1,4-DCB eq	Kg of 1,4- dichlorobenzene equivalent
	HuNCarTox	Human Non-Carcinogenic Toxicity	Kg 1,4-DCB eq	Kg of 1,4- dichlorobenzene equivalent
	LandUse	Land use	m2a crop eq	Square metre per year crop equivalent
	MinResScar	Mineral Resources Scarcity	Kg Cu eq	Kg of Copper equivalent
	FosResScar	Fossil Resource Scarcity	Kg oil eq	Kg of oil equivalent
	WaterUse	Water Consumption	m3	Cubic metre
Endpoint damage categories	HH	Human Health	DALYs	Disability-Adjusted Life Years
	Ecosys	Ecosystems	Species/yr	Species per year
	Res	Resources	USD2013	US dollar in 2013
Single score			mPt	milli Point

5.2 Extending the analysis: Persistence, employment and affordability

5.2.1 Persistence as a proxy for plastic pollution

The impacts of plastic leakage into the environment is currently a significant issue; but the exact nature of these impacts and their magnitude are not well understood. Plastic pollution can cause entanglement, suffocation and reduced feeding ability of biota; resulting in reduced fecundity and lifespan. Plastics also break down into microplastic particles that are ingested by many organisms and accumulate in the soil. There are growing societal concerns regarding plastics polluting the environment and the risks from the widespread dissemination of microplastics. However, there is currently a lack of quantified scientific data linking specific quantities of plastic leaking into the environment, to specific impacts. This is a notable research gap, given the current global concern relating to the impacts of plastic pollution. As such, current LCA modelling and databases do not cover these impacts, and there is considerable global research aimed at filling this knowledge gap (see for example http://marilca.org/).

As such, in order to provide some assessment relating to the potential impacts associated with plastic pollution, we developed a persistence metric that consists of the time taken for the material to biodegrade in the receiving environment. The underlying assumption is that, all things being equal, the longer a material persists in the environment, the higher the potential environmental impact. As such, persistence is assumed to be a useful proxy for impact. However, it should be noted that persistence will need to be combined with the degree of exposure of various biota and ecosystems to the material, as well as the extent of damage or detriment, in order to more accurately quantify the environmental impact. Nonetheless, in the absence of such information, persistence of the material in the environment was used as a proxy to assess the potential for impacts associated with plastic pollution, i.e. the broad ecological and ecosystem-related impacts of plastic leakage beyond that captured by the data and methods currently available in ecoinvent or other LCA datasets.

Persistence is a measure of how long the material is likely to persist in the environment. The fate of materials that are disposed at a product's end of life, and particularly the extent to which it will decompose, depends on both physical and biological factors. In contrast to disintegration, which is simply the physical breakdown of a material into smaller fragments, biodegradation is the breakdown of material by microorganisms into carbon dioxide and water. Taking the premise that the materials persist in the environment until complete biodegradation, the annual disposal of shopping bags disposed to the receiving environment and the corresponding biodegradation rate was used to determine the degree of persistence.

Carrier bag consumption and disposal at end of life was allocated to these receiving environments according to the waste EOL model described in detail in Section 4.4. In order to develop a metric for persistence, we considered the amount of carrier bag material that leaks into the environment (mass) based on the EOL modelling described in Section 4.4, with appropriate adjustments for the different recycling rates of the different bags, together with the modelled rate of biodegradation in the receiving environment. Biodegradability data according to ASTM[1] composting and marine biodegradation tests was used to simulate the biodegradability of bag materials in the receiving environment after disposal (Greene

[1] (ASTM International, formerly known as the American Society for Testing and Materials, www.astm.org)

2018). Although the bags end up in other receiving environments (landfill, open-soil, freshwater rivers and lakes), we do not have data for biodegradation in these environments for all bag types, and so the composting and marine environment simulated tests effectively represent receiving environments reflecting the 'best case' and 'worst case' biodegradation scenarios, respectively.

The rate of biodegradation of bag material in these receiving environments was modelled according to available data. Standardized testing procedures have been defined by the International Organization for Standardization (ISO) and ASTM International. As mentioned above, biodegradation data for the materials associated with the bag types in our study could not be found for all receiving environments, only industrial composting and marine environments. Therefore, we model the material after disposal and determine the biodegradation of the material in landfill and open-dump under simulated composting conditions, and the material that leaks into the environment under simulated marine conditions.

The biodegradation data was sourced from simulated laboratory tests for 180 days using either compost soil at 58 °C (industrial composting) or sea-water at 30°C (marine environment). The evolution of carbon dioxide was used to determine the amount of carbon lost from the sample to calculate the biodegradation (Greene 2018; Muniyasamy et al. 2017 Ecmbiofilms 2019). The specific standards under which the tests were carried out were ASTM D5538 for compost, and ASTM D7081 and ASTM D6691 for the marine test. The results were used to calculate the biodegradation rate constant for each material type in marine and compost receiving environments, assuming first order kinetics of exponential decay (Abu Qdais and Al-Widyan 2016, Chem.libretexts 2019). The rate of biodegradation was calculated from the first order rate equation:

$\partial A / \partial t = - k't$

Where A is the amount of shopping bag material at time t, and k' is the apparent biodegradation rate constant.

Integrating the above, we get: $A = A_0 e^{-k't}$

Or, $\ln A / A_0 = -k't$

Where A_0 is the amount of shopping bag material at time 0

Therefore:

$k' = -(\ln A/A_0) / t$

The half-life can also be calculated by:

$t_{1/2} = \ln 2 / k'$

The calculated apparent rate constants (k') in marine and compost were used to model shopping bag material disposed of and entering these receiving environments in order to simulate the biodegradation. Assuming weekly shopping trips, the accumulation of materials in the environment is accounted for in the model through the weekly addition of new carrier bag material into the receiving environment as a result of use and disposal of carrier bags (based on the end of life scenarios described in Section 4.4), and the discrete biodegradation of the material in weekly time-steps. The quantity of bag material (in kg) persisting in the environment will be a combination of the rate of accumulation of material in the environment from carrier bag use and disposal, and the rate of biodegradation.

The results for the different bag types are assessed based on the amount of material remaining in the environment from one person's carrier bag use for one year, after 3 years of biodegradation in the environment. In other words, we ignore accumulation associated with further consumption of carrier bags in future years; and look only what has happened to the material from one year's worth of carrier bag usage, after being in the environment for three years. A three-year period was selected, as this time period illustrates the contrast between biodegradable and non-biodegradable bag types fairly well – after three years, the biodegradable bag types have almost fully degraded, while the fossil-based bags have hardly degraded at all. The results of this analysis are presented in Section 6.2.1.

An alternative approach would have been to take into account further accumulation of materials as a result of continued carrier bag usage in subsequent years, and to look at the mass of material once a steady state is reached; i.e. when the rate of new addition of material into the environment = the rate of degradation of accumulated material. The mass at steady state (N) can be calculated by dividing the disposal rate (D) by the apparent biodegradation rate constant, k':

$N = D / k'$

However, this approach is not consistent with the functional unit for the study, which is based on one year's use of carrier bags. For illustration purposes, the results of the analysis based on steady state are also shown in Section 6.2.1; where it can be seen that this approach would have resulted in an identical ranking of the bag types. However, for assessment purposes, the results based on one year's worth of carrier bag usage (after three years of biodegradation) are preferred, in order to be consistent with the functional unit adopted for the study.

5.2.2 Employment

In addition to comparing the bags based on their environmental impacts, this study aims to extend the analysis by assessing differences between the different bag types in terms of key socio-economic variables. In the South African context, employment is a particularly relevant consideration. Impacts on employment were assessed based on an understanding of the number of jobs associated with the production and recycling of each bag type along the value chain. In many cases, of course, a specific job will be focused on multiple products in addition to just the carrier bags. For example, jobs in the production of ethylene (the main component of HDPE and LDPE bags) cannot be attributed solely to HDPE or LDPE bags; but must instead be apportioned across the broader range of products which use ethylene as an input. As such, job numbers were apportioned to the specific bag types using the same economic allocation approach that has been applied throughout the LCA modelling.

Data on job numbers were retrieved from publicly available sources for relevant material processes involved in the value chains associated with the various bag types. This information is summarised in Table 5.

Table 5: Source of job data across the value chain of the various bag types

Material process	Processes for which job numbers were apportioned to bags	For which bag types	Source
Kraft paper production	Forestry, Pulp and Paper production, and Paper recycling	Paper	Forestry South Africa (2019), PAMSA (2019)
Starch production	Maize Agriculture and Wet Milling	PBAT+Starch and HDPE+ECM (starch used as proxy for ECM)	GrainSA (2019), NAMC 2019
Ammonia production	Sasol Mining Operations and Performance Chemicals	Adipic Acid used in PBAT production; and as component in Succinic Acid used in PBS production	SASOL (2019)
Generic organic chemical production	Sasol Mining Operations and Performance Chemicals	PBAT	SASOL (2019)
Ethylene production	Sasol Mining Operation and Base Chemicals	Main component of all HDPE bags, LDPE, and one of the components of PBS and PBAT (ethylene in Butane-1,4 diol)	SASOL (2019)
Propylene production	Sasol Mining Operations and Base Chemicals	Main component of PP bag	SASOL (2019)
Bag manufacture	Jobs to produce a generic shopping bag from any of the above-mentioned raw materials/polymers	All bags	Transpaco (2019)
Recycling of plastic	Jobs in formal recycling plants as well as informal collectors	All recyclable plastic bags	PlasticsSA (2019)

Employment figures for the relevant industries or sectors were allocated to the bag types based on the portion of material in the bag, as a proportion of the total industry or sector production. Economic allocation is used, rather than mass allocation, in order to be consistent with the approach adopted throughout the study.

Table 6 shows the number of jobs per 1000 tonnes of the main material produced in the various processes. It can be seen that the bag manufacturing and plastic recycling stages of the value chain are relatively more labour intensive as compared to the production of raw materials and polymers.

Table 6: Number of jobs per 1000 tonnes of main material produced per process

Material process	Jobs per 1000 tonnes of main material
Kraft paper production	38.31
Starch production	26.88
Ammonia production	2.69
Generic organic chemical production	2.69
Ethylene production	4.23
Propylene production	4.23
Bag manufacture	61.58
Recycling of plastic	94.79

The results were calculated based on each bag type's material requirements:

- For bags with only one main material: jobs for the specific material production were accounted for, plus jobs for bag manufacture. Note that in the case of the paper bag, jobs associated with "Kraft paper production" are also inclusive of jobs in paper recycling.
- For bags with more than one virgin material component (e.g. PBS+PBAT): jobs for each of the components were accounted for according to the specific material shares, plus the jobs for bag manufacture.
- For bags with a mix of virgin and recycled material components (e.g. some of the HDPE and polyester bags): jobs for virgin and recyclate production were accounted for according to the relative shares, plus jobs for the bag manufacture. Jobs to produce the virgin material that eventually becomes recyclate for the bags (i.e. either HDPE and PET bottles) were also included.
- For bags produced with imported polymers: only jobs for the bag manufacture (in South Africa) were accounted for; since the focus is on employment in South Africa.

In Section 6.2.2, we present the results in terms of the number of jobs per bag type.

5.2.3 Affordability

Given existing disparities between South African consumers in terms of purchasing power, affordability of bags to the consumer is an important socio-economic consideration. Reusable bags tend to be more expensive as compared to single-use bags, which could disproportionately affect low income consumers. However, the number of times that reusable bags can be reused, as compared to single-use bags, should be factored in. In other words, the cost of using carrier bags over a period of, say, one year, should ideally be considered; rather than the cost of a once-off bag purchase.

Affordability to the consumer was assessed based on average prices paid for each type of bag at supermarket till points (including the plastic bag levy, where applicable), across the major supermarket retailers in South Africa. Note that prices were correct as at January 2020, and therefore do not take into account the increase in levies that came into effect on 1 April 2020.

It should be borne in mind that the bag types differ both in terms of their capacity, and in terms of the extent to which they can be reused. The reusable bag types are generally more expensive than single-use bag types (per bag). As such, to enable a fair comparison across the bag types, affordability was calculated as the cost per annum; i.e. the cost to purchase the quantity of bag(s) needed to fulfil the functional unit in terms of annual grocery shopping requirements; rather than the cost per individual bag. The results are presented in Section 6.2.3.

5.3 Integrating persistence, employment and affordability with the ReCiPe 2016 indicator results

Within the ReCiPe 2016 hierarchy of indicators, the three new indicators developed and applied in this analysis (persistence, employment and affordability) could best be seen as midpoint impact categories; rather than as endpoints.

Ideally, the new midpoint impact categories should be integrated into the overall results by adapting an existing life cycle impact assessment method (such as ReCiPe 2016) to include the new indicators. This would involve the application of characterisation, normalisation and weighting factors, which would allow for the scores on these midpoints to be incorporated into the calculation of endpoints. However, this level of integration was beyond the scope of the current study; but is the focus of ongoing work being conducted by the team.

Instead, for the purposes of this study, the main results are presented primarily at a midpoint level. This allows us to present the results for the new indicators alongside the existing ReCiPe 2016 midpoint categories.

In addition, we derive a methodology for integration at the midpoint level, which allows us to provide an overall ranking of the bag types, based on scores across all of the midpoint impact categories, including both ReCiPe 2016 midpoint impact categories, as well as our three new indicators.

This was as done by calculating relative or 'dimensionless' scores for each bag on each midpoint impact category; by dividing the actual score for each bag by the score for the reference bag; in this case the HDPE_24_100 bag. This overcomes the problem of different impact categories being specified in different units; allowing for the scores to be aggregated across impact categories. An aggregate score is then calculated by summing the dimensionless scores for each bag on each midpoint impact category. However, in the case of the employment impact category; the score is subtracted from the total rather than added; since for this impact category only, a higher score is better.

Note that this aggregation approach assumes an equal weighting of each midpoint impact category. In principle, differential weighting could be applied to emphasise specific midpoint categories of relevance to a particular decision making context; or to highlight impact categories where carrier bags make a disproportionately high contribution to the overall problem. For example, in the South African context; it could be argued that employment should receive a higher weighting as compared to some of the other midpoint impact categories. Similarly, it could be argued that persistence should receive a higher weighting in an assessment of carrier bags, since plastic bags would be expected to make a disproportionately high contribution to the overall problem of plastic pollution, as compared to their contribution to other environmental issues (such as global warming), which would be expected to be far lower, in relative terms. It is therefore suggested that a set of weightings appropriate to the South African context be developed, through a multi-criteria decision analysis approach, incorporating government and other relevant stakeholders.

In certain circumstances, such as for the purposes of contribution analysis and sensitivity analysis, we do also provide results at an endpoint and single score level, based on the ReCiPe 2016 methodology. However, it should be borne in mind that the endpoint and single score results provided do not incorporate the results for the new indicators (persistence, employment and affordability).

6 Main results

In this section, we present the results of the environmental life cycle impact assessment, based on the ReCiPe 2016 impact assessment method; as well as for the additional indicators (persistence, as a proxy for the impacts associated with plastic leakage to the environment; as well as for the socio-economic indicators, employment and affordability). Results are presented in terms of scores and rankings of the bag types on each of the indicators; as well as an overall ranking across all indicators; based on our standard set of assumptions spelled out in Sections 3 and 4. Finally, we also provide an indication of the number of reuse times required for each bag to match the environmental performance of the reference bag.

The results provided in this section are based on our main set of assumptions, provided in Sections 3 and 4. In particular, it is based on our assumptions regarding the number of times each type of bag will be reused, and the number of each type of bag needed to fulfil the functional unit (fulfilling one person's grocery shopping requirements (870.48 litres of groceries) over the course of a year); taking into account differences in the volumetric capacity of each bag (see Section 3.4). Specifically, we assume that the bags that are intended for single use will only be used once each; such that a new bag is purchased for each shopping trip. On the other hand, we assume that the bags intended for reuse will only be purchased once, and reused over the course of the entire year. The resulting number of each bag type required to fulfil the functional unit is summarised again in Table 7 for ease of reference.

Note of course that, in reality, bags that are intended for single-use may be used multiple times, whereas reusable bags may in theory only be used once, or a small number of times, with an additional bag being purchased frequently. In Section 7 (sensitivity analysis), we alter some of our assumptions regarding the number of times each type of bag is reused, and the number of each type of bag needed to fulfil the functional unit, in order to analyse the extent to which these assumptions affect the results.

6.1 Environmental LCA results based on ReCiPe 2016

6.1.1 Results for ReCiPe 2016 midpoints, endpoints and single score

In this section, we present the results of the environmental LCA using the ReCiPe 2016 impact assessment method (see Section 5.1). Recall that this methodology excludes our three new indicators (persistence, employment and affordability). The results for these three indicators are presented in Section 6.2, and integrated with the ReCiPe 2016 results in Section 6.3.

Recall from Section 5.1 that the ReCiPe 2016 methodology consists of 18 'midpoint' impact categories (environmental indicators); three endpoint damage categories (damage to human health, damage to ecosystems, and damage to resource availability), and an overall single score. The endpoint damage categories are calculated by aggregating and weighting normalised midpoint scores. In turn, the single score is calculated by aggregating and weighting across the three damage categories. In this section, we present results for the ReCiPe 2016 midpoint and endpoint impact categories; as well as a single score. The Hierarchist (H) weighting perspective is applied in deriving endpoint and single scores. For more details on the methodology, refer to Section 5.1, as well as Huijbregts et al. (2016 and 2017).

Table 7: Assumed number of times each type of bag is used, and number of bags needed to fulfil the functional unit

Single-use / reusable	Bag type	Capacity (litres)	Number of times each bag is used	Number of bags needed per year to fulfil the functional unit (870.48 litres)
Single-use	HDPE_24_100	16.74	1	52.00
	HDPE_24_75	16.74	1	52.00
	HDPE_24_50	16.74	1	52.00
	HDPE_24_25	16.74	1	52.00
	HDPE_24_0	16.74	1	52.00
	LDPE	24.00	1	36.27
	HDPE_ECM	13.00	1	66.96
	PBS+PBAT_ZA	14.73	1	59.10
	PBS+PBAT_IMP	14.73	1	59.10
	PBAT+Starch_ZA	19.00	1	45.81
	PBAT+Starch_IMP	19.00	1	45.81
	Paper	19.97	1	43.59
Reusable	HDPE_70	23.23	52	0.72
	PP	18.98	52	0.88
	Polyester_W	13.69	52	1.22
	Polyester_NW	26.75	52	0.62

Table 8 presents the scores for each bag per ReCiPe 2016 midpoint impact category, in the relevant unit for the indicator in question. These scores are also presented graphically in Appendix B, in the form of a contribution analysis for each bag type on each impact category. The indicators and units are defined in Section 5.1. Note that for all of the environmental impact categories, a higher score indicates poorer performance (higher environmental impact); while a lower score indicates better performance (lower environmental impact). Note also that all scores relate to the functional unit; i.e. to the number of bags required to carry one person's groceries per year. All scores are therefore essentially on a *per capita, per year* basis; and would need to be aggregated across the South African population in order to indicate the overall potential impact per year. Finally, note that in this table and hereafter, colour coding is used to illustrate the best and worst performers; with light green shading used to indicate the best score on each impact category; and grey shading used to indicate the worst score.

Table 9 presents the results for the endpoint damage categories (damage to human health, damage to ecosystems, and damage to resource availability); and for the overall integrated single score. The scores for the endpoint damage categories are also presented graphically in Appendix B, in the form of a contribution analysis; while the contribution analysis for the single score is presented in Section 6.1.2. The indicators and units are defined in Section 5.1. Again, for all three damage categories as well as the single score, a higher score indicates poorer performance (greater damage); while a lower score indicates better performance (less damage). The single score results are also presented graphically in Figure 5.

Note however that our three new indicators (persistence, employment and affordability) are not yet integrated into these endpoint and single score results. The results for these new indicators are presented in Section 6.2, and integrated with the ReCiPe 2016 results in Section 6.3.

Table 8: Score of each bag per ReCiPe 2016 midpoint impact category; based on assumed number of reuse times in fulfilling annual shopping requirements. Best and worst score for each impact category shaded in green and grey, respectively. See Appendix B for results in graphical form.

Impact categories		Global warming	SOD	IR	OF,HH	FPM	OF,TE	Terr Acid	FW Eutr	Mar Eutr	Terr Ecotox	FW Ecotox	Mar Ecotox	HuCar Tox	HuNCarTox	Land Use	MinResScar	FosResScar	Water Use
Units[1]		Kg CO2-eq	Kg CFC11-eq	Kg Co-60 eq	Kg NOx eq	Kg PM2.5 eq	Kg NOx eq	Kg SO2 eq	Kg P eq	Kg N 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	m2a crop eq	Kg Cu eq	Kg oil eq	m3
Single-use / reusable	**Bag type**																		
Single-use	HDPE_24_100	4.2073	0.000003	0.0999	0.0134	0.0073	0.0135	0.0229	0.0026	0.00022	8.1305	0.2550	0.3550	0.2745	4.3173	0.1058	0.0084	1.3462	0.032
	HDPE_24_75	5.4738	0.000005	0.1059	0.0171	0.0091	0.0173	0.0288	0.0037	0.00028	8.4272	0.2788	0.3864	0.3757	5.1670	0.1204	0.0106	1.8299	0.036
	HDPE_24_50	6.7383	0.000006	0.1119	0.0209	0.0109	0.0211	0.0348	0.0047	0.00034	8.7139	0.3021	0.4206	0.4768	6.0178	0.1347	0.0128	2.3096	0.040
	HDPE_24_25	8.0028	0.000007	0.1184	0.0246	0.0127	0.0248	0.0407	0.0058	0.00041	9.0107	0.3263	0.4559	0.5779	6.8685	0.1490	0.0150	2.8013	0.043
	HDPE_24_0	9.2673	0.000008	0.1243	0.0284	0.0145	0.0286	0.0467	0.0068	0.00047	9.2974	0.3496	0.4901	0.6800	7.7192	0.1634	0.0172	3.2830	0.047
	LDPE	7.3802	0.000007	0.1095	0.0228	0.0119	0.0230	0.0384	0.0054	0.00038	7.1843	0.2869	0.4026	0.5352	5.2642	0.1324	0.0131	2.5741	0.039
	HDPE_ECM	6.8662	0.000006	0.0930	0.0209	0.0108	0.0211	0.0346	0.0050	0.00036	7.4718	0.2894	0.4060	0.4981	6.0702	0.1211	0.0126	2.4024	0.035
	PBS+PBAT_ZA	13.0305	0.000050	0.2405	0.0267	0.0171	0.0271	0.0459	0.0039	0.00069	13.9845	0.2386	0.3354	0.4658	6.5304	0.1928	0.0184	2.9671	0.161
	PBS+PBAT_IMP	9.2505	0.000046	0.3515	0.0146	0.0116	0.0151	0.0239	0.0021	0.00059	12.1845	0.1626	0.2284	0.2048	4.7404	0.1678	0.0100	2.2771	0.173
	PBAT+Starch_ZA	6.9873	0.000050	0.0766	0.0141	0.0086	0.0143	0.0250	0.0016	0.00034	5.4718	0.1096	0.1469	0.2368	2.7182	0.0891	0.0099	1.0729	0.062
	PBAT+Starch_IMP	4.0872	0.000047	0.0699	0.0057	0.0043	0.0058	0.0095	0.0007	0.00029	4.1918	0.1995	0.0802	0.0711	1.6982	0.0668	0.0036	0.7719	0.059
	Paper	3.2098	0.000003	0.0432	0.0101	0.0050	0.0101	0.0177	0.0013	0.00044	6.5940	0.0799	0.1131	0.1187	3.4467	2.3520	0.0024	0.5707	0.058
Reusable	HDPE_70	0.2526	0.000000	0.0060	0.0008	0.0004	0.0008	0.0014	0.0002	0.00001	0.4954	0.0153	0.0211	0.0165	0.2593	0.0064	0.0005	0.0809	0.002
	PP	0.7466	0.000001	0.0092	0.0026	0.0021	0.0024	0.0040	0.0006	0.00004	0.7750	0.0312	0.0435	0.0559	0.1712	0.0104	0.0014	0.2504	0.003
	Polyester_W	0.7971	0.000000	0.0242	0.0027	0.0017	0.0027	0.0054	0.0004	0.00005	1.1918	0.0357	0.0477	0.0427	0.5441	0.0089	0.0004	0.1985	0.003
	Polyester_NW	0.2746	0.000000	0.0091	0.0010	0.0005	0.0010	0.0016	0.0001	0.00004	0.7508	0.0188	0.0260	0.0152	0.2809	0.0051	0.0002	0.0859	0.002

Notes:

1: All scores provided in the table relate to the functional unit; i.e. to the number of bags required to carry one person's groceries per year. All units are therefore on a per capita per year basis. For all impact categories, a lower score indicates better performance

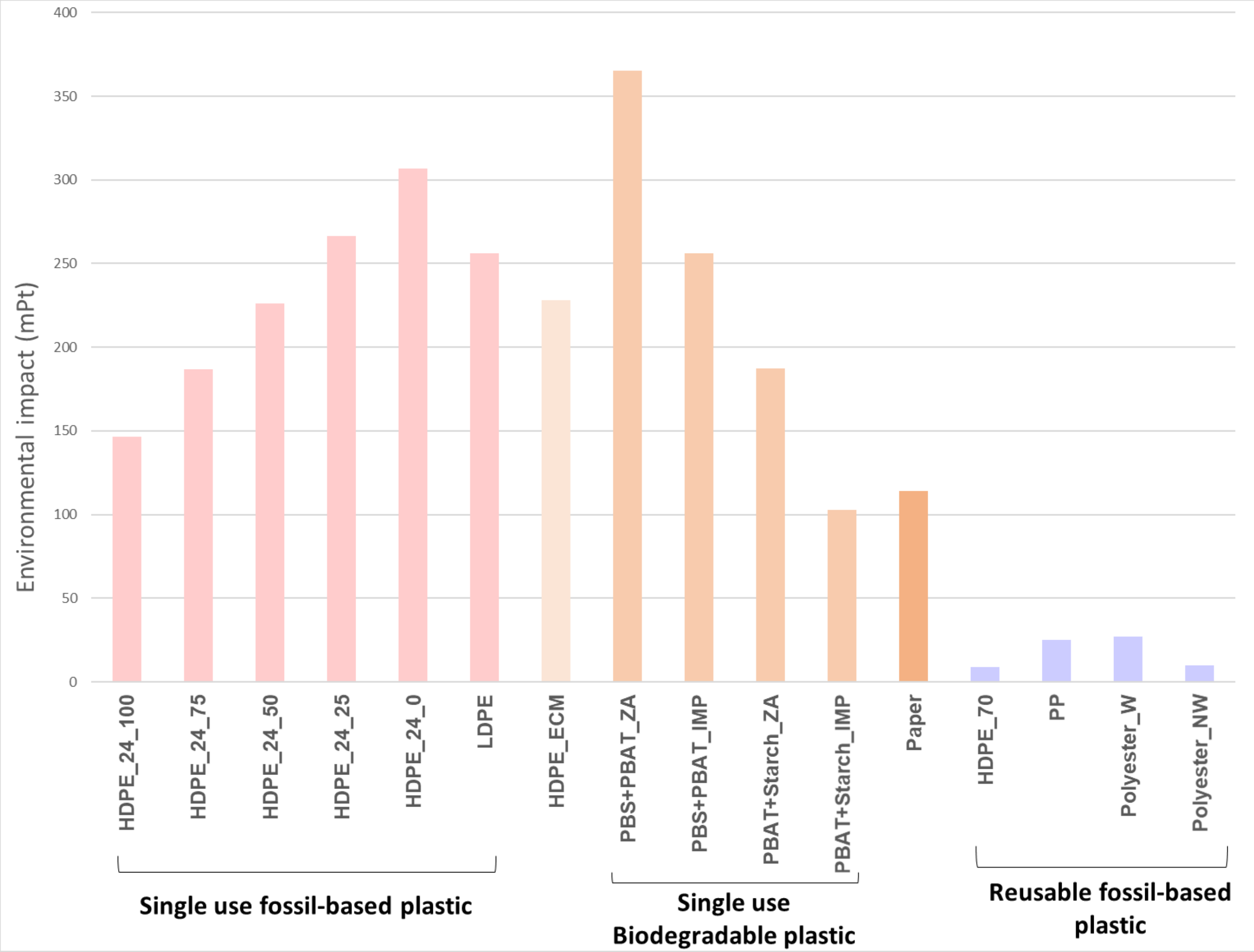

Figure 5: Environmental impact per bag type; based on assumed number of reuse times in fulfilling annual shopping requirements (ReCiPe 2016 Single score, in mPt).

Table 9: Score of each bag per ReCiPe 2016 endpoint damage category and single score, calculated using the Hierarchist (H) weighting option; based on assumed number of reuse times in fulfilling annual shopping requirements. Best and worst scores shaded green and grey, respectively. See Appendix B and Section 6.1.2 for results in graphical form.

Impact categories		Human health	Ecosystems	Resources	Single score
Units[1]		DALYs	Species/yr	USD2013	mPt
Single-use/ reusable	**Bag types**				
Single-use	HDPE_24_100	1.05×10^{-5}	2.19×10^{-8}	0.24	146.70
	HDPE_24_75	1.33×10^{-5}	2.81×10^{-8}	0.30	186.61
	HDPE_24_50	1.61×10^{-5}	3.43×10^{-8}	0.36	226.31
	HDPE_24_25	1.90×10^{-5}	4.05×10^{-8}	0.42	266.41
	HDPE_24_0	2.18×10^{-5}	4.67×10^{-8}	0.48	306.52
	LDPE	1.76×10^{-5}	3.75×10^{-8}	0.37	256.13
	HDPE_ECM	1.62×10^{-5}	3.46×10^{-8}	0.35	228.21
	PBS+PBAT_ZA	2.56×10^{-5}	5.79×10^{-8}	0.75	365.12
	PBS+PBAT_IMP	1.79×10^{-5}	3.84×10^{-8}	0.71	256.12
	PBAT+Starch_ZA	1.33×10^{-5}	2.99×10^{-8}	0.24	187.21
	PBAT+Starch_IMP	7.22×10^{-6}	1.62×10^{-8}	0.23	102.81
	Paper	7.27×10^{-6}	3.70×10^{-8}	0.09	113.83
Reusable	HDPE_70	6.30×10^{-7}	1.30×10^{-9}	0.01	8.81
	PP	1.81×10^{-6}	3.80×10^{-9}	0.03	25.27
	Polyester_W	1.94×10^{-6}	3.80×10^{-9}	0.03	26.98
	Polyester_NW	7.10×10^{-7}	1.40×10^{-9}	0.02	10.10

Notes:
1: All scores provided in the table relate to the functional unit; i.e. to the number of bags required to carry one person's groceries per year. All units are therefore on a per capita per year basis. For all impact categories, a lower score indicates better performance

It can be seen from Tables 8 and 9, and Figure 5, that the reusable bag types have lower impacts across all of the impact categories as compared to the single-use bags; and are therefore superior from an environmental perspective; at least based on the set of indicators within the ReCiPe 2016 methodology; and based on our assumptions regarding the number times each type of bag is reused over the course of a year. Specifically, the reusable, fossil-based HDPE 70 µm bag (HDPE_70) is seen to have the best scores (lowest environmental burden) across most of the ReCiPe 2016 midpoint impact categories (see green highlighted cells in Table 8), as well as across all of the endpoint damage categories, and the single score (Table 9). This is the followed by the reusable, fossil-based non-woven polyester bag (Polyester_NW), which achieves the best score on most of the remaining midpoint impact categories (Table 8).

On the other hand, for most midpoint impact categories (Table 8), the worst performers are the single-use, fossil-based HDPE 24 µm bag with 0% recycled content (HDPE_24_0), and the biodegradable

PBS+PBAT bag with locally produced polymers (PBS+PBAT_ZA). The latter bag type is also the worst performer on each of the endpoint damage categories, as well as on the single score (Table 9).

In terms of specific indicators of interest; it can be seen that the HDPE_70 bag performs best in terms of both global warming and water use; while the Polyester_NW bag performs best in terms of land use. The four fossil-based, reusable bag types are the top four performing bag types across all three of these indicators. By contrast, the single-use biodegradable bag types tend to perform poorly, particularly in terms of water use, where the worst five performers are the biodegradable plastic and Paper bags. Paper bags perform particularly poorly in terms of land use; while the biodegradable PBS+PBAT bags perform poorly across all three of these indicators.

It can also be seen that the higher the recycled content of the bags, the better the environmental performance. Across all impact categories; the HDPE 24 µm bag with 100% recycled content (HDPE_24_100) shows the lowest environmental burden among the HDPE 24 µm bags; while the HDPE_24 bags with lower recycled content have progressively higher burdens. Table 10 shows how an increase in recycled content (compared to the HDPE 24 µm bag with zero recycled content, HDPE_24_0) affects environmental performance across the impact categories; taking into account the burdens carried by the recyclate material. For example, on average across the ReCiPe 2016 impact categories, the HDPE 24 µm bag with 100% recycled content (HDPE_24_100) performs approximately 52% better than the bag with 0% recycled content (HDPE_24_0). Stated differently, the HDPE_24_100 bag shows an average 52% reduction in the overall environmental burden as compared to HDPE_24_0, inclusive of the burdens carried by the recyclate material.

Table 10: Median, minimum and maximum reduction in environmental burden across impact categories (ReCiPe 2016) associated with an increase in recycled content

Bag Type	Median	Min	Max	STD	Variance
HDPE_24_0	0,0%	0,0%	0,0%	0,00	0,0%
HDPE_24_25	12,9%	3,1%	15,5%	0,03	26,6%
HDPE_24_50	25,8%	6,3%	31,0%	0,07	26,4%
HDPE_24_75	38,7%	9,4%	46,5%	0,10	26,4%
HDPE_24_100	51,7%	12,65	62,15	0,14	26,4%

Recall that for both the PBS+PBAT and PBAT+Starch bags; different scenarios were modelled to assess the environmental burdens where polymer production takes place in South Africa, as compared to when it takes place overseas and polymers are imported. The results show that for both PBS+PBAT and PBAT+Starch, the bags using locally produced polymers (PBS+PBAT_ZA and PBAT+Starch_ZA) show higher environmental impacts across most impact categories, as compared to the imported versions (PBS+PBAT_IMP and PBAT+Starch_IMP). On average across impact categories, there is a 30% higher environmental burden for PBS+PBAT_ZA as compared to PBS+PBAT_IMP, and a 43% higher environmental burden for PBAT+Starch_ZA as compared to PBAT+Starch_IMP. Table 11 shows the relative increase in environmental impact (across the ReCiPe 2016 impact categories) for each bag type when made from locally produced as compared to imported polymers.

Table 11: Median, minimum and maximum increase in environmental burden (ReCiPe 2016) across impact categories associated with locally produced polymers, as compared to imported polymers

Bag Type	Median	Min	Max	STD	Variance
PBS+PBAT (increase in burden for PBS+PBAT_ZA as compared to PBS+PBAT_IMP)	29,9%	-46,2%	56,0%	0,22	73.3%
PBAT+Starch (increase in burden for PBAT+Starch_ZA as compared to PBAT+Starch_IMP)	43,3%	-82,0%	70,0%	0,32	74,3%

However, it should be recalled that the results in this section are based only on the ReCiPe 2016 environmental impact categories; and exclude our three new indicators (persistence, employment, and affordability). In Section 6.2 and 6.3, we will assess the bag types against these additional indicators, and provide an overall ranking of the bags across the broader set of indicators.

Furthermore, it should be borne in mind that these results are based on our assumptions as set out in Sections 3 and 4; and in particular our assumptions regarding the number of times each type of bag will be reused, and therefore the number of each bag type required per year (Section 3.4). In Section 7, we conduct sensitivity analysis to assess the extent to which the results change when we alter some of these assumptions.

6.1.2 Contribution analysis

In LCA studies, contribution analysis involves breaking down the overall environmental impact (for each impact category) into specific stages within the product life cycle. In other words, contribution analysis shows the contribution of each stage within the product life cycle towards the overall impact (per impact category). This is done so as to be able to identify specific stages in the life cycle which contribute most significantly toward the negative environmental burdens. This information can then be used to provide an understanding of where interventions should be targeted (i.e., at which specific stages in the life cycle) in order to improve environmental performance in the most cost-effective way.

Contribution analyses were conducted for each of the ReCiPe 2016 midpoint impact categories, endpoint damage categories, as well as the single score. In this sub-section, we show only the contribution analysis for the aggregated ReCiPe 2016 single score (Figure 6). For contribution analyses relating to each individual ReCiPe 2016 midpoint impact category, as well as the endpoint damage categories, please refer to Appendix B.

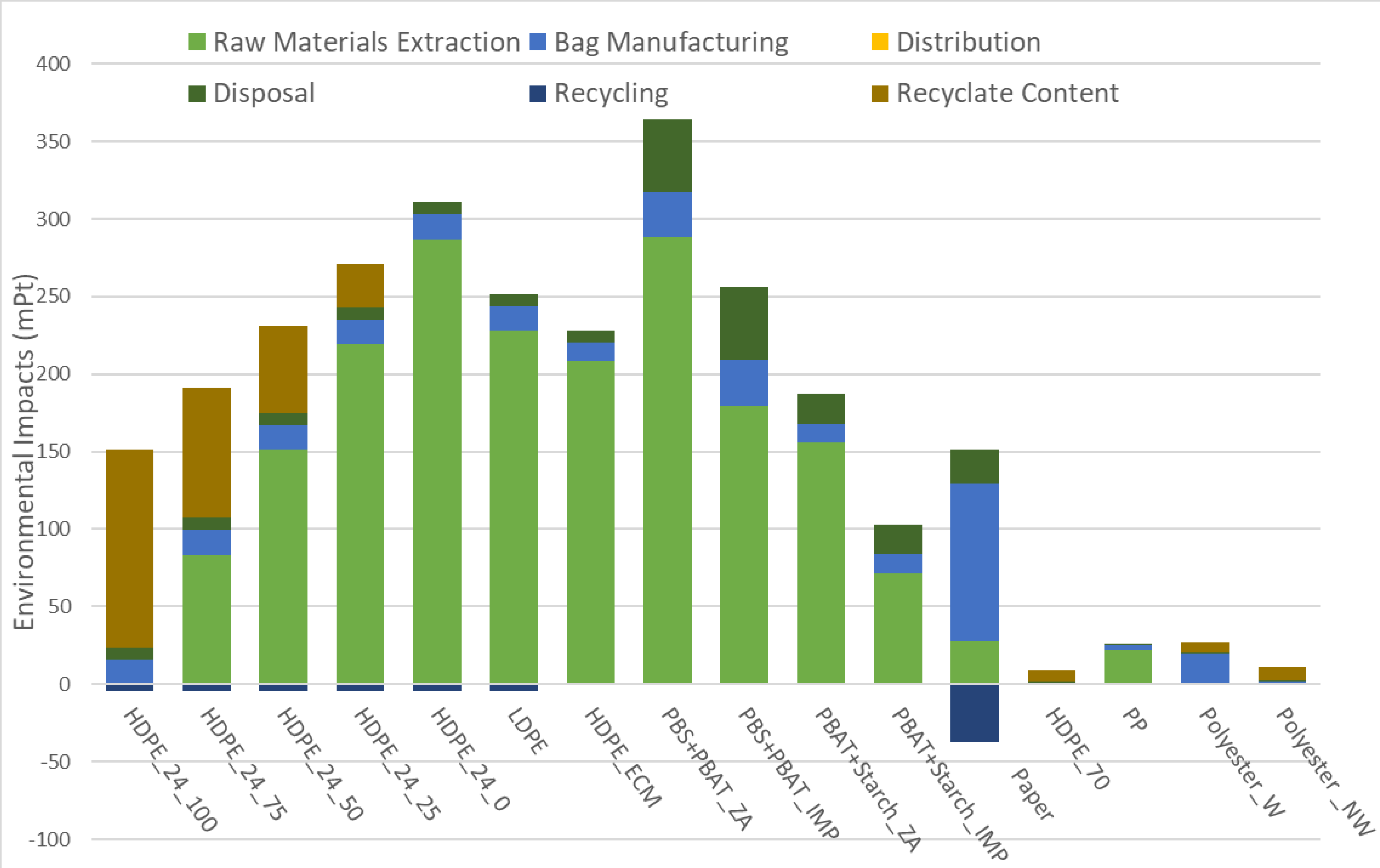

Figure 6: Contribution analysis for the ReCiPe 2016 single score

Note: For Paper bags, the burden for recyclate production is included within the recycling stage.

For most bags, by far the main contributing stage to overall environmental impact is the material extraction phase (light green bar in Figure 6); with a contribution to the total single score ranging from 24% to 92%, depending on the bag type. On average, this stage accounts for approximately 71% of the total single score.

An exception is represented by those bags with no virgin material content, namely HDPE_24_100, HDPE_70 and Polyester_W, for which there is no contribution from raw material extraction. For the HDPE_24_100 and HDPE_70 bags, the recyclate production stage (brown bar) contributes to the majority of the impact (87% for both bags). For HDPE_24_75, raw material extraction and recyclate production each contribute 45%.

For the Paper and Polyester_W bags, the bag manufacturing stage (light blue bar) is the most significant contributor (89% and 75% respectively). For most other bags, the bag manufacturing stage is the second largest contributing stage to overall environmental impact; with a contribution ranging from 5% to 89% of the total; or 18% on average.

For those bags that are produced with recycled content (i.e. most of the HDPE bags, as well as the polyester bags); the recyclate production stage (brown bar) is also a significant contributor to the overall impact, with a contribution ranging from 10% to 87%. Among the bags with recycled content, this stage contributes an average of 40% to the overall impact. Note that for Paper bags, which were modelled using an ecoinvent dataset adapted for the South African context, the burden for recyclate production is included within the end of life recycling stage, which provides the recycled material to substitute the production of sulphate pulp.

Recycling of the bags at end of life contributes toward a “positive” environmental impact (a credit); which is illustrated as a ‘minus’ score in Figure 6 (dark blue bar). Among those bag types that are recycled, the positive contribution ranges from -1% to -33% of the total impact, or -5% on average among the bag types that are recycled. The bag type for which recycling contributes the highest overall ‘credit’ (-33%) is Paper.

Together, the raw material extraction, bag production and recyclate production stages contribute toward the bulk of the environmental impacts (94.5% on average across all bags); with the other stages contributing comparatively little to the overall impact. Impacts associated with final disposal range from 1% to 20% of the total, depending on the bag type; or 7% on average (dark green bar). Distribution shows a negligible contribution of around 0.01% across all bag types.

Finally, it should be recalled that the contribution analysis in this section relates to the ReCiPe 2016 indicators only; it excludes the impacts associated with our three new indicators (persistence, employment and affordability. The results for these three indicators are discussed in the following sub-section.

6.2 Results for the new indicators: Persistence, employment and affordability

6.2.1 Persistence

Given the absence of quantitative data on plastic pollution impacts associated with specific quantifies of plastic entering the environment; we use the persistence of carrier bag material in the receiving environment as a proxy for impacts. The methodology employed in developing this indicator was described in Section 5.2.1.

The data (Figure 7) shows that over 180 days, Paper, PBS+PBAT and PBAT+Starch are biodegraded by >90% in compost and >30% in marine environments, and would therefore justify claims of biodegradability and certification according to ASTM standards. In contrast, the conventional plastics do not biodegrade significantly under these conditions (generally <2%, although the HDPE_ECM achieved 22% degradation over 180 days); and could not claim biodegradability according to ASTM 6400 standards (Figure 7).

The time taken for the material to biodegrade to half its original value, i.e. the half-life (Table 12), shows that conventional plastics have a half-life of 15-17 years, while bioplastics and paper have a half-life of 1-2 months in compost conditions. It is also noteworthy that biodegradation is drastically slower (at least five-fold) in marine as compared to compost environments (Figure 7 and Table 12).

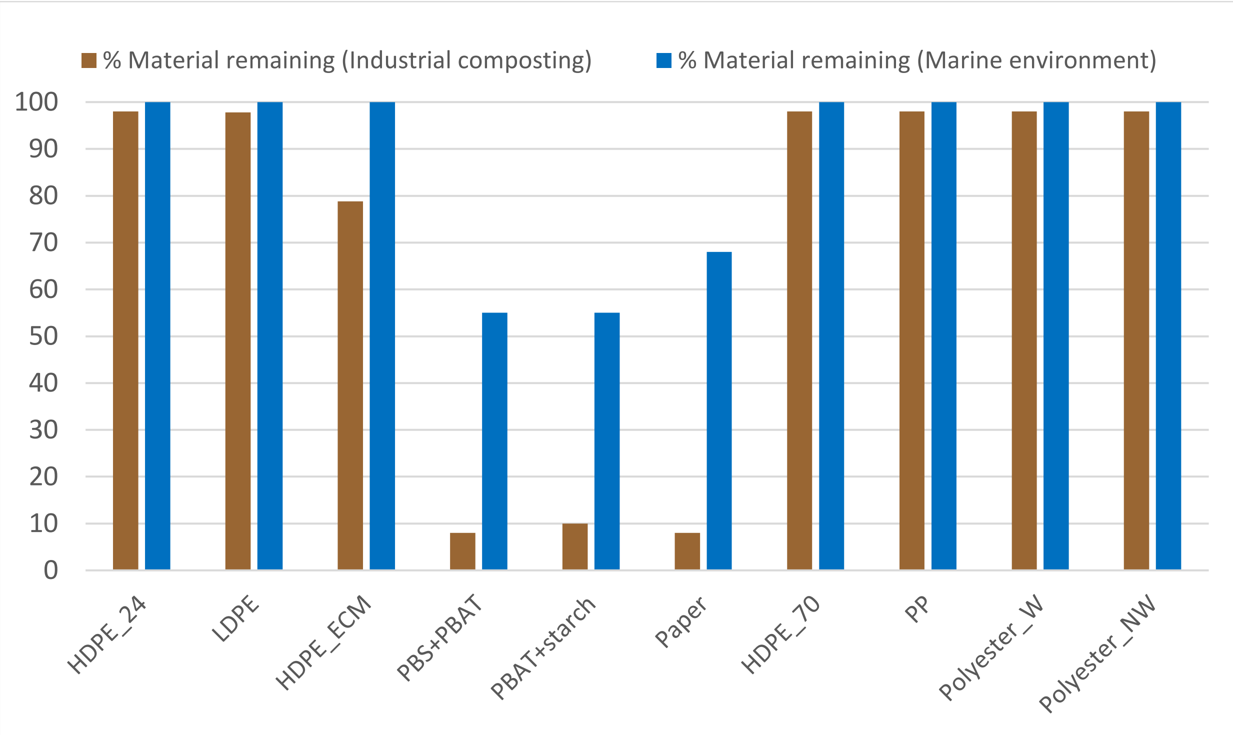

Figure 7: Remaining material as a percentage of material input in simulated marine and compost conditions after 180 days, for different bag types. HDPE_24 refers to all the HDPE 24µm bags with varying recycled content; while PBS+PBAT and PBAT+Starch include both the imported and locally produced variations.

To summarise; the bags produced from paper, PBAT+Starch and PBS+PBAT would pass the ASTM test of biodegradability, which requires <10% remaining material in compost and <70% remaining material in marine conditions after biodegradation for 180 days (>90% biodegraded in compost and >30% material biodegraded in marine conditions). By contrast, the bags produced from HDPE (including HDPE_ECM), LDPE, PP and polyester would all fail; and cannot be considered biodegradable in either marine or compost environments.

The rate of biodegradation of different shopping bag materials can be compared by modelling first order kinetics to calculate the apparent rate constant (k') and half-life of the shopping bag materials (Table 12). The fact that the rate of consumption of carrier bags, and therefore of material entering the environment, exceeds the rate of biodegradation; means that even those bag types passing the biodegradability test can accumulate and persist in the environment. For example, the biodegradation half-life of paper (i.e. the time taken for the material to biodegrade to half of its original mass) is 49 days. However, assuming that a paper bag is consumed and disposed to the environment each week, paper bags will accumulate and persist in the environment.

Table 12. The apparent biodegradation half-life of shopping bag material in compost and marine simulated conditions. HDPE_24 refers to all the HDPE 24µm bags with varying recycled content; while PBS+PBAT and PBAT+Starch include both the imported and locally produced variations

Type of material	Bag type	Apparent half-life, $t_{1/2}$ (days)	
		Marine	Compost
Fossil-based plastic (single-use)	HDPE_24	1.248×10^{13}	6175
	LDPE	1.248×10^{13}	5608
Fossil-based with bio-additive	HDPE_ECM	1.248×10^{13}	874
Biodegradable plastic	PBS+PBAT	208	49
	PBAT+Starch	209	54
Paper	Paper	323	49
Fossil-based plastic (reusable)	HDPE_70	1.248×10^{13}	6175
	PP	1.248×10^{13}	6175
	Polyester_W	1.248×10^{13}	6175
	Polyester_NW	1.248×10^{13}	6175

The fate of shopping bag material disposed of at end of life was assessed in this study using the end of life material flows as described in Section 4.4, and based on the above data on biodegradation in marine and compost receiving environments. The accumulation of materials in the environment is accounted for in the model through the addition of new carrier bag material into the receiving environment as a result of use and disposal of carrier bags, as well as the biodegradation of this material over time. The single-use bags are assumed to be used and disposed of weekly; while the reusable bags are assumed to be reused throughout the year and disposed of at the end of the year.

As explained in Section 5.2.1, the results for the different bag types are assessed based on the amount of material remaining in the environment after three years, based on one year's worth of grocery shopping. Specifically, we focus on the amount of material from one person's use of carrier bags in one year, and look at how much is still remaining after 3 years in the environment. In other words, we ignore accumulation associated with further consumption of carrier bags in future years; and look only what has happened to the material from one year's worth of carrier bag usage, after being in the environment for three years.

Figure 8 shows the degradation of material (from one year's use of carrier bags) over time; based on our assumptions regarding the quantity of each type of bag used over the year, the end of life scenarios described in Section 4.4, and the rate of biodegradation for each type of material. For Year 0 (red coloured bars), it shows the amount of material entering the environment as a result of carrier bag use and disposal in that year; less any degradation that may have occurred in that year. It then shows how much of this material remains in the environment after one year (yellow bars), two years (blue bars), and three years (green bars); based on the variable rates of degradation of each type of material over time. Note that the amount of material shown for Years 1-3 is based on the material that entered the environment due to carrier bag usage in Year 0; ignoring further accumulation of material from carrier bag use in subsequent years. The initial amount of material entering the environment in Year 0 is primarily a function of the mass of each type of bag, multiplied by the number of bags used. In Years 1 – 3, it can be seen how the rates of degradation differ markedly between the bag types. In particular, it can be seen that for the biodegradable bag types (PBAT+Starch, PBS+PBAT and paper), the amount of material remaining in the environment falls dramatically after Year 0. On the other hand, for the fossil-based plastic bags, the rate of degradation is far slower. As a result, after three years, the biodegradable bag types have almost fully degraded, while the fossil-based bags have hardly degraded at all.

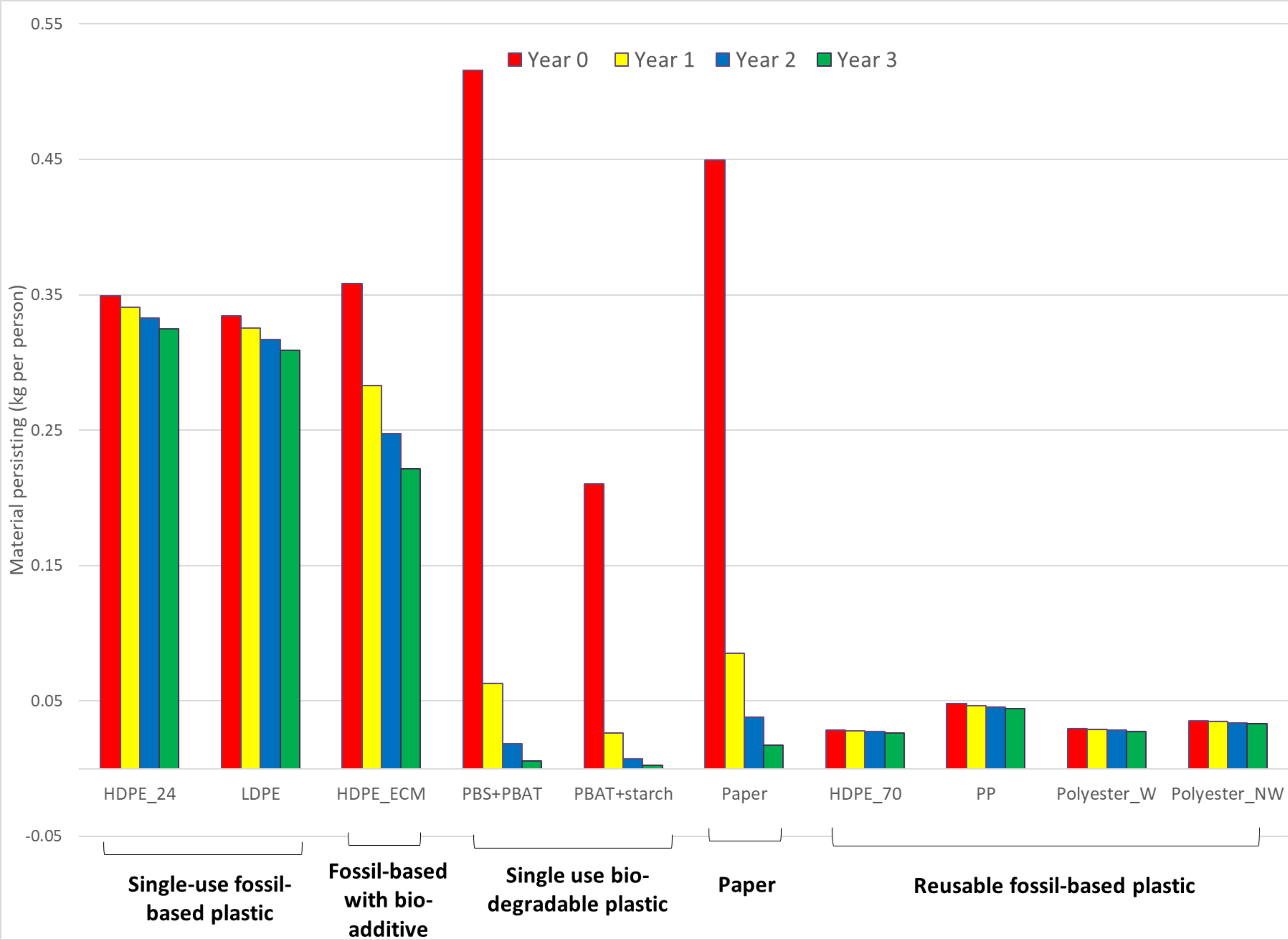

Figure 8: Degradation of carrier bag material (from one year's worth of grocery shopping) over time. HDPE_24 refers to all the HDPE 24µm bags with varying recycled content; while PBS+PBAT and PBAT+Starch include both the imported and locally produced variations.

Table 13 ranks the bag types in terms of their persistence in the environment after three years; from best (least material persisting in the environment) to worst (most material persisting in the environment). Note that the results are based on the degradation of material (after three years) from one person's carrier bag use over one year; and on the modelled end of life mix (see Section 4.4).

Table 13: Mass of material persisting in the environment after three years; from one person's use of carrier bags in one year.

Rank	Bag type	Mass of material after 3 years (kg)	Type of material
1	PBAT+Starch_IMP	0.0022	Biodegradable plastic
2	PBAT+Starch_ZA	0.0022	
3	PBS+PBAT_IMP	0.0054	
4	PBS+PBAT_ZA	0.0054	
5	Paper	0.0175	Paper
6	HDPE_70	0.0265	Fossil-based plastic (reusable)
7	Polyester _W	0.0276	
8	Polyester _NW	0.0330	
9	PP	0.0445	
10	HDPE_ECM	0.2213	Fossil-based with bio-additive
11	LDPE	0.3091	Fossil-based plastic (single- use)
12	HDPE_24_100	0.3251	
13	HDPE_24_75	0.3251	
14	HDPE_24_50	0.3251	
15	HDPE_24_25	0.3251	
16	HDPE_24_0	0.3251	

The results show that the biodegradable bag types occupy the top five positions, as expected. In particular, the biodegradable plastic bags (made from PBAT+Starch and PBS+PBAT) are the best performers, followed by Paper. This is followed by the reusable bag types, who fare relatively well on this indicator under the assumption that they are reused continuously throughout the year, and then discarded at the end of the year; which implies that only a relatively small amount of material is disposed of each year. However, it should be noted that, given the larger amount of material embedded in reusable bags (per bag), they would perform very poorly in terms of persistence if they are instead assumed to be used only a small number of times before being discarded. The HDPE_ECM bag type, which is marketed as being biodegradable, fares relatively poorly; which is consistent with the contested nature of its biodegradability claims. Finally, as expected, the single-use fossil-based plastic bags perform worst in terms of persistence.

In reality, the amount of material in the environment will accumulate over time, as a result of carrier bag use and disposal beyond the first year. For purposes of additional information, Table 14 shows the mass of material remaining in the environment at steady state, where the rate of addition of new material into the environment = the rate of degradation of accumulated material. It also shows how long it takes (in years) for each type of material to reach steady state. Table 14 illustrates the contrast between the biodegradable and non-biodegradable bag types even more vividly than the results in Table 13 above;

since in the case of the fossil-based plastic bags, steady state is reached only over very long periods of time, after which large amounts of material have accumulated. However, as described in Section 5.2.1, the persistence results for this study are based on the amount of material remaining after three years, from one year's usage of carrier bags (Table 13).

Table 14: Mass of material persisting in the environment at steady state (kg).

Bag type	Time taken to reach steady state (years)	Mass of material at steady state (kg)	Type of material
PBAT+Starch_IMP	0.46	0.12	Biodegradable plastic
PBAT+Starch_ZA	0.46	0.12	
PBS+PBAT_IMP	0.44	0.29	
PBS+PBAT_ZA	0.44	0.29	
Paper	0.63	0.34	Paper
HDPE_70	196 902.50	4 135.12	Fossil-based plastic (reusable)
Polyester _W	195 465.76	5 800.72	
Polyester _NW	195 465.76	6 941.03	
PP	196 335.76	7 802.97	
HDPE_ECM	28 176.83	10 790.87	Fossil-based with bio-additive
LDPE	196 901.15	66 138.23	Fossil-based plastic (single- use)
HDPE_24_100	196 902.50	69 084.77	
HDPE_24_75	196 902.50	69 084.77	
HDPE_24_50	196 902.50	69 084.77	
HDPE_24_25	196 902.50	69 084.77	
HDPE_24_0	196 902.50	69 084.77	

In summary, carrier bag material will persist in the environment whenever the rate of biodegradation is less than the rate of accumulation from continued consumption and disposal. Even biodegradable materials can persist in the environment when the rate of biodegradation is less than the rate of accumulation from continued disposal. This is in line with what has been found in other studies (e.g. University of Plymouth, 2019). This suggests that reduced consumption of bags through an emphasis on reuse should be a focus of intervention to reduce plastic pollution. From a persistence perspective, the ideal bag would be one that is reusable, but that biodegrades upon disposal and waste treatment. Cotton or other natural fibres could potentially offer such benefits and should form part of future LCA studies in the South African context; although bearing in mind that studies conducted elsewhere (e.g. Danish EPA 2018) have shown that such materials are inferior in terms of some of the other impact categories.

6.2.2 Employment

In this section, we present the results in terms of the number of jobs per bag type, in order to illustrate differences between the bags in terms of their contribution to employment. Since the number of jobs associated with one person's annual carrier bag requirements is of course a very small number, we present aggregated job numbers across the South African population's annual carrier bag consumption, in order to put these numbers into context and understand the overall significance of carrier bags towards employment numbers in South Africa.

Table 15 shows the number of each type of bag that would be required to be manufactured to fulfil South Africa's annual shopping needs, if only that type of bag was produced. These estimates are based on the current consumption of 2.9 billion standard HDPE 24 µm bags per annum, adjusted for differences in the volumetric capacity and reusability of each bag type.

Table 15 also shows the resulting number of jobs per bag type, associated with the South African population's consumption of carrier bags, per annum. The numbers are based on the assumption that only one type of bag is produced; i.e. assuming that there was a switch towards producing only one type of bag or another, and taking into account the quantity of each bag type required to fulfil the South African population's annual shopping requirements.

Table 15: Number of each type of bag required to fulfil South Africa's annual grocery shopping requirements, and associated number of jobs, if no other type of bag was produced

Bag Type	Total number of bags of each type required per year to fulfil total population's shopping needs (assuming only one type of bag is produced)	Total number of jobs per annum (assuming only one type of bag is produced)	Single-use / reusable
Paper	2 891 200 000	9 242	Single-use
HDPE_24_100	2 900 000 000	5 870	Single-use
HDPE_24_75	2 900 000 000	4 937	Single-use
HDPE_24_50	2 900 000 000	4 004	Single-use
PBS+PBAT_ZA	3 295 968 000	3 660	Single-use
PBS+PBAT_IMP	3 295 968 000	3 653	Single-use
HDPE_24_25	2 900 000 000	3 071	Single-use
HDPE_24_0	2 900 000 000	2 138	Single-use
LDPE	2 023 840 000	2 041	Single-use
PBAT+Starch_ZA	2 544 256 000	1 652	Single-use
HDPE_ECM	3 729 648 000	1 550	Single-use
PBAT+Starch_IMP	2 544 256 000	1 116	Single-use
Polyester_NW	35 028 000	516	Reusable
Polyester_W	65 052 000	431	Reusable
HDPE_70	40 032 000	350	Reusable
PP	48 928 000	214	Reusable

Figure 9 illustrates the number of jobs per bag type associated with annual shopping needs across the South African population (assuming that only one bag type or the other is produced).

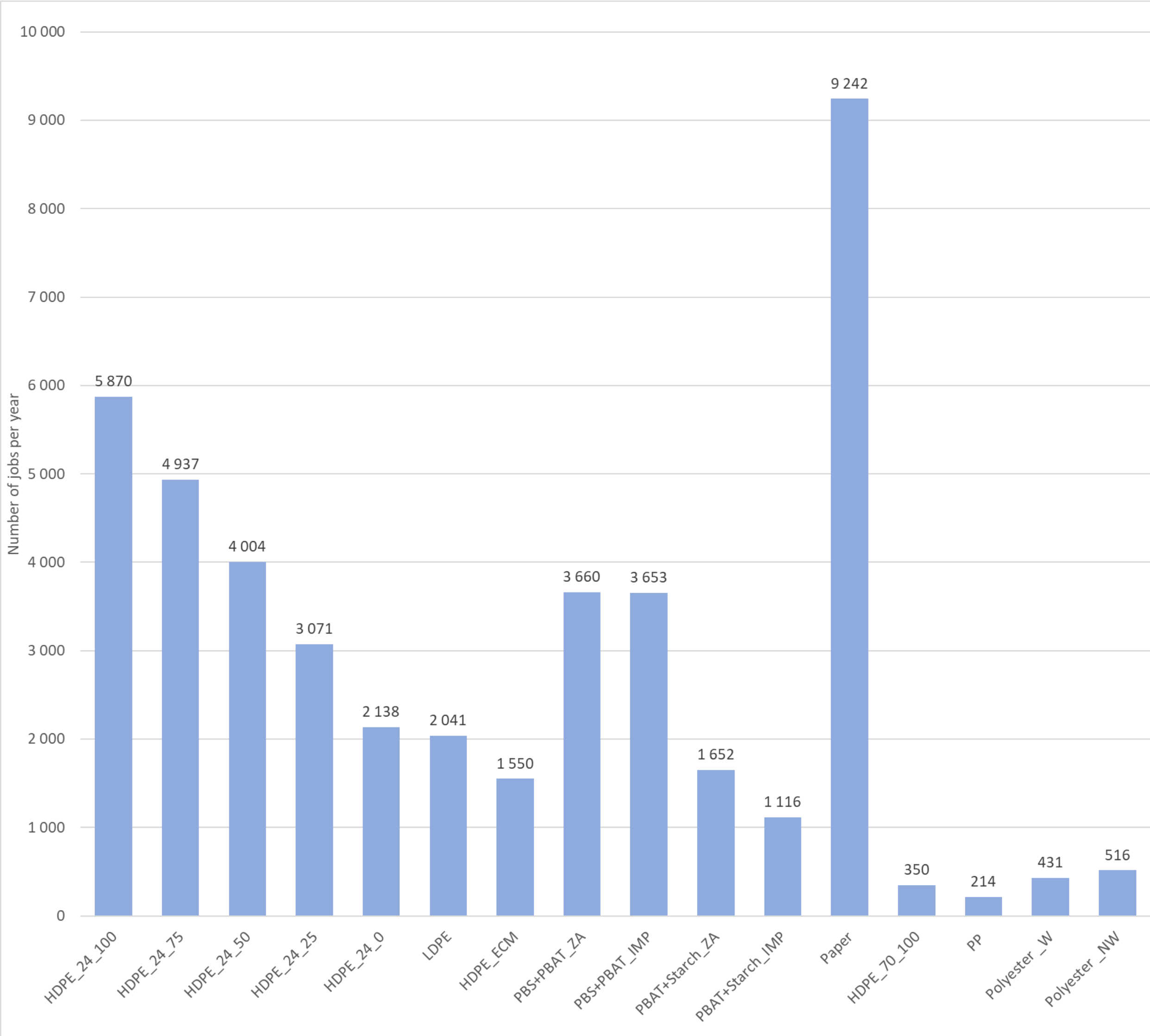

Figure 9: Number of jobs per bag type associated with annual carrier bag consumption for entire SA population (assuming only one bag type of bag was produced)

Finally, Table 16 ranks the bags in terms of the number of jobs associated with an individual consumers' annual carrier bag usage, that is, in terms of the functional unit for the study.

Table 16: Ranking of bag types on employment (based on jobs per functional unit; i.e. number of jobs associated with the carrier bags needed to fulfil an individual's annual grocery shopping requirements)

Rank	Bag type	Jobs per functional unit (Number of jobs associated with the carrier bags needed to fulfil an individual's annual grocery shopping requirements)	Single-use / reusable
1	Paper	0.000166	Single-use
2	HDPE_24_100	0.000105	Single-use
3	HDPE_24_75	0.000089	Single-use
4	HDPE_24_50	0.000072	Single-use
5	PBS+PBAT_ZA	0.000066	Single-use
6	PBS+PBAT_IMP	0.000066	Single-use
7	HDPE_24_25	0.000055	Single-use
8	HDPE_24_0	0.000038	Single-use
9	LDPE	0.000037	Single-use
10	PBAT+Starch_ZA	0.000030	Single-use
11	HDPE_ECM	0.000028	Single-use
12	PBAT+Starch_IMP	0.000020	Single-use
13	Polyester_NW	0.000009	Reusable
14	Polyester_W	0.000008	Reusable
15	HDPE_70	0.000006	Reusable
16	PP	0.000004	Reusable

The results show that Paper bags would be preferable from an employment perspective, with significantly more jobs involved in producing the number of Paper bags that would be required to fulfil annual shopping needs as compared to any of the plastic options. This can be explained by the relative labour intensity of the forestry, pulp and paper industries, and the higher material content of the Paper bags (taking into account annual shopping bag requirements) as compared to the other bag types (see Table 2).

Interestingly, the second best bag type from an employment perspective is the standard single-use HDPE 24 µm bag, specifically the variant with 100% recycled content; followed by the versions with 75% and 50% recycled content, respectively. This suggests that the current status quo bag type does indeed perform relatively well from an employment point of view. It also indicates that the higher the recycled content, the better the performance in terms of employment, owing to the labour intensive nature of the recycling industry (collection, sorting etc.) in South Africa.

In general, the results show that, in terms of employment, the single-use bag types are in fact preferable to reusable bags. This is simply because more single-use bags would need to be produced to fulfil annual grocery shopping requirements, as compared to reusable bags. The reusable bags are produced once-off with the aim to fulfil their function over a long period of time (i.e., significantly fewer reusable bags need to be produced per annum than single-use bags). In other words, if there was a switch away from producing single-use bags towards producing only reusable bags, a decrease in employment could be expected.

Recall from Sections 6.1.1 and 6.2.1 that the reusable bag types were shown to be superior from an environmental perspective; in terms of both the ReCiPe 2016 impact assessment methodology, as well as our new persistence indicator. There is therefore a clear trade-off between environmental performance and impacts on employment when considering single-use versus reusable bags. In Section 6.3, we attempt to integrate the results for our new indicators (including employment) with those for the ReCiPe 2016 methodology; in order to work towards an overall ranking.

It is also important to note the stages in the value chain which contribute toward employment, and how this varies for the different bag types. For example, for single-use bags with a relatively high material content as compared to the HDPE 24 µm bags (such as paper and PBS+PBAT); there are more jobs involved in production; whereas in the case of the HDPE bags, there are jobs involved in recycling; which is not the case for the non-recyclable, biodegradable bags. Finally, for the biodegradable bags, the bulk of the jobs occur in bag manufacture rather than in polymer production; thus the results are similar irrespective of whether the polymers are produced in South Africa or imported.

6.2.3 Affordability

Figure 10 illustrates the average purchase price per individual bag, based on average prices paid for each type of bag at supermarket till points. Prices include the plastic bag levy (where applicable), and were correct as at January 2020. The 1 April 2020 increase in levies is therefore not taken into account.

As is well known, the reusable bag types are more expensive per unit. This is often cited as a rationale for the continued preference among many consumers for single-use bags.

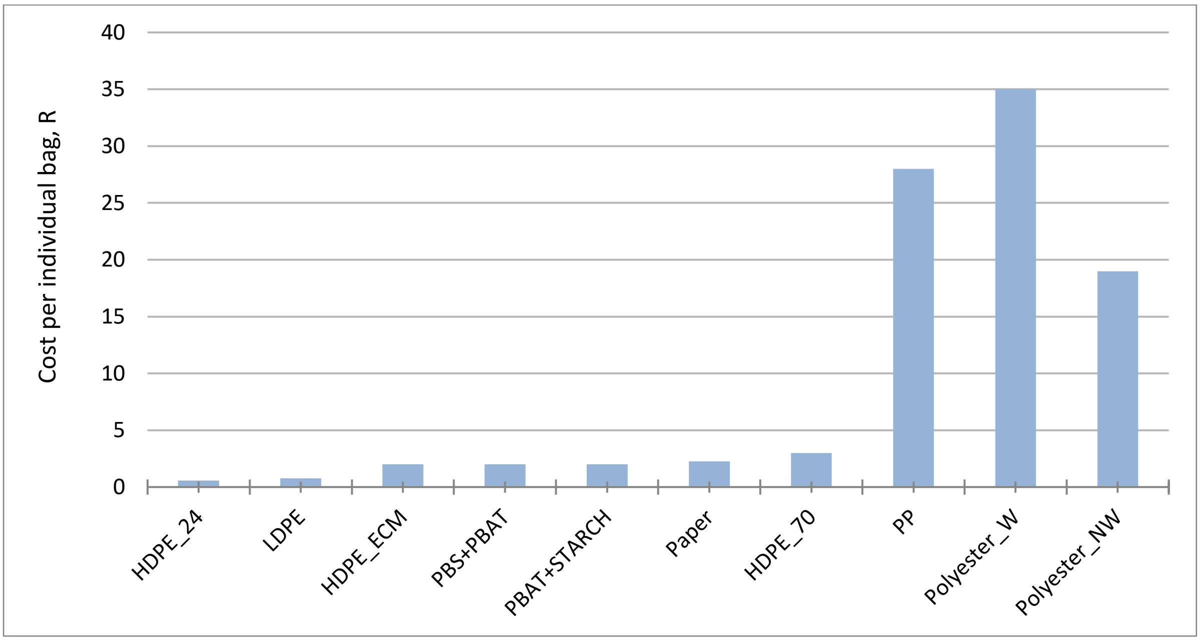

Figure 10: Cost per bag (prices as at January 2020, in Rands). HDPE_24 refers to all the HDPE 24µm bags with varying recycled content; while PBS+PBAT and PBAT+Starch include both the imported and locally produced variations.

However, given that the bags differ significantly in terms of the extent to which they can be reused; affordability should ideally be assessed over a period of time; rather than per individual bag. In Figure 11, we present the cost for an individual to purchase the number of bags associated with annual shopping requirements; based on our assumptions regarding the number of each type of bag required per year (see Section 3.4).

It can be seen from Figure 11 that, despite the higher initial cost, the reusable bag types start to pay off after a certain number of reuses. Specifically, three of the reusable bag types (HDPE_70, PP and Polyester_NW) become more cost-effective than the standard HDPE 24 µm single-use bag over the course of a year, based on our assumptions regarding the number of each type of bag required. The exception is the woven polyester bag (Polyester_W); for which the high unit price implies that affordability remains inferior to that of the standard HDPE 24 µm bag, even over the course of a year.

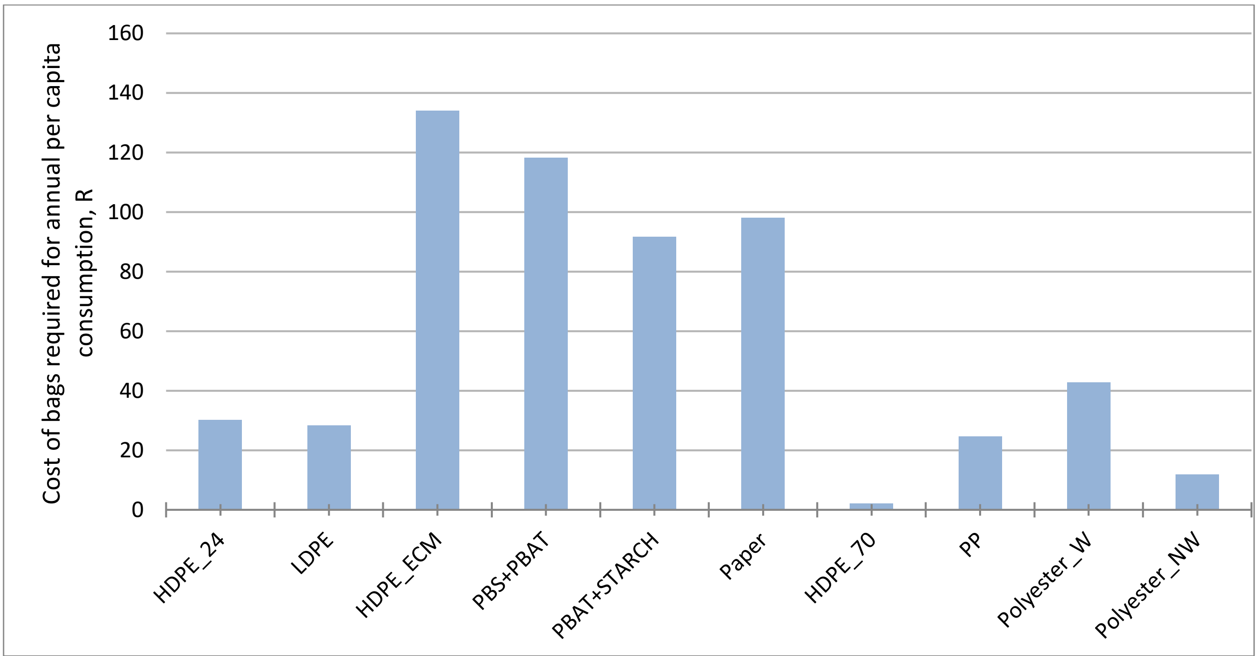

Figure 11: Cost per annum to fulfil an individual's carrier bag requirements (prices as at January 2020, in Rands). HDPE_24 refers to all the HDPE 24µm bags with varying recycled content; while PBS+PBAT and PBAT+Starch include both the imported and locally produced variations.

In Table 17, the bag types are ranked in terms of affordability over the course of a year; from lowest cost per annum, to highest cost per annum (per capita).

Table 17: Ranking of bag types based on affordability (cost of bags required to fulfil an individual's annual grocery shopping requirements).

Rank	Bag type	Cost (ZAR per year)	Single-use / reusable
1	HDPE_70	2.16	Reusable
2	Polyester_NW	11.89	Reusable
3	PP	24.69	Reusable
4	LDPE	28.29	Single-use
5	HDPE_24_100	30.16	Single-use
6	HDPE_24_75	30.16	Single-use
7	HDPE_24_50	30.16	Single-use
8	HDPE_24_25	30.16	Single-use
9	HDPE_24_0	30.16	Single-use
10	Polyester_W	42.80	Reusable
11	PBAT+Starch_ZA	91.63	Single-use
12	PBAT+Starch_IMP	91.63	Single-use
13	Paper	98.09	Single-use
14	PBS+PBAT_ZA	118.19	Single-use
15	PBS+PBAT_IMP	118.19	Single-use
16	HDPE_ECM	133.92	Single-use

Specifically, the 70 µm HDPE bag (HDPE_70) is by far the most cost-effective bag type over the course of a year; based on our assumptions regarding the extent to which each bag type can be reused, and the number of bags required per year. While the standard HDPE 24 µm bag has a lower cost per unit (R0.58 on average); purchasing a reusable bag (and particularly the HDPE_70 bag) would bring savings to the consumer. The HDPE 24 µm single-use bags would cost the consumer R30 to fulfil annual grocery shopping requirements if each bag is only used once, while a HDPE_70 µm would cost significantly less if one bag is reused for the entire year (R2.16, taking into account that the higher capacity of this bag implies that "less" than one bag is needed to fulfil the functional unit).

Furthermore, while the upfront cost of the reusable polyester and PP reusable bags may be prohibitive for very low income consumers, the HDPE_70 reusable bag has a far lower upfront cost, i.e. R3 as at January 2020, which is closer to the unit cost of the single-use bags than to that of the other reusable bags (see Figure 10). It is also worth noting that the single-use biodegradable bags (Paper, PBS+PBAT, and PBAT+Starch) are the least cost-effective bag types, over the course of a year.

Again, however, these results are based on our assumptions regarding the number of times each type of bag is reused, and therefore the number of each type of bag required per year. In particular; there is uncertainty regarding the number of times that the HDPE 70 µm bag can be reused. The extent to which the results would change in response to changes in these and other assumptions is assessed in the sensitivity analysis (Section 7).

6.3 Synthesis of results and overall ranking of bags

In this section, we attempt to synthesise the results from Section 6.1 (environmental LCA using the standard ReCiPe 2016 impact assessment methodology), with the results from Section 6.2 regarding our new indicators (persistence, employment and affordability).

As described in Section 5.3, the three new indicators developed and applied in this analysis should be seen as midpoint impact categories; rather than as endpoints. As such, in this section, we present the results for the three new indicators alongside the existing ReCiPe 2016 midpoint categories. This allows us to work towards an overall ranking of the bags across all indicators.

First, Table 18 presents the scores of each bag per midpoint impact category, in the relevant unit for the indicator in question. Note that this table repeats the information already presented in Table 8 for the ReCiPe 2016 midpoint impact categories; although it adds the three new indicators as well; so that all midpoint indicator results can be seen side by side. The indicators and units are defined in Sections 5.1 (ReCiPe indicators) and 5.2 (new indicators).

Note that for most indicators, with the exception of employment, a lower score is ‘better’. For the environmental indicators, a lower score indicates a lower environmental impact. For the socio-economic indicators; affordability is assessed in terms of the cost to consumers of purchasing bags; and as such, a lower score is also better; whereas for employment, where the score relates to the number of jobs associated with one person’s annual consumption of bags, a higher score is better.

In Table 19, the bags are ranked from best (top) to worst (bottom) in terms of their performance on each of the midpoint impact categories. As mentioned above, for all indicators with the exception of employment, a lower score is ‘better’; bags with a lower score on a particular impact category are ranked higher on that impact category. In the case of employment; a higher score is better – bags with a higher score for the employment impact category are ranked higher. Light green shading is used to indicate the best score on each impact category; while grey indicates the poorest performer on each impact category.

It can be seen from Table 19 that the fossil-based, reusable bag types are the top-ranked bag types across most of the environmental impact categories (see Section 6.1); with the exception of persistence, for which the biodegradable plastic and Paper options occupy the top five positions (see Section 6.2.1). The reusable bag types also perform well in terms of affordability (see Section 6.2.3); but poorly in terms of employment, where the single-use bags, and in particular Paper, are the top performers (Section 6.2.2).

Table 18: Score of each bag per midpoint impact category (including ReCiPe 2016 midpoints and the three new indicators); based on assumed number of reuse times in fulfilling annual shopping requirements

Impact categories	Global warming	SOD	IR	OF,HH	FPM	OF,TE	Terr Acid	FW Eutr	Mar Eutr	Terr Ecotox	FW Ecotox	Mar Ecotox	HuCar Tox	HuNCa rTox	Land Use	MinRe sScar	FosRes Scar	Water Use	Persist -ence	Employ-ment[2]	Afford-ability
Units[1]	Kg CO2-eq	Kg CFC11-eq	Kg Co-60 eq	Kg NOx eq	Kg PM2.5 eq	Kg NOx eq	Kg SO2 eq	Kg P eq	Kg N 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	m2a crop eq	Kg Cu eq	Kg oil eq	m3	Kg material	No. of jobs	ZAR
Bag type																					
HDPE_24_100	4.2073	0.000003	0.0999	0.0134	0.0073	0.0135	0.0229	0.0026	0.00022	8.1305	0.2550	0.3550	0.2745	4.3173	0.1058	0.0084	1.3462	0.032	0.325	0.000105	30.16
HDPE_24_75	5.4738	0.000005	0.1059	0.0171	0.0091	0.0173	0.0288	0.0037	0.00028	8.4272	0.2788	0.3864	0.3757	5.1670	0.1204	0.0106	1.8299	0.036	0.325	0.000089	30.16
HDPE_24_50	6.7383	0.000006	0.1119	0.0209	0.0109	0.0211	0.0348	0.0047	0.00034	8.7139	0.3021	0.4206	0.4768	6.0178	0.1347	0.0128	2.3096	0.040	0.325	0.000072	30.16
HDPE_24_25	8.0028	0.000007	0.1184	0.0246	0.0127	0.0248	0.0407	0.0058	0.00041	9.0107	0.3263	0.4559	0.5779	6.8685	0.1490	0.0150	2.8013	0.043	0.325	0.000055	30.16
HDPE_24_0	9.2673	0.000008	0.1243	0.0284	0.0145	0.0286	0.0467	0.0068	0.00047	9.2974	0.3496	0.4901	0.6800	7.7192	0.1634	0.0172	3.2830	0.047	0.325	0.000038	30.16
LDPE	7.3802	0.000007	0.1095	0.0228	0.0119	0.0230	0.0384	0.0054	0.00038	7.1843	0.2869	0.4026	0.5352	5.2642	0.1324	0.0131	2.5741	0.039	0.309	0.000037	28.29
HDPE_ECM	6.8662	0.000006	0.0930	0.0209	0.0108	0.0211	0.0346	0.0050	0.00036	7.4718	0.2894	0.4060	0.4981	6.0702	0.1211	0.0126	2.4024	0.035	0.221	0.000028	133.92
PBS+PBAT_ZA	13.0305	0.000050	0.2405	0.0267	0.0171	0.0271	0.0459	0.0039	0.00069	13.9845	0.2386	0.3354	0.4658	6.5304	0.1928	0.0184	2.9671	0.161	0.005	0.000066	118.19
PBS+PBAT_IMP	9.2505	0.000046	0.3515	0.0146	0.0116	0.0151	0.0239	0.0021	0.00059	12.1845	0.1626	0.2284	0.2048	4.7404	0.1678	0.0100	2.2771	0.173	0.005	0.000066	118.19
PBAT+Starch_ZA	6.9873	0.000050	0.0766	0.0141	0.0086	0.0143	0.0250	0.0016	0.00034	5.4718	0.1096	0.1469	0.2368	2.7182	0.0891	0.0099	1.0729	0.062	0.002	0.000030	91.63
PBAT+Starch_IMP	4.0872	0.000047	0.0699	0.0057	0.0043	0.0058	0.0095	0.0007	0.00029	4.1918	0.1995	0.0802	0.0711	1.6982	0.0668	0.0036	0.7719	0.059	0.002	0.000020	91.63
Paper	3.2098	0.000003	0.0432	0.0101	0.0050	0.0101	0.0177	0.0013	0.00044	6.5940	0.0799	0.1131	0.1187	3.4467	2.3520	0.0024	0.5707	0.058	0.017	0.000166	98.09
HDPE_70	0.2526	0.000000	0.0060	0.0008	0.0004	0.0008	0.0014	0.0002	0.00001	0.4954	0.0153	0.0211	0.0165	0.2593	0.0064	0.0005	0.0809	0.002	0.026	0.000006	2.16
PP	0.7466	0.000001	0.0092	0.0026	0.0021	0.0024	0.0040	0.0006	0.00004	0.7750	0.0312	0.0435	0.0559	0.1712	0.0104	0.0014	0.2504	0.003	0.045	0.000004	24.69
Polyester_W	0.7971	0.000000	0.0242	0.0027	0.0017	0.0027	0.0054	0.0004	0.00005	1.1918	0.0357	0.0477	0.0427	0.5441	0.0089	0.0004	0.1985	0.003	0.028	0.000008	42.80
Polyester_NW	0.2746	0.000000	0.0091	0.0010	0.0005	0.0010	0.0016	0.0001	0.00004	0.7508	0.0188	0.0260	0.0152	0.2809	0.0051	0.0002	0.0859	0.002	0.033	0.000009	11.89

Notes:

1: All scores provided in the table relate to the functional unit; i.e. to the number of bags required to carry one person's groceries per year. All units are therefore on a per capita per year basis.

2: For employment, a higher score indicates better performance; for all other impact categories, a lower score indicates better performance.

Table 19: Ranking of bags per midpoint impact category (listed from best to worst); based on annual shopping requirements

Rank	Global warming	SOD	IR	OF,HH	FPM	OF,TE	Terr Acid	FW Eutr	Mar Eutr	Terr Ecotox	FW Ecotox	Mar Ecotox	HuCar Tox	HuNCarTox	Land Use	MinResScar	FosResScar	Water Use	Persist-ence	Employ-ment	Afford-ability
1	HDPE_ 70	Polyester _NW	HDPE_ 70	HDPE_ 70	HDPE_ 70	HDPE_ 70	HDPE_ 70	Polyester _NW	HDPE_ 70	HDPE_ 70	HDPE_ 70	HDPE_ 70	Polyester _NW	PP	Polyester _NW	Polyester _NW	HDPE_ 70	HDPE_ 70	PBAT+ Starch _IMP	Paper	HDPE_ 70
2	Polyester _NW	HDPE_ 70	Polyester _NW	Polyester _NW	Polyester _NW	Polyester _NW	Polyester _NW	HDPE_ 70	Polyester _NW	Polyester _NW	Polyester _NW	Polyester _NW	HDPE_ 70	HDPE_ 70	HDPE_ 70	Polyester _W	Polyester _NW	Polyester _NW	PBAT+ Starch_ ZA	HDPE_ 24_100	Polyester _NW
3	PP	Polyester _W	PP	PP	Polyester _W	PP	PP	Polyester _W	PP	PP	PP	PP	Polyester _W	Polyester _NW	Polyester _W	HDPE_ 70	Polyester _W	Polyester _W	PBS+ PBAT_ IMP	HDPE_ 24_75	PP
4	Polyester _W	PP	Polyester _W	Polyester _W	PP	Polyester _W	Polyester _W	PP	Polyester _W	Polyester _W	Polyester _W	Polyester _W	PP	Polyester _W	PP	PP	PP	PP	PBS+ PBAT_ ZA	HDPE_ 24_50	LDPE
5	Paper	Paper	Paper	PBAT+ Starch _IMP	PBAT+ Starch _IMP	PBAT+ Starch _IMP	PBAT+ Starch _IMP	PBAT+ Starch _IMP	HDPE_ 24_100	PBAT+ Starch _IMP	Paper	PBAT+ Starch _IMP	PBAT+ Starch _IMP	PBAT+ Starch _IMP	PBAT+ Starch _IMP	Paper	Paper	HDPE_ 24_100	Paper	PBS+ PBAT _ZA	HDPE_ 24_100
6	PBAT+ Starch_ IMP	HDPE_ 24_100	PBAT+ Starch _IMP	Paper	Paper	Paper	Paper	Paper	HDPE_ 24_75	PBAT+ Starch _ZA	PBAT+ Starch _ZA	Paper	Paper	PBAT+ Starch _ZA	PBAT+ Starch _ZA	PBAT+ Starch _IMP	PBAT+ Starch _IMP	HDPE_ ECM	HDPE_ 70	PBS+ PBAT _IMP	HDPE_ 24_75
7	HDPE_ 24_100	HDPE_ 24_75	PBAT+ Starch _ZA	HDPE_ 24_100	HDPE_ 24_100	HDPE_ 24_100	HDPE_ 24_100	PBAT+ Starch _ZA	PBAT+ Starch _IMP	Paper	PBS+ PBAT _IMP	PBAT+ Starch _ZA	PBS+ PBAT _IMP	Paper	HDPE_ 24_100	HDPE_ 24_100	PBAT+ Starch _ZA	HDPE_ 24_75	Polyester _W	HDPE_ 24_25	HDPE_ 24_50
8	HDPE_ 24_75	HDPE_ 24_50	HDPE_ ECM	PBAT+ Starch _ZA	PBAT+ Starch _ZA	PBAT+ Starch _ZA	PBS+ PBAT _IMP	PBS+ PBAT _IMP	HDPE_ 24_50	LDPE	PBAT+ Starch _IMP	PBS+ PBAT _IMP	PBAT+ Starch _ZA	HDPE_ 24_100	HDPE_ 24_75	PBAT+ Starch _ZA	HDPE_ 24_100	LDPE	Polyester _NW	HDPE_ 24_0	HDPE_ 24_25
9	HDPE_ 24_50	HDPE_ ECM	HDPE_ 24_100	PBS+ PBAT _IMP	HDPE_ 24_75	PBS+ PBAT _IMP	PBAT+ Starch _ZA	HDPE_ 24_100	PBAT+ Starch _ZA	HDPE_ ECM	PBS+ PBAT _ZA	PBS+ PBAT _ZA	HDPE_ 24_100	PBS+ PBAT _IMP	HDPE_ ECM	PBS+ PBAT _IMP	HDPE_ 24_75	HDPE_ 24_50	PP	LDPE	HDPE_ 24_0
10	HDPE_ ECM	LDPE	HDPE_ 24_75	HDPE_ 24_75	HDPE_ ECM	HDPE_ 24_75	HDPE_ 24_75	HDPE_ 24_75	HDPE_ ECM	HDPE_ 24_100	HDPE_ 24_100	HDPE_ 24_100	HDPE_ 24_75	HDPE_ 24_75	LDPE	HDPE_ 24_75	PBS+ PBAT _IMP	HDPE_ 24_25	HDPE_ ECM	PBAT+ Starch _ZA	Polyester _W
11	PBAT+ Starch_ ZA	HDPE_ 24_25	LDPE	HDPE_ 24_50	HDPE_ 24_50	HDPE_ 24_50	HDPE_ ECM	PBS+ PBAT _ZA	LDPE	HDPE_ 24_75	HDPE_ 24_75	HDPE_ 24_75	PBS+ PBAT _ZA	LDPE	HDPE_ 24_50	HDPE_ ECM	HDPE_ 24_50	HDPE_ 24_0	LDPE	HDPE_ ECM	PBAT+ Starch _ZA
12	LDPE	HDPE_ 24_0	HDPE_ 24_50	HDPE_ ECM	PBS+ PBAT _IMP	HDPE_ ECM	HDPE_ 24_50	HDPE_ 24_50	HDPE_ 24_25	HDPE_ 24_50	LDPE	LDPE	HDPE_ 24_50	HDPE_ 24_50	HDPE_ 24_25	HDPE_ 24_50	HDPE_ ECM	Paper	HDPE_ 24_100	PBAT+ Starch _IMP	PBAT+ Starch _IMP
13	HDPE_ 24_25	PBS+ PBAT _IMP	HDPE_ 24_25	LDPE	LDPE	LDPE	LDPE	HDPE_ ECM	Paper	HDPE_ 24_25	HDPE_ ECM	HDPE_ ECM	HDPE_ ECM	HDPE_ ECM	HDPE_ 24_0	LDPE	LDPE	PBAT+ Starch _IMP	HDPE_ 24_75	Polyester _NW	Paper
14	PBS+ PBAT_ IMP	PBAT+ Starch _IMP	HDPE_ 24_0	HDPE_ 24_25	HDPE_ 24_25	HDPE_ 24_25	HDPE_ 24_25	LDPE	HDPE_ 24_0	HDPE_ 24_0	HDPE_ 24_50	HDPE_ 24_50	LDPE	PBS+ PBAT _ZA	PBS+ PBAT _IMP	HDPE_ 24_25	HDPE_ 24_25	PBAT+ Starch _ZA	HDPE_ 24_50	Polyester _W	PBS+ PBAT _ZA
15	HDPE_ 24_0	PBAT+ Starch _ZA	PBS+ PBAT _ZA	PBS+ PBAT _ZA	HDPE_ 24_0	PBS+ PBAT _ZA	PBS+ PBAT _ZA	HDPE_ 24_25	PBS+ PBAT _IMP	PBS+ PBAT _IMP	HDPE_ 24_25	HDPE_ 24_25	HDPE_ 24_25	HDPE_ 24_25	PBS+ PBAT _ZA	HDPE_ 24_0	PBS+ PBAT _ZA	PBS+ PBAT _ZA	HDPE_ 24_25	HDPE_ 70	PBS+ PBAT _IMP
16	PBS+ PBAT_ ZA	PBS+ PBAT _ZA	PBS+ PBAT _IMP	HDPE_ 24_0	PBS+ PBAT _ZA	HDPE_ 24_0	HDPE_ 24_0	HDPE_ 24_0	PBS+ PBAT _ZA	PBS+ PBAT _ZA	HDPE_ 24_0	HDPE_ 24_0	HDPE_ 24_0	HDPE_ 24_0	Paper	PBS+ PBAT _ZA	HDPE_ 24_0	PBS+ PBAT _IMP	HDPE_ 24_0	PP	HDPE_ ECM

Table 20 presents the rankings in a slightly different way; indicating the numerical rank of each bag against each impact category.

In working towards an overall ranking, a number of options could be considered. For example, the bags could simply be ranked on the ReCiPe 2016 single score (see Section 6.1); however, doing so would exclude the results for our new indicators (persistence, employment and affordability) from the overall ranking; and could therefore be misleading; while the Eurocentric weightings used in calculating the ReCiPe 2016 single score are not necessarily relevant to the South African context.

Another option is simply to take an average of the rankings of each bag on each impact category (including the new indicators). The last column of Table 20 provides the average ranking across each of the midpoint impact categories. Indeed, the bags in Table 20 are listed according to the average ranking (from best to worst); so this could be seen as one way of ranking the bags in terms of their overall performance.

However, this approach is perhaps too simplistic; as it doesn't take into account the variation in actual scores between bags on the different impact categories – that is, it doesn't take into account extremely high or extremely low scores for specific bags on specific impact categories. On the other hand, since the actual scores per impact category are specified in different units, these cannot be simply aggregated to derive an overall score.

As such, we develop an alternative approach to determining an overall ranking, based on relative (as opposed to absolute) scores. Specifically, we derive 'dimensionless' scores for each bag on each midpoint impact category; by dividing the actual score for each bag by the score for the reference bag; in this case the HDPE_24_100 bag. This overcomes the problem of different impact categories being specified in different units; allowing for the scores to be aggregated across impact categories; while also allowing for extremely high or low scores to be reflected. The resulting dimensionless scores are provided in Table 21.

Table 20: Numerical ranking of bags per midpoint impact category (from best (1) to worst (16)), based on assumed number of reuse times in fulfilling annual shopping requirements; listed by average ranking (from best to worst)

Bag type	GW	SOD	IR	OF,HH	FPM	OF,TE	Terr Acid	FW Eutr	Mar Eutr	Terr Ecotox	FW Ecotox	Mar Ecotox	HuCar Tox	HuNCarTox	Land Use	MinRes Scar	FosRes Scar	Water Use	Persist-ence	Employ-ment	Afford ability	Average rank
HDPE_70	1	2	1	1	1	1	1	2	1	1	1	1	2	2	2	3	1	1	6	15	1	2.24
Polyester_NW	2	1	2	2	2	2	2	1	2	2	2	2	1	3	1	1	2	2	8	13	2	2.62
PP	3	4	3	3	4	3	3	4	3	3	3	3	4	1	4	4	4	4	9	16	3	4.19
Polyester_W	4	3	4	4	3	4	4	3	4	4	4	4	3	4	3	2	3	3	7	14	10	4.48
PBAT+Starch_IMP	6	14	6	5	5	5	5	5	7	5	8	5	5	5	5	6	6	13	1	12	12	6.71
Paper	5	5	5	6	6	6	6	6	13	7	5	6	6	7	16	5	5	12	5	1	13	6.95
HDPE_24_100	7	6	9	7	7	7	7	9	5	10	10	10	9	8	7	7	8	5	12	2	5	7.48
PBAT+Starch_ZA	11	15	7	8	8	8	9	7	9	6	6	7	8	6	6	8	7	14	2	10	11	8.24
HDPE_24_75	8	7	10	10	9	10	10	10	6	11	11	11	10	10	8	10	9	7	13	3	6	9.00
PBS+PBAT_IMP	14	13	16	9	12	9	8	8	15	15	7	8	7	9	14	9	10	16	3	6	15	10.62
HDPE_24_50	9	8	12	11	11	11	12	12	8	12	14	14	12	12	11	12	11	9	14	4	7	10.76
HDPE_ECM	10	9	8	12	10	12	11	13	10	9	13	13	13	13	9	11	12	6	10	11	16	11.00
LDPE	12	10	11	13	13	13	13	14	11	8	12	12	14	11	10	13	13	8	11	9	4	11.19
HDPE_24_25	13	11	13	14	14	14	14	15	12	13	15	15	15	15	12	14	14	10	15	7	8	13.00
PBS+PBAT_ZA	16	16	15	15	16	15	15	11	16	16	9	9	11	14	15	16	15	15	4	5	14	13.24
HDPE_24_0	15	12	14	16	15	16	16	16	14	14	16	16	16	16	13	15	16	11	16	8	9	14.29

Table 21: Overall ranking of bags based on aggregation of dimensionless scores across midpoint impact categories (equal weighting); listed by overall rank. Scores are based on assumed number of reuse times in fulfilling annual shopping requirements;

Rank	**Bag type**	GW	SOD	IR	OF,HH	FPM	OF,TE	Terr Acid	FW Eutr	Mar Eutr	Terr Ecotox	FW Ecotox	Mar Ecotox	HuCar Tox	HuNCar Tox	Land Use	MinRes Scar	FosRes Scar	Water Use	Persist-ence	Employ-ment	Afford-ability	Total[2]
1	HDPE_70	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.08	0.06	0.07	1.17
2	Polyester_NW	0.07	0.05	0.09	0.07	0.08	0.07	0.07	0.05	0.17	0.09	0.07	0.07	0.06	0.07	0.05	0.02	0.06	0.06	0.10	0.09	0.39	1.68
3	PP	0.18	0.21	0.09	0.19	0.29	0.18	0.17	0.22	0.17	0.10	0.12	0.12	0.20	0.04	0.10	0.16	0.19	0.09	0.14	0.04	0.82	3.74
4	Polyester_W	0.19	0.14	0.24	0.20	0.23	0.20	0.24	0.16	0.23	0.15	0.14	0.13	0.16	0.13	0.08	0.04	0.15	0.09	0.08	0.07	1.42	4.33
5	HDPE_24_100	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	19.00
6	HDPE_24_75	1.30	1.38	1.06	1.28	1.24	1.28	1.26	1.41	1.27	1.04	1.09	1.09	1.37	1.20	1.14	1.27	1.36	1.11	1.00	0.84	1.00	23.31
7	PBAT+Starch_IMP	0.97	14.00	0.70	0.42	0.58	0.43	0.42	0.26	1.31	0.52	0.78	0.23	0.26	0.39	0.63	0.44	0.57	1.83	0.01	0.19	3.04	27.60
8	HDPE_24_50	1.60	1.75	1.12	1.56	1.49	1.56	1.52	1.82	1.55	1.07	1.18	1.18	1.74	1.39	1.27	1.53	1.72	1.23	1.00	0.68	1.00	27.62
9	LDPE	1.75	1.98	1.10	1.70	1.63	1.70	1.68	2.08	1.71	0.88	1.13	1.13	1.95	1.22	1.25	1.57	1.91	1.21	0.95	0.35	0.94	29.13
10	HDPE_ECM	1.63	1.86	0.93	1.56	1.47	1.56	1.51	1.93	1.63	0.92	1.13	1.14	1.81	1.41	1.14	1.51	1.78	1.07	0.68	0.26	4.44	30.88
11	HDPE_24_25	1.90	2.13	1.19	1.84	1.73	1.84	1.78	2.23	1.84	1.11	1.28	1.28	2.11	1.59	1.41	1.79	2.08	1.34	1.00	0.52	1.00	31.94
12	PBAT+Starch_ZA	1.66	14.90	0.77	1.05	1.17	1.06	1.09	0.62	1.56	0.67	0.43	0.41	0.86	0.63	0.84	1.19	0.80	1.91	0.01	0.28	3.04	34.40
13	HDPE_24_0	2.20	2.51	1.24	2.12	1.98	2.12	2.04	2.64	2.12	1.14	1.37	1.38	2.48	1.79	1.54	2.06	2.44	1.45	1.00	0.36	1.00	36.26
14	Paper	0.76	0.82	0.43	0.75	0.68	0.75	0.77	0.51	2.00	0.81	0.31	0.32	0.43	0.80	22.22	0.29	0.42	1.78	0.05	1.58	3.25	36.60
15	PBS+PBAT_IMP	2.20	13.78	3.52	1.09	1.58	1.12	1.05	0.81	2.66	1.50	0.64	0.64	0.75	1.10	1.59	1.20	1.69	5.34	0.02	0.62	3.92	45.54
16	PBS+PBAT_ZA	3.10	15.07	2.41	1.99	2.33	2.01	2.01	1.51	3.13	1.72	0.94	0.94	1.70	1.51	1.82	2.21	2.20	4.97	0.02	0.63	3.92	54.87

Notes:

1. Since dimensionless scores are calculated as scores relative to the reference bag (HDPE_24_100); the score for this bag on each impact category equals 1.
2. A lower total score indicates better overall performance. Total calculated by summing scores across all impact categories, with the exception of employment, which is subtracted; since for this indicator, a higher score indicates better performance.

In the last column of Table 21, we calculate an aggregate score for each bag across the midpoint impact categories; with a lower score indicating better overall performance; and a higher score indicating poorer performance. The aggregate score is calculated by summing the dimensionless scores for each bag on each impact category. However, in the case of the employment impact category; the score is subtracted from the total rather than added; since for this impact category only, a higher score is better. The bags can then be ranked from best (lowest total score) to worst (highest total score). The bags are listed in Table 21 in terms of their overall ranking, from best to worst.

It is worth noting that the overall ranking in Table 21 is similar to that obtained through the alternative approach in Table 20, with a few exceptions. However, for reasons explained above, we argue that the rankings in Table 21 are a truer reflection of the overall ranking across impact categories, as compared to Table 20.

Note that the aggregate scores in Table 21 are based on an equal weighting of each midpoint impact category; although differential weighting could be applied to emphasise specific midpoint categories of relevance to a particular decision making context; or to highlight impact categories where carrier bags make a disproportionately high contribution to the overall problem. For example, in the South African context; it could be argued that employment should receive a higher weighting as compared to some of the other midpoint impact categories. Similarly, it could be argued that persistence should receive a higher weighting in an assessment of carrier bags, since plastic bags would be expected to make a disproportionately high contribution to the overall problem of plastic pollution, as compared to their contribution to other environmental issues (such as global warming), which would be expected to be far lower, in relative terms. It is therefore suggested that a set of weightings appropriate to the South African context be developed, through a multi-criteria decision analysis approach, incorporating government and other relevant stakeholders.

From Table 21, it can be seen that, over the course of a year, based on our assumptions regarding the number of times each bag is reused (i.e., how many of each bag type needs to be purchased over the course of the year), the best performing bag overall is the HDPE 70 µm reusable bag (HDPE_70), closely followed by the non-woven polyester bag type (Polyester_NW). The four reusable bag types (HDPE_70, Polyester_NW, PP and Polyester_W) occupy the top four positions in the rankings. The worst performing among the reusable bags (fourth overall) is the woven polyester (Polyester_W) bag; although this bag still performs better than any of the single-use bags.

However, it is important to note that the analysis is based on a one-year timeframe, and on our assumptions that single-use bags will only be used once each, and that reusable bags will be reused over the entire year (e.g., 52 times assuming weekly shopping trips). In reality, the PP and polyester bags are likely to be able to last beyond 52 uses (i.e., beyond one year); while it is also possible that, in their current design, the HDPE_70 bags may *not l*ast for 52 uses (the handles are noted as a potential weak point in the current design). Furthermore, bags that are intended for single use can in fact be reused to a certain extent.

It is therefore important to assess the extent to which the results would change if we change the assumptions regarding the number of times the reusable bags can in fact be reused; and regarding whether the single-use bags will be reused. This is done in the sensitivity analysis (see Section 7).

From Table 21, it is also evident that the worst performing bag overall over the course of a year (based on our assumptions regarding the number of bags required to fulfil annual shopping requirements) is the PBS+PBAT bag made using locally produced PBS and PBAT (PBS+PBAT_ZA). Note that we have modelled this bag based on PBS and PBAT components both being fossil-based, as this is how they are currently being developed in South Africa; although there is a potential to switch to bio-based feedstocks. Specifically, they are modelled as being produced by the SASOL CTL process. Table 21 shows that the version of this bag produced using imported PBS and PBAT (PBS+PBAT_IMP) is ranked one place higher. Likewise, the PBAT+Starch_IMP bag is ranked higher than the local variant, PBAT+Starch_ZA. These trends arise mainly due to the gasification of coal in the SASOL CTL process used to produce the PBS and PBAT polymers in South Africa; which is more resource intensive and polluting as compared to the process involved in producing the imported PBS and PBAT, which uses natural gas.

It is also interesting to note that the best performing single-use bag is the HDPE 24 µm bag with 100% recycled content (HDPE_24_100), which is currently the most common bag type found in formal sector grocery stores in South Africa. It can also be seen that the higher the recycled content of the bags, the better the overall environmental and socio-economic performance. The HDPE 24 µm bag with 100% recycled content (HDPE_24_100) achieves the highest ranking from among the HDPE 24 µm bags, while the HDPE bags with lower recycled content rank progressively worse.

6.4 How many times does each type of bag need to be used?

In sections 6.1 to 6.3, we applied fixed assumptions regarding the number of times each type of bag is reused over the course of a year, and therefore how many of each type of bag is purchased during the year; in order to fulfil our functional unit. That analysis is useful in order to be able to rank the different bag types in terms of overall performance over the course of a year.

However, it is also useful to look at the impact per individual bag (adjusted for differences in volumetric capacity and material mass); without making any assumptions regarding the number of times each bag type is likely to be reused. The intention is to illustrate how many times each type of bag *needs* to be reused in order to match (break even with) the environmental performance of the standard single-use bag.

The standard HDPE 24 µm bag with 100% recycled content (HDPE_24_100) is used as a reference bag, since this is the most common bag type currently found in formal sector grocery stores in South Africa. Based on the impact associated with a single use of each bag, it is possible to rank the bags in terms of the number of times each needs to be reused, in order to match the environmental performance of the HDPE_24_100 bag. Note that in this analysis, we confine ourselves to environmental impacts as per the ReCiPe 2016 single score. Recall that this excludes our new indicators (persistence, employment and affordability). This is because it was not yet possible to integrate the results for the new indicators into a combined single score, which would allow an assessment of the number of reuse times required across all indicators.

Table 22 shows the ReCiPe 2016 single score results associated with a *single use* of each bag type. It then shows the number of times each type of bag needs to be used in order to break even with the reference bag (HDPE_24_100). It is interesting to note that both PBAT+Starch_IMP and Paper bags perform better than the reference bag on the ReCiPe 2016 single score (based on a single use); all the others show a higher environmental impact; with an increasing number of times each type of bag needs to be used to break-even with the HDPE_24_100 bag.

As can be expected, the single-use bags perform better as compared to the reusable bags when assessed from the perspective of a one-time use; as they have a lower material requirement (and therefore lower environmental impact) per bag. However, the reusable bags can achieve parity with the reference bag after a reasonably low number of reuses (ranging from just three times in the case of the HDPE 70 µm bag, to ten times in the case of woven polyester bags).

However, it should be clear that for all types of bags (whether intended for single use or for reuse); the more times a bag can be reused, the better its environmental performance becomes. When used only once, the entire environmental burden associated with the bag's life cycle is attributed to that one shopping trip. Purchasing a new bag for each shopping trip over the course of a year implies that the environmental burden per bag is multiplied by the number of trips. On the other hand, when bags are reused, the environmental burden associated with just one bag is spread out across numerous uses. As such, one of the most important recommendations that can be made to the consumer is to reuse his or her bag as many times as possible, irrespective of the type of bag.

Table 22: Performance of bag types on ReCiPe 2016 single score for a single use; and number of uses required to break even with the reference bag (HDPE_24_100)

Bag type	Environmental impact (single score, mPt) for one use	Number of uses required to break even with HDPE_24_100
PBAT+Starch_IMP	1.98	0.70
Paper	2.19	0.78
HDPE_24_100	2.82	1.00
HDPE_24_75	3.59	1.27
PBAT+Starch_ZA	3.60	1.28
HDPE_24_50	4.35	1.54
HDPE_ECM	4.39	1.56
PBS+PBAT_IMP	4.93	1.75
LDPE	4.93	1.75
HDPE_24_25	5.12	1.82
HDPE_24_0	5.89	2.09
PBS+PBAT_ZA	7.02	2.49
HDPE_70	8.81	3.12
Polyester_NW	10.10	3.58
PP	25.27	8.96
Polyester_W	26.98	9.56

7 Sensitivity Analysis

As discussed in section 4.6, sensitivity analysis is conducted on four key assumptions relating to reuse and recycling; in order to assess the robustness and sensitivity of the model to changes in these assumptions, and to examine how the results are affected when some of these key parameters change.

7.1 Lifespan of the HDPE 70 µm reusable bag

Recall from Section 6 that, based on our assumptions regarding the number of times each bag type would be reused (and therefore the number of bags required) over the course of a year, the HDPE 70 µm bag (HDPE_70) was the highest ranked bag overall. It has the lowest overall environmental impact on most of the ReCiPe 2016 midpoint impact categories; all of the endpoint damage categories, and the single score. It also performs best on two of our three additional indicators; namely persistence and affordability (although, it performs second worst in terms of employment).

However, the results in Section 6 are based on the assumption that the HDPE_70 bag could be reused the same number of times as the other reusable bags (PP and polyester); Specifically, we assumed that the reusable bags (including the HDPE_70 bag) would be used 52 times over the course of a year; assuming weekly shopping trips. That is, we assumed that these bags would only be purchased once, and reused over the course of the entire year, to fulfil an individual's annual shopping requirements.

However, there is uncertainty regarding the lifespan of the HDPE 70 µm bag (i.e., the number of times the bag can be reused); particularly in relation to the PP and polyester bags, which are thicker and, presumably, more durable. As such, it is not clear whether the HDPE_70 bag will be able to last for 52 uses. (At the same time, it could well be that the PP and polyester bags can last for more than 52 uses – sensitivity analysis on this assumption is conducted in Section 7.2). Thus, given that the HDPE_70 bag comes out as most favourable overall based on the assumption that it will last for 52 uses, it is crucial to test the extent to which this result will change with a change in assumptions regarding the lifespan of this type of bag.

Specifically, we conduct sensitivity analysis based on two shorter assumed lifespans for the HDPE_70 bag: One in which the lifespan is 50% of the baseline (26 uses, rather than 52); and one in which the lifespan is only 25% of the baseline (13 uses).

Table 23 shows the rankings of the bags (based on annual shopping requirements) for all three scenarios; namely the baseline scenario, in which the HDPE_70 bag is assumed to last for 52 uses; followed by the alternative scenarios in which it is assumed to last respectively for only 26 or 13 uses. In this table, and in the tables that follow, the bag types that are being subjected to sensitivity analysis (HDPE_70 in this case) are highlighted. Note that the analysis in Table 23 is based on the ReCiPe 2016 single score only; similar analysis for the new indicators (persistence, employment and affordability) is shown in Table 24.

Table 23: Change in ranking of bags based on environmental performance (ReCiPe 2016 single score) with different assumptions on the lifespan of the HDPE 70 µm bag

Rank	Baseline: HDPE_70 bag lasts for 52 uses	HDPE_70 bag lasts for 26 uses	HDPE_70 bag lasts for 13 uses
1	HDPE_70	Polyester_NW	Polyester_NW
2	Polyester_NW	HDPE_70	HDPE_70
3	PP	PP	PP
4	Polyester_W	Polyester_W	Polyester_W
5	PBAT+Starch_IMP	PBAT+Starch_IMP	PBAT+Starch_IMP
6	Paper	Paper	Paper
7	HDPE_24_100	HDPE_24_100	HDPE_24_100
8	HDPE_24_75	HDPE_24_75	HDPE_24_75
9	PBAT+Starch_ZA	PBAT+Starch_ZA	PBAT+Starch_ZA
10	HDPE_24_50	HDPE_24_50	HDPE_24_50
11	HDPE_ECM	HDPE_ECM	HDPE_ECM
12	PBS+PBAT_IMP	PBS+PBAT_IMP	PBS+PBAT_IMP
13	LDPE	LDPE	LDPE
14	HDPE_24_25	HDPE_24_25	HDPE_24_25
15	HDPE_24_0	HDPE_24_0	HDPE_24_0
16	PBS+PBAT_ZA	PBS+PBAT_ZA	PBS+PBAT_ZA

From Table 23 it can be seen that, with a reduction in its assumed lifespan from 52 to 26 uses, the HDPE_70 bag falls to being the 2nd ranked bag; behind the non-woven polyester bag, which now becomes the top-ranked bag. The same ranking holds if the assumed lifespan of the HDPE_70 bag is further reduced to 13 uses. In all of these scenarios, however, the HDPE_70 and Polyester_NW bags retain the top two positions in the rankings. Indeed, reviewing the results and overall rankings from Section 6, it can be seen that the scores for these two bag types (e.g. in terms of the ReCiPe 2016 single score in Section 6.1, or in terms of the average rank (Table 20) or overall score (Table 21) across all indicators) are fairly close; and far superior to the other bag types.

Table 24: Change in ranking of bags on persistence, employment and affordability with different assumptions on the lifespan of the HDPE 70 µm bag

Persistence				Employment				Affordability			
Rank	**Baseline: HDPE_70 bag lasts for 52 uses**	**HDPE_70 bag lasts for 26 uses**	**HDPE_70 bag lasts for 13 uses**	**Rank**	**Baseline: HDPE_70 bag lasts for 52 uses**	**HDPE_70 bag lasts for 26 uses**	**HDPE_70 bag lasts for 13 uses**	**Rank**	**Baseline: HDPE_70 bag lasts for 52 uses**	**HDPE_70 bag lasts for 26 uses**	**HDPE_70 bag lasts for 13 uses**
1	PBAT+Starch_IMP	PBAT+Starch_IMP	PBAT+Starch_IMP	1	Paper	Paper	Paper	1	HDPE_70	HDPE_70	HDPE_70
2	PBAT+Starch_ZA	PBAT+Starch_ZA	PBAT+Starch_ZA	2	HDPE_24_100	HDPE_24_100	HDPE_24_100	2	Polyester_NW	Polyester_NW	Polyester_NW
3	PBS+PBAT_IMP	PBS+PBAT_IMP	PBS+PBAT_IMP	3	HDPE_24_75	HDPE_24_75	HDPE_24_75	3	PP	PP	PP
4	PBS+PBAT_ZA	PBS+PBAT_ZA	PBS+PBAT_ZA	4	HDPE_24_50	HDPE_24_50	HDPE_24_50	4	LDPE	LDPE	LDPE
5	Paper	Paper	Paper	5	PBS+PBAT_ZA	PBS+PBAT_ZA	PBS+PBAT_ZA	5	HDPE_24_100	HDPE_24_100	HDPE_24_100
6	HDPE_70	Polyester _W	Polyester _W	6	PBS+PBAT_IMP	PBS+PBAT_IMP	PBS+PBAT_IMP	6	HDPE_24_75	HDPE_24_75	HDPE_24_75
7	Polyester _W	Polyester _NW	Polyester _NW	7	HDPE_24_25	HDPE_24_25	HDPE_24_25	7	HDPE_24_50	HDPE_24_50	HDPE_24_50
8	Polyester _NW	PP	PP	8	HDPE_24_0	HDPE_24_0	HDPE_24_0	8	HDPE_24_25	HDPE_24_25	HDPE_24_25
9	PP	HDPE_70	HDPE_70	9	LDPE	LDPE	LDPE	9	HDPE_24_0	HDPE_24_0	HDPE_24_0
10	HDPE_ECM	HDPE_ECM	HDPE_ECM	10	PBAT+Starch_ZA	PBAT+Starch_ZA	PBAT+Starch_ZA	10	Polyester_W	Polyester_W	Polyester_W
11	LDPE	LDPE	LDPE	11	HDPE_ECM	HDPE_ECM	HDPE_ECM	11	PBAT+Starch_IMP	PBAT+Starch_IMP	PBAT+Starch_IMP
12	HDPE_24_100	HDPE_24_100	HDPE_24_100	12	PBAT+Starch_IMP	PBAT+Starch_IMP	HDPE_70	12	PBAT+Starch_ZA	PBAT+Starch_ZA	PBAT+Starch_ZA
13	HDPE_24_75	HDPE_24_75	HDPE_24_75	13	Polyester_NW	HDPE_70	PBAT+Starch_IMP	13	Paper	Paper	Paper
14	HDPE_24_50	HDPE_24_50	HDPE_24_50	14	Polyester_W	Polyester_NW	Polyester_NW	14	PBS+PBAT_IMP	PBS+PBAT_IMP	PBS+PBAT_IMP
15	HDPE_24_25	HDPE_24_25	HDPE_24_25	15	HDPE_70	Polyester_W	Polyester_W	15	PBS+PBAT_ZA	PBS+PBAT_ZA	PBS+PBAT_ZA
16	HDPE_24_0	HDPE_24_0	HDPE_24_0	16	PP	PP	PP	16	HDPE_ECM	HDPE_ECM	HDPE_ECM

In Table 24, we assess the effect of changes in the assumed lifespan of the HDPE_70 bag on our new indicators (persistence, employment and affordability).

In terms of persistence, it can be seen that, with a reduction in the lifespan from 52 to 26 or 13 uses; the HDPE_70 bag falls from being the best to the worst among the fossil-based plastic reusable bag types; and from sixth place to ninth place overall. This occurs because with a reduction in lifespan, more HDPE_70 bags must be used, and therefore more material enters the environment.

On the other hand, with a reduction in the number of reuses, the HDPE_70 bag improves slightly in terms of employment (recall that the HDPE_70 bag is the second worst of all bag types from an employment perspective in the baseline scenario). This is because, with a lower number of reuses, more bags must be produced, thereby supporting more jobs.

Finally, the HDPE_70 bag remains the most preferable bag from an affordability perspective, across all scenarios. In fact, the relatively low cost per bag implies that one could use about 14 of the HDPE_70 bags per annum before they become less cost-effective than the standard HDPE_24 µm single-use bags; assuming that the latter are only used once per bag.

In conclusion, assuming that it will last as long as the other reusable bag types, then the HDPE_70 bag is the best bag from an environmental perspective, since it has significantly lower material requirements (and therefore environmental impact) as compared to the other reusable bag types. However, since the ranking of the HDPE_70 bag does change (at least for certain impact categories) with a shorter assumed lifespan; it is important to obtain a more accurate understanding of how many times the HDPE_70 bag will last in reality. While the results of the study generally show that the reusable bags outperform the single-use bags in terms of fulfilling annual shopping requirements, the ranking among the reusable bags (and particularly between the two top-ranked bags, HDPE_70 and Polyester_NW) is dependent on the lifespan of the HDPE_70 bag relative to the other reusable bag types. Section 7.2 provides the results of sensitivity analysis on the lifespan of the PP and polyester reusable bags.

7.2 Lifespan of PP and Polyester reusable bags

In contrast to the HDPE_70 bag, for which there is uncertainty regarding whether it will last for an entire year's worth of shopping; there is a wide perception that the PP and polyester bag types could last beyond the one-year time frame that was assumed for this study (i.e., beyond 52 uses).

In this section, we conduct sensitivity analysis on the assumed lifespan of these bag types (PP, Polyester_W and Polyester_NW). Specifically, we increase their lifespans from 1 year (52 uses) to 2 years (104 uses) and 4 years (208 uses), respectively. These variations were modelled, and the results compared to the baseline scenario. The results are shown in Table 25 and 26. Table 25 shows the change in rankings based on the ReCiPe 2016 single score; while Table 26 shows the change in rankings on our new indicators (persistence, employment and affordability).

Table 25: Change in ranking of bags based on environmental performance (ReCiPe 2016 single score) with different assumptions on the lifespan of the PP and Polyester reusable bags

Rank	Baseline: PP and polyester bags last 1 year	PP and polyester bags last 2 years	PP and polyester bags last 4 years
1	HDPE_70	Polyester_NW	Polyester_NW
2	Polyester_NW	HDPE_70	PP
3	PP	PP	HDPE_70
4	Polyester_W	Polyester_W	Polyester_W
5	PBAT+Starch_IMP	PBAT+Starch_IMP	PBAT+Starch_IMP
6	Paper	Paper	Paper
7	HDPE_24_100	HDPE_24_100	HDPE_24_100
8	HDPE_24_75	HDPE_24_75	HDPE_24_75
9	PBAT+Starch_ZA	PBAT+Starch_ZA	PBAT+Starch_ZA
10	HDPE_24_50	HDPE_24_50	HDPE_24_50
11	HDPE_ECM	HDPE_ECM	HDPE_ECM
12	PBS+PBAT_IMP	PBS+PBAT_IMP	PBS+PBAT_IMP
13	LDPE	LDPE	LDPE
14	HDPE_24_25	HDPE_24_25	HDPE_24_25
15	HDPE_24_0	HDPE_24_0	HDPE_24_0
16	PBS+PBAT_ZA	PBS+PBAT_ZA	PBS+PBAT_ZA

From Table 25 it can be seen that increasing the assumed lifespan of the PP and polyester bags has a similar effect on the rankings (based on ReCiPe 2016 single score) as reducing the assumed lifespan of the HDPE_70 bag (see Section 7.1). Specifically, it results in a switch in ranking between the two top-ranked bags in the baseline scenario; i.e. the HDPE_70 and Polyester_NW bags. In particular, doubling the assumed lifespan of the PP and Polyester bags sees Polyester_NW replace HDPE_70 (which falls to second) as the top-ranked bag. With an increase in lifespan to 4 years, the PP bag now rises to second; replacing HDPE_70, which now falls to third. In all of these scenarios, the Polyester_W bag remains as the fourth-ranked bag; i.e. the lowest ranked among the reusable bags.

In terms of persistence (Table 26), an increase in the lifespan of the PP and polyester bags leads to an improvement in their performance, moving ahead of HDPE_70 in the rankings. Indeed, with a doubling in their lifespan from one to two years, the polyester bags move ahead of Paper, which is more readily biodegradable; while with a four-year lifespan, the PP bag also moves ahead of Paper. These results occur because an increase in the lifespan of these bags means that less material enters the environment.

In terms of employment (Table 26); there is only a marginal change – the two Polyester bags now slip below HDPE_70 in the rankings. Recall that the reusable bag types generally fare worst in terms of employment; since reuse of bags means that fewer bags will be produced, and less people employed. With an increase in the lifespan of the Polyester bags, their performance in terms of employment deteriorates even further.

Finally, in terms of affordability (Table 26), there is a significant improvement in the ranking for the Polyester_W bag with an increase in its assumed lifespan; up from 10th to 4th overall. In other words, the high cost of this bag begins to pay off after a longer assumed lifespan; such that it now becomes more cost-effective than any of the single-use options (assuming that the latter are still only used one time each); although it remains the least affordable of the reusable bags.

Again, similarly to Section 7.1, this analysis highlights the importance of obtaining an improved understanding of the extent to which the reusable bags can (and, in fact will) be reused; in order to assess which of HDPE_70 and Polyester_NW is in fact the most preferable bag type overall.

Table 26: Change in ranking of bags on persistence, employment and affordability with different assumptions on the lifespan of the PP and Polyester bags

Persistence				Employment				Affordability			
Rank	**Baseline: PP and polyester bags last 1 year**	**PP and polyester bags last 2 years**	**PP and polyester bags last 4 years**	**Rank**	**Baseline: PP and polyester bags last 1 year**	**PP and polyester bags last 2 years**	**PP and polyester bags last 4 years**	**Rank**	**Baseline: PP and polyester bags last 1 year**	**PP and polyester bags last 2 years**	**PP and polyester bags last 4 years**
1	PBAT+Starch_IMP	PBAT+Starch_IMP	PBAT+Starch_IMP	1	Paper	Paper	Paper	1	HDPE_70	HDPE_70	HDPE_70
2	PBAT+Starch_ZA	PBAT+Starch_ZA	PBAT+Starch_ZA	2	HDPE_24_100	HDPE_24_100	HDPE_24_100	2	Polyester_NW	Polyester_NW	Polyester_NW
3	PBS+PBAT_IMP	PBS+PBAT_IMP	PBS+PBAT_IMP	3	HDPE_24_75	HDPE_24_75	HDPE_24_75	3	PP	PP	PP
4	PBS+PBAT_ZA	PBS+PBAT_ZA	PBS+PBAT_ZA	4	HDPE_24_50	HDPE_24_50	HDPE_24_50	4	LDPE	Polyester_W	Polyester_W
5	Paper	Polyester _W	Polyester _W	5	PBS+PBAT_ZA	PBS+PBAT_ZA	PBS+PBAT_ZA	5	HDPE_24_100	LDPE	LDPE
6	HDPE_70	Polyester _NW	Polyester _NW	6	PBS+PBAT_IMP	PBS+PBAT_IMP	PBS+PBAT_IMP	6	HDPE_24_75	HDPE_24_100	HDPE_24_100
7	Polyester _W	Paper	PP	7	HDPE_24_25	HDPE_24_25	HDPE_24_25	7	HDPE_24_50	HDPE_24_75	HDPE_24_75
8	Polyester _NW	PP	Paper	8	HDPE_24_0	HDPE_24_0	HDPE_24_0	8	HDPE_24_25	HDPE_24_50	HDPE_24_50
9	PP	HDPE_70	HDPE_70	9	LDPE	LDPE	LDPE	9	HDPE_24_0	HDPE_24_25	HDPE_24_25
10	HDPE_ECM	HDPE_ECM	HDPE_ECM	10	PBAT+Starch_ZA	PBAT+Starch_ZA	PBAT+Starch_ZA	10	Polyester_W	HDPE_24_0	HDPE_24_0
11	LDPE	LDPE	LDPE	11	HDPE_ECM	HDPE_ECM	HDPE_ECM	11	PBAT+Starch_IMP	PBAT+Starch_IMP	PBAT+Starch_IMP
12	HDPE_24_100	HDPE_24_100	HDPE_24_100	12	PBAT+Starch_IMP	PBAT+Starch_IMP	PBAT+Starch_IMP	12	PBAT+Starch_ZA	PBAT+Starch_ZA	PBAT+Starch_ZA
13	HDPE_24_75	HDPE_24_75	HDPE_24_75	13	Polyester_NW	HDPE_70	HDPE_70	13	Paper	Paper	Paper
14	HDPE_24_50	HDPE_24_50	HDPE_24_50	14	Polyester_W	Polyester_NW	Polyester_NW	14	PBS+PBAT_IMP	PBS+PBAT_IMP	PBS+PBAT_IMP
15	HDPE_24_25	HDPE_24_25	HDPE_24_25	15	HDPE_70	Polyester_W	Polyester_W	15	PBS+PBAT_ZA	PBS+PBAT_ZA	PBS+PBAT_ZA
16	HDPE_24_0	HDPE_24_0	HDPE_24_0	16	PP	PP	PP	16	HDPE_ECM	HDPE_ECM	HDPE_ECM

7.3 Re-using “single-use” bags

It is important to note that bag types intended for “single use” can (and, in fact, should) be reused several times before being disposed. We refer to these bag types (the HDPE 24 µm bags, as well as the LDPE, HDPE_ECM, PBS+PBAT, PBAT+Starch and Paper bags) as “single-use” bags in this report mainly for purposes of comparison with the thicker, more durable bag types that are designed for a large number of reuses (that, is, the HDPE 70 µm, PP and Polyester bag types). This is because our main set of results (Section 6) is based on the assumption that the bag types intended for single use will in fact only be used once; while the bags intended for reuse will be reused continuously over the course of a year.

Nevertheless, the “single-use” bag types can potentially be reused a number of times (although, in all probability, not as many times as the truly “reusable” bag types). Since, in our main set of results (which are based on the assumption that single-use bag types will in fact only be used once), the reusable bag types are shown to outperform the single-use bag types in fulfilling annual shopping requirements; it is important to assess the extent to which the results of the study would change if we allow for the single-use bag types to be reused. As such, we conducted sensitivity analysis on two additional scenarios; one in which we assume that each single-use bag would be used twice, and another in which they would be used four times, in addition to the baseline scenario in which each bag would only be used once. These variations were modelled and the results compared to the baseline scenario. Table 27 shows the change in rankings based on the ReCiPe 2016 single score; while Table 28 shows the change in rankings on our three new indicators.

Table 27: Ranking of bags based on environmental performance (ReCiPe 2016 single score) with different assumptions regarding reuse of "single-use" bags

Rank	Baseline: Single-use bags used once each	Each single-use bag used twice	Each single-use bag used four times
1	HDPE_70	HDPE_70	HDPE_70
2	Polyester_NW	Polyester_NW	Polyester_NW
3	PP	PP	PP
4	Polyester_W	Polyester_W	PBAT+Starch_IMP
5	PBAT+Starch_IMP	PBAT+Starch_IMP	Polyester_W
6	Paper	Paper	Paper
7	HDPE_24_100	HDPE_24_100	HDPE_24_100
8	HDPE_24_75	HDPE_24_75	HDPE_24_75
9	PBAT+Starch_ZA	PBAT+Starch_ZA	PBAT+Starch_ZA
10	HDPE_24_50	HDPE_24_50	HDPE_24_50
11	HDPE_ECM	HDPE_ECM	HDPE_ECM
12	PBS+PBAT_IMP	LDPE	LDPE
13	LDPE	PBS+PBAT_IMP	PBS+PBAT_IMP
14	HDPE_24_25	HDPE_24_25	HDPE_24_25
15	HDPE_24_0	HDPE_24_0	HDPE_24_0
16	PBS+PBAT_ZA	PBS+PBAT_ZA	PBS+PBAT_ZA

Table 27 shows that, in terms of the ReCiPe 2016 single score, there is no change in rankings when the single-use bags are used twice instead of only once. When used four times, however, the best performing of the single-use bag types (PBAT+Starch_IMP) moves up to third place in the overall rankings, ahead of one of the reusable bag types (Polyester_W).

Table 28: Change in ranking of bags on persistence, employment and affordability with different assumptions regarding reuse of "single- use" bags

Persistence				Employment				Affordability			
Rank	**Baseline: Single-use bags used once each**	**Each single-use bag used twice**	**Each single-use bag used four times**	**Rank**	**Baseline: Single-use bags used once each**	**Each single-use bag used twice**	**Each single-use bag used four times**	**Rank**	**Baseline: Single-use bags used once each**	**Each single-use bag used twice**	**Each single-use bag used four times**
1	PBAT+Starch_IMP	PBAT+Starch_IMP	PBAT+Starch_IMP	1	Paper	Paper	Paper	1	HDPE_70	HDPE_70	HDPE_70
2	PBAT+Starch_ZA	PBAT+Starch_ZA	PBAT+Starch_ZA	2	HDPE_24_100	HDPE_24_100	HDPE_24_100	2	Polyester_NW	Polyester_NW	LDPE
3	PBS+PBAT_IMP	PBS+PBAT_IMP	PBS+PBAT_IMP	3	HDPE_24_75	HDPE_24_75	HDPE_24_75	3	PP	LDPE	HDPE_24_100
4	PBS+PBAT_ZA	PBS+PBAT_ZA	PBS+PBAT_ZA	4	HDPE_24_50	HDPE_24_50	HDPE_24_50	4	LDPE	HDPE_24_100	HDPE_24_75
5	Paper	Paper	Paper	5	PBS+PBAT_ZA	PBS+PBAT_ZA	PBS+PBAT_ZA	5	HDPE_24_100	HDPE_24_75	HDPE_24_50
6	HDPE_70	HDPE_70	HDPE_70	6	PBS+PBAT_IMP	PBS+PBAT_IMP	PBS+PBAT_IMP	6	HDPE_24_75	HDPE_24_50	HDPE_24_25
7	Polyester _W	Polyester _W	Polyester _W	7	HDPE_24_25	HDPE_24_25	HDPE_24_25	7	HDPE_24_50	HDPE_24_25	HDPE_24_0
8	Polyester _NW	Polyester _NW	Polyester _NW	8	HDPE_24_0	HDPE_24_0	HDPE_24_0	8	HDPE_24_25	HDPE_24_0	Polyester_NW
9	PP	PP	PP	9	LDPE	LDPE	LDPE	9	HDPE_24_0	PP	PBS+PBAT_IMP
10	HDPE_ECM	HDPE_ECM	HDPE_ECM	10	PBAT+Starch_ZA	PBAT+Starch_ZA	PBAT+Starch_ZA	10	Polyester_W	Polyester_W	PBS+PBAT_ZA
11	LDPE	LDPE	LDPE	11	HDPE_ECM	HDPE_ECM	HDPE_ECM	11	PBAT+Starch_IMP	PBS+PBAT_IMP	Paper
12	HDPE_24_100	HDPE_24_100	HDPE_24_100	12	PBAT+Starch_IMP	PBAT+Starch_IMP	PBAT+Starch_IMP	12	PBAT+Starch_ZA	PBS+PBAT_ZA	PP
13	HDPE_24_75	HDPE_24_75	HDPE_24_75	13	Polyester_NW	Polyester_NW	Polyester_NW	13	Paper	Paper	PBS+PBAT_IMP
14	HDPE_24_50	HDPE_24_50	HDPE_24_50	14	Polyester_W	Polyester_W	Polyester_W	14	PBS+PBAT_IMP	PBS+PBAT_IMP	PBS+PBAT_ZA
15	HDPE_24_25	HDPE_24_25	HDPE_24_25	15	HDPE_70	HDPE_70	HDPE_70	15	PBS+PBAT_ZA	PBS+PBAT_ZA	HDPE_ECM
16	HDPE_24_0	HDPE_24_0	HDPE_24_0	16	PP	PP	PP	16	HDPE_ECM	HDPE_ECM	Polyester_W

In terms of persistence (Table 28), there is no change in rankings if single-use bags are used twice or even four times instead of only once each – the single-use biodegradable bags remain the best performing bag types; while the single-use, fossil-based bag types are not able to displace the truly reusable bag types, which are still assumed to be reused far more times.

Similarly, in terms of employment (Table 28), there is no change in the rankings when the single-use bags are used two or four times rather than once. The single-use bag types remain preferable from an employment perspective, even if they are used two or four times rather than just once.

Finally, in terms of affordability (Table 28); there is an improvement for some of the single-use bag types relative to the reusable bag types associated with reusing the former. Specifically, if used twice rather than just once; the LDPE and HDPE 24 µm bag types move ahead of PP in the rankings. If used four times, they move ahead of the Polyester_NW bag type as well; and end up behind only the HDPE_70 bag type; while the other single-use bag types also move ahead of some of the reusable bag types in the rankings. This shows that consumers can make savings from reusing their single-use bags; the more times they reuse them, the more they will be able to save.

The results from Table 27 and 28 suggest that, particularly for the environmental indicators (ReCiPe 2016 single score and persistence); there is very little change in the overall rankings when the single-use bags are assumed to be used two or four times, instead of once. To test whether further increasing the number of reuse times would make any difference to the rankings, we ran an additional scenario for the environmental indicators (ReCiPe 2016 single score and persistence) in which we assume, hypothetically, that the single-use bags are each used 10 times. Table 29 shows the change in rankings for both the ReCiPe 2016 single score and persistence when using single-use bags ten times as compared to only once.

From Table 29 it can be seen that the environmental performance of the single-use bags improves when used a larger number of times (ten in this case), with many of them moving up the rankings. Many of the single-use bags now outperform some of the reusable bag types (particularly PP and Polyester_W) in terms of the ReCiPe 2016 single score. It is worth noting that, in terms of the ReCiPe 2016 single score, the top-two performing bags (the reusable HDPE_70 and Polyester_NW bag types) remain the top-ranked bag types; even when the single-use bags are used as many as ten times. In terms of persistence, the fossil-based single-use bags now all move up the rankings, ahead of some of the reusable bags (PP and Polyester_NW); assuming that the latter are only used for one year. In fact, the HDPE_ECM bag now moves ahead of all of the reusable bag types (including HDPE_70 and Polyester_W). These results suggest that the more times single-use bags are reused, the better their environmental performance relative to reusable bags.

Table 29: Change in rankings for both the ReCiPe 2016 single score and persistence when using single-use bags ten times as compared to only once

ReCiPe 2016 single score			Persistence		
Rank	**Baseline: Single-use bags used once**	**Single-use bags used ten times**	**Rank**	**Baseline: Single-use bags used once**	**Single-use bags used ten times**
1	HDPE_70	HDPE_70	1	PBAT+Starch_IMP	PBAT+Starch_IMP
2	Polyester_NW	Polyester_NW	2	PBAT+Starch_ZA	PBAT+Starch_ZA
3	PP	PBAT+Starch_IMP	3	PBS+PBAT_IMP	PBS+PBAT_IMP
4	Polyester_W	Paper	4	PBS+PBAT_ZA	PBS+PBAT_ZA
5	PBAT+Starch_IMP	HDPE_24_100	5	Paper	Paper
6	Paper	HDPE_24_75	6	HDPE_70	HDPE_ECM
7	HDPE_24_100	PBAT+Starch_ZA	7	Polyester _W	HDPE_70
8	HDPE_24_75	HDPE_24_50	8	Polyester _NW	Polyester _W
9	PBAT+Starch_ZA	HDPE_ECM	9	PP	LDPE
10	HDPE_24_50	LDPE	10	HDPE_ECM	HDPE_24_100
11	HDPE_ECM	PP	11	LDPE	HDPE_24_75
12	PBS+PBAT_IMP	PBS+PBAT_IMP	12	HDPE_24_100	HDPE_24_50
13	LDPE	Polyester_W	13	HDPE_24_75	HDPE_24_25
14	HDPE_24_25	HDPE_24_25	14	HDPE_24_50	HDPE_24_0
15	HDPE_24_0	HDPE_24_0	15	HDPE_24_25	Polyester _NW
16	PBS+PBAT_ZA	PBS+PBAT_ZA	16	HDPE_24_0	PP

It is also worth providing a break-even analysis in terms of the number of times that each of the single-use bag types should be used in order to provide the same environmental performance as the best performing reusable bag (HDPE_70); assuming that the latter bag type is reused continuously over the course of a year to fulfil the functional unit in terms of annual grocery shopping requirements. In Table 30, the ReCiPe 2016 single score results from Section 6 are repeated; based on our standard assumptions regarding the number of times each type of bag is reused (i.e., assuming that single-use bags are each used once; and that the reusable HDPE_70 bag is reused continuously over the course of one year to fulfil an individual's annual shopping requirements). It then indicates the number of times each single-use bag type needs to be used in order to match the environmental performance of the HDPE_70 bag, in terms of the ReCiPe 2016 single score.

Table 30: Number of times each "single-use" bag type needs to be used to match the environmental performance (ReCiPe 2016 single score) of the HDPE_70 bag type in fulfilling annual shopping requirements; assuming the latter is reused continuously over the course of the year.

Bag type	Environmental impact (single score, mPt) for fulfilling annual shopping requirements	Number of uses required to break even with HDPE_70
HDPE_70	8.81	
PBAT+Starch_IMP	102.81	11.67
Paper	113.83	12.92
HDPE_24_100	146.7	16.65
HDPE_24_75	186.61	21.18
PBAT+Starch_ZA	187.21	21.25
HDPE_24_50	226.31	25.69
HDPE_ECM	228.21	25.90
PBS+PBAT_IMP	256.12	29.07
LDPE	256.13	29.07
HDPE_24_25	266.41	30.24
HDPE_24_0	306.52	34.79
PBS+PBAT_ZA	365.12	41.44

7.4 End of life recycling rates

End of life recycling rates were varied in order to determine both the sensitivity of the model results to the recycling rates applied (since actual recycling rates for the various bag types are not well understood); and also to illustrate how the results would be affected by changes in recycling rates. In the base case, our best estimate of the 'actual' recycling rate for each bag type is applied, based on best available data and/or discussions with experts (see Section 4.4). In the sensitivity analysis, we applied a range of alternative recycling rates (0%, 60% and 100%) for each bag type.

For this analysis, we present the change in results for the ReCiPe 2016 single score only (i.e., our new indicators are excluded from this sensitivity analysis). The biodegradable bag types (PBAT+Starch_ZA, PBAT+Starch_IMP, PBS+PBAT_ZA, PBS+PBAT_IMP, and HDPE_ECM) are excluded from the analysis; since they are non-recyclable. Although the polyester bag types (Polyester_W and Polyester_NW) are not currently recycled in South Africa, scenarios in which they could be recycled were also implemented; as polyester is potentially recyclable.

Figure 12 shows how environmental impact (based on the ReCiPe 2016 single score) associated with each of the recyclable bags changes with changes in the recycling rate. For each bag type, the yellow coloured bars refer to single score results for the baseline recycling rate (as per Section 6.1.1) for each of the bags. The red, blue and green bars refer to the single score results for the different recycling rates (0%, 60% and

100% respectively) for each of the bag types. It can be seen that, as expected, for each bag type, a higher recycling rate gives rise to a lower overall environmental impact.

Table 31 summarises the percentage change in the ReCiPe 2016 single score associated with the different scenarios for recycling rates, for each recyclable bag type. For example, increasing the recycling rate from current rates to 60% leads to a reduction in environmental impact ranging from 0.99% to 5.68%, or 4% on average.

Finally, in Table 32, we show how changes in recycling rates affect the environmental performance and rankings among all bag types; based on the ReCiPe 2016 single score. Note that the non-recyclable bag types are included in this table (although their environmental performance remains the same across the scenarios); in order to see if there are any changes in the overall rankings. It can be seen that changing the recycling rate has very little impact on the rankings (although note that this is based on ReCiPe 2016 single score only, excluding the new indicators). This suggests that the model and results are robust to changes in the recycling rate.

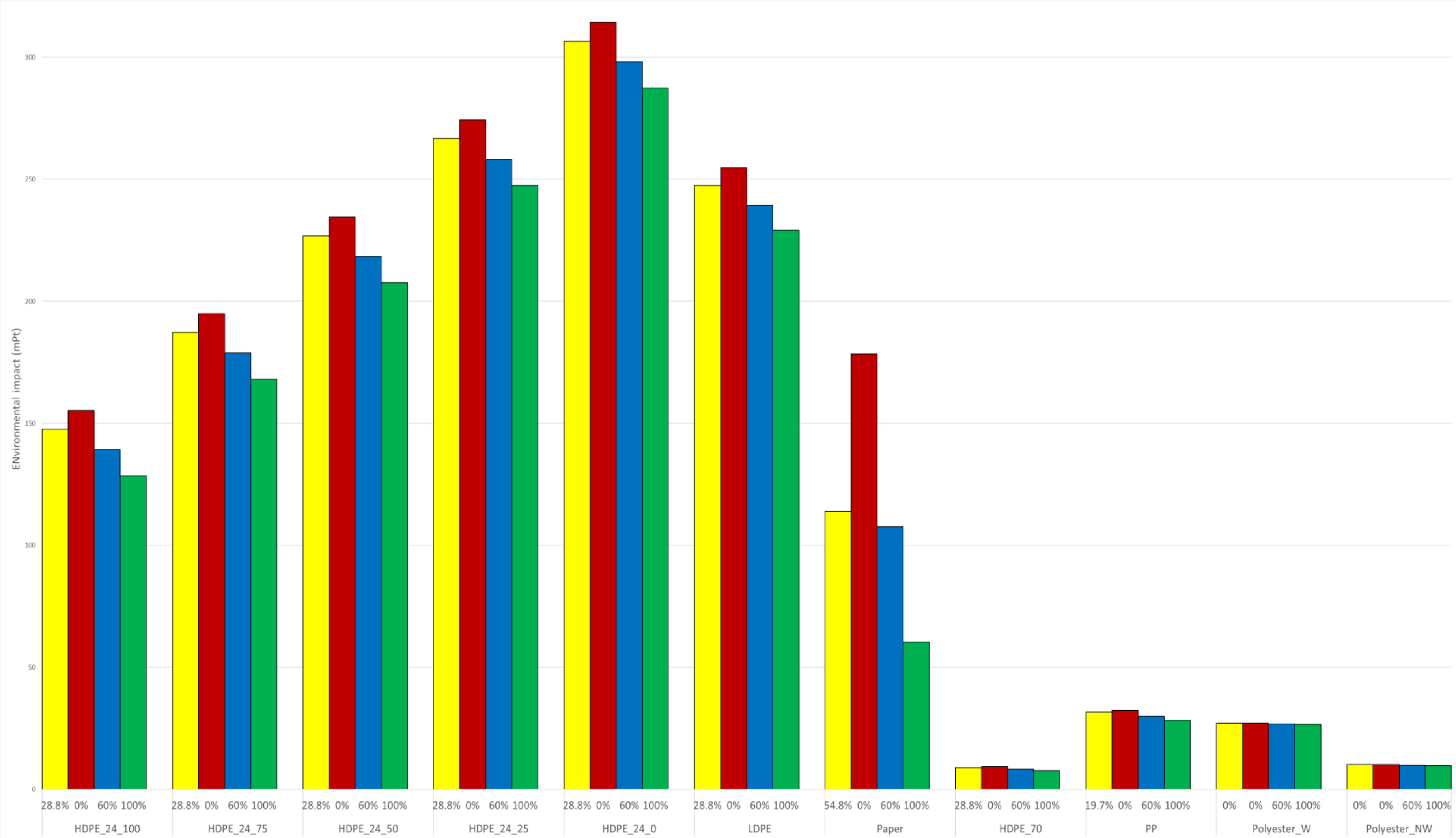

Figure 12: Environmental impact (ReCiPe 2016 single score) of each bag type with varying recycling rate (baseline recycling rate in yellow bar; followed by 0% (red bar), 60% (blue bar) and 100% (green bar))

Table 31: Percentage change in environmental impact (ReCiPe 2016 single score) for each bag type with different recycling rates.

Scenario	Bag types										
	HDPE_24_100	HDPE_24_75	HDPE_24_50	HDPE_24_25	HDPE_24_0	LDPE	Paper	HDPE_70	PP	Polyester_W	Polyester_NW
	Percentage change in environmental impact										
Baseline Scenario	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0% recycling rate	5.21%	4.11%	3.39%	2.88%	2.51%	2.94%	56.75%	5.21%	2.53%	0.00%	0.00%
60% recycling rate	-5.68%	-4.47%	-3.70%	-3.14%	-2.73%	-3.30%	-5.45%	-5.65%	-5.19%	-3.16%	-0.99%
100% recycling rate	-12.95%	-10.20%	-8.43%	-7.17%	-6.23%	-7.44%	-46.91%	-13.01%	-10.32%	-5.25%	-1.65%

Table 32: Change in environmental impact (ReCiPe 2016 single score) and ranking with changes in recycling rate

Baseline scenario (current recycling rate)			0% recycling rate		60% recycling rate		100% recycling rate	
Baseline recycling rate	Ranking (best to worst)	Environmental impact (mPt)	Ranking (best to worst)	Environmental impact (mPt)	Ranking (best to worst)	Environmental impact (mPt)	Ranking (best to worst)	Environmental impact (mPt)
28.8%	HDPE_70	8.86	HDPE_70	9.32	HDPE_70	8.36	HDPE_70	7.71
0%	Polyester_NW	10.18	Polyester_NW	10.18	Polyester_NW	9.86	Polyester_NW	9.65
0%	Polyester_W	27.05	Polyester_W	27.05	Polyester_W	26.78	Polyester_W	26.60
19.67%	PP	31.57	PP	32.37	PP	29.93	PP	28.31
N/A	PBAT+Starch_IMP	102.81	PBAT+Starch_IMP	102.81	PBAT+Starch_IMP	102.81	Paper	60.43
54.8%	Paper	133.83	HDPE_24_100	155.30	Paper	107.63	PBAT+Starch_IMP	107.11
28.8%	HDPE_24_100	147.61	Paper	178.43	HDPE_24_100	139.23	HDPE_24_100	128.50
N/A	PBAT+Starch_ZA	187.21	PBAT+Starch_ZA	187.21	HDPE_24_75	178.91	HDPE_24_75	168.18
28.8%	HDPE_24_75	187.29	HDPE_24_75	194.50	PBAT+Starch_ZA	187.21	PBAT+Starch_ZA	191.51
28.8%	HDPE_24_50	226.76	HDPE_ECM	232.60	HDPE_24_50	218.38	HDPE_24_50	207.65
N/A	HDPE_ECM	228.21	HDPE_24_50	234.45	HDPE_ECM	232.60	LDPE	229.11
28.8%	LDPE	247.53	LDPE	254.81	LDPE	239.35	HDPE_ECM	232.60s
N/A	PBS+PBAT_IMP	256.12	PBS+PBAT_IMP	256.12	PBS+PBAT_IMP	256.12	HDPE_24_25	247.53
28.8%	HDPE_24_25	266.64	HDPE_24_25	274.33	PBS+PBAT_IMP	266.72	PBS+PBAT_IMP	266.72
28.8%	HDPE_24_0	306.52	HDPE_24_0	341.21	HDPE_24_0	303.91	HDPE_24_0	287.41
N/A	PBS+PBAT_ZA	365.12	PBS+PBAT_ZA	365.12	PBS+PBAT_ZA	378.72	PBS+PBAT_ZA	378.72

8 Conclusions and recommendations

In this study, we have conducted a Life Cycle Sustainability Assessment of alternative carrier bag options in South Africa. The goal of the study was to compare different types of carrier bags that are (or could be) offered by South African retailers, in terms of environmental and socio-economic performance across the product life cycle. We include bags that are already available in retail stores in South Africa, as well as a number of bag types that are not yet commercially available. The intention is to provide evidence to inform current discussions among policymakers, retailers and the general public around single-use plastic carrier bags and their alternatives (including reusable bags, biodegradable/compostable bags, and paper bags). In short, the study aims to answer the question of which type of bag is “best” in the South African context.

Sixteen types of carrier bags were assessed; made from a range of different materials; varying in terms of their recycled content; and with varying degrees of reusability, recyclability and biodegradability. The types of carrier bags included in the assessment are summarised in Table 33 for ease of reference.

The bag types were assessed and compared against a broad range of environmental indicators, as well as two key socio-economic indicators. Environmental indicators were based on the ReCiPe 2016 impact assessment methodology, as well as the addition of a new indicator developed in the study, namely persistence of plastic material in the environment, which is used as a proxy for impacts associated with plastic pollution. We also incorporated two key socio-economic indicators that are seen as particularly relevant in the South African context and in the current debate around alternative carrier bags, namely employment and affordability.

The functional unit for the study was: “Carrying one person’s annual groceries (870.48 litres) from the supermarket to the home in South Africa”. The number of each type of bag required to fulfil this functional unit was determined on the basis of the volumetric capacity of each bag type, as well as the number of times that each type of bag is assumed to be reused.

Table 33: Bag types assessed in the LCSA study

Single-use/ reusable	Type of material	Name	Description	Modelled % of recycled content
Single-use	Fossil-based plastic	HDPE_24_100	HDPE; with thickness of 24 microns (24 µm)	100%
		HDPE_24_75	HDPE 24 µm	75%
		HDPE_24_50	HDPE 24 µm	50%
		HDPE_24_25	HDPE 24 µm	25%
		HDPE_24_0	HDPE 24 µm	0%
		LDPE	Low density polyethylene	0%
	Fossil-based with bio-additive	HDPE_ECM	HDPE bags with ECM additive	0%
	Biodegradable plastic	PBS+PBAT_ZA	PBS+PBAT, using locally produced PBS and PBAT	0%
		PBS+PBAT_IMP	PBS+PBAT, using imported PBS and PBAT	0%
		PBAT+Starch_ZA	PBAT+Starch, using locally produced PBAT and locally grown maize	0%
		PBAT+Starch_IMP	PBAT+Starch, using imported PBAT+Starch	0%
	Paper	Paper	Brown (Kraft) paper bags	54.8%
Reusable	Fossil-based plastic	HDPE_70	HDPE bags with a thickness of 70 µm	100%
		PP	Polypropylene bags	0%
		Polyester_W	Woven fabric polyester	100% (rPET)
		Polyester_NW	Non-woven (spun-bond and stitched) polyester	85% (rPET)

The main results of the study (presented in Section 6 of the report) are based on the following assumptions:

- bags that are intended for single use will only be used once each; such that a new bag is purchased for each shopping trip
- bags intended for reuse will only be purchased once, and reused over the course of the entire year (i.e., 52 times, assuming a weekly shopping trip) to fulfil the functional unit

Based on these assumptions, the overall ranking of bags (across all indicators) is as per Table 34.

From Table 34 it can be seen that, in fulfilling the functional unit, and based on our assumptions regarding the number of times each bag is reused over the course of a year, the four fossil-based, reusable bag types (HDPE_70, Polyester_NW, PP and Polyester_W) occupy the top four positions. In fact, the top six bag types are all made from conventional fossil-based plastics (HDPE, polyester and polypropylene). Of the seven worst performing bag types, five are made from alternative types of materials (Paper, biodegradable plastics, and the HDPE bag made with an ECM additive intended to aid biodegradation).

Table 34: Overall ranking of bags across all environmental and socio-economic indicators (equal weighting); based on assumption that single-use bags are used once each and that reusable bags are reused continuously to fulfil one year's grocery shopping requirements

Rank	Bag type	Type of material	Single-use / reusable
1	HDPE_70	Fossil-based plastic	Reusable
2	Polyester_NW	Fossil-based plastic	Reusable
3	PP	Fossil-based plastic	Reusable
4	Polyester_W	Fossil-based plastic	Reusable
5	HDPE_24_100	Fossil-based plastic	Single-use
6	HDPE_24_75	Fossil-based plastic	Single-use
7	PBAT+Starch_IMP	Biodegradable plastic	Single-use
8	HDPE_24_50	Fossil-based plastic	Single-use
9	LDPE	Fossil-based plastic	Single-use
10	HDPE_ECM	Fossil-based with bio-additive	Single-use
11	HDPE_24_25	Fossil-based plastic	Single-use
12	PBAT+Starch_ZA	Biodegradable plastic	Single-use
13	HDPE_24_0	Fossil-based plastic	Single-use
14	Paper	Paper	Single-use
15	PBS+PBAT_IMP	Biodegradable plastic	Single-use
16	PBS+PBAT_ZA	Biodegradable plastic	Single-use

The best performing bag overall is the HDPE 70 µm reusable bag (HDPE_70), closely followed by the non-woven polyester bag type (Polyester_NW). The four reusable bag types (HDPE_70, Polyester_NW, PP and Polyester_W) occupy the top four positions in the rankings. The worst performing among the reusable bags (fourth overall, and still ahead of the best single-use bag) is the woven polyester (Polyester_W) bag.

Interestingly, the best performing among the single-use bags is the HDPE 24 µm bag with 100% recycled content (HDPE_24_100), which is currently the most common bag among formal sector grocery stores in South Africa. It can also be seen that the higher the recycled content of the bags, the better the overall performance. The HDPE 24 µm bag with 100% recycled content (HDPE_24_100) achieves the highest ranking from among the HDPE 24 µm bags, while the HDPE bags with lower recycled content rank progressively worse. When the recycled content of the HDPE 24 µm bags decreases to 50% or less, they become out-ranked by the imported biodegradable alternative (PBAT+Starch_IMP).

From Table 34, it is also evident that the worst performing bag overall over the course of a year (based on our assumptions regarding the number of bags required to fulfil annual shopping requirements) is the PBS+PBAT bag made using locally produced PBS and PBAT (PBS+PBAT_ZA).

It should be borne in mind that the rankings in Table 34 are based on an equal weighting across indicators. In principle, differential weighting could be applied to emphasise specific issues of relevance to a particular decision making context; or to highlight impact categories where carrier bags make a disproportionately high contribution to the overall problem. For example, in the South African context; it could be argued that employment should receive a higher weighting as compared to some of the other midpoint impact categories. Similarly, it could be argued that persistence should receive a higher weighting in an assessment of carrier bags, since plastic bags would be expected to make a disproportionately high contribution to the overall problem of plastic pollution, as compared to their contribution to other environmental issues (such as global warming), which would be expected to be far lower, in relative terms. Normalisation is an optional step sometimes used in LCA studies to assess the extent to which the environmental impacts associated with the product under consideration contribute toward the total (per capita, national or global) burden; under each impact category. Normalisation factors for the new indicators developed in this study have not yet been developed; this will be the focus of future work. At the same time, it is suggested that a set of weightings appropriate to the South African context be developed, through a multi-criteria decision analysis process, incorporating government and other relevant stakeholders.

Table 35 presents the rankings for some specific indicators of interest; namely global warming, land use, water consumption, persistence (as a proxy for impacts associated with plastic pollution), employment, and affordability. Again, these results are based on the assumption that single-use bags will only be used once, and that reusable bags will be reused throughout the year to fulfil the functional unit.

Table 35: Ranking of bags on specific midpoint impact categories of interest (listed from best to worst); based on assumed number of reuse times in fulfilling annual shopping requirements

Rank	Global warming	Land use	Water use	Persistence	Employment	Affordability
1	HDPE_70	Polyester_NW	HDPE_70	PBAT+Starch_IMP	Paper	HDPE_70
2	Polyester_NW	HDPE_70	Polyester_NW	PBAT+Starch_ZA	HDPE_24_100	Polyester_NW
3	PP	Polyester_W	Polyester_W	PBS+PBAT_IMP	HDPE_24_75	PP
4	Polyester_W	PP	PP	PBS+PBAT_ZA	HDPE_24_50	LDPE
5	Paper	PBAT+Starch_IMP	HDPE_ 24_100	Paper	PBS+PBAT_ZA	HDPE_24_100
6	PBAT+Starch_IMP	PBAT+Starch_ZA	HDPE_ECM	HDPE_70	PBS+PBAT_IMP	HDPE_24_75
7	HDPE_ 24_100	HDPE_24_100	HDPE_ 24_75	Polyester _W	HDPE_24_25	HDPE_24_50
8	HDPE_ 24_75	HDPE_24_75	LDPE	Polyester _NW	HDPE_24_0	HDPE_24_25
9	HDPE_ 24_50	HDPE_ECM	HDPE_24_50	PP	LDPE	HDPE_24_0
10	HDPE_ECM	LDPE	HDPE_24_25	HDPE_ECM	PBAT+Starch_ZA	Polyester_W
11	PBAT+Starch_ZA	HDPE_24_50	HDPE_24_0	LDPE	HDPE_ECM	PBAT+Starch_ZA
12	LDPE	HDPE_24_25	Paper	HDPE_24_100	PBAT+Starch_IMP	PBAT+Starch_IMP
13	HDPE_24_25	HDPE_24_0	PBAT+Starch_IMP	HDPE_24_75	Polyester_NW	Paper
14	PBS+PBAT_IMP	PBS+PBAT_IMP	PBAT+Starch_ZA	HDPE_24_50	Polyester_W	PBS+PBAT_ZA
15	HDPE_24_0	PBS+PBAT_ZA	PBS+PBAT_ZA	HDPE_24_25	HDPE_70	PBS+PBAT_IMP
16	PBS+ PBAT_ ZA	Paper	PBS+PBAT_IMP	HDPE_24_0	PP	HDPE_ECM

The rankings for most environmental indicators (e.g. global warming, land use and water use in Table 35) are similar to the overall rankings presented in Table 34; with the four fossil-based plastic reusable bags occupying the top four positions. Single-use Paper bags perform particularly poorly in terms of land use, while the biodegradable plastic bags perform poorly in terms of water use.

By contrast, in terms of persistence (a proxy for the impacts associated with plastic pollution), the biodegradable bag types occupy the top five positions, as expected. In particular, the biodegradable plastic bags (made from PBAT+Starch and PBS+PBAT) are the best performers, followed by Paper. This is followed by the reusable bag types, which fare relatively well on this indicator under the assumption that they are reused continuously throughout the year, and then discarded at the end of the year; which implies that only a relatively small amount of material is disposed of each year. However, it should be noted that, given the larger amount of material embedded in reusable bags (per bag), they would perform very poorly in terms of persistence if they are instead assumed to be used only a small number of times before being discarded. The HDPE_ECM bag type, which is marketed as being biodegradable, fares relatively poorly; which is consistent with the contested nature of its biodegradability claims. Finally, as expected, the single-use fossil-based plastic bags perform worst in terms of persistence.

However, the results show that even biodegradable materials can persist in the environment when the rate of biodegradation is less than the rate of accumulation from continued disposal. This suggests that reduced consumption of bags through an emphasis on reuse should be a focus of intervention to reduce plastic pollution.

Turning to the socio-economic indicators, it is worth noting that the rankings for employment are the opposite of what is found for most of the environmental indicators, suggesting a trade-off between environmental and socio-economic outcomes. Based on our assumptions regarding the number of times each type of bag is used, the reusable bags are least preferable from an employment perspective. This is because significantly fewer reusable bags would need to be produced per annum to fulfil annual grocery shopping requirements as compared to single-use bags; resulting in fewer jobs as compared to single-use bags, for which more bags would need to be produced. In other words, if there was a switch away from producing single-use bags towards producing only reusable bags, a decrease in employment could be expected.

In particular, Paper bags perform best from an employment perspective, with significantly more jobs involved in producing the number of Paper bags that would be required to fulfil annual shopping needs as compared to any of the plastic options. Interestingly, the second best bag type from an employment perspective is the standard single-use HDPE 24 µm bag, specifically the variant with 100% recycled content; followed by the versions with 75% and 50% recycled content, respectively. This suggests that the current status quo bag type does indeed perform relatively well from an employment point of view. It also indicates that the higher the recycled content, the better the performance in terms of employment, owing to the labour intensive nature of the recycling industry (collection, sorting etc.) in South Africa.

In terms of affordability, it is interesting to note that, contrary to what may have been expected, the rankings are similar to those associated with the environmental indicators; with the reusable bags generally performing better than the single-use bags (based on the assumed number of bags required to fulfil annual shopping requirements). Although reusable bags are more expensive than single-use bags (per bag), they begin to pay off the more often they are reused. Over the course of a year, assuming that single-use bags are only used once, and that reusable bags are reused continuously to fulfil annual grocery shopping requirements, the reusable bags actually become more cost-effective. While the upfront cost of the polyester and PP reusable bags may be prohibitive for very low income consumers, the HDPE_70 reusable bag has a far lower upfront cost.

Finally, sensitivity analysis was conducted on the key assumptions of the study; namely that single-use bags will only be used once each, and that reusable bags will be reused continuously over the course of one year to fulfil annual grocery shopping requirements. In reality, the PP and polyester bags are likely to be able to last beyond one year; while it is also possible that the HDPE_70 bags may not last for an entire year's worth of grocery shopping (the handles are noted as a potential weak point in the current design). Furthermore, bags that are intended for single use can in fact be reused to a certain extent. As such, we conducted sensitivity analysis on these assumptions, as follows:

- Assuming that the HDPE_70 bag will only last for 6 months, or 3 months (as opposed to the baseline of one year)
- Assuming that the PP and Polyester bags will last for 2 years, or 4 years (as opposed to the baseline of one year)
- Assuming that the single-use bags will be used twice, or 4 times (as opposed to the baseline of once).

The results of the sensitivity analysis show that the overall ranking of bags is robust to changes in these assumptions. Across all of these scenarios, the HDPE_70 and Polyester_NW bags remain the top two-ranked bags overall. However, if we assume that the HDPE_70 bag will not last for an entire year, *or* that the Polyester_NW bag will last for beyond one year; then the two bags trade places; with Polyester_NW becoming the top-ranked bag, and HDPE_70 falling to second.

Some specific findings and recommendations regarding these two bags are as follows:

- The HDPE 70 µm bag (HDPE_70) is the top-performing bag overall, assuming an equivalent lifespan as the second best performing bag (Polyester_NW). However, in its current design (this bag type is currently only available from one retail group), the HDPE_70 bag does not appear to be as durable as the other reusable bag types (Polyester or Polypropylene). In particular, the handles are noted as a weak point, which could potentially limit the number of times this type of bag can be reused. Nevertheless, this limitation could potentially be overcome through improved design; while the break-even analysis finds that this bag type only needs to be used three times to match the performance of the reference bag.
- The non-woven (spun-bond and stitched) polyester bag type (Polyester_NW) is the second best performing bag overall, assuming an equivalent lifespan with the HDPE_70 bag; while assuming a longer lifespan as compared to HDPE_70, the Polyester_NW bag overtakes the HDPE_70 bag as the top-ranked bag. Discussions with experts suggest that polyester bags are not currently recycled in South Africa; they were therefore modelled with a 0% recycling rate in this study. However, polyester can in principle be recycled through reheating, thereby converting back into polymer fibres for further reuse. The feasibility of this technology should therefore be investigated for South Africa; as recycling of these bags would further improve their performance (although not to the extent that it would overtake the HDPE_70 bag).

The only time that these two bags fall out of the top two is if we assume that the reusable bag types will only be used a very small number of times; or that single-use bags will be used many times over. The break-even analysis shows that these two bag types only need to be used 3 and 4 times respectively to match the environmental performance of the single-use reference bag (HDPE_24_100), if the latter is used only once. On the other hand, single use bags need to be used between 12 and 41 times (depending on the bag) in order to match the performance of the HDPE_70 bag, if the latter is used continuously over the course of a year.

In general, the analysis shows that for all bag types, the more times a bag is reused, the better its performance, particularly from an environmental perspective. The number of times a bag is reused is the single largest contributing factor to its environmental performance, across all bag types. Doubling the amount of times a bag is used (e.g. using a bag twice instead of just once) results in a halving of its environmental impact.

As such, the general recommendation is that all bags be reused for their primary purpose (to carry groceries) as many times as possible. Even bags intended for 'single use' should be reused as many times as possible. On the other hand, using a reusable bag only once is the worst possible outcome; since these bags have a higher material content as compared to single-use bags; and therefore a higher environmental impact (per bag) if they are only used once. As such, approaches to behavioural change to encourage reuse of bags (such as economic incentives, behavioural 'nudges', etc.) should be considered.

Only when primary reuse is no longer possible, should bags be reused for a secondary purpose, e.g. as a bin liner (Danish EPA, 2018). Modelling secondary reuse was beyond the scope of this study; although this is unlikely to have significantly affected the overall rankings.

Finally, only when all options for primary and secondary reuse have been exhausted, should bags be recycled or composted (as appropriate). The analysis shows that increasing recycling rates does lead to some improvement in environmental performance; although not to the same extent as an increase in the number of times bags are reused. For example, an increase in recycling rates from current rates to 60% leads to a 4% reduction in environmental impact, on average. In terms of recycled content, the HDPE 24 µm bag with 100% recycled content performs 52% better as compared to the virgin HDPE bag. However, increasing the number of times bags are reused remains the single most effective way of improving their environmental performance.

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Appendix A: Datasets modelled and their main modelling features

This appendix provides details of the datasets used to model the production of materials used in the manufacturing of the various bag types, the processing stages involved in the manufacture of the bags, and the waste treatment processes. It shows processes that were created as well as adaptations that were made to represent the South African context. Table A1 indicates the processes created and/or adapted to model each of the materials used in producing the bags.

Table A1: Material processes created and/or adapted to represent ZA context

Name	Product	Adaptation
Adipic Acid {RoW-ZA adapted} | production	Adipic acid	ZA electricity mix, ZA water, Nitric acid from Ammonia from Sasol
Ammonia, liquid, production {ZA}| from coal, FTS	Ammonia	FT synthesis from coal, ZA electricity mix, ZA water, ZA hard coal
Butane-1,4-diol, {RoW-ZA adapted}| production	1,4 butane-diol	Production of 1,4 DB from acetylene in Europe; ZA electricity mix, ZA water
Chemical organics, production {ZA}| from coal, FTS	chemical organics	FT synthesis from coal, ZA electricity mix, ZA water, ZA hard coal
Ethylene production {ZA}| from coal, FTA	ethylene	FT synthesis from coal, ZA electricity mix, ZA water, ZA hard coal
Ethylene production {RoW-ZA adapted} TOR	ethylene	ethylene production from TOR: ZA hard coal, ZA water
HDPE, average {ZA}	HDPE, granulate, average mix	To represent the correct market mix for HDPE in ZA
High density polyethylene resin Virgin, at plant/RNA-ZA adapted	HDPE, granulate, virgin	Production of virgin HDPE in a ZA context: ZA electricity mix, ZA ethylene FTS and TOR {RoW-ZA adapted}
Kraft paper, unbleached {RoW-ZA adapted}| production	Kraft paper unbleached	Production of kraft paper in a ZA context; ZA electricity mix, ZA water
Liquified petroleum gas production {ZA}| from coal, FTs	LPG	FT synthesis from coal, ZA electricity mix, ZA water, ZA hard coal
Low density polyethylene resin Virgin, at plant/RNA-ZA adapted	LDPE, granulate, virgin	Production of virgin LDPE in a ZA context: ZA electricity mix, ZA ethylene FTA and TOT {RoW-ZA adapted}
Nitric acid, without water, in 50% solution state {RoW-ZA adapted}	nitric acid	Production of nitric acid in a ZA context: ZA electricity mix, ZA ammonia FTS and ZA water
PBAT production {GLO}	PBAT	Polymer from overseas
PBAT production {ZA}	PBAT	Production of PBAT in a ZA context: adipic acid {RoW-ZA}; 1,4 DB {RoW-ZA adapted}, chemical organics {ZA} as a proxy for terephthaliic acid

Name	Product	Adaptation
PBS production {GLO}	PBS	Polymer from overseas
PBS production {ZA}	PBS	Production of PBS in a ZA context: succinic acid {GLO}; 1,4 DB {RoW-ZA adapted}
PET, average amorphous {ZA}	PET granulate, amorphous, average	To represent the correct market mix for PET granulate amorphous in ZA
PET, average bottle grade {ZA}	PET granulate, bottle grade, average	To represent the correct market mix for PET granulate bottle grade in ZA
Polyethylene terepthalate, granulate, amorphous, reccyled {RoW-ZA adapted}	PET granulate, amorphous, recycled	Production of amorphous recycled PET in a ZA context: ZA electricity mix, ZA water, polyethylene resin {RNA/ZA adapted}
Polyethylene terepthalate, granulate, amorphous, virgin {RoW-ZA adapted}	PET granulate, amorphous, recycled	Production of amorphous virgin PET in a ZA context: ZA electricity mix, ZA water, ZA ethylene FTS
Polyethylene terepthalate, granulate, bottle grade, virgin {RoW-ZA adapted}	PET granulate, bottle grade, virgin	Production of virgin bottle grade PET in a ZA context: ZA electricity mix, ZA water, ZA ethylene FTS
Polyethylene terepthalate, granulate, bottle grade, recycled {RoW-ZA adapted}	PET granulate, bottle grade, recycled	Production of recycled bottle grade PET in a ZA context: ZA electricity mix, ZA water, ZA polypropylene from FTS, ZA chemical organic from FTS
Polyethylene, high density, granulate, recycled {RoW-ZA adapted}|production	HDPE, granulate, recycled	Production of recycled HDPE in a ZA context: ZA electricity mix
Polypropylene, resin at plant/RNA-ZA adapted	PP virgin	Production of virgin PP in a ZA context: ZA electricity mix, ZA ethylene FTS and TOR {RoW-ZA adapted}, propylene from FTS and TOR {RoW-ZA adapted}
Propylene production {RoW-ZA adapted} TOR	propylene	Propylene production from TOR: ZA hard coal, ZA water
Propylene production {ZA}| from coal	propylene	FT synthesis from coal, ZA electricity mix, ZA water, ZA hard coal
Succinic acid {GLO-ZA adapted} | production	Succinic acid	ZA electricity mix; ZA water
Waste PET for recycling, sorted{RoW-ZA adapted}| treatment of PET for recycling, unsorted, sorting	PET sorted ready to recycled	ZA electricity mix; ZA waste plastic mix
Waste PE for recycling, sorted{RoW-ZA adapted}| PET production, granulate, amorphous, recycled	PE granulate, amorphous, recycled	ZA electricity mix; ZA waste plastic mix; Waste PET for recycling, sorted{RoW-ZA adapted}
Waste PET for recycling, sorted{RoW-ZA adapted}| PET production, granulate, bottle grade, recycled	PE granulate, bottle grade recycled	ZA electricity mix; ZA waste plastic mix; Waste PET for recycling, sorted{RoW-ZA adapted}

Name	Product	Adaptation
Waste PE for recycling, sorted{RoW-ZA adapted}| treatment of PE for recycling, unsorted, sorting	PE sorted ready to recycled	ZA electricity mix; ZA waste plastic mix; Extrusion of plastic sheets and thermoforming, inline {Row-ZA adapted}
Xylenes, mixed, at plant/RNA-ZA adapted	Xylene as a proxy to Terepthalic acid (1:1 ratio)	Xylene production: ZA electricity, ZA LPG from FTS
Irrigation, drip {ZA}	1m3 of irrigation provided by dripping system	water input ZA context; adjusted shares for water pump operation by diesel and by electricity; waste markets for PE, PP and PVC
Irrigation, sprinkler {ZA}	1m3 of irrigation provided by sprinkler system	water input ZA context; adjusted shares for water pump operation by diesel and by electricity; waste markets for PE, PP and PVC
Irrigation, surface {ZA}	1m3 of irrigation provided by surface system	water input ZA context; adjusted shares for water pump operation by diesel and by electricity
Market for irrigation {ZA}	1 m3 of water pumped for irrigation	adjusted shares of drip, sprinkler and surface water for ZA context
Maize grain, market for {ZA}	1 kg of average maize grain produce in ZA	adjusted shares of maize grain rainfed and irrigated, as well as transport, freight by train and road for the ZA context
Maize grain, production, irrigated {ZA}	1 kg of maize grain irrigated produce in ZA	market for irrigation {ZA}
Maize grain, production, rainfed {ZA}	1 kg of maize grain rainfed produce in ZA	
Maize starch, production {ZA}	1 kg of maize starch produce	ZA electricity; maize grain market {ZA}; water emission to water {ZA}
Transport, freight, train, market for {ZA}	1tkm of average train freight transport	adjusted share for ZA train freight market between diesel and electric train
Water pump 22kw production {GLO}	1 water pump 22 kW	water pump 22kW globally produced
Water pump operation, diesel {ZA}	1 MJ of power exerted by a water pump 22kW powered by diesel	
Water pump operation, electric {ZA}	1 MJ of power exerted by a water pump 22kW powered by electricity	ZA electricity

Table A2 refers to support processes (processing) used to model the manufacture of the bags.

Table A2: Support processes created and/or adapted to represent ZA context

Name	Product	Adaptation
Extrusion of plastic sheets {Row-ZA adapted}| processing	Extrusion of plastic sheets	ZA electricity, RoW tap water; ZA Waste plastic mix
Extrusion of plastic sheets and thermoforming, inline {Row-ZA adapted}| processing	Extrusion of plastic sheets	ZA electricity, RoW tap water; ZA Waste PP, ZA waste PE: ZA waste plastic mix
Stretch blow moulding {RoW-ZA adapted}	Stretch blow moulding	ZA electricity, ZA water; ZA waste plastic mixture
Textile production, non woven, spun-bond PP {GLO-ZA adapted}	Textile production, non woven, spun- bond PP	ZA electricity, GLO tap water
Process-specific burdens, sanitary landfill {GLO-ZA adapted}| production	Process-specific burdens, sanitary landfill	ZA electricity

Table A3 indicates how the transport stages during the life cycle of the bags were modelled, and the associated assumptions.

Table A3: Modelling of transportation

Transportation stage	Assumptions
Coal mines in Secunda to Sasolburg	200 km, truck and rail haulage
Oil from Middle East imported by ship to Durban	6000 km, oil tanker (550000 t)
Oil transported from Durban to Sasolburg	720 km, pipelines
Polymer transported to bag manufacturer (CT, Durban or JHB)	1300, 650 and 84km for CT, Durban and JHB; average 680km
Bag/bottle to retailer	50km, 3-7 t truck
Bag/bottle to home	Transport associated with the use phase (and with reuse) was set to zero in the model; since the consumer is assumed to travel to the retailer to purchase groceries, rather than specifically to purchase a bag. The bag is required in order to carry the groceries.
Home to landfill/dump	For most serviced households the distance to landfill is 20km, while self-help dump is within 2km. Weighted average 6km
From recycling plant (MRF) to manufacturer (bottle)	50 km, 3-7 t truck

Table A4 indicates the waste treatment processes used model the final disposal of the material types.

Table A4: Waste treatment processes created and/or adapted to represent ZA context

Name	Product	Adaptation
EOL Paper, Waste packaging paper {ZA}, market for	1 kg of paper to waste treatments (open burning, open dump, sanitary and unsanitary landfill)	Sanitary landfill added to the waste treatment options and share fo the waste flows adapted to ZA context
EOL PE, Waste polyethylene {ZA}, market for	1 kg of PE to waste treatments (open burning, open dump, sanitary and unsanitary landfill)	Sanitary landfill added to the waste treatment options and share fo the waste flows adapted to ZA context
EOL PET, Waste polyethylene terephtalate {ZA}, market for	1 kg of PET to waste treatments (open burning, open dump, sanitary and unsanitary landfill)	Sanitary landfill added to the waste treatment options and share fo the waste flows adapted to ZA context
EOL PP, Waste polypropylene {ZA}, market for	1 kg of PP to waste treatments (open burning, open dump, sanitary and unsanitary landfill)	Sanitary landfill added to the waste treatment options and share fo the waste flows adapted to ZA context
EOL Polybutylene, Waste plastic, mixture {ZA}, market for	1 kg of Polybutylene to waste treatments (open burning, open dump, sanitary and unsanitary landfill)	Sanitary landfill added to the waste treatment options and share fo the waste flows adapted to ZA context
PE (waste treatment) {GLO-ZA adapted} | recycling of PE	1 kg of PE sorted to be recycled	ZA electricity
PET (waste treatment) {GLO-ZA adapted} | recycling of PET	1 kg of PET sorted to be recycled	ZA electricity
Waste packaging paper {GLO-ZA adapted} | treatment of waste packaging paper, sanitary landfill	1 kg of packaging paper treated in a sanitary landfill site	Incineration deleted; process-specific burdens, sanitary landfill {GLO-ZA adapted}; ZA electricity; ZA waste flows (plastic mix, graphical paper)
Waste plastic mix {GLO-ZA adapted} | treatment of waste plastic mix, sanitary landfill	1 kg of plastic mix treated in a sanitary landfill site	Incineration deleted; process-specific burdens, sanitary landfill {GLO-ZA adapted}; ZA electricity; ZA waste flows (plastic mix, graphical paper)
Waste PE {GLO-ZA adapted} | treatment of waste PE sanitary landfill	1 kg of PE treated in a sanitary landfill site	Incineration deleted; process-specific burdens, sanitary landfill {GLO-ZA adapted}; ZA electricity; ZA waste flows (plastic mix, graphical paper)
Waste PET {GLO-ZA adapted} | treatment of waste PET sanitary landfill	1 kg of PET treated in a sanitary landfill site	Incineration deleted; process-specific burdens, sanitary landfill {GLO-ZA adapted}; ZA electricity; ZA waste flows (plastic mix, graphical paper)
Waste PP {GLO-ZA adapted} | treatment of waste PP sanitary landfill	1 kg of PP treated in a sanitary landfill site	Incineration deleted; process-specific burdens, sanitary landfill {GLO-ZA adapted}; ZA electricity; ZA waste flows (plastic mix, graphical paper)

Appendix B: Contribution analysis per impact category

Section 6.1.2 of the main report showed the contribution analysis for the ReCiPe 2016 aggregated single score. In this appendix, we provide the corresponding contribution analysis for each individual midpoint and endpoint category in the ReCiPe 2016 method. The midpoint impact categories are illustrated in Figures B1 – B18; and the endpoint damage categories in Figures 19 – 21.

The different coloured bars refer to the various stages of the life cycle, as follows:

- Light green: Raw materials extraction
- Light blue: Bag manufacturing
- Yellow: Distribution
- Dark green: Final Disposal
- Dark blue: Recycling at end of life (where applicable)
- Brown: Production of recyclate, for bag types produced with recycled content

Note that for paper bags, the burden for recyclate production is included within the recycling stage.

Midpoint impact categories

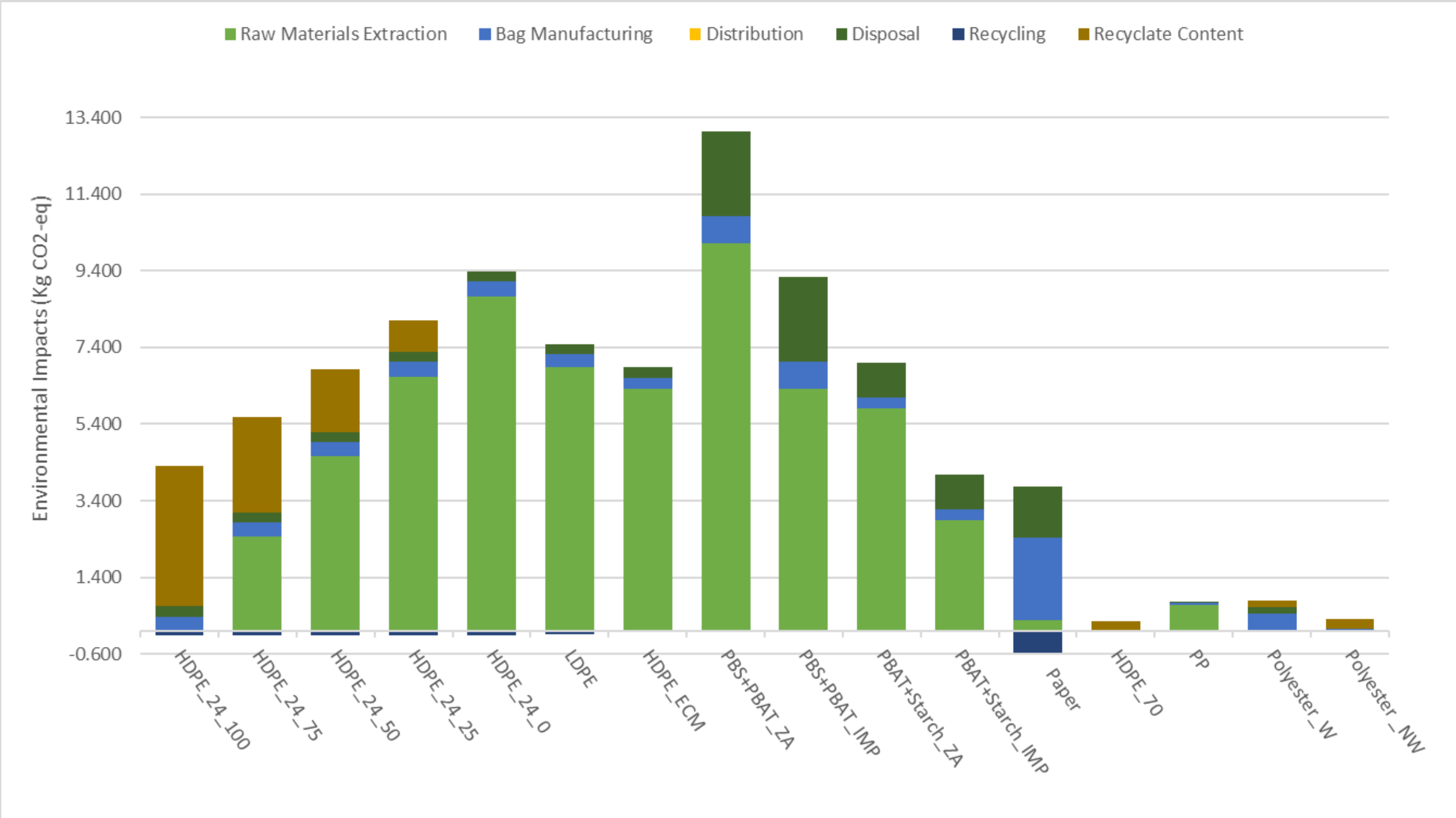

Figure B1: Contribution analysis: Global Warming

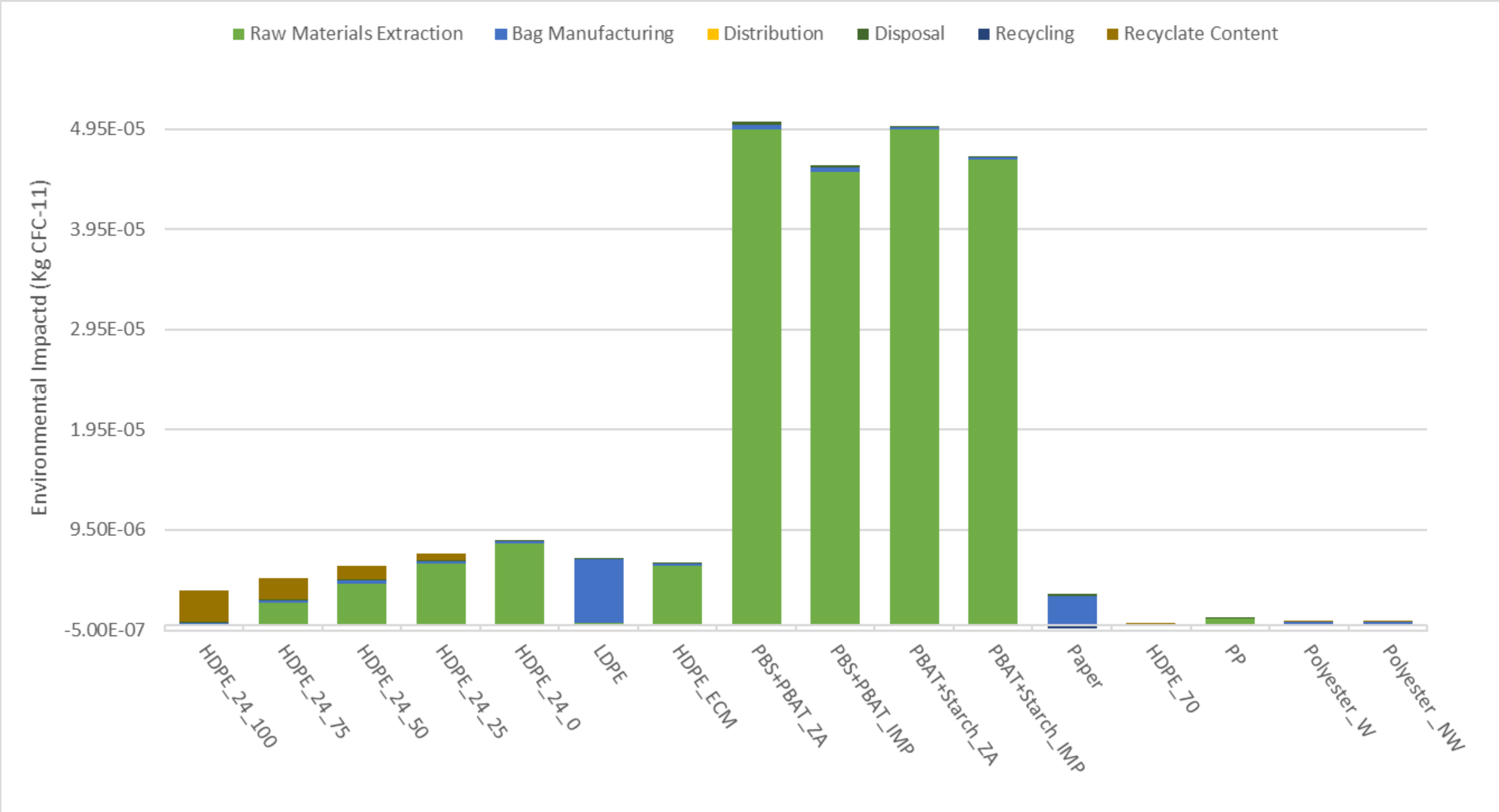

Figure B2: Contribution analysis: Stratospheric Ozone Depletion

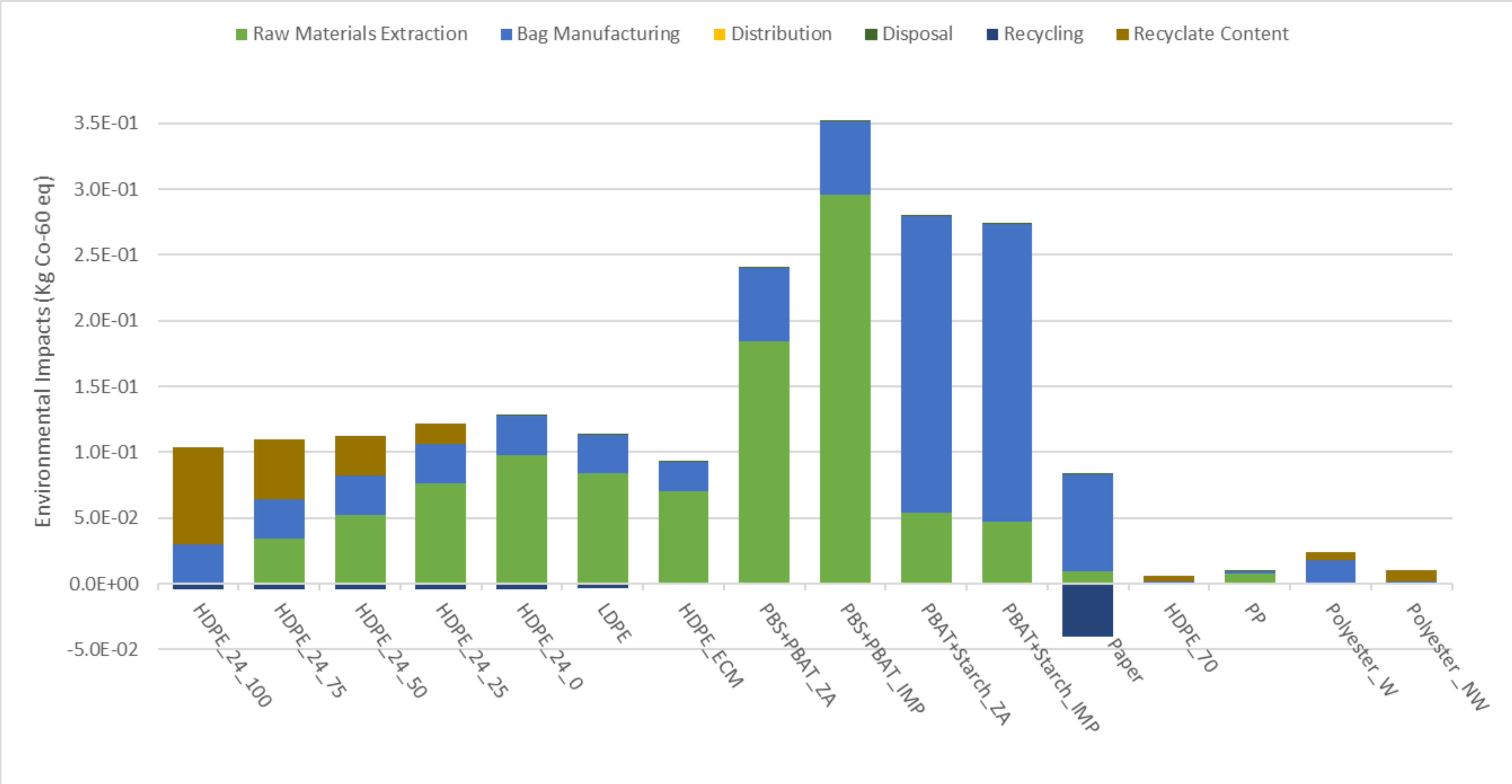

Figure B3: Contribution analysis: Ionizing Radiation

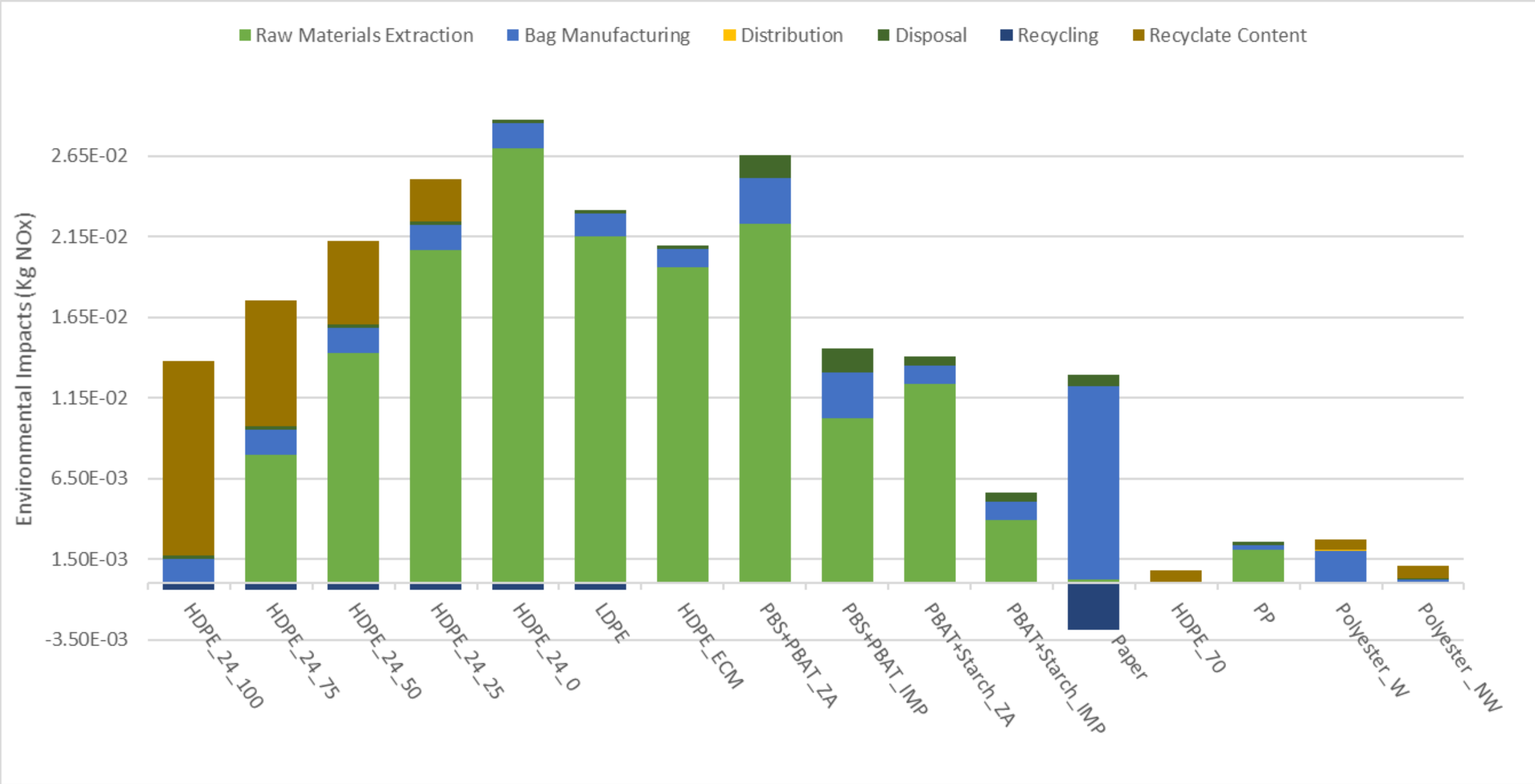

Figure B4: Contribution analysis: Ozone Formation, Human Health

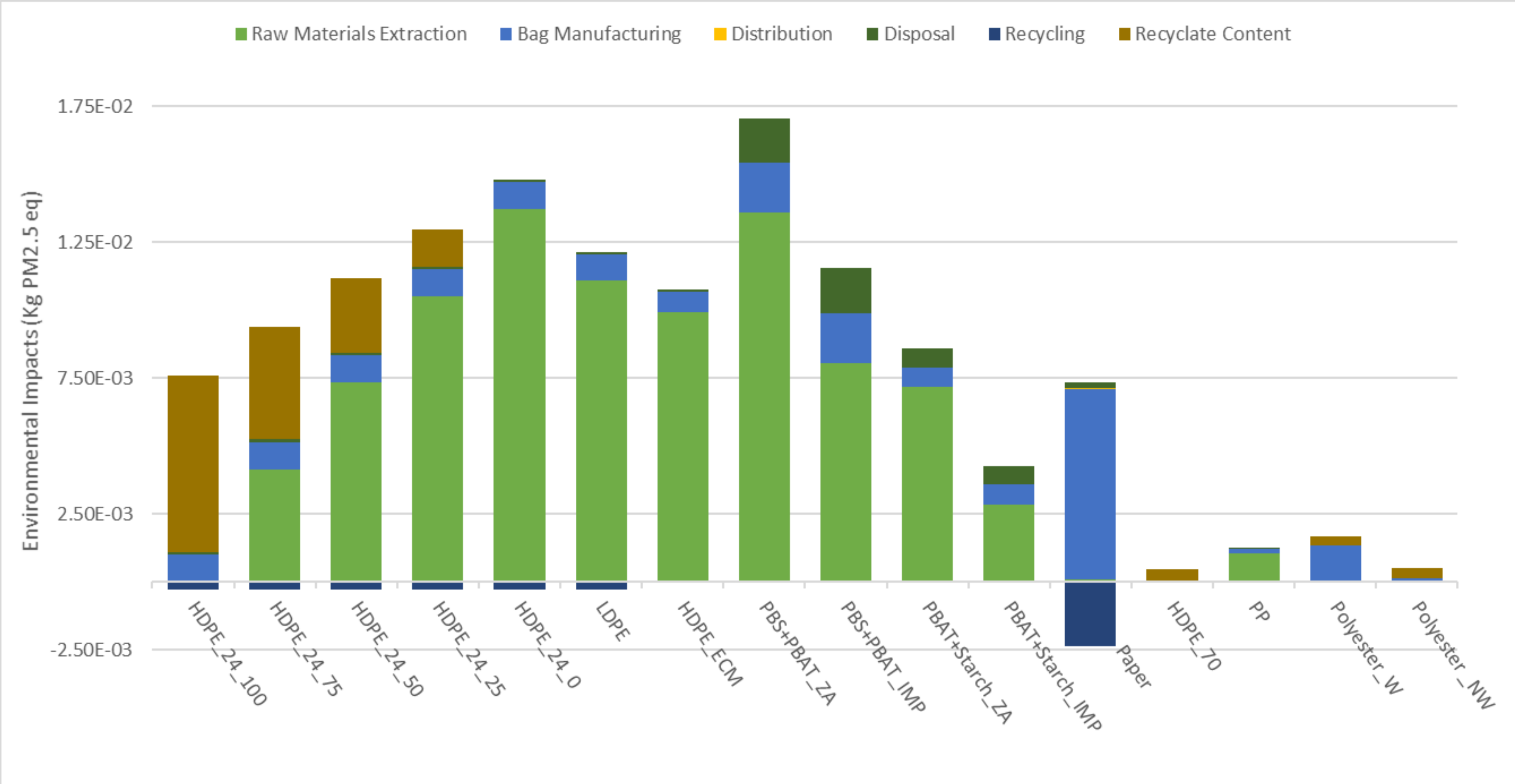

Figure B5: Contribution analysis: Fine Particulate Matter Formation

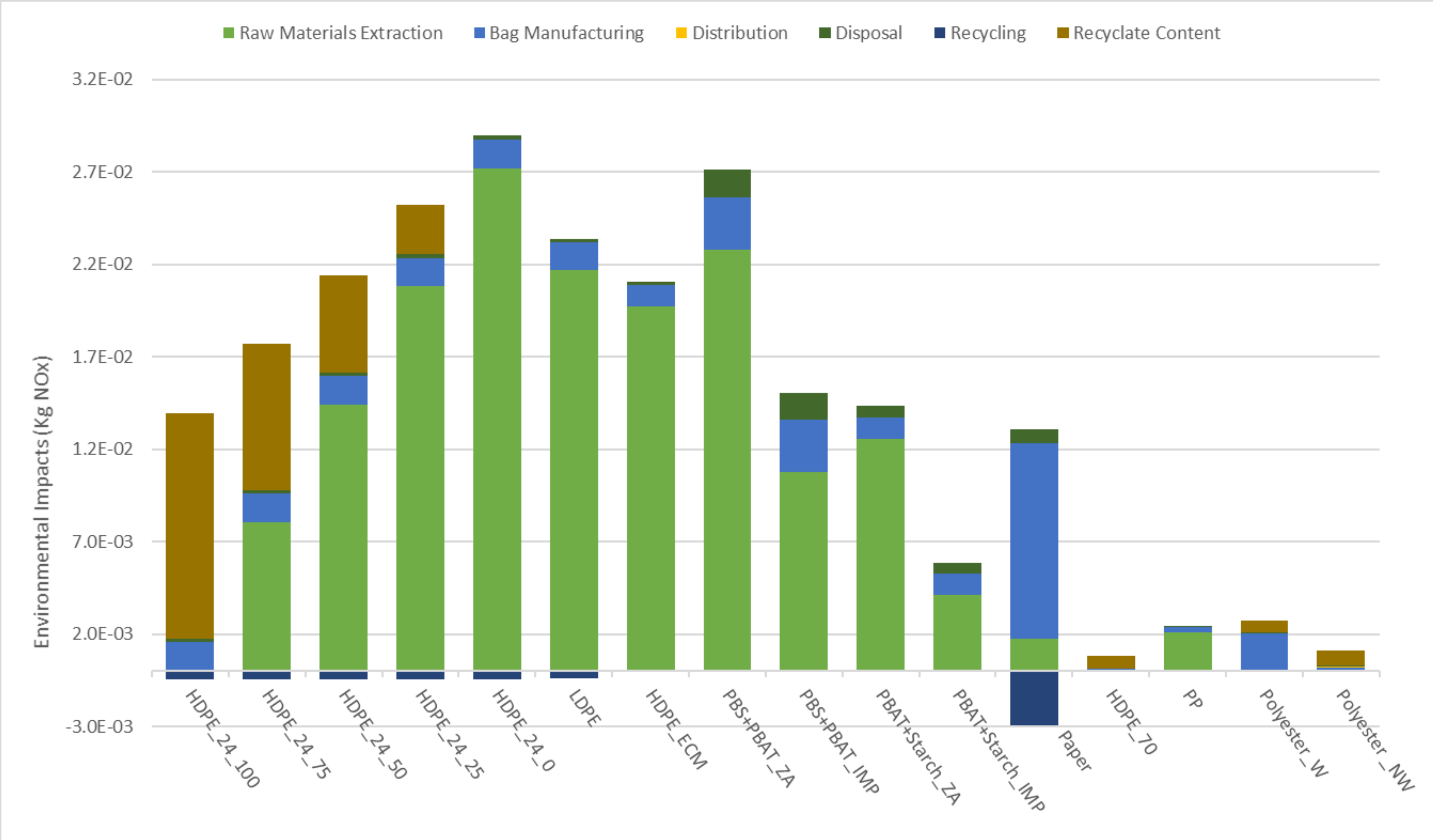

Figure B6: Contribution analysis: Ozone Formation, Terrestrial Ecosystem

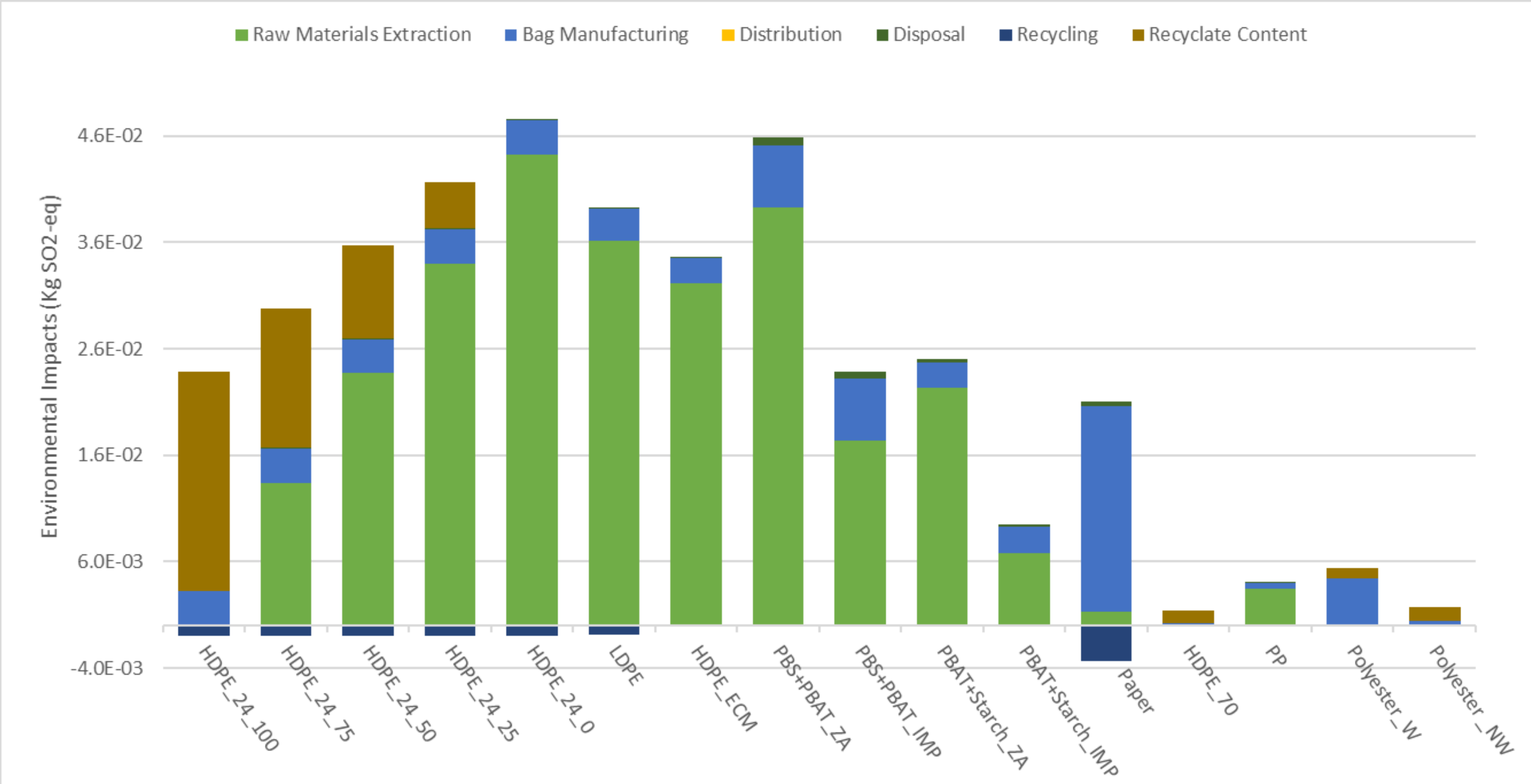

Figure B7: Contribution analysis: Terrestrial Acidification

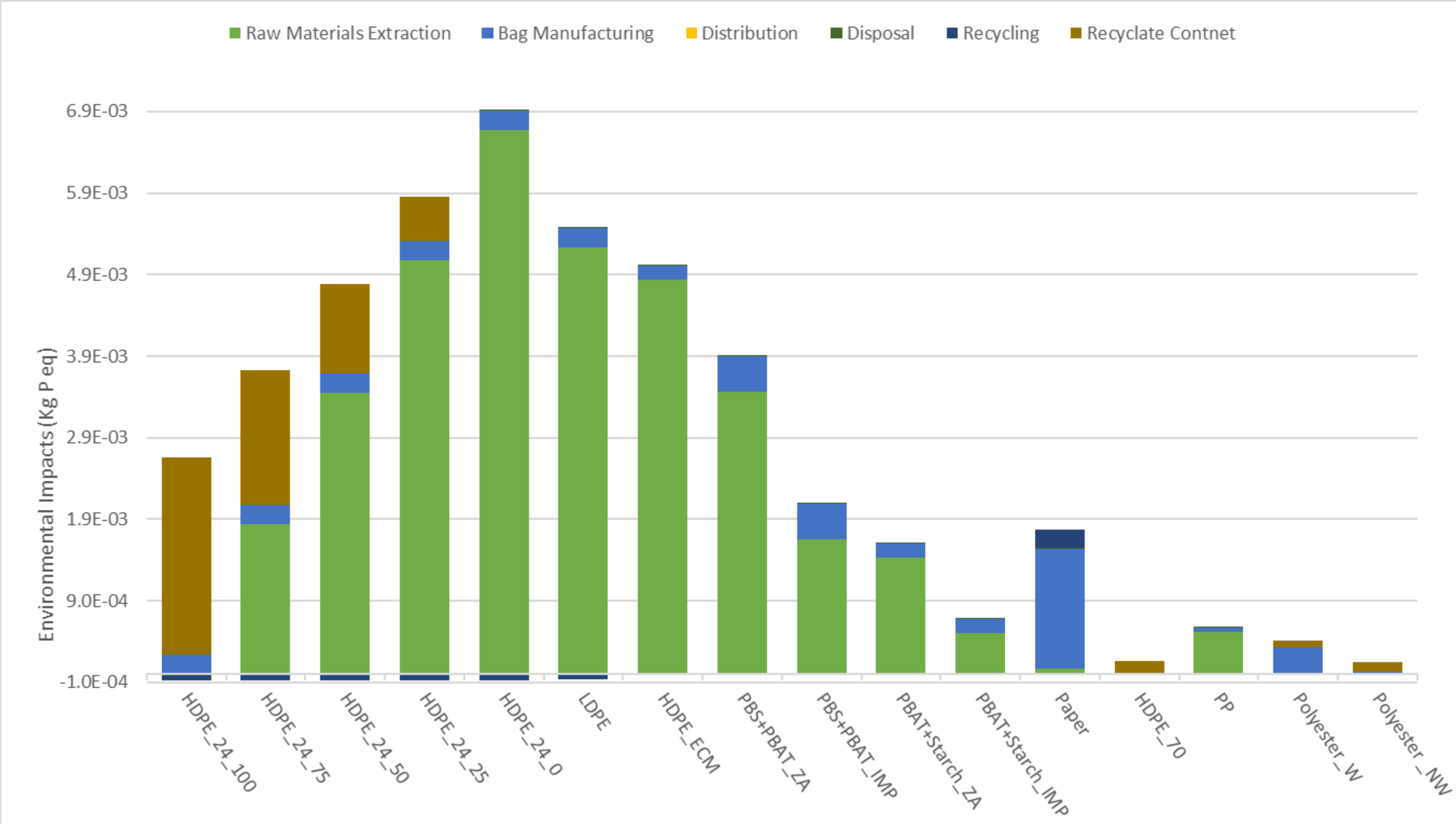

Figure B8: Contribution analysis: Freshwater Eutrophication

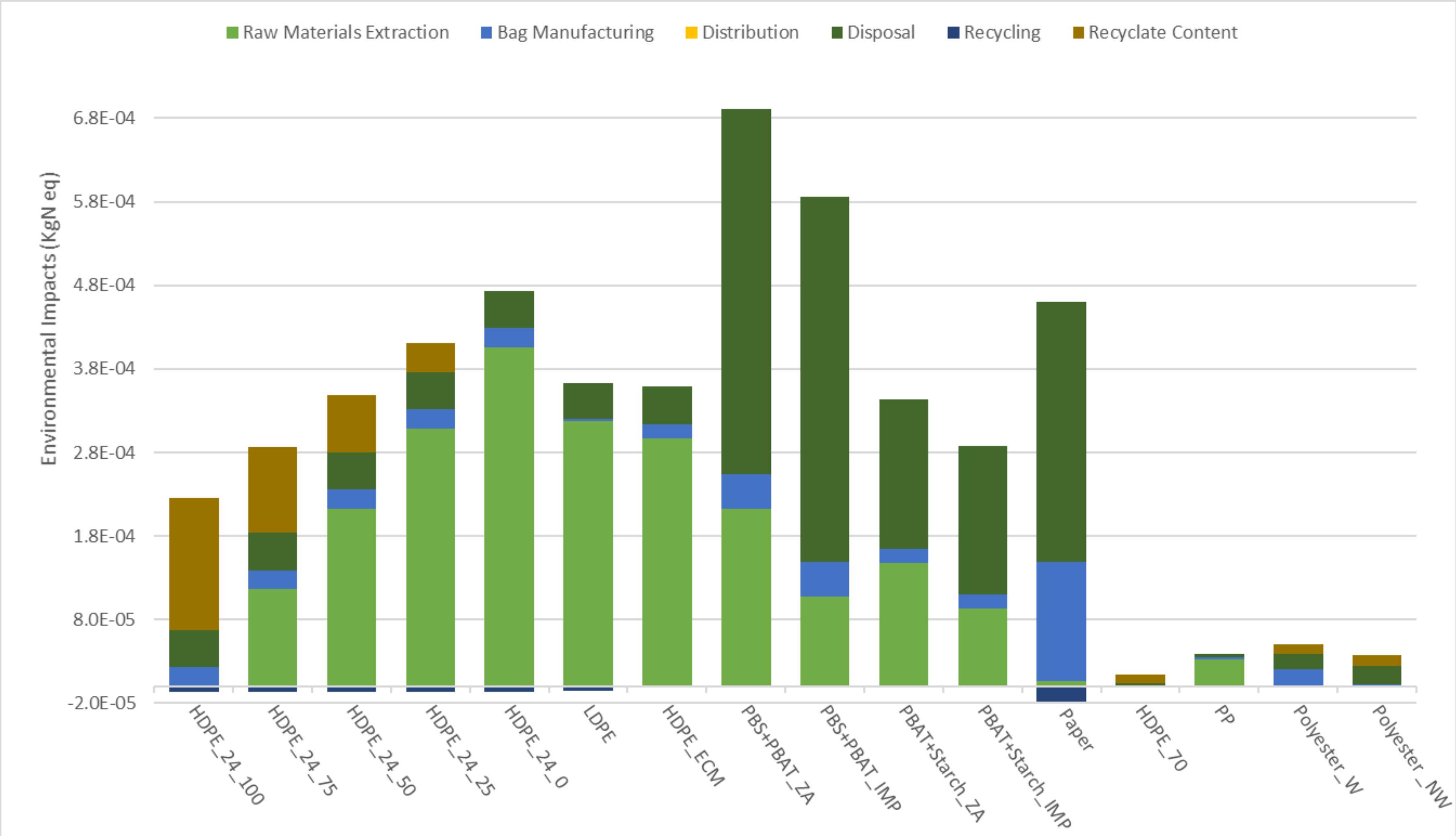

Figure B9: Contribution analysis: Marine Eutrophication

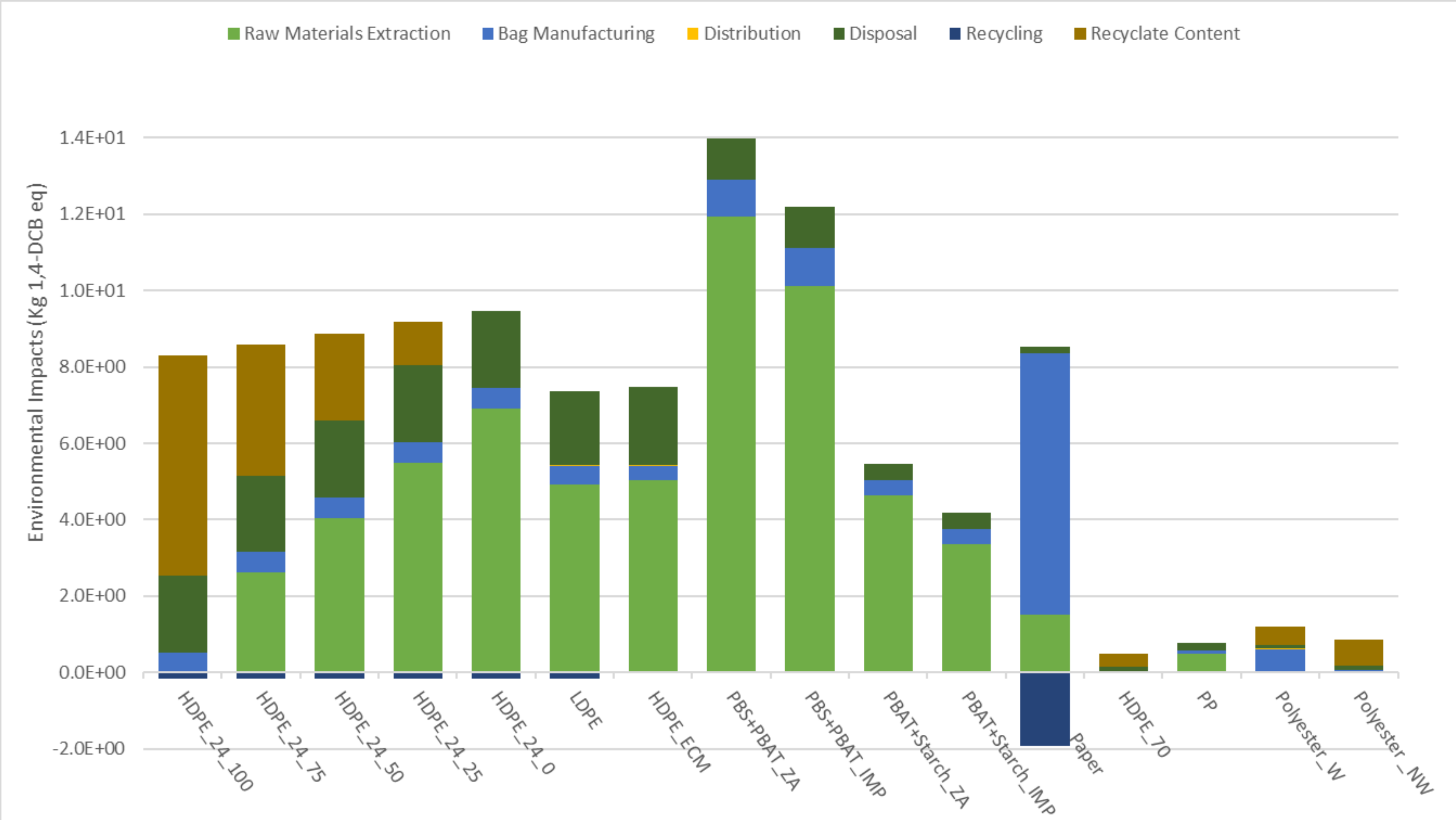

Figure B10: Contribution analysis: Terrestrial Ecotoxicity

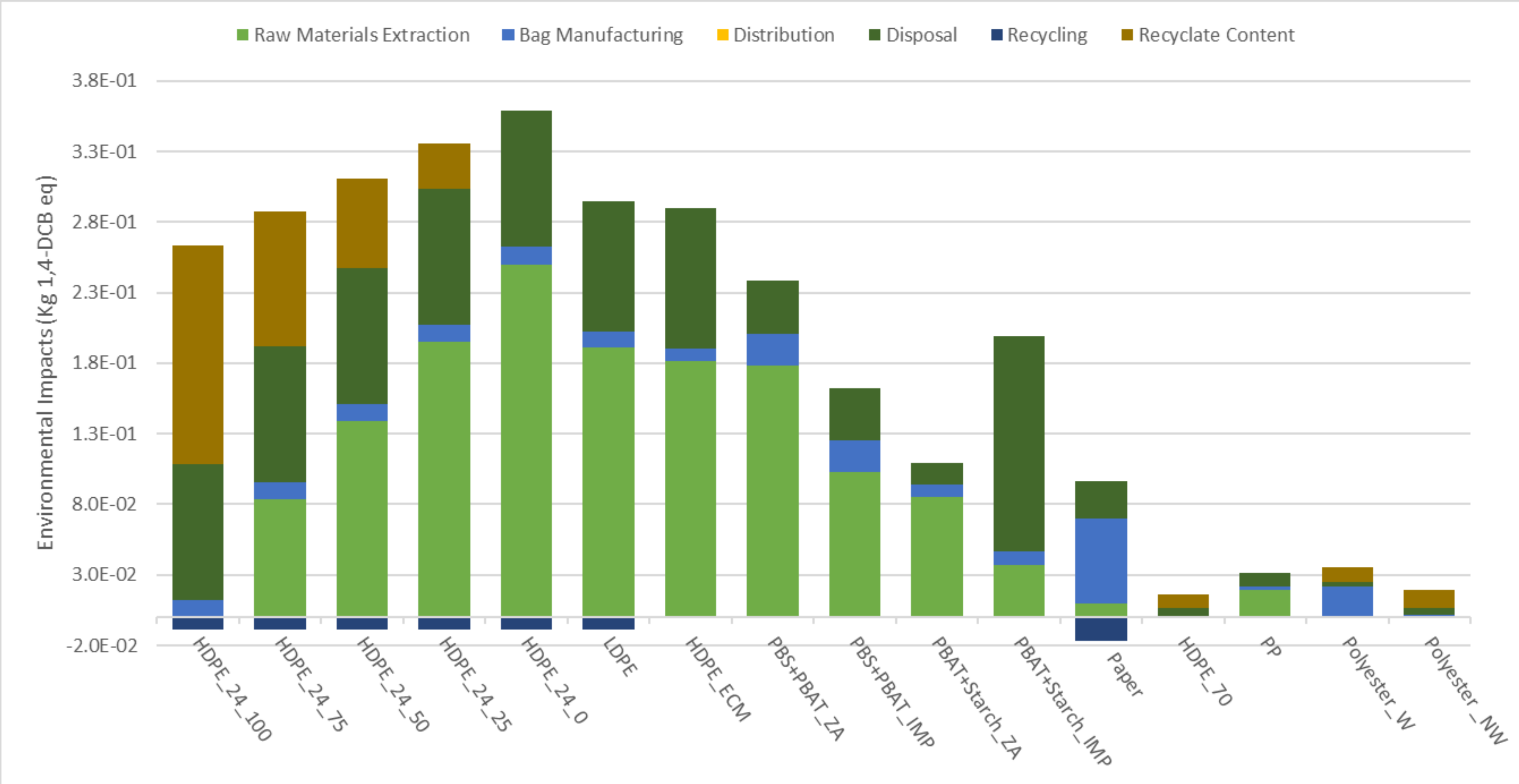

Figure B11: Contribution analysis: Freshwater Ecotoxicity

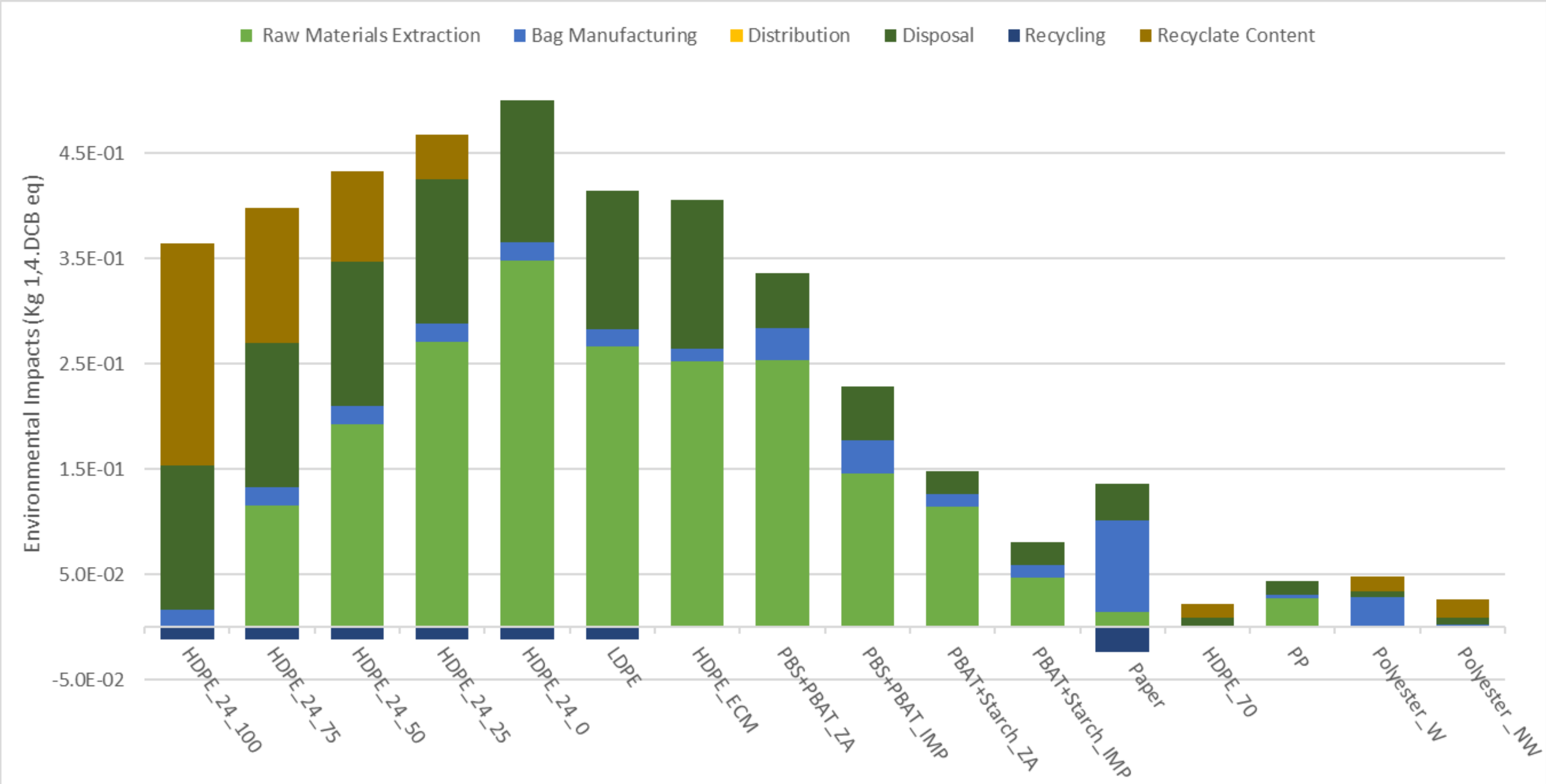

Figure B12: Contribution analysis: Marine Ecotoxicity

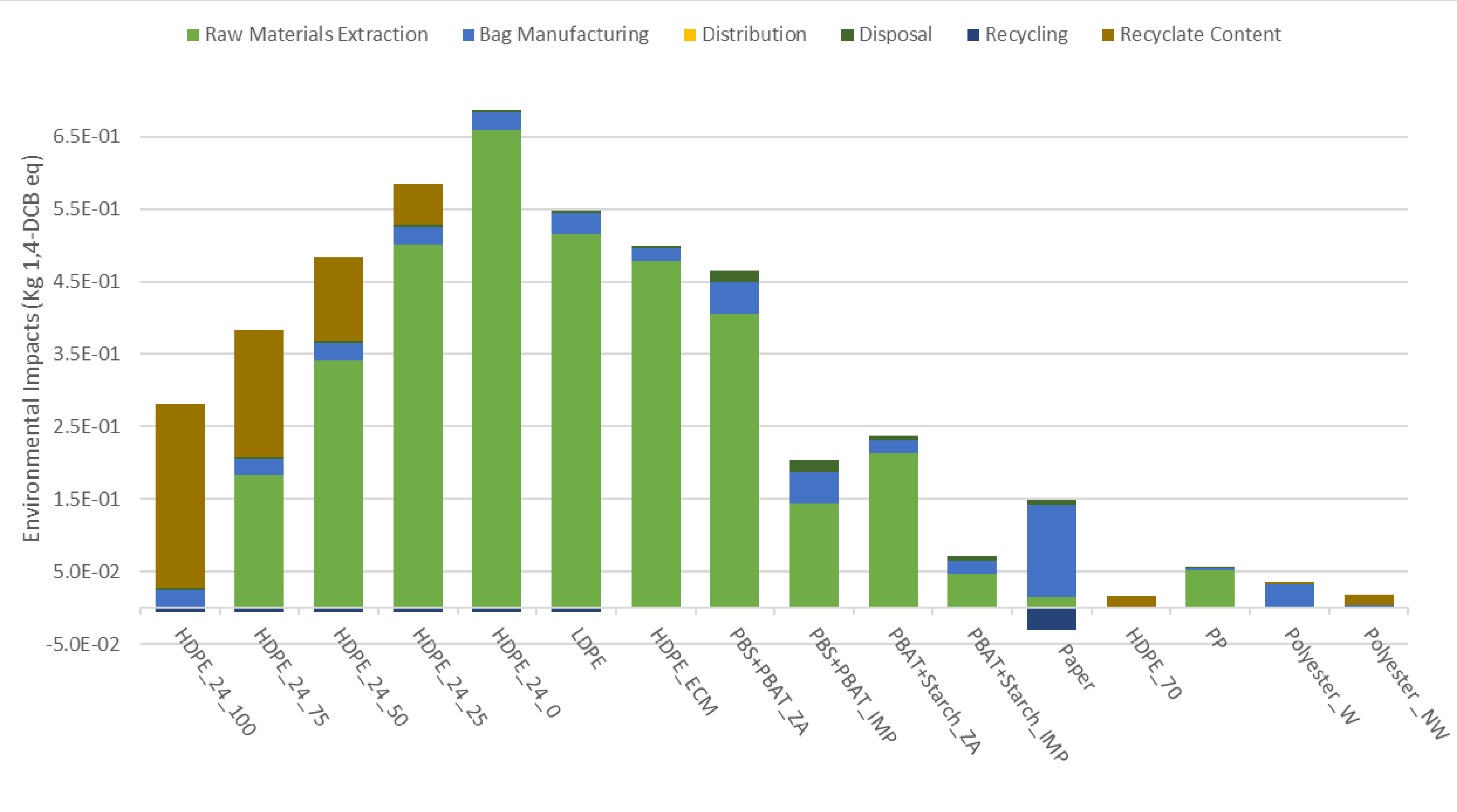

Figure B13: Contribution analysis: Human Carcinogenic Toxicity

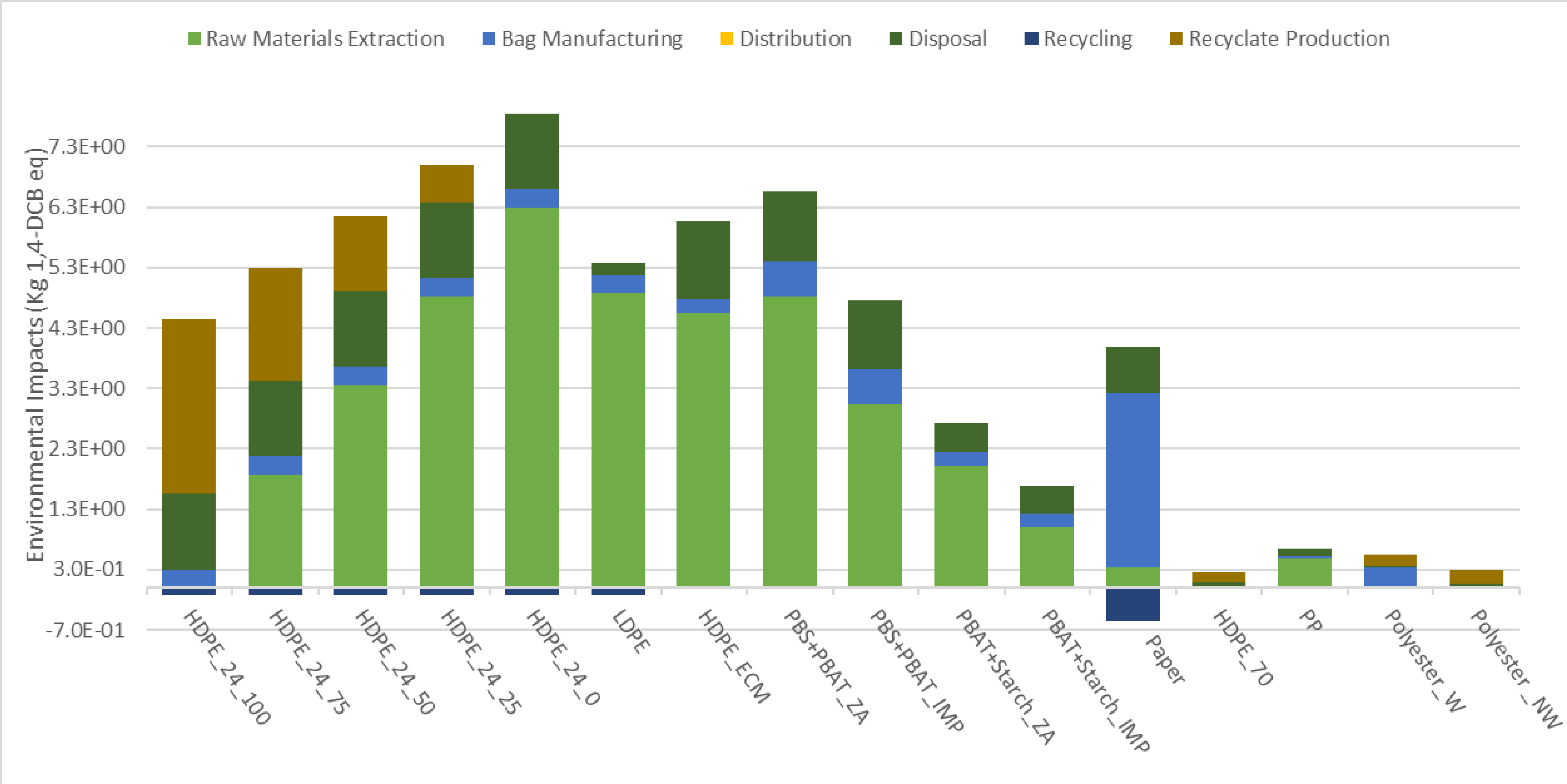

Figure B14: Contribution analysis: Human Non-Carcinogenic Toxicity

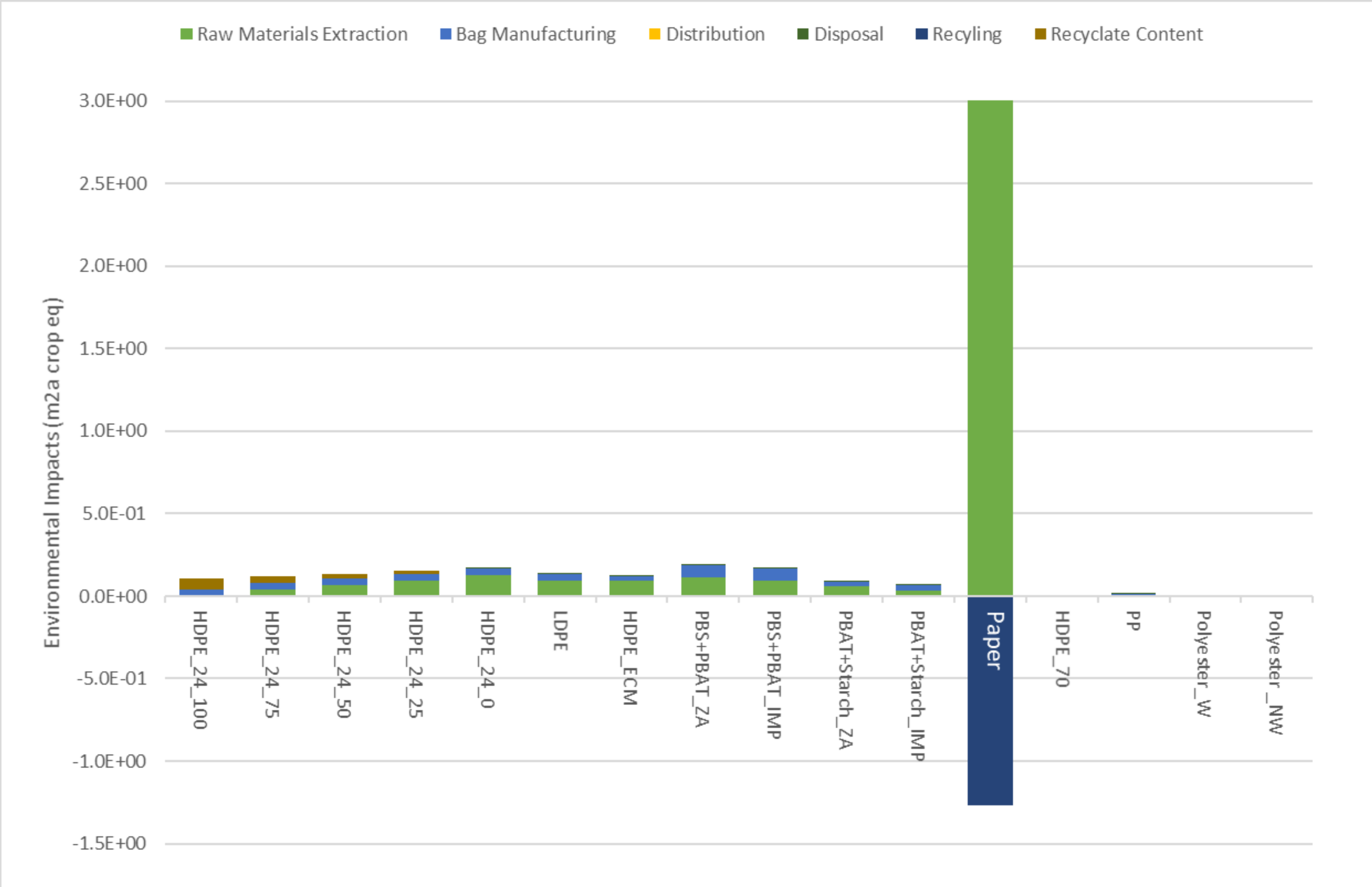

Figure B15: Contribution analysis: Land use

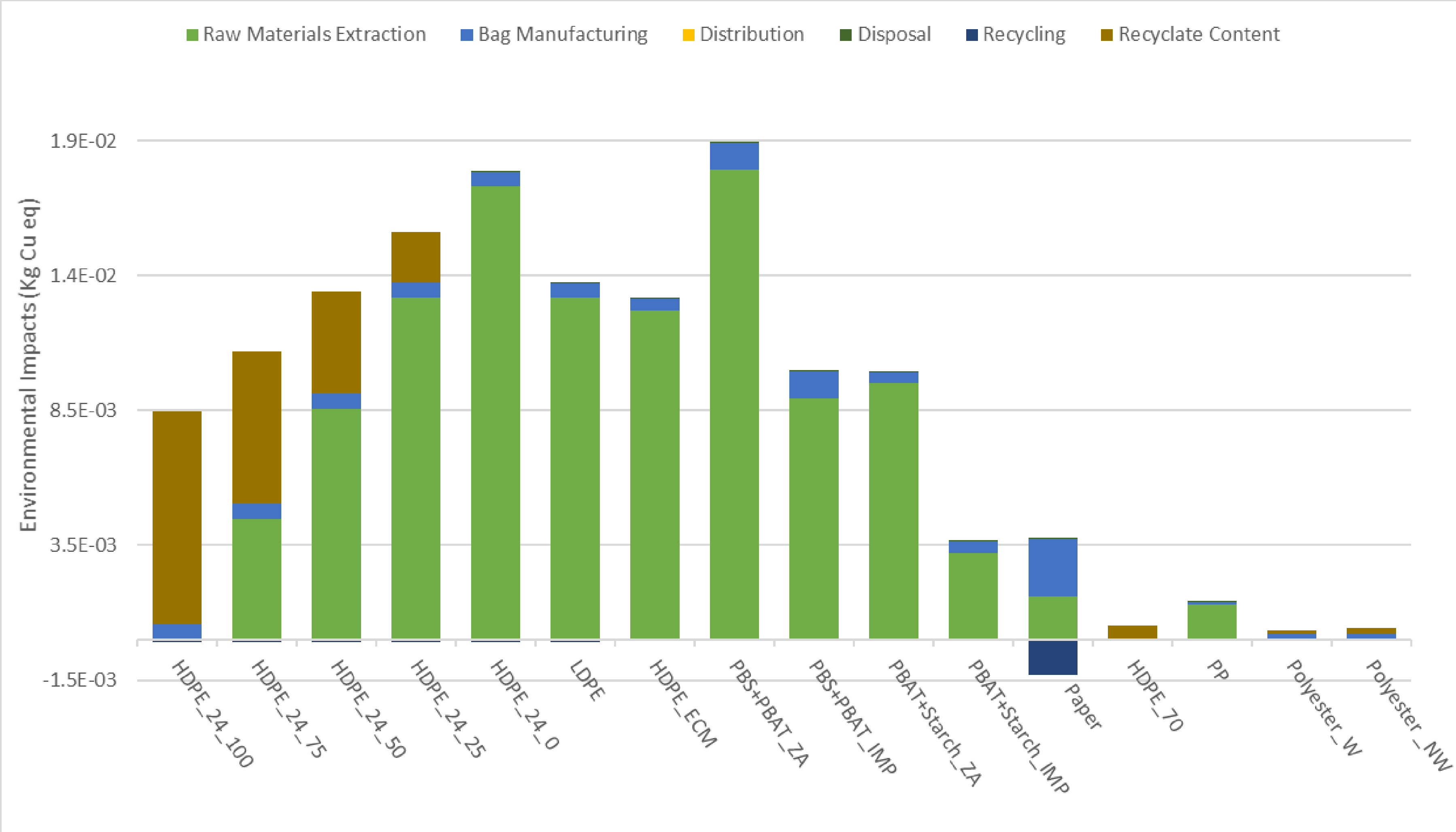

Figure B16: Contribution analysis: Mineral Resources Scarcity

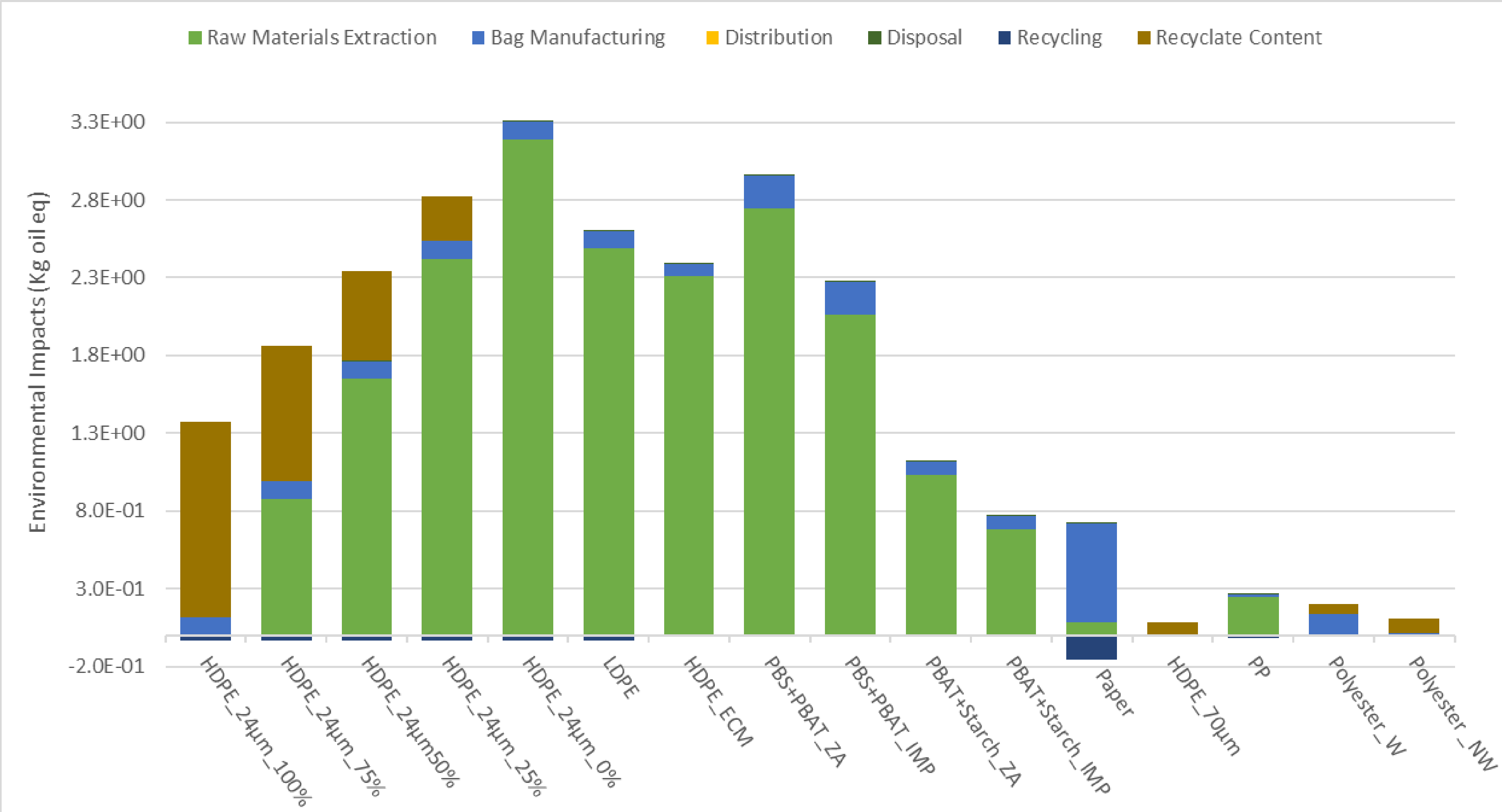

Figure B17: Contribution analysis: Fossil Resource Scarcity

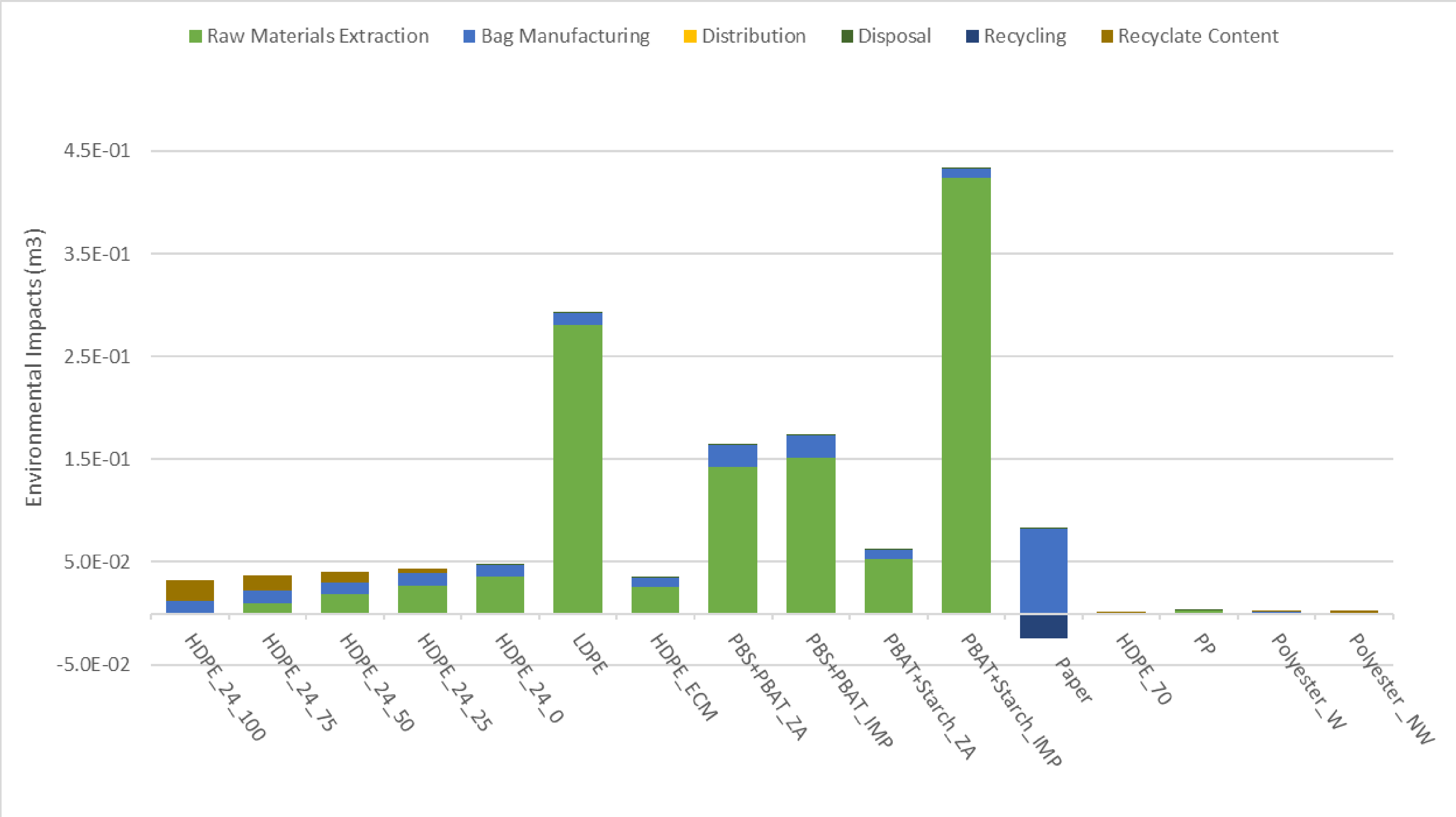

Figure B18: Contribution analysis: Water Consumption

Endpoint damage categories

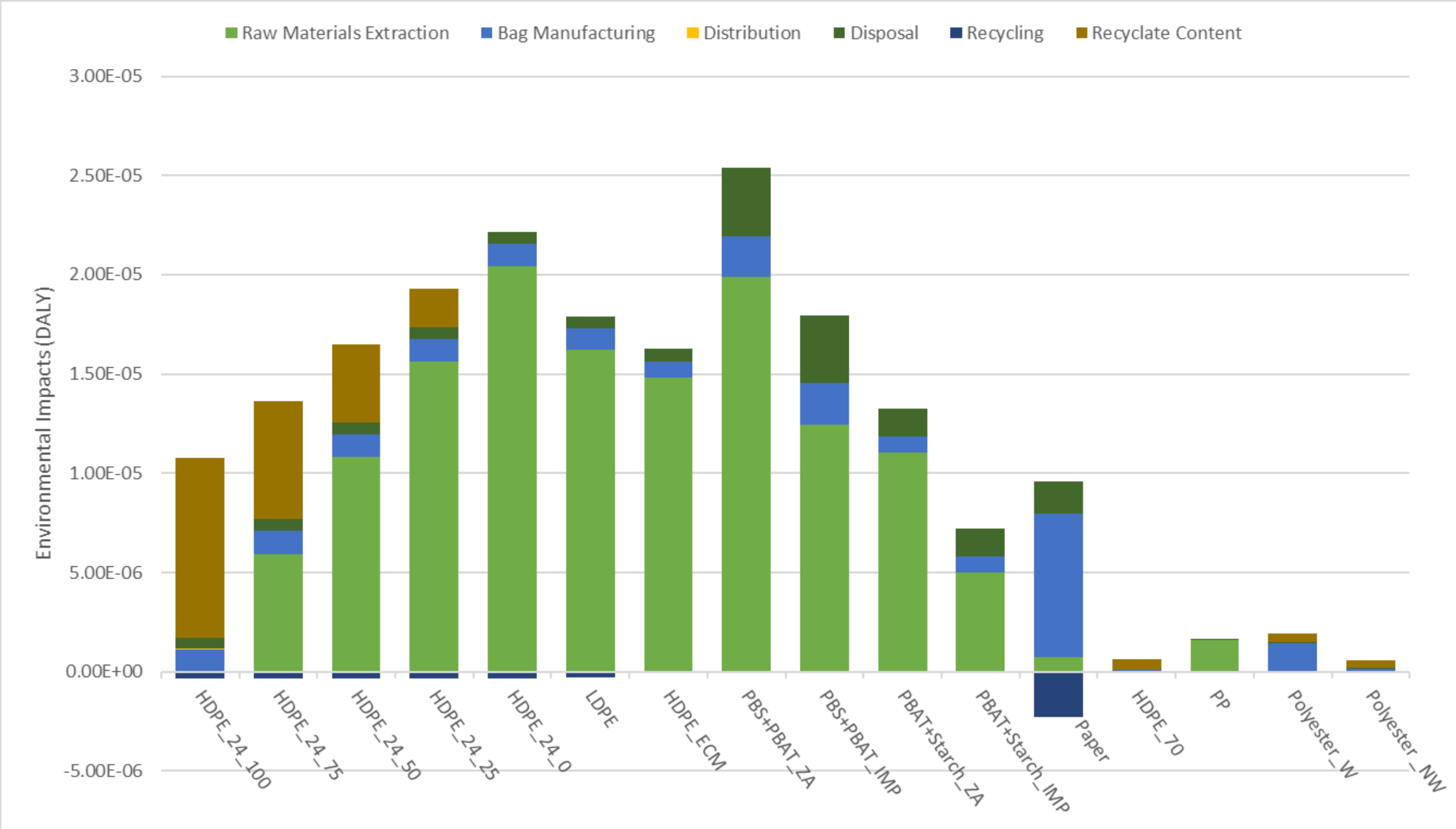

Figure B19: Contribution analysis: Human Health

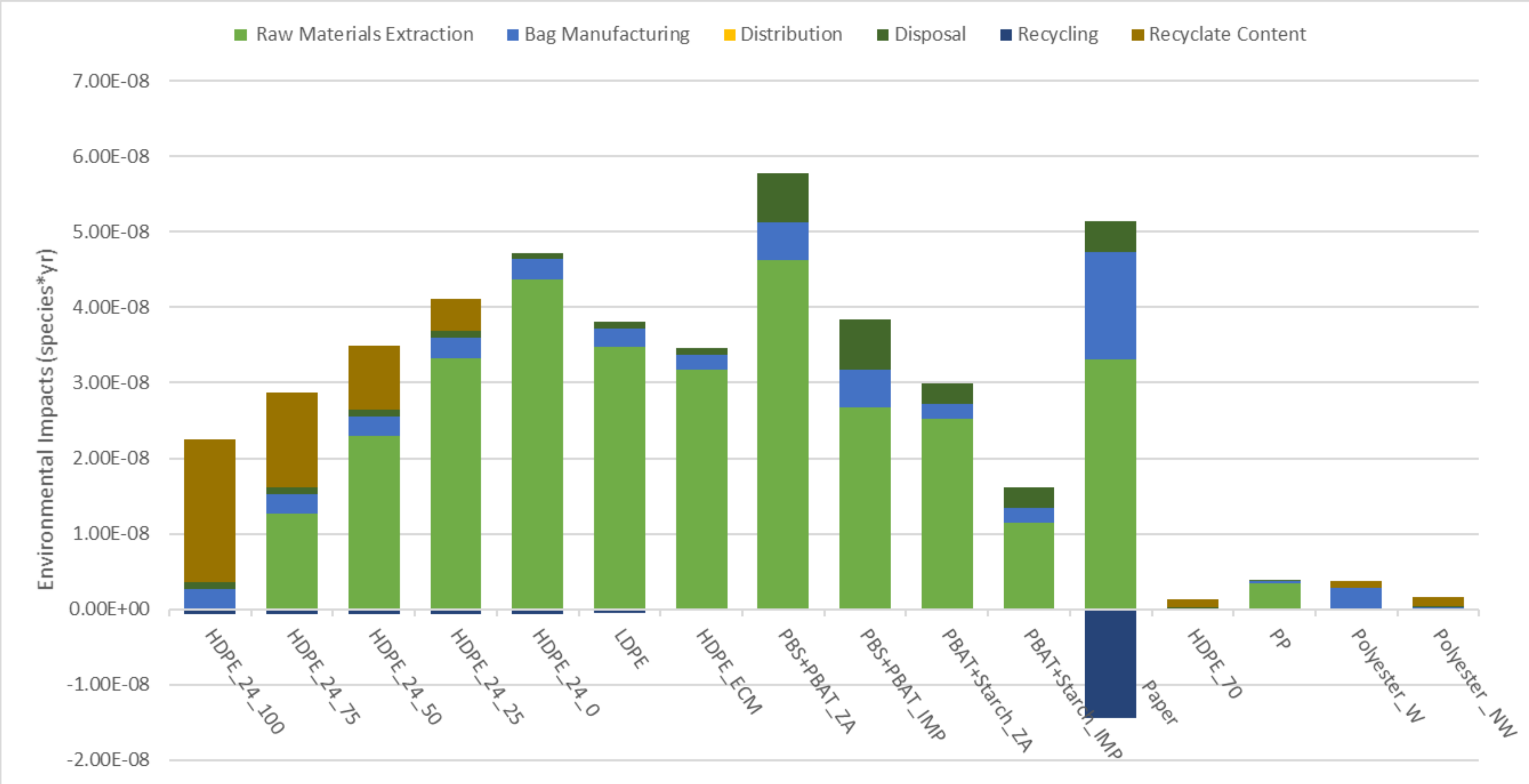

Figure B20: Contribution analysis: Ecosystems

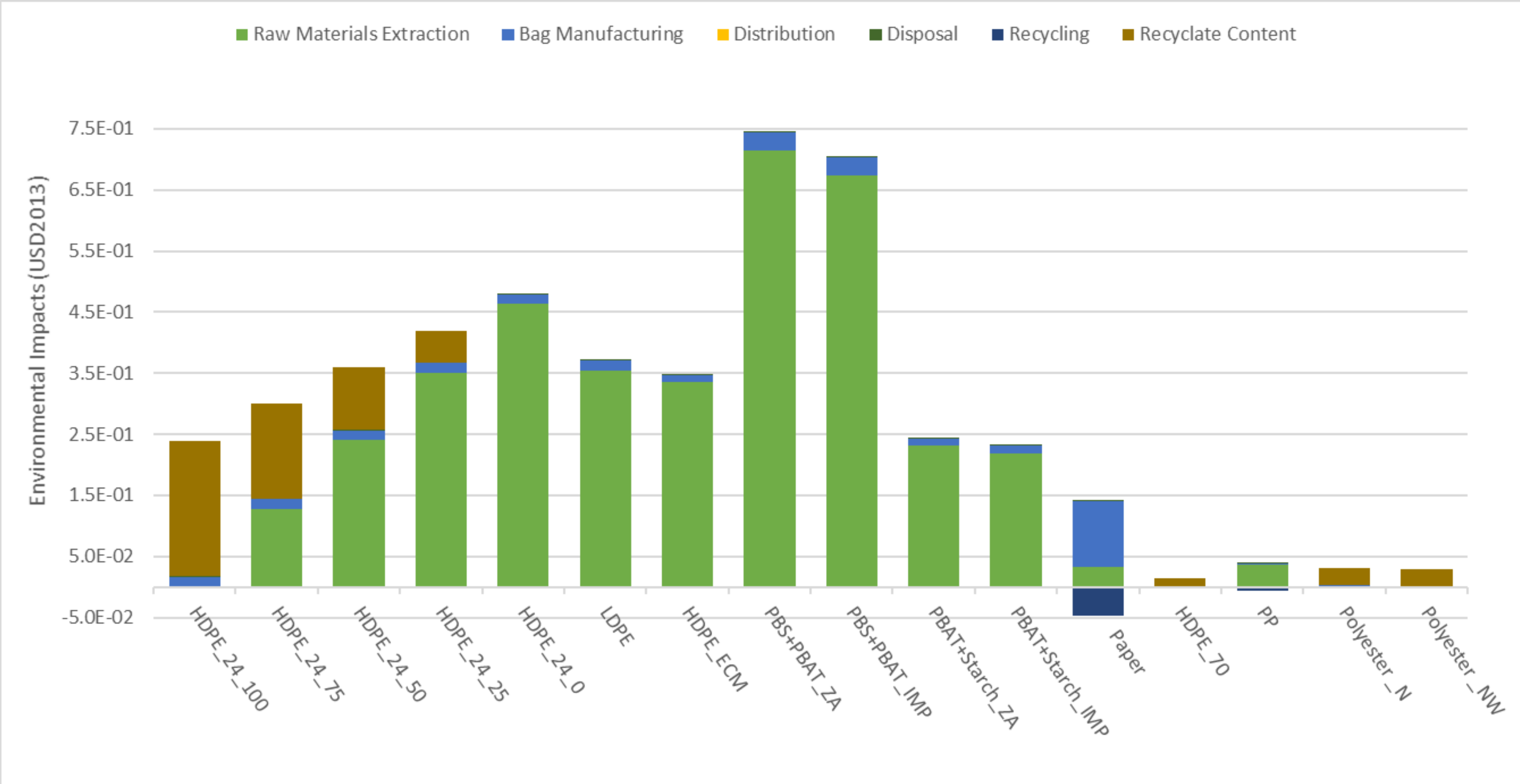

Figure B21: Contribution analysis: Resources

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