WHICH BAG IS BEST? A LIFE CYCLE SUSTAINABILITY ASSESMENT OF GROCERY CARRIER BAGS IN SOUTH AFRICA

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ABSTRACT

The environmental impacts of plastic waste have received significant attention from both policy makers and the general public. A number of countries have banned certain single-use plastic products, including plastic carrier bags. However, alternatives to plastic carrier bags come with their own set of impacts. The economic, social and environmental impacts associated with plastic bags should be assessed alongside those of the various alternatives, across their respective life cycles.

This paper presents results from a Life Cycle Sustainability Assessment of 16 different grocery carrier bag options in South Africa. The aim was to compare the bags in terms of environmental and socio-economic performance, and to inform policymakers, retailers and the general public about which type of bag is "best" in the South African context.

Environmental indicators were based primarily on the ReCiPe 2016 impact assessment methodology. However, current life cycle assessment methodologies exclude indicators relating to the impacts of plastic pollution. We therefore develop a new indicator, namely persistence of plastic material in the environment, as a proxy for impacts associated with plastic pollution. We also add two key socio-economic indicators; namely employment and affordability.

Overall, reusable plastic bags (particularly the 70 micron HDPE bag) perform better than single-use bags, assuming that they are reused at least 3 to 10 times. The best single-use bag is the common 24 µm HDPE bag with 100% recycled content. Biodegradable bags perform poorly overall, except on the plastic pollution indicator. Single-use bags perform best in terms of employment, particularly paper bags.

KEYWORDS

Life Cycle Assessment, Life Cycle Sustainability Assessment, Single-use plastic, Reusable, Recycling, Recycled content, Plastic pollution, Persistence, Biodegradable.

INTRODUCTION

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) has been 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. 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 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 a range of different types of carrier bags that are (or could be) offered by South African retailers. The intention is to provide objective, evidence-based information to inform decision making regarding single-use plastic carrier bags in South Africa. 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 indicators of relevance to the developing country context; namely impacts on employment, and affordability for consumers. The methodology to be employed is referred to as 'Life Cycle Sustainability Assessment'.

METHODOLOGY

Life Cycle Sustainability Assessment

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

In line with the three 'pillars' of sustainability (environmental, social and economic); two additional approaches have also been developed, namely Social LCA (S-LCA), and Life Cycle Costing (LCC), aimed at assessing the social and economic impacts (respectively) of products across their life cycles.

Life Cycle Sustainability Assessment (LCSA) is a fairly new approach 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 (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, this type of approach fails to take into account the interactions and inter-dependencies between the three 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 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.

Bag types and functional unit

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 1).

Table 1: Bag types assessed in the LCSA study

Single-use / reusable	Type of material	Name	Description	Modelled % of recycled content	Modelled output recycling rate at end of life
Single-use	Fossil-based plastic	HDPE_24_100	High density polyethylene; with thickness of 24 micrometres (24 μm)	100%	29%
		HDPE_24_75		75%	29%
		HDPE_24_50		50%	29%
		HDPE_24_25		25%	29%
		HDPE_24_0		0%	29%

		LDPE	Low density polyethylene	0%	29%
	Fossil-based with bio-additive	HDPE_ECM	HDPE bags with ECM additive	0%	0%
	Biodegradable plastic	PBS+PBAT_ZA	Polybutylene Succinate and Polybutylene Adipate Terephthalate, using locally produced PBS and PBAT	0%	0%
		PBS+PBAT_IMP	PBS+PBAT, using imported PBS and PBAT	0%	0%
		PBAT+Starch_ZA	PBAT+Starch, using locally produced PBAT and maize	0%	0%
		PBAT+Starch_IMP	PBAT+Starch, using imported PBAT+Starch	0%	0%
	Paper	Paper	Brown (Kraft) paper bags	54.8%	54.8%
Reusable	Fossil-based plastic	HDPE_70	HDPE, thickness of 70 µm	100%	29%
		PP	Polypropylene bags	0%	19.7%
		Polyester_W	Woven fabric polyester	100%	0%
		Polyester_NW	Non-woven (spun-bond and stitched) polyester	85%	0%

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 annual quantity of groceries purchased per person (870.48 litres) is an estimate based on the annual 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 is used as the 'reference product', that is, the baseline against which all the alternatives are compared. The current consumption of this bag 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[1] were purchased in South Africa (BusinessTech 2019). 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). The carrying capacity of the reference bag (measured by taking the dimensions of the bag, excluding handles) is 16.74 litres. Therefore, the annual consumption of groceries per person (used to define the functional unit) can be estimated as 52 bags * 16.74 litres per bag = 870.48 litres.

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 number of times that each type of bag is assumed to 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 2

Table 2: 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 assumed to be 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

[1] 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.

	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

Data sources and modelling approach

The product 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. Secondary data, such as data related to product manufacturing, was sourced from the ecoinvent v3.6 database, available online at https://v36.ecoquery.ecoinvent.org/), as well as literature (e.g. Van der Velden et al, 2014). Background data was based on datasets available in SimaPro v 9.0, i.e. the ecoinvent v3.5 and USLCI databases.

Wherever possible, background datasets were adapted to the South African context by replacing the electricity and water inputs to match the South African energy mix and geography, as well as relevant sub-processes. Relevant experts 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 modelling was done following an attributional LCA approach, which focuses on the environmentally relevant physical flows to and from a product's life cycle and its associated subsystems (Ekvall 2019). In the case of multi-functional processes (e.g. production processes in which more than one type of output is produced), environmental burdens were allocated based on economic (as opposed to physical) allocation, to ensure that burdens are allocated mainly to the primary product being produced.

In the case of HDPE bags and polyester bags (made from rPET), combined production using recyclate and virgin sources was modelled by expanding the system boundary to include HDPE and PET bottles respectively (from which the recyclate is generated), each of which were modelled separately. The end of life of the bottles (waste collection and treatment, recycling and upgrading) were modelled explicitly, following Nordelöf et al (2019). To be consistent with the system model, we applied economic allocation to account for the respective burden carried by virgin and recycled materials, using the prices of virgin and recycled HDPE and PET.

Finally, the end of life for each bag was modelled based on the Materials Flow Analysis (MFA) compiled by von Blottnitz et al. (2017), as well as output recycling rates for each material type, estimated based on publicly available sources and discussions with experts (PlasticsSA 2019; PAMSA 2018, Pretorius 2020; Scholtz 2020). The recycling rates applied in the end of life modelling are presented in Table 1. Recycling rates were also varied in sensitivity analysis. Based on the MFA, 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. The MFA data suggests that, of the plastic entering these various disposal options, 32% goes to open dumping, 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).

Impact assessment methodology and indicators

Environmental indicators were based primarily on the ReCiPe 2016 impact assessment methodology (Huijbregts et al. 2016, 2017). This methodology comprises 18 impact categories (indicators) at midpoint level, three damage categories (endpoints), as well as an aggregated single score index (see Table 3). 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.

We then expand on the ReCiPe 2016 impact assessment in two important ways. Firstly, none of the established LCA impact assessment methodologies, ReCiPe 2016 included, contain an impact category relating to plastic leakage, or plastic pollution. This can 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 plastic pollution, particularly in the marine environment, we add an additional environmental indicator, to reflect these impacts. 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. For each type of bag, persistence is assessed in terms of the amount of material remaining in the environment (per functional unit), after 3 years of biodegradation. All else being equal, we assume that the more material persisting in the environment after three years, the more likely it is to cause damage to terrestrial, aquatic or marine ecosystems.

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 particularly pertinent in the South African context, namely impacts on employment, and affordability of bags to consumers. Employment is assessed in terms of the number of jobs involved throughout the life cycle, per functional unit. Affordability is assessed in terms of the cost of purchasing the number of bags required to fulfil the functional unit. All of the indicators used in the assessment, including the three new indicators (persistence, employment and affordability), are listed in Table 3, alongside their units of measurement.

The three new indicators enter the model as mid-point impact categories. In order to determine an overall ranking of the bags across the different indicators, we calculated 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. (Note that we use the HDPE 24 micron bag with 100% recycled content (HDPE_24_100) as the reference 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 should be applied to emphasise specific indicators 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; employment should arguably 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, in relative terms. However, it was beyond the scope of this study to determine a set of weightings applicable to the South African context; although it is recommended that such weightings be developed in future work, with input from all relevant stakeholders.

Table 3: 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 CFC-11-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	m^2a crop eq
		Mineral Resources Scarcity	Kg Cu eq
		Fossil Resource Scarcity	Kg oil eq
		Water Consumption	m^3
	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

RESULTS

Environmental LCA Results based on ReCiPe 2016

Based on the assumptions in Table 2 regarding the number of times each bag is reused, the environmental impact associated with each type of bag is illustrated in Figure 1. 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 2. Note that the results in Figure 1 are based on the ReCiPe 2016 aggregated single score, and exclude for now the three new indicators developed in this study (persistence, employment and affordability). 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). Among the single use bags, it can be seen that two biodegradable bags (namely the PBAT+Starch bag with imported content (PBAT+Starch_IMP), as well as paper bags) have a lower environmental impact as compared to the conventional fossil-based bags, based on the ReCiPe 2016 single score. In the next sub-section, however, the three new indicators will be incorporated in the results.

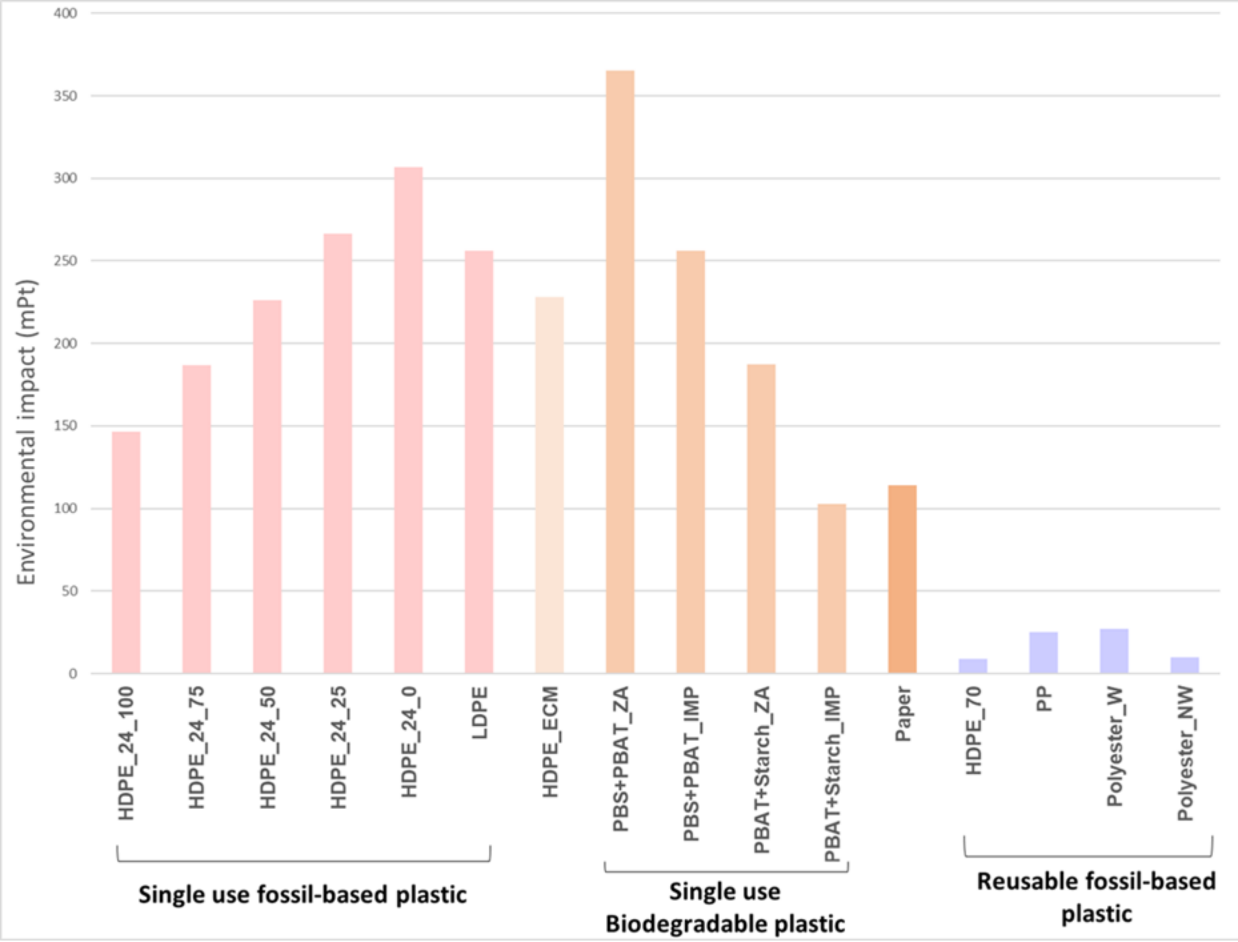

Figure 1: Environmental impact per bag type, based on ReCiPe 2016 single score (excluding persistence, employment and affordability). Based on assumption that single-use bags are used once each, and that reusable bags are used continuously over the course of the year to fulfil annual grocery shopping requirements.

Overall results: Incorporating persistence, employment and affordability

The results for the three new indicators developed in the study (persistence, employment and affordability) were integrated with the ReCiPe 2016 results as described in the Methodology section, to derive an overall ranking of the bags. The overall ranking (across all environmental and socio-economic indicators) is as per Table 4. 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 (see Methodology section).

Table 4: 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 4 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 conventional fossil-based HDPE 24 µm bag with 100% recycled content (HDPE_24_100), which outperforms any of the biodegradable options. 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. With a recycled content of 50% or lower, the HDPE bags begin to be outranked by some of the biodegradable options, particularly PBAT+Starch_IMP.

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).

Sensitivity analysis and break-even points

The results presented above 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. 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 a certain number of times.

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 2 regarding how many times each type of bag is reused, Table 5 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 reference bag, i.e. the single use HDPE 24 µm bag with 100% recycled content (HDPE_24_100). The break-even points in Table 5 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 5: 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, sensitivity analysis was conducted on the end of life recycling rates used in the modelling. Again, the model was shown to be robust even to extreme changes in recycling rates, with very little change in the overall rankings. On average across the recyclable bag types, an increase in recycling rates from current rates to 60% leads to a 4% reduction in environmental impact.

Results for specific mid-point impact categories of interest

Table 6 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 6: 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
1	HDPE_70	Polyester_NW	HDPE_70	PBAT+Starch_IMP	Paper
2	Polyester_NW	HDPE_70	Polyester_NW	PBAT+Starch_ZA	HDPE_24_100
3	PP	Polyester_W	Polyester_W	PBS+PBAT_IMP	HDPE_24_75
4	Polyester_W	PP	PP	PBS+PBAT_ZA	HDPE_24_50
5	Paper	PBAT+Starch_IMP	HDPE_ 24_100	Paper	PBS+PBAT_ZA
6	PBAT+Starch_IMP	PBAT+Starch_ZA	HDPE_ECM	HDPE_70	PBS+PBAT_IMP
7	HDPE_ 24_100	HDPE_24_100	HDPE_ 24_75	Polyester _W	HDPE_24_25
8	HDPE_ 24_75	HDPE_24_75	LDPE	Polyester _NW	HDPE_24_0
9	HDPE_ 24_50	HDPE_ECM	HDPE_24_50	PP	LDPE
10	HDPE_ECM	LDPE	HDPE_24_25	HDPE_ECM	PBAT+Starch_ZA
11	PBAT+Starch_ZA	HDPE_24_50	HDPE_24_0	LDPE	HDPE_ECM
12	LDPE	HDPE_24_25	Paper	HDPE_24_100	PBAT+Starch_IMP
13	HDPE_24_25	HDPE_24_0	PBAT+Starch_IMP	HDPE_24_75	Polyester_NW
14	PBS+PBAT_IMP	PBS+PBAT_IMP	PBAT+Starch_ZA	HDPE_24_50	Polyester_W
15	HDPE_24_0	PBS+PBAT_ZA	PBS+PBAT_ZA	HDPE_24_25	HDPE_70

16	PBS+ PBAT_ ZA	Paper	PBS+PBAT_IMP	HDPE_24_0	PP

The rankings for most environmental indicators (e.g. global warming, land use and water use in Table 6) are similar to the overall rankings presented in Table 4; 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. 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). 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.

CONCLUSIONS

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 reusable fossil-based plastic bags (HDPE_70, Polyester_NW, PP and Polyester_W). Specifically, 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).

The best performing among the single-use bags is the conventional fossil-based HDPE 24 µm bag with 100% recycled content (HDPE_24_100), which outperforms any of the biodegradable options. The biodegradable bags (particularly PBAT+Starch bags with imported content) only start to outrank the HDPE bags if the latter have a recycled content of 50% or less. A sensitivity analysis indicates that these rankings are robust to changes in key assumptions.

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; while the HDPE bag with an ECM additive fares relatively poorly, as do the other single-use fossil-based plastic bags.

In terms of affordability, the reusable bags generally perform 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, 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.

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. This affirms the preference for reuse over recycling within the waste management hierarchy.

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REFERENCES

BusinessTech (2019). *South Africa’s war on plastic bags appears to be working*. Online. Available at: https://businesstech.co.za/news/lifestyle/294392/south-africas-war-on-plastic-bags-appears-to-be-working/

Danish EPA (2018). *Life Cycle Assessment of Grocery Carrier Bags*. Copenhagen: The Danish Environmental Protection Agency

Ekvall T (2019). *Attributional and Consequential Life Cycle Assessment*. Online. Available at: https://www.intechopen.com/books/sustainability-assessment-at-the-21st-century/attributional-and-consequential-life-cycle-assessment

Gbededo M, Liyanage K and Garza-Reyes J (2018). Towards a Life Cycle Sustainability Analysis: A systematic review of approaches to sustainable manufacturing. *Journal of Cleaner Production* 184, 20: 1002-1015

Gloria T, Guinee J, Wei Kua H, Singh B and Lifset R (2017). Charting the Future of Life Cycle Sustainability Assessment: A Special Issue (Editorial). *Journal of Industrial Ecology* 21 (6): 1449 – 1453.

Guinee J, Heijungs R, Huppes G, et al. (2011). Life Cycle Assessment: Past, Present, and Future. *Environmental Science and Technology* 45: 90–96

Huijbregts M, Steinmann Z, Elshout P, Stam G, Verones F, Vieira M, Hollander A and Van Zelm R (2016). *ReCiPe2016: A harmonized life cycle impact assessment method at midpoint and endpoint level*. RIVM Report 2016-0104. Bilthoven, The Netherlands: National Institute for Public Health and the Environment

Huijbregts M, Steinmann Z, Elshout P, Stam G, Verones F, Vieira M, Hollander A and Van Zelm R (2017). *ReCiPe2016 v1.1: A harmonized life cycle impact assessment method at midpoint and endpoint level.* RIVM Report 2016-0104a. Bilthoven, The Netherlands: National Institute for Public Health and the Environment

ISO (2006a). ISO 14040*: Environmental Management – Life Cycle Assessment – Principles and Framework.* Geneva: International Organization for Standardization.

ISO (2006b). ISO 14044: *Environmental Management – Life Cycle Assessment – Requirements and guidelines*. Geneva: International Organization for Standardization.

Kloepffer W (2008). Life Cycle Sustainability Assessment of Products. *International Journal of Life Cycle Assessment* 13 (2), 89–95

Nordelöf A, Poulikidou S, Chordia M, Bitencourt de Oliveira F, Tivander J and Arvidsson R (2019). Methodological Approaches to End-Of-Life Modelling in Life Cycle Assessments of Lithium-Ion Batteries. *Batteries* 5, 51: doi:10.3390/batteries5030051

PAMSA (2018). *South African Pulp and Paper Industry: Summary findings on 2017 production, import and export statistics*. Online. Available at: https://www.thepaperstory.co.za/wp-content/uploads/2018/10/PAMSA-stats-report-2017-final.pdf

PlasticsSA (2019). *National Plastics Recycling Survey 2018*. Johannesburg: PlasticsSA

Pretorius A (2020). Personal communication by email. Plastix911

Scholtz C (2020). Personal Communication by email. Chief Executive Officer: PETCO

Sevitz J, Brent A and Fourie A (2003). An environmental comparison of plastic and paper consumer carrier bags in South Africa. *SA Journal of Industrial Engineering* 14(1): 67-82

Statistics South Africa (2016). *Mid-year population estimates, 2016*. Online. Available at: http://www.statssa.gov.za/?p=8176

Statistics South Africa (2017). *Mid-year population estimates, 2017*. Statistical Release P0302. Pretoria: Statistics South Africa

UK Environment Agency (2011). *Life cycle assessment of supermarket carrier bags*. London: UK Environment Agency

UNEP (2011). *Towards a Life Cycle Sustainability Assessment*. Nairobi, Kenya: UNEP/SETAC Life Cycle Initiative

Van der Velden N, Patel M and Vogtländer J (2014). LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. *International Journal of Life Cycle Assessment* 19, 331–356

Von Blottnitz H (2019). Personal Communication. University of Cape Town, Department of Chemical Engineering.

Von Blottnitz H, Chitaka T and Rodseth C (2017). *South Africa beats Europe at plastics recycling, but also is a top 20 ocean polluter. Really?* Online. Available at: http://www.epse.uct.ac.za/sites/default/files/image_tool/images/363/Publications/SA%20plastics%20MFA%20commentary%20by%20E%26PSE%20rev1.pdf