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REVIEW OF LIFE CYCLE ASSESSMENTS COMPARING PAPER AND PLASTIC PRODUCTS

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About this report:

This report examines life cycle assessments (LCAs) comparing disposable paper and plastic products. It finds that, although the body of existing studies is often used to support the conclusion that low-weight plastic bags generally yield better environmental results than paper bags, this finding: (1) depends on a variety of factors and cannot necessarily be extended to other products where paper can be used as a replacement for plastic, such as cups and plates for food packaging applications; and (2) except in a few studies does not include any consideration of material littering. The few LCA studies that did include some consideration of material littering in the environment showed a clear advantage of paper over plastic for this indicator.

About NCASI:

NCASI (National Council for Air and Stream Improvement, Inc.) is a non-profit environmental research organization that seeks to create credible scientific information required to address the environmental information needs of the forest products industry in North America. NCASI conducts surveys, performs field measurements, undertakes scientific research, and sponsors research by universities and others to document the environmental performance of industry facility operations and forest management, and to gain insight into opportunities for further improvement in meeting sustainability goals.

REVIEW OF LIFE CYCLE ASSESSMENTS COMPARING PAPER AND PLASTIC PRODUCTS

SUMMARY

Although the body of existing life cycle assessment (LCA) studies is often used to support the conclusion that low-weight plastic bags generally yield better scores on several environmental indicators than paper bags, this finding: (1) depends on a variety of factors and cannot necessarily be extended to other products where paper can be used as a replacement for plastic, such as cups and plates or other food packaging applications; and (2) except in a few studies, does not include any consideration of material littering. Moreover, the key attribute–light weight–that generally yields favorable scores for plastic bags on indicators such as climate change also significantly increases the likelihood of abandonment in the environment. No assessment was made of the actual effects of various materials abandoned in the environment on human health, wildlife, and ecosystems in the current literature.

Specific findings of NCASI's review of LCAs comparing paper and plastic in various applications are summarized here.

- In most published LCA studies, paper shopping bags showed higher environmental indicator scores (i.e., lower environmental performance) than single-use plastic bags for several impact categories[1] including climate change, eutrophication, and acidification. However, literature shows that paper bags can perform better than plastic bags for the climate change impact category if the plastic bag is heavy, the paper mill producing the product uses primarily renewable fuels, the paper bag is reused multiple times, and/or the waste bag is burned with energy recovery rather than deposited in a landfill. In addition, LCA studies made different assumptions about relative volumes and weights of merchandise that consumers pack into paper and plastic bags of identical volumetric size. For identical volumetric bag sizes, if consumers were to pack greater volumes of merchandise into paper bags than into plastic bags, LCA results would show a reduction in the relative environmental benefits of single-use plastic bags. Therefore, the different assumptions used in these LCA studies have a direct impact on the results of the studies. Finally, findings from this literature review demonstrated that in cases where LCA showed that paper bags had a higher climate change indicator score (i.e., worse performance) than plastic bags, the magnitude of the differences was very small in relation to total US greenhouse gases (GHGs). Specifically, replacing 998 million kg of paper bags with a functionally equivalent amount of plastic bags would decrease US GHG emissions by 0.01 to 0.05% if applying results of existing US LCA studies.
- Findings from LCAs comparing bags from various materials cannot necessarily be generalized to other applications (e.g., cups and plates, food packaging) in which paper can be used as a replacement for plastic.

[1] An impact category is a representation of an environmental issue of concern for which an LCA indicator exists (adapted from ISO 2006).

- The relative weight of paper and plastic products (weight ratio) is an important driver for several LCA indicators including climate change, fossil fuel consumption, particulates, ozone depletion, and eutrophication. There may be other significant drivers explaining the results for some indicators, such as the types of paper and plastic compared, the choice of impact assessment method, end-of-life assumptions, and so on. These other drivers were not studied in detail in NCASI's review.
- Some applications with paper to plastic weight ratios below 1.5 showed at least equivalent environmental performance for paper compared to plastic in many scenarios and for several LCA indicators. Specifically, use of paper instead of plastic in cups and plates and in food packaging applications had better indicator scores for fossil fuel consumption, acidification, and photochemical oxidation indicators. In many cases paper showed better results than plastic for the climate change indicator for weight ratios up to 3.0.
- The ozone depletion indicator rarely shows environmental benefits from paper over plastic, irrespective of the weight ratio.
- Results for acidification, eutrophication, water use, and water consumption indicators are mixed and indicate that the relative environmental performance of paper compared to plastic probably depends on a variety of factors.
- Data used in most studies, even the most recent ones, are very old. Improvements in the environmental performance of paper mills in the last 15 or 20 years are not reflected in these results. However, facilities producing plastic have probably also improved their performance in that period, making it difficult to assess the effect of old data on the relative environmental performance of paper versus plastic.
- Littering was an environmental issue considered in only a few LCA studies and only for shopping bag applications. All LCA studies that included a qualitative or quantitative evaluation of the environmental risk of abandoning the product in the environment (i.e., littering) showed significantly less littering risk from paper than from plastic. However, the literature lacks a reliable and robust indicator for littering. Indeed, littering indicators included in LCA studies were limited to an evaluation of the risk of the material ending up in the environment and not being biodegraded. No assessment was made of the actual effects on human health, ecosystems, or wildlife of materials abandoned in the environment. Application of the proposed indicators in these LCA studies used a conservative approach that considers that 1 kg of paper left in the environment and not biodegraded would have the same effect as 1 kg of plastic. This suggests a need for further research to explore these issues.

KEYWORDS
LCA, life cycle assessment, litter, paper products, plastic products

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REVIEW OF LIFE CYCLE ASSESSMENTS COMPARING PAPER AND PLASTIC PRODUCTS

1.0 INTRODUCTION

With recent anti-plastic campaigns oriented towards reducing ocean pollution, paper products are increasingly viewed as a replacement because of their biodegradability. At the same time, it is commonly believed that life cycle assessments (LCA) show plastic to have a lower footprint than paper on several environmental indicators. Because of this perceived overall environmental performance when proposed as an alternative to plastic, the paper sector is at risk of being seen as a less favorable replacement. This report investigates the extent to which plastic has a better overall environmental footprint than paper using three steps:

1) synthesizing the findings of a study published by the United Nations Environment Programme (UNEP) and the UNEP-hosted Life Cycle Initiative to provide “guidance to policy makers and other actors on how to interpret results from comparative LCAs on shopping bags” and to “summarize what can be concluded on the environmental drawbacks and benefits of single-use plastic bags (SUPBs), compared to other bags, based on existing LCAs” (UNEP 2020);
2) evaluating weight ratios (WR, Section 3.1) for which paper would show an equivalent or better LCA environmental performance than plastic for a variety of applications including shopping bags (grocery or others), cups and plates, food packages (e.g., trays, egg cups), beverage containers, and other; and
3) summarizing methods used in LCA for assessing marine litter as well as how paper products compare with plastic products when applying those methods.

2.0 UNITED NATIONS ENVIRONMENT PROGRAMME STUDY ON SHOPPING BAGS

UNEP (2020) sponsored a meta-analysis of seven LCAs (Khoo and Tan 2010; Khoo et al. 2010; Edwards and Meyhoff Fry 2011; Mattila et al. 2011; Muthu et al. 2011, 2012; Kimmel 2014; Civancik-Uslu et al. 2019; COWI A/S and Utrecht University 2019) comparing SUPBs to alternatives. These alternatives included bags made from other materials (such as paper, textile, bioplastics, composite), as well as bags made from plastics with higher durability and/or greater thickness. Evaluated studies represented various geographic contexts including Spain, Europe, United States, United Kingdom, Hong Kong, China, India, Finland, and Singapore.

One of the main findings of the UNEP meta-analysis comparing plastic bags to paper bags was that in most cases paper bags showed higher (i.e., “worse”) LCA indicator scores than SUPBs for several impact categories including climate change, eutrophication, and acidification. However, some studies showed that paper bags could be better than SUPBs for the climate change indicator if the plastic bag is heavy, the paper mill producing the product uses mostly renewable fuels, the paper bag is reused multiple times, and/or the waste bag is burned rather than deposited in a landfill. More specifically:

- The weight of the bag was shown to be an important driver in terms of relative environmental performances of the different bags. The meta-analysis showed that typical SUPBs weigh approximately 6 g in China, India, Singapore, and the US, but 18 to 20 g in Finland, Spain, and the UK. In contrast, the weight of the paper bag is almost the same in all the studies, at approximately 55 g (which results in a paper-to-plastic WR from 2.8 to 9.2).
- Energy used in production of paper bags can have a significant effect on reported environmental performance. For instance, the UNEP report indicated that "*the climate impact of paper bags varies greatly, depending on what fuel is used in the pulp and paper production*."
- The waste management process is also an important factor affecting environmental performance of paper and plastic bags. The UNEP report noted that "*paper bags that end up in landfills cause emissions of methane with high climate change effect, while plastic bags are relatively inert. On the other hand, incineration of used plastic bags affects the climate through emissions of fossil carbon dioxide (CO_2), while the CO_2 emitted from incineration of paper bags is part of the natural carbon cycle*."
- While the meta-analysis showed that SUPBs score poorly in terms of marine litter and microplastics, they score relatively well compared to alternatives, including paper, in other environmental impact categories such as climate change, acidification, eutrophication, water use, and land use. However, the relative environmental performance of paper bags improves significantly when compared to heavy SUPBs and/or if production of paper bags uses mainly renewable fuels and/or if paper bags are burned with or without energy recovery instead of being landfilled.
- The number of times a bag can be reused is a critical parameter affecting the environmental performance of a given type of bag.

In addition, the UNEP report mentioned that there are several impacts of littering, including visual impacts, physical impacts on animals, and the impacts of microplastics in the environment. The report underlined that while assessment of littering potential in LCA is still under development and only a minority of the reviewed studies addressed littering potential, results of those studies show that SUBPs rank worst in terms of littering potential.

3.0 WEIGHT RATIO ANALYSIS

3.1 Characterization of Literature Reviewed

NCASI compiled information on WRs for different applications where both paper and plastic can be used, under the assumption that the main driver for results of LCAs comparing paper products with plastic alternatives was the relative weight of the materials. Literature was limited to studies that could be easily found and obtained in English and in French. NCASI focused on single-use applications that were classified into these categories: shopping bags (grocery or other); cups and plates; food packaging (e.g., trays, egg cups); beverage containers; and other (e.g., shipping packages, envelopes). Reusable consumer products were not included in the analysis. Applications for which the paper-based or plastic-based product would be made from a combination of several materials, including both paper and plastic (hence making it difficult to discuss the environmental score of paper versus plastic), were also excluded. An example of one excluded study is that undertaken by Markwardt et al. (2017) that compared Tetra Pak® carton packages to alternatives. Finally, if a given study had been updated, only the most recent version was included.

Table 1 presents an overview of the studies included in this report. The table shows that the data in most studies, even the most recent ones, are very old. Thus, improvements in the environmental performance of paper mills in the last 15 or 20 years are not reflected in the results. For example, based upon information from the US Environmental Protection Agency's (EPA) Greenhouse Gas (GHG) Reporting Program (USEPA 2020a, 2020b), the US Energy Information Administration (EIA) Manufacturing Energy Consumption Surveys (USEIA 2005, 2009, 2013, 2017), and the Food and Agriculture Organization (FAO) of the United Nations (FAO 2019), NCASI estimates that there has been a decrease in direct GHG emission intensity of approximately 30% between 2002 and 2017 for the US pulp and paper industry. However, facilities producing plastic have probably also improved their performance during that same period, making it difficult to assess the effect of old data on the relative environmental performances of paper versus plastic.

Table 1 also presents functional unit considerations that are especially important in the case of shopping bags. This is discussed further in Section 3.3.1.

Table 1. Characteristics of Studies Reviewed

Author(s)	Materials Compared		Geography	Age of Data[a]		Functional Unit (FU) Considerations
	Paper	Plastic		Paper	Plastic	
Shopping Bags						
Bisinella et al. 2018[b]	Unbleached kraft paper	Virgin LDPE, recycled LDPE (both thick bags)	Europe	Probably older than 2000	Probably older than 2000	The FU was to carry 22 L or 12 kg of groceries; the number of bags needed was adjusted accordingly. For example, a paper bag was assumed to have a volume capacity of 23 L and a weight carrying capacity of 12 kg; to account for relative uncertainty, it was assumed that two paper bags would be needed.
Chaffee and Yaros 2007	Unbleached kraft paper w/ 30% RC	HDPE	US	Older than 2003	Older than 2003	The study compared the number of bags needed for a typical grocery trip. It was assumed that 1.2 1/6th barrel plastic bags would be needed to carry the same amount of groceries as 1 1/7th barrel paper bag.
CIRAIG 2017	Unbleached kraft paper	HDPE (thin bags), LDPE (thick bags)	Quebec	2006	2002-2004	The study looked at two FUs, one in which a single bag would be needed irrespective of its size (e.g., if you stop by a convenience store to purchase a few items) and one in which several bags would be used and where the size of the bags would influence how many would be needed. In the second case, the volume of the paper bags was greater than that of the plastic bags, so fewer bags were required for the same FU.
Civancik-Uslu et al. 2019	Recycled paper	HDPE	Spain	Older than 2008	Older than 2005	The FU was related to one year's groceries on a per volume and mass basis. Despite having greater volume, it was assumed that the same number of paper bags would be required as plastic bags based on the assumption that paper bags would have lower weight-carrying capacity.
Edwards and Meyhoff Fry 2011	Average of unbleached kraft and bleached kraft paper	HDPE	UK	2003	Older than 2005	The FU was related to one month's groceries on a number-of-items basis. The number of bags needed for each material was based on their volume as well as consumer behavior regarding how many items can be placed in each bag type. Although the paper bag's volume was 5% more than that of the plastic bag, the study assumed that 20% fewer paper bags would be needed.

(Continued on next page. See notes at end of table.)

Table 1. Cont'd

Author(s)	Materials Compared		Geography	Age of Data[a]		Functional Unit (FU) Considerations
	Paper	Plastic		Paper	Plastic	
Shopping Bags (continued)						
Kimmel 2014	Unbleached kraft paper w/ 40% RC, recycled paper	HDPE, HDPE w/ 30% RC	US	Older than 2006	Older than 2000	This study looked at various FUs. The number of bags needed was determined based on the perceived capacity of a bag from a weight perspective (determined via survey). It was assumed that 15% fewer paper bags than plastic bags were needed.
Muthu et al. 2011, 2012	Unbleached kraft paper	HDPE or LDPE	China, Hong Kong, India	Older than 2004	Older than 2004	The FU was related to one year's groceries. The authors assumed that plastic and paper bags were directly comparable, with no discussion as to their volumes.
PwC/ Ecobilan 2004	Recycled paper[c]	HDPE	France	2000	Older than 2003	The FU was related to one year's groceries on a volumetric basis. The number of bags needed for each material was based on their respective volumetric carrying capacities.
Verghese et al. 2009	Unbleached kraft paper	HDPE, HDPE w/ 15% RC	Australia	Older than 2007	Older than 2007	The FU was related to one year's groceries on a number-of-items basis. Paper bags were assumed to have a carrying capacity of 90% that of plastic bags, even though their volumetric carrying capacity was 27% less.
Beverage Containers						
FAL 2006	Bleached kraft paperboard	PET	US/Canada	Older than 2003	Older than 2003	A FU of equivalent volume (1000 L) was chosen for this analysis.
FAL 2008	Bleached kraft paperboard	PLA/HDPE	US	Older than 2003	HDPE: Older than 2003; PLA: 2006	A FU of equivalent consumer use (10,000 containers, all containers contain equivalent milk amounts) was chosen.

(Continued on next page. See notes at end of table.)

Table 1. Cont'd

Author(s)	Materials Compared		Geography	Age of Data[a]		Functional Unit (FU) Considerations
	Paper	Plastic		Paper	Plastic	
Cups and Plates						
FAL 2011	PE-coated paperboard, wax-coated paperboard	EPS, GPPS	US	Probably older than 2003	PLA: 2004-2005; others: 2000-2003	Cups were compared based on the same volumetric capacity. Plates were compared based on the same diameter.
Ligthart and Ansems 2007	PE-coated paperboard[d]	Mix of GPPS and HIPS	Europe	1998-2002	1999-2002	Cups were compared based on the same volumetric capacity.
Pro.mo 2015	PE-coated paperboard	PP, PLA	Belgium	2004	PP: 2000-2005; PLA: 2004-2005	Cups were compared based on the same volumetric capacity.
Pro.mo 2015	Cellulose pulp[e], PE-coated paperboard	PP, GPPS, HIPS, PLA	Europe	Cellulose pulp: 1993-2001 PE-coated paperboard[f]: 1998-2002	PLA: 2004-2005, others: 1999-2002	Cups were compared based on the same volumetric capacity. Plates were compared based on a number-of-plates basis.
Food Packaging						
Belley 2011	Recycled molded pulp	EPS, OPS w/ 10% RC, PET w/ 10% PET, rPET, PLA w/ 10% RC, PP w/ 10% RC	Quebec	Older than 2011	PLA: 2004-2005; others: 1999-2002	Food trays were compared based on the same volumetric capacity.

(Continued on next page. See notes at end of table.)

Table 1. Cont'd

Author(s)	Materials Compared		Geography	Age of Data[a]		Functional Unit (FU) Considerations
	Paper	Plastic		Paper	Plastic	
Others						
Evrard et al. 2019; support wires	Unbleached kraft paper	PP	France	Unknown	Unknown	The FU was based on the amount of supporting wire needed to support a plant over the growing season. Paper and plastic were compared based on the same length of material.
FAL 2004; delivery package	Containerboard, bleached kraft paper, bleached kraft paper w/ 30% RC	LDPE	US	1990-1997	1990-1997	The FU was based on packaging a given number of representative packages of soft goods items.
Schnabl and Siegrist 2014; layer pads for glass containers	Containerboard	PP	European	Unknown	Unknown	The FU was based on the same surface area of layer pad.
Yi et al. 2017; delivery package	Containerboard	Unspec-ified	China	Unknown	Unknown	The definition of the FU was not transparent. Authors assumed it would take 160 g of corrugated box to perform the same as 10 g of plastic bag.

EPS: expanded polystyrene; GPPS: general purpose polystyrene; HDPE: high density polyethylene; HIPS, high impact polystyrene; LDPE: low density polyethylene; OPS: oriented polystyrene; PET: polyethylene terephthalate; PLA: polylactide; PP: polypropylene; RC: recycled content; rPET: 100% recycled polyethylene terephthalate

[a] paper and plastic production only

[b] used consequential LCA framework

[c] authors used recycled linerboard as a proxy for recycled bag paper

[d] authors used liquid packaging board as a proxy

[e] authors used thermochemical pulp data as a proxy, which is questionable given that cellulose pulp is more likely to be made of kraft pulp, as recognized by authors

[f] authors used liquid packaging board as a proxy but modified it by removing aluminum and glue components (not present in the cup) and increasing polyethylene content to 10%

3.2 Calculation of Weight Ratios

WRs were calculated as:

$$WR = \frac{W_{Paper}}{W_{Plastic}}$$

where W_{Paper} is the weight of paper needed to fulfill the same function[2] as a plastic product of weight $W_{Plastic}$

After compiling information on WRs, NCASI correlated these WRs with the relative indicator scores (RIS) of paper and plastic alternatives for each of the impact categories for which sufficient data were available.

3.3 Distribution of Weight Ratios by Application

3.3.1 Shopping Bags

Figure 1 shows WRs found in the literature for shopping bags (PwC/Ecobilan 2004; Chaffee and Yaros 2007; Verghese et al. 2009; Edwards and Meyhoff Fry 2011; Muthu et al. 2011, 2012; Kimmel 2014; CIRAIG 2017; Bisinella et al. 2018; Civancik-Uslu et al. 2019). Some authors included more than one scenario for paper vs. plastic products; hence, the same author may be listed several times in the figure.

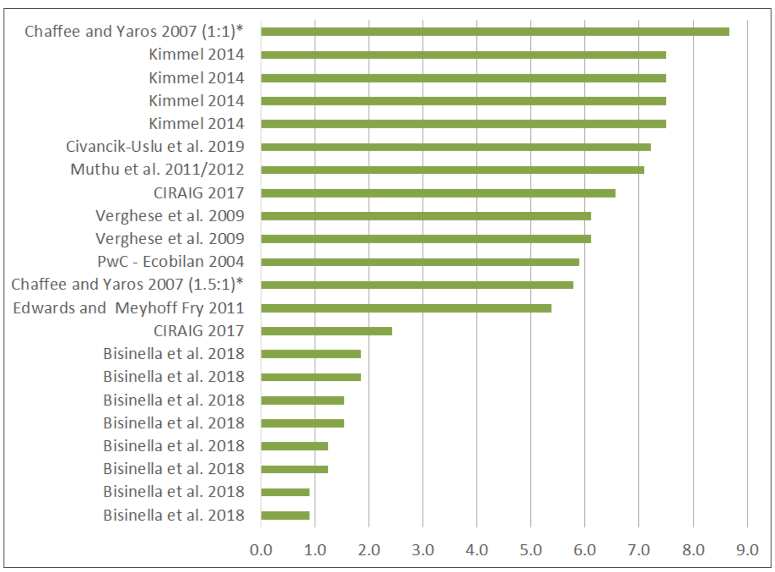

Figure 1. Weight Ratio Distribution for Shopping Bags

[*Chaffee and Yaros (2007) looked at effects of different assumptions regarding the number of plastic bags of the same volume needed to achieve the same functional unit as a paper bag: 1:1 and 1:1.5 ratios]

[2] LCA requires that products be compared only if they are functionally equivalent. The weight of plastic bags needed to carry an equivalent amount of merchandise (the function) is typically lower than that of paper bags; however, these different weights of plastic and paper bags are functionally equivalent when used to carry the same amount of merchandise.

With the exception of Bisinella et al. (2018), all authors showed WRs between 5 and 9, meaning that typically it takes 5 to 9 times more paper on a mass basis to achieve the same function as a plastic bag. Two main factors explain the difference in the WRs observed: the thickness of the plastic bag (the thicker the bag, the smaller the WR) and the assumption regarding the number of paper and plastic bags needed to achieve the same functional unit. Three components affect the number of paper and plastic bags needed to fulfill the same function:

- the actual size of the bag (volume);
- its weight-carrying capacity; and
- consumers' behavior in terms of the volume of merchandise they put into bags of the same size but of different material.

Chaffee and Yaros (2007) assumed that 1 to 1.5 plastic bags would be needed to pack the same volume of merchandise as 1 paper bag of an identical size, although they noted that some studies they reviewed showed that up to 3 plastic bags would be needed. Several studies ignored differences in merchandise volumes that could be placed in paper and plastic bags of the same size. Others assumed, with little justification, that more paper bags than plastic bags of the same size would be needed because of their perceived weight-carrying capacity (e.g., Bisinella et al. 2018). Assuming that paper bags offer more packaging space than plastic bags of the same size would significantly reduce the relative environmental benefits of SUPBs.

All shopping bag comparisons involved bleached or unbleached kraft paper with 0% to 100% recycled content and plastic bags made of either low-density or high-density polyethylene.

3.3.2 Beverage Containers

Only two studies comparing materials for beverage containers were evaluated (FAL 2006, 2008). In those studies, WRs for paper to plastic varied from 0.5 to 1.5.

3.3.3 Cups and Plates

Figure 2 shows WRs found in the literature for cups and plates (OVAM 2006; Ligthart and Ansems 2007; FAL 2011; Pro.mo 2015). WRs varied from 1.0 to 4.1 depending on the type of paper and plastic being compared. The highest WR (4.1) was for polyethylene-coated paperboard cups with a containerboard sleeve, which have been compared to expanded polyethylene.

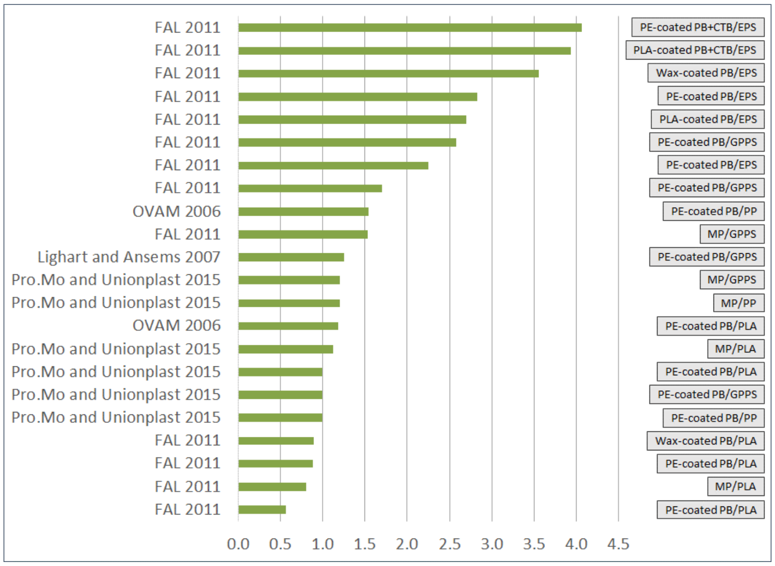

Figure 2. Weight Ratio Distribution for Cups and Plates

[PE: polyethylene (low density); PB: paperboard; CTB: containerboard sleeve; EPS: expanded polystyrene; GPPS: general purpose polystyrene; MP: molded pulp; PP: polypropylene; PLA: polylactic acid]

3.3.4 Food Packaging

Figure 3 shows WRs found in the literature for food packaging systems, including food trays, clamshells, egg packaging, and strawberry punnets/clamshells (Zabaniotou and Kassidi 2003; Singh and Krasowski 2010; Belley 2011; FAL 2011). WRs varied from 0.4 to 2.1 depending the type of paper and plastic that were compared, with most of the highest WRs observed for comparison with polystyrene.

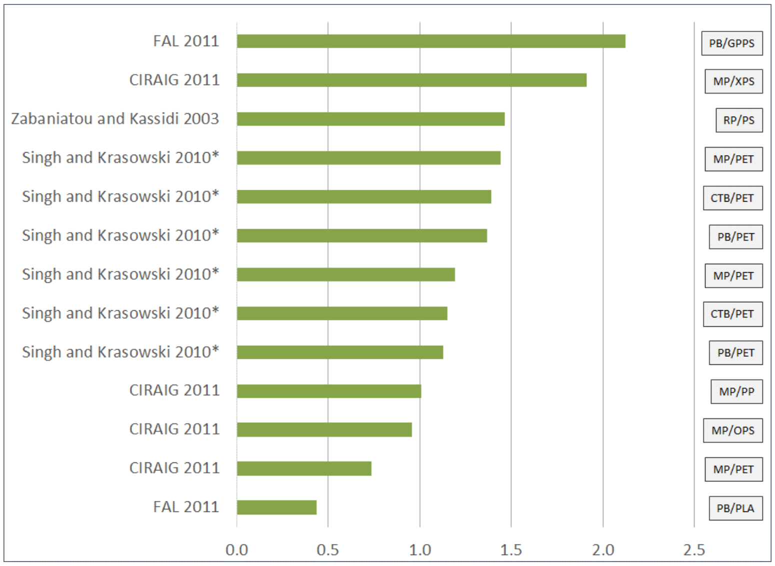

Figure 3. Weight Ratio Distribution for Food Packaging
[CTB: containerboard; GPPS: general purpose polystyrene; MP: molded pulp; XPS: extruded polystyrene; RP: recycled paper; PS: unspecified polystyrene; PET: polyethylene terephthalate; OPS: oriented polystyrene.*Several scenarios (e.g., recycled content or material used for pillow wrap) of the same material combinations with the same WR only depicted once.]

3.3.5 Other Applications

Figure 4 shows WRs found in the literature for other applications of paper and plastic. Yi et al. (2017) compared a plastic bag to a corrugated box (WR=16.0). Franklin Associates (FAL 2004) compared various delivery systems, including corrugated boxes and plastic bags (WR=11.9 and 23.1) and kraft paper shipping bags and plastic bags (WR=1.7 and 3.2). Schnabl and Siegrist (2014) compared corrugated and polypropylene layer pad options for glass container transport (WR=7.8). Evrard et al. (2019) compared kraft paper and polypropylene support wires for tomato farming (WR=2.5).

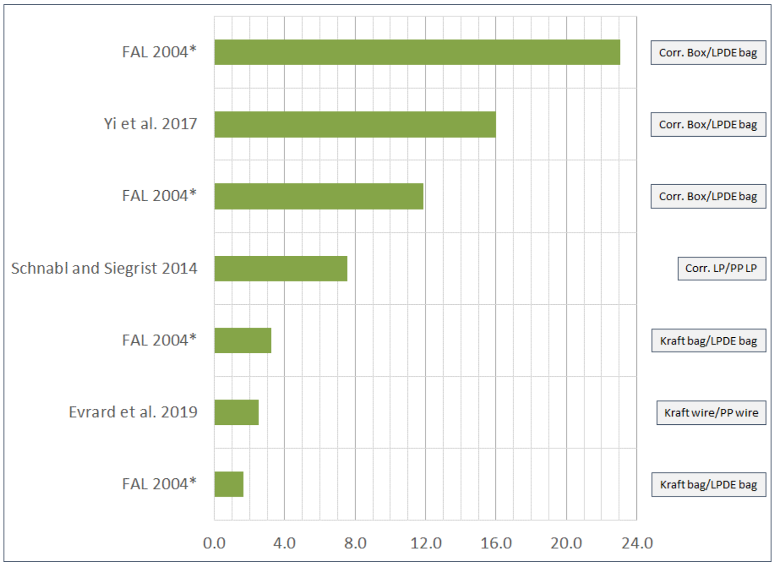

Figure 4. Weight Ratio Distribution for Other Applications
[Corr: corrugated; LPDE: low density polyethylene; LP: layer pad; PP: polypropylene. *Several scenarios of the same material combinations with the same WR only depicted once.]

3.4 Relationship between Weight Ratios and Relative Indicator Scores

NCASI investigated the relationship between the RIS of paper compared to plastic and the WRs. For each LCA impact category (i), the RIS_i is calculated as the ratio of the indicator score for paper ($IS_{i,Paper}$) to that of plastic ($IS_{i,Plastic}$):

$$RIS_i = \frac{IS_{i,Paper}}{IS_{i,Plastic}}$$

Interpretation of relative environmental indicator scores is presented in Table 2.

Table 2. Interpretation of Relative Life Cycle Assessment Indicator Score

RIS	Interpretation
RIS < 1	IS of paper is lower than that of plastic: paper performs better than plastic for that specific LCA indicator
RIS = 1	IS of paper is the same as that of plastic: paper and plastic perform equally for that specific LCA indicator
RIS > 1	IS of paper is higher than that of plastic: plastic performs better than paper for that specific LCA indicator

In cases where the same study applied more than one life cycle impact assessment method (one as primary and another as a sensitivity analysis), only results from the primary method were analyzed unless an environmental indicator was covered only in the sensitivity analysis.

Although listed for documenting WRs, the study by Bisinella et al. (2018) was excluded from analyses in this section because it was the only one that used a consequential LCA approach. That choice was found to have greater influence on results than the actual WRs. Results from the study are presented in Section 3.6.

3.4.1 Energy-Related Indicators (Global Warming, Fossil Fuels, and Total Energy)

Figure 5 shows that there is an important correlation between WR and global warming and total energy indicator scores, and some correlation between WR and fossil fuel indicator scores. One factor explaining the lower correlation with fossil fuel indicator scores is that a significant share of energy use in paper production is from biomass fuels.

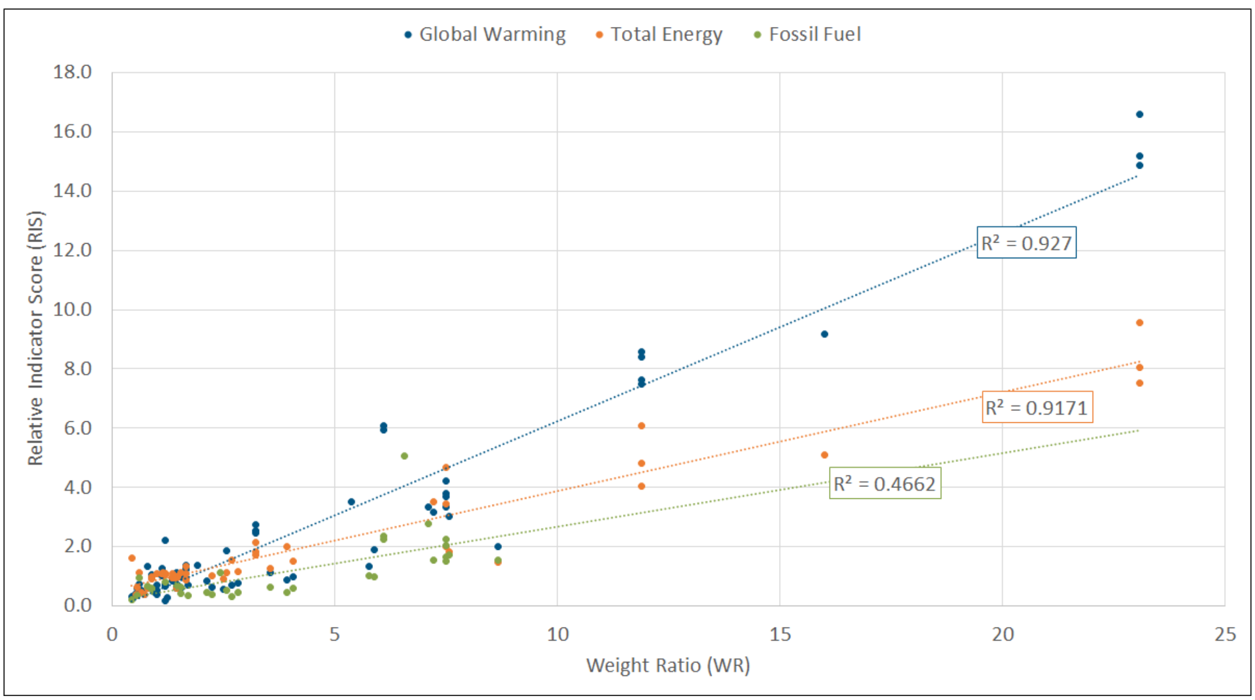

Figure 5. Overall Correlation between Energy-Related Life Cycle Assessment Indicator Scores and Weight Ratios

Figure 6 shows that for most applications for which WR is ≤1.1, paper performs at least as well as plastic in terms of global warming, fossil fuel, and total energy LCA indicators. Applications with WRs <1.1 include wine containers (FAL 2006), some milk containers (FAL 2008), some cups and plates (Pro.mo 2015), and some food trays (Belley 2011).

In several cases, paper shows a lower or equal indicator score than plastic for WRs between 1.1 and 2.9. This includes some cups and plates (OVAM 2006; Ligthart and Ansems 2007; Pro.mo 2015) and some food packaging applications (Singh and Krasowski 2010).

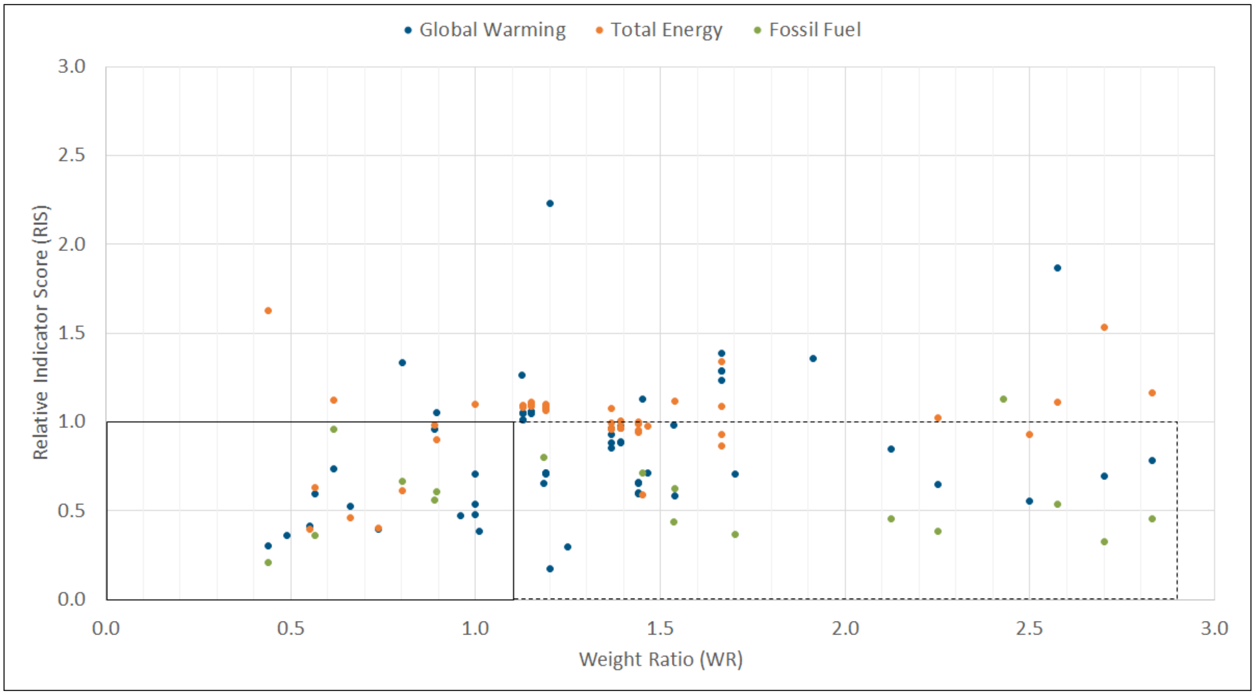

Figure 6. Correlation between Energy-Related Life Cycle Assessment Indicator Scores and Weight Ratios: Identification of Weight Ratios for which Relative Indicator Score is ≤1

3.4.2 Acidification

Figure 7 shows moderate correlation between RIS for the acidification indicator and WRs if all data points are considered but would show little correlation if what appears to be an outlier was removed. Some but not all cup and plate applications with WRs between 1 and 1.5 show lower (i.e., "better") indicator scores for paper than for plastic alternatives. Literature indicated that for the acidification impact category, use of paperboard for cups and plates might result in a lower or equivalent indicator score than polypropylene, polystyrene, and polylactic acid, but use of molded pulp for the same purpose might not (Ligthart and Ansems 2007; Pro.mo 2015). This finding is not generalized, however. For instance, OVAM (2006) showed that use of paperboard for cups and plates resulted in a higher (i.e., "worse") indicator score than polypropylene. Zabaniotou and Kassidi (2003) showed a lower indicator score for recycled paper than for polystyrene used in egg packaging. Despite a higher WR, Kimmel (2014) showed a lower indicator score for 100% recycled paper bags compared to plastic bags, but this result was obtained by giving significant credit to recycled paper for avoiding use of virgin material, an LCA allocation method that is debatable (NCASI 2012).

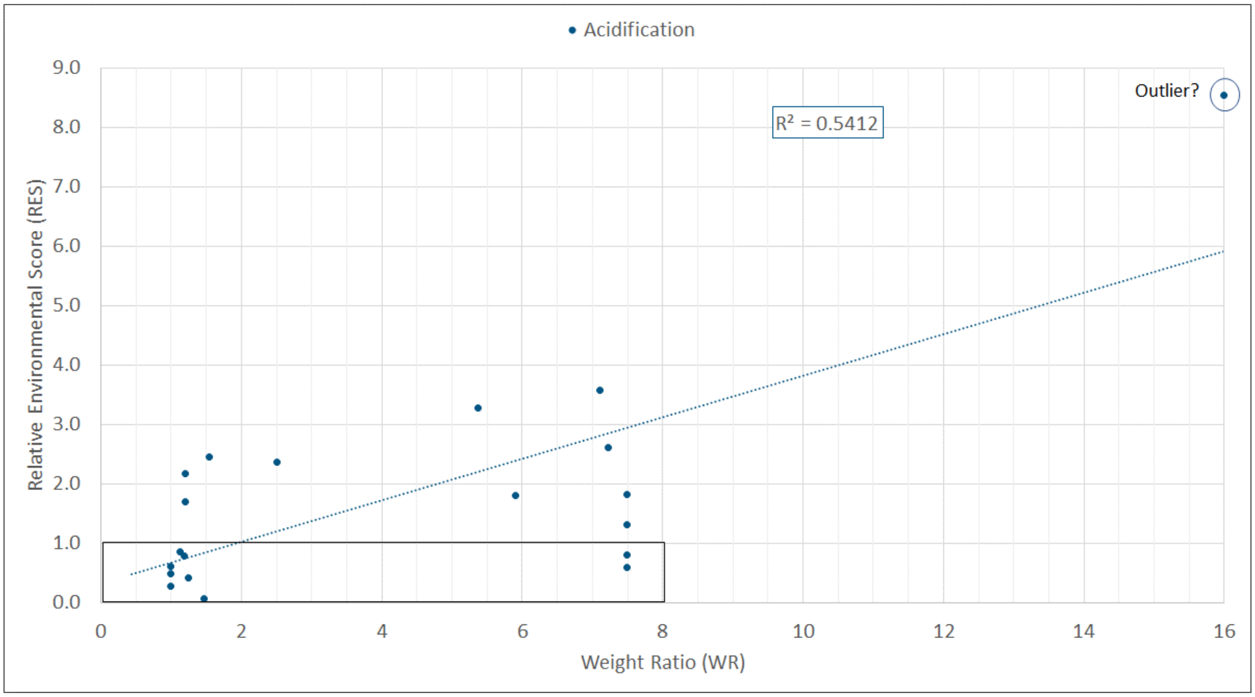

Figure 7. Overall Correlation between Acidification Indicator Scores and Weight Ratios: Identification of Weight Ratios for which Relative Indicator Score is ≤1

3.4.3 Photochemical Oxidation (Smog)

Figure 8 shows moderate correlation between photochemical oxidation indicator scores and WRs. In several cup and plate applications with WRs between 1.3 and 1.5, paper alternatives showed lower (i.e., "better") indicator scores than plastic ones (OVAM 2006; Ligthart and Ansems 2007; Pro.mo 2015). Other applications in which paper showed lower indicator scores than plastic include egg packaging (WR=1.5; Zabaniotou and Kassidi 2003), some shopping bags for which thicker plastic is used (WR=0.9; Bisinella et al. 2018), and one case of a shopping bag where paper was compared to thinner plastic bags (WR=5.9, PwC/Ecobilan 2004). Figure 8 does not include one outlier data point from Yi et al. (2017) that showed a score 250 times greater for corrugated boxes than for a plastic shipping bag. The authors indicated that this score was driven mainly by incineration of boxes at their end-of-life, which is not very common in North America (e.g., NCASI 2017).

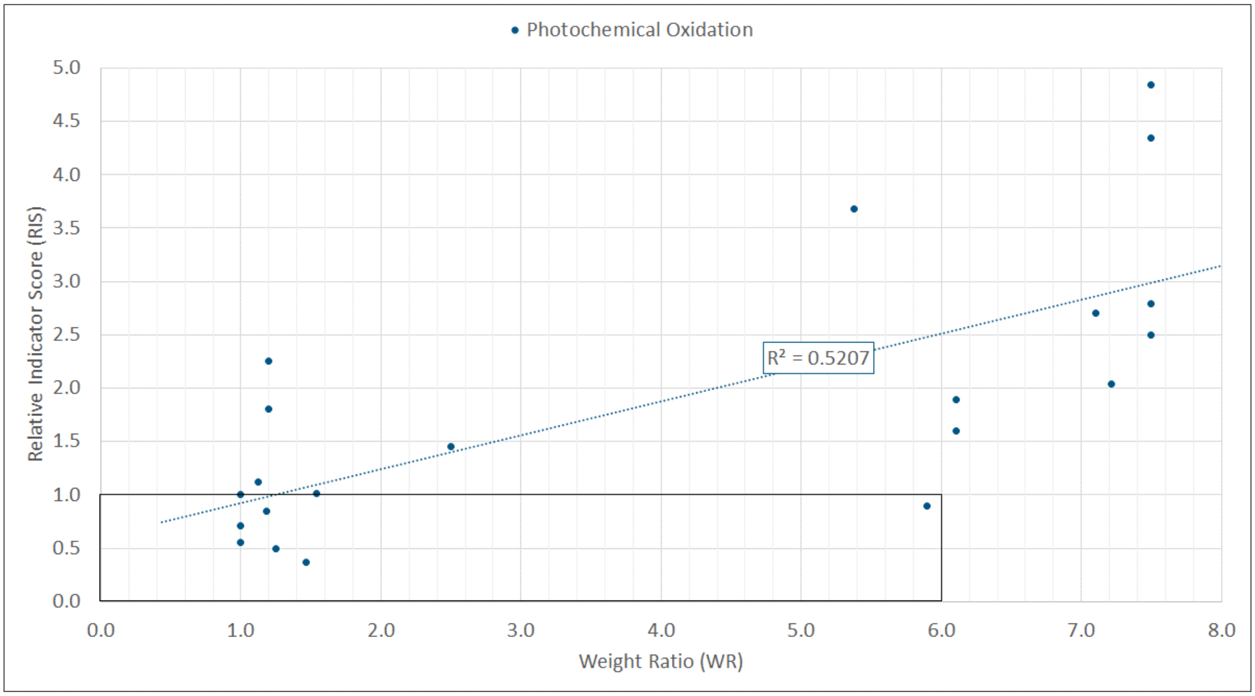

Figure 8. Overall Correlation between Photochemical Oxidation Indicator Scores and Weight Ratios: Identification of Weight Ratios for which Relative Indicator Score is ≤1

3.4.4 Particulates

Figure 9 shows relatively strong correlation between WRs and indicator scores for particulates. However, as depicted in Figure 10, it is not possible to identify a WR below which paper systematically performs at least as well as plastic. Instead, it seems that specific applications achieve this result:

- WRs below 1.5: PE-coated paperboard cups compared to PLA cups (Pro.mo 2015); and
- WRs between 5 and 8: 100% recycled paper bags compared to HDPE bags (PwC/Ecobilan 2004; Kimmel 2014).

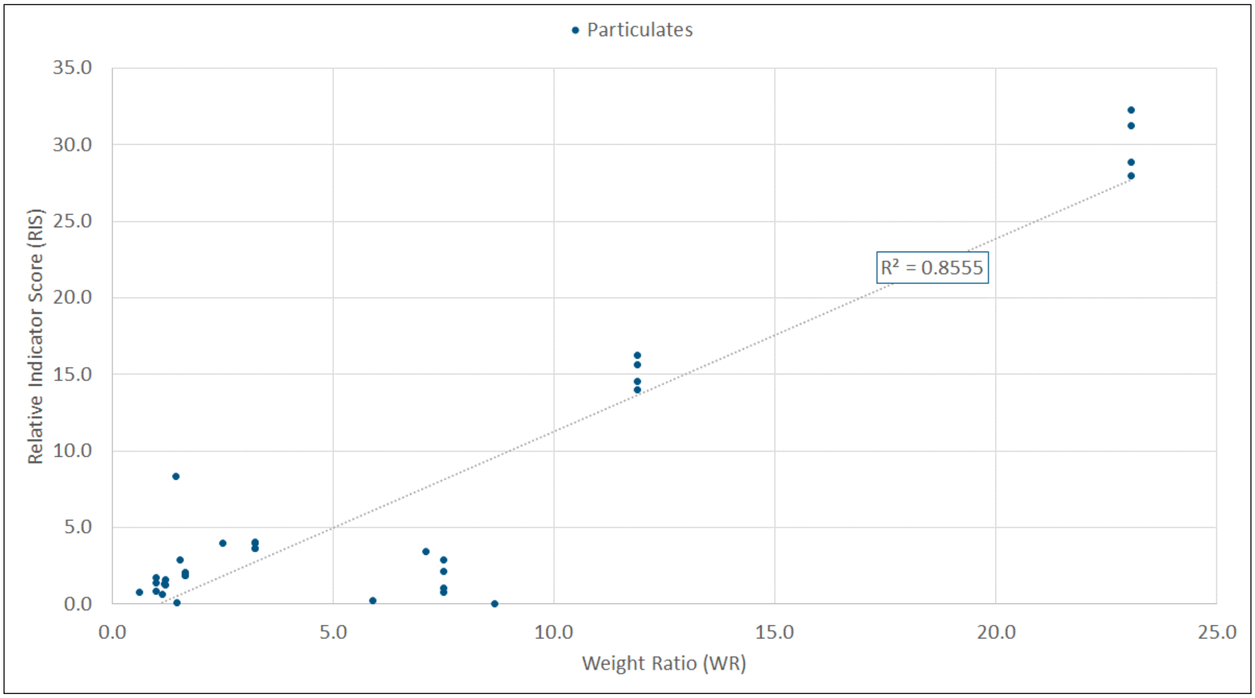

Figure 9. Overall Correlation between Particulates Indicator Scores and Weight Ratios

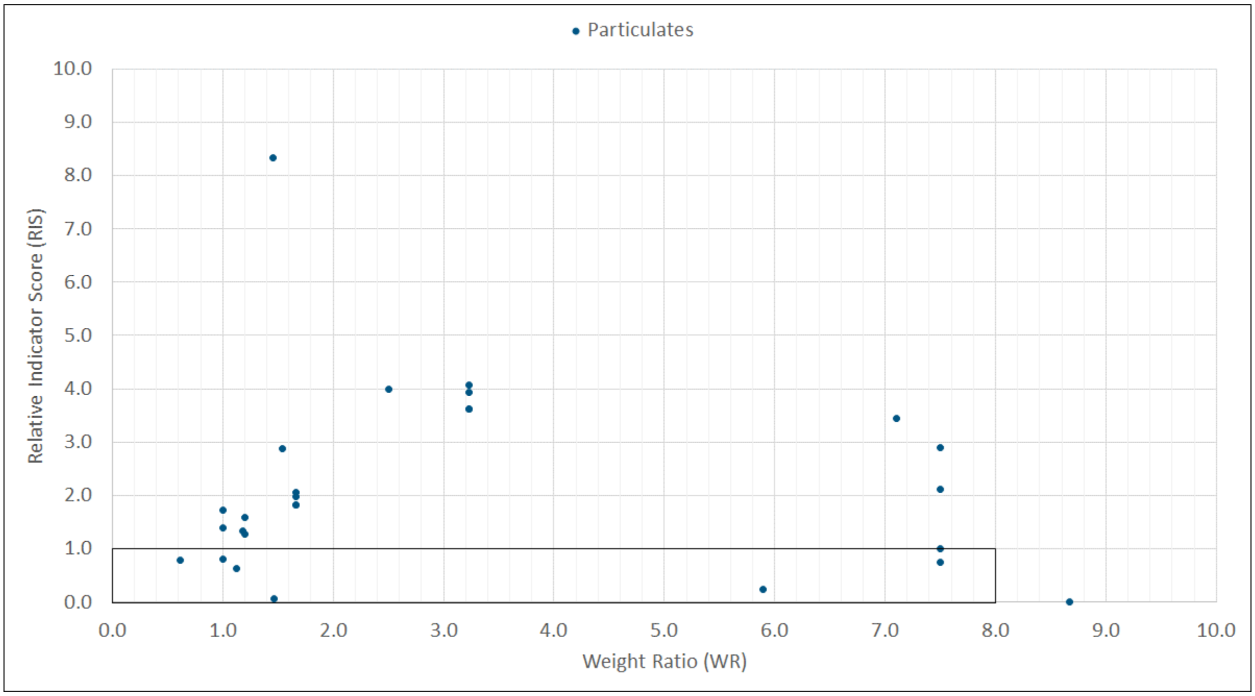

Figure 10. Correlation between Particulates Indicator Scores and Weight Ratios: Identification of Weight Ratios for which Relative Indicator Score is ≤1

3.4.5 Ozone Depletion

Fewer studies reported ozone depletion results; therefore, the correlation analysis discussed herein needs to be interpreted with care. However, with the exception of one result reported by Ligthart and Ansems (2007), there seems to be reasonable correlation between WRs and ozone depletion indicator scores (Figure 11). Interestingly, Ligthart and Ansems (2007) reported that the conversion process (i.e., transforming paperboard into cups) contributes the most to ozone depletion indicator results, without providing further transparency about the associated cause. This is, therefore, difficult to explain. For instance, NCASI (2017) showed that containerboard production was contributing to 90% of ozone depletion indicator results for the LCA of a corrugated product (box) versus 9% for box production.

Figure 12 shows that despite the WR, in most cases paper showed a higher (i.e., "worse") indicator score than plastic for the ozone depletion indicator. Only one case where paper resulted in a lower environmental score than plastic (Zabaniotou and Kassidi 2003) was found.

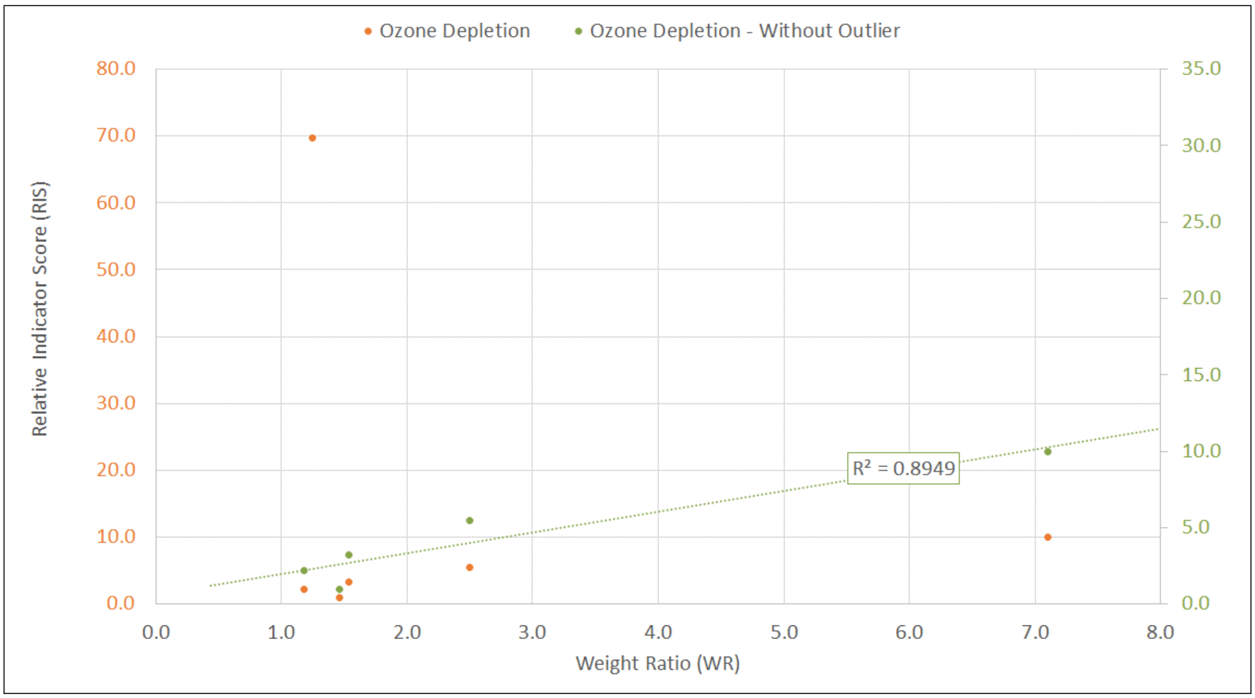

Figure 11. Overall Correlation between Ozone Depletion Indicator Scores and Weight Ratios

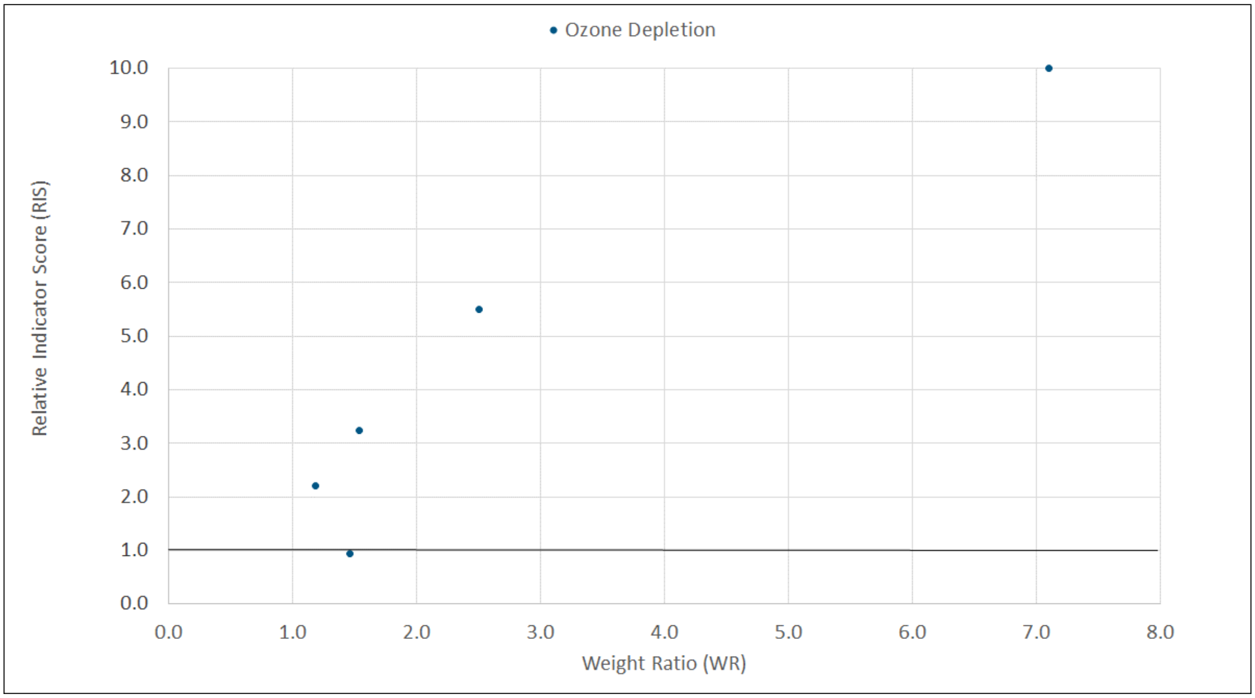

Figure 12. Correlation between Ozone Depletion Indicator Scores and Weight Ratios: Identification of Weight Ratios for which Relative Indicator Score is ≤1

3.4.6 Eutrophication

Figure 13 shows the correlation between WRs and indicator scores for water eutrophication impact categories. Reasonable correlation is observed for marine water indicator scores, with relatively low correlation for freshwater eutrophication indicator scores, indicating that other factors are driving results for the latter.

For the freshwater and marine eutrophication impact categories, Figure 14 shows that it is not possible to identify a WR below which paper would systematically perform better than plastic, but some applications at WRs up to 1.47 do so. These include some cups and plates (Pro.mo 2015) and egg cups (Zabaniotou and Kassidi 2003).

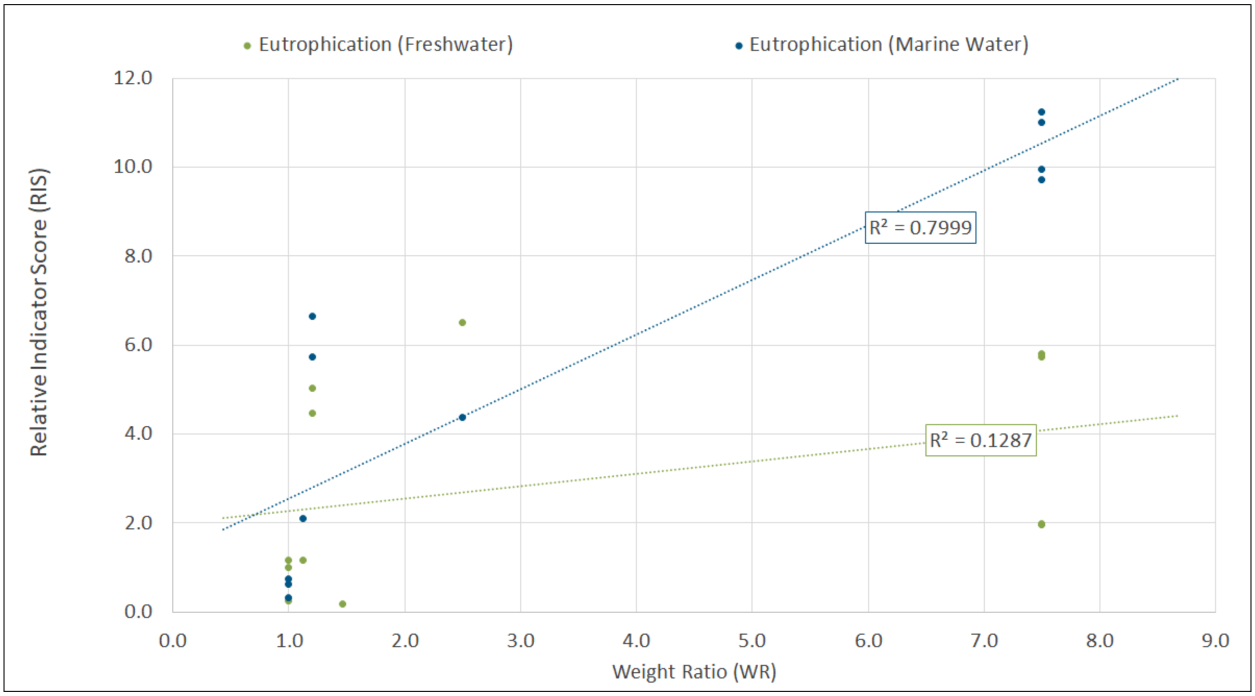

Figure 13. Overall Correlation between Water Eutrophication Indicator Scores and Weight Ratios

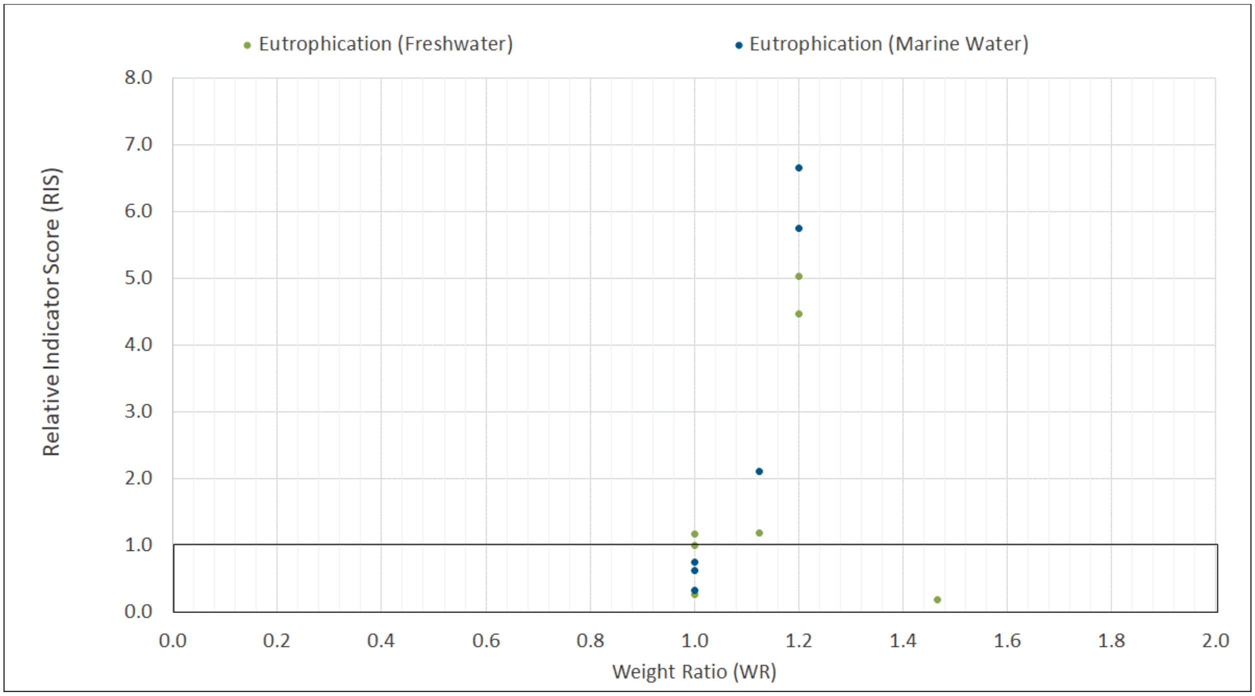

Figure 14. Correlation between Water Eutrophication Indicator Scores and Weight Ratios: Identification of Weight Ratios for which Relative Indicator Score is ≤1

Figure 15 shows the correlation between WRs and indicator scores for the terrestrial and combined eutrophication[3] impact categories, where relatively good correlation is observed. As depicted in Figure 16, in some applications the paper alternative outperforms the plastic alternative.

Table 3 presents specific applications found in the literature for which the relative environmental score (RES) <1 for all eutrophication impact categories.

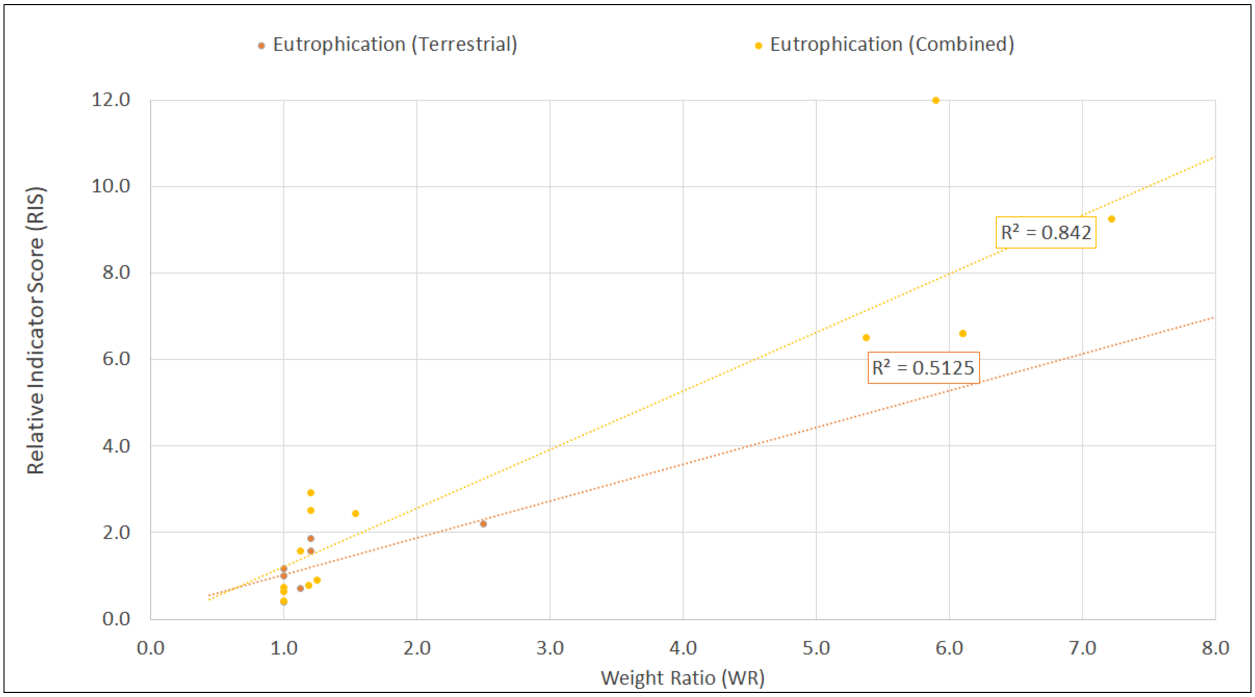

Figure 15. Overall Correlation between Terrestrial and Combined Eutrophication Indicator Scores and Weight Ratios

[3] Instead of using multiple eutrophication impact categories, some authors used methods that combined terrestrial and water eutrophication into a single impact category.

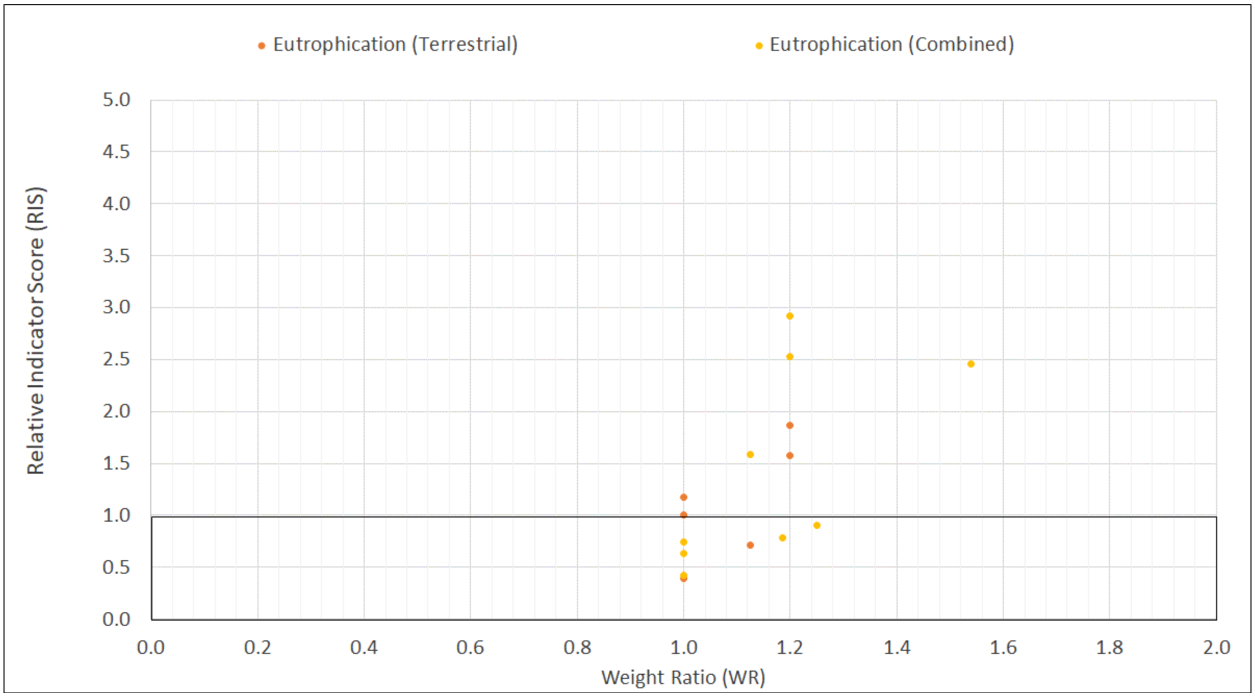

Figure 16. Correlation between Terrestrial and Combined Eutrophication Indicator Scores and Weight Ratios: Identification of Weight Ratios for which Relative Indicator Score is ≤1

Table 3. Applications for which Paper Alternative Outperforms Plastic Alternative for Four Eutrophication Indicators

Application	Paper Type	Plastic Type	Weight Ratio	Relative Environmental Score (RES)			
				FW	MA	TER	COM
Cups and plates (Pro.mo 2015)	PE-coated paperboard	PP	1.00	0.99	>1	0.74	0.74
Cups and plates (Pro.mo 2015)	PE-coated paperboard	GPPS	1.00	>1	1.00	0.62	0.64
Cups and plates (Pro.mo 2015)	PE-coated paperboard	PLA	1.00	0.26	0.39	0.33	0.43
Cups and plates (Pro.mo 2015)	Cellulose pulp	PLA	1.18	>1	>1	0.71	>1
Cups and plates (Ligthart and Ansems 2007)	PE-coated paperboard	GPPS	1.25	N/Av	N/Av	N/Av	0.90
Food packaging (Zabaniotou and Kassidi 2003)	Recycled paper	XPS	1.47	0.18	N/Av	N/Av	N/Av

PE: polyethylene; PP: polypropylene; GPPS: general purpose polystyrene; PLA: polylactic acid; XPS: expanded polystyrene; FW: freshwater eutrophication; MA: marine eutrophication; TER: terrestrial eutrophication; COM: combined aquatic and terrestrial eutrophication; N/Av: not available. Cells highlighted in blue are those for which paper performs at least as well as plastic.

3.5 Water Use and Consumption

Authors of LCA studies very often do not distinguish effectively between water use and water consumption and introduce an impact category identified as “water consumption” that quantifies water use instead. Therefore, to establish the correlations provided in Figure 17, NCASI assumed an author meant water use instead of water consumption unless it was possible to determine by the methodology that the impact category indeed represented water consumption.

Results in Figure 17 show some correlation between the two water indicator scores (water use and water consumption) and WRs. The correlation for water consumption indicator scores needs to be interpreted with care because it is based on a very limited number of studies, but it is stronger than that for the water use impact category. Other than WR, the type of paper and plastic compared and to what extent each includes recycled content were important drivers to the RIS for paper and plastic.

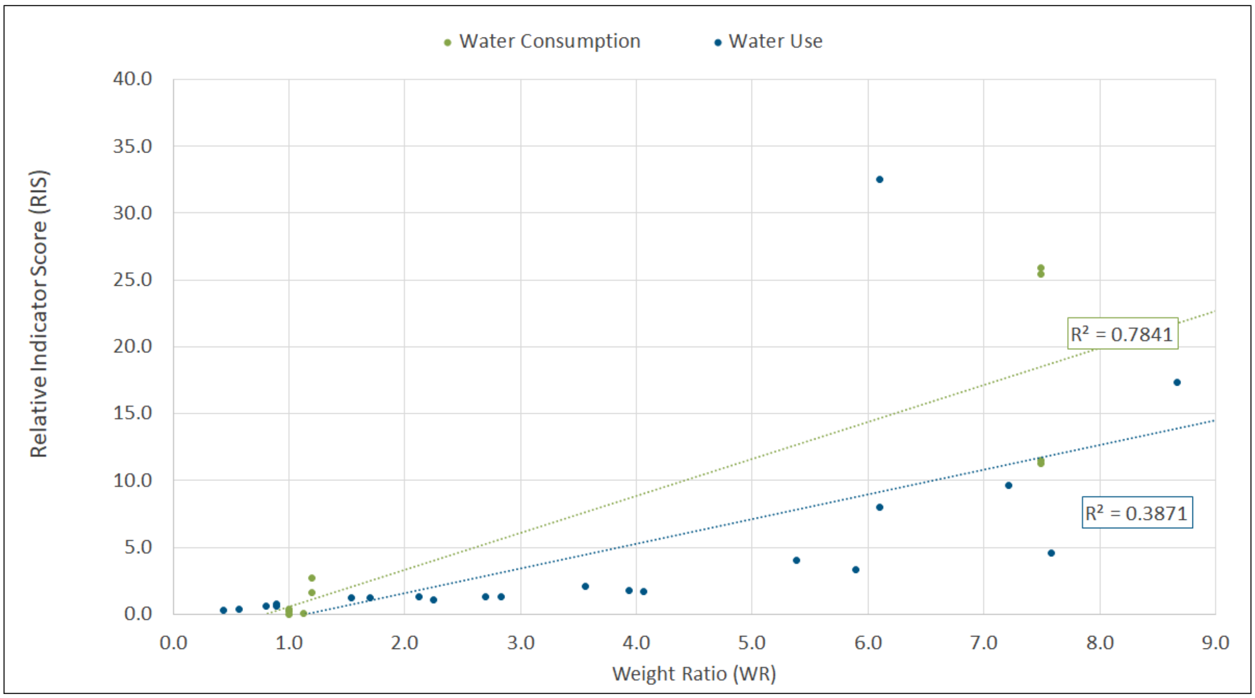

Figure 17. Overall Correlation between Water Use and Consumption Indicator Scores and Weight Ratios: Overall Correlation; Identification of Weight Ratios for which Relative Indicator Score is ≤1

Figure 18 shows that for applications with WRs <1.1, the paper alternative uses and consumes less water than the plastic alternative. WRs <1.1 reflect cups and plates, where the paper alternative was compared to a polylactide alternative (FAL 2011; Pro.mo 2015).

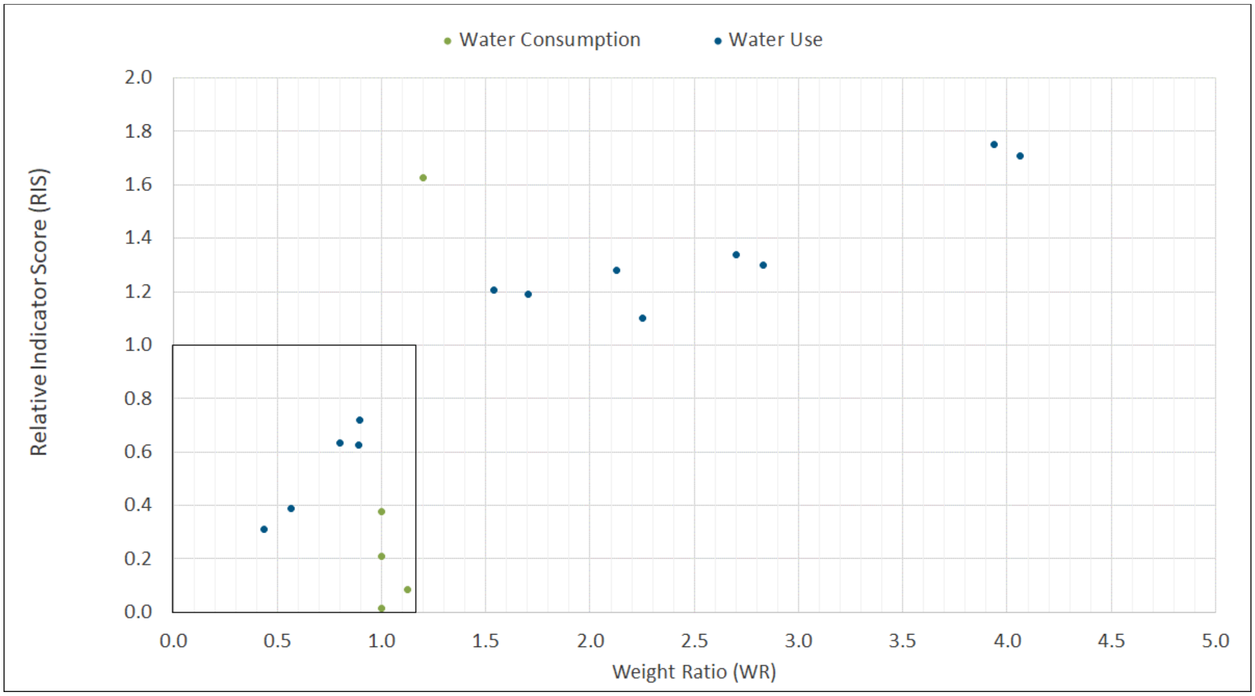

Figure 18. Correlation between Water Use and Consumption Indicator Scores and Weight Ratios: Identification of Weight Ratios for which Relative Indicator Score is ≤1

3.6 Study by Bisinella et al. 2018

Bisinella et al. (2018) employed an LCA framework fundamentally different than the other studies. Hence, their results were not considered in the correlation analyses because they would probably not be comparable. However, an interesting feature of the study is that it includes a comparison of paper bags with thicker, heavier plastic bags (WRs between 0.9 and 1.9). Results showed that in this case unbleached paper bags would release lower GHGs and use less energy than equivalent plastic bags. Plastic bags would also perform better on other impact categories such as acidification, smog, and water use, which is consistent with other studies.

4.0 CONSIDERATION OF LITTER IN LIFE CYCLE ASSESSMENTS

4.1 Existing Indicators

It is not common practice to characterize environmental impacts of litter in LCA. However, a few authors introduced a littering impact category for which they proposed their own indicator or discussed the relative environmental performance of plastic versus paper alternatives in the context of litter. The main findings of these authors are summarized here.

CIRAIG (2017) introduced an impact category of "abandonment in the environment" to consider the persistence of plastic left in nature and affecting wildlife when comparing plastic with alternatives. Its indicator considered the quantity of material potentially abandoned, as well as the persistence of the material in the environment. Indicator scores for a conventional plastic bag were between 277 and 388 times higher (i.e., "worse") than scores for a paper bag.

Civancik-Uslu et al. (2019) used a “littering potential” impact category to compare various types of bags. It was defined as a combination of parameters: the probability of the bag being abandoned in the environment (using the price of bags at the supermarket as a proxy[4]); bag floatability and the probability of flying out (for which the weight of the bags is a determining factor); and environmental persistence (biodegradability). Using this approach, the authors found that plastic bags had a littering potential about 1000 times greater than paper bags.

PwC/Ecobilan (2004) used a qualitative approach to evaluate risks of abandonment in the environment that included consideration of the probability that a bag would be abandoned in the environment (high for low-weight disposable plastic bags, low for paper bags), the “probability of bags escaping by take-off” estimated by the volume-to-weight ratio (somewhat high for low-weight disposable plastic bags, somewhat low for paper bags), and persistence in the environment (primarily marine environment [high for low-weight disposable plastic bags, low for paper bags]). Based on these considerations, the risk of abandonment in the environment was found to be high for low-weight disposable plastic bags and low for paper bags.

Some authors provided only discussions of the issue of littering. Bisinella et al. (2018) considered the relative effect of littering of paper and plastic to be negligible in the context of Denmark, where the study was undertaken. Edwards and Meyhoff Fry (2011) characterized the littering risk of paper bags as low and that of plastic bags as high. Chaffee and Yaros (2007) argued that there was no scientific evidence supporting the argument that banning SUPBs in favor of paper bags would reduce litter. Kimmel (2014) reported that an extensive compilation of literature in the US and Canada showed that plastic bags (including trash bags, grocery bags, retail bags, and dry-cleaning bags) make up a very small portion of roadway litter, usually less than 1%. The author also estimated that that <0.5% of plastic bags end their life as litter, and hence did not include further consideration of it. The analysis did not include marine litter. Verghese et al. (2009) highlighted that although bags comprise <1% of litter, they are highly visible and persistent in the environment. They added that although some paper bags might also be littered, they break down relatively quickly and, unlike plastic bags, are not easily dispersed by wind or water.

NCASI did not find discussion of littering in LCA applications other than for shopping bags.

4.2 Weighting Environmental Indicators

4.2.1 Methods

Weighting is an optional step in LCA, through which indicator scores obtained for different impact categories are evaluated by assigning numerical factors based on value-choices, after which these factors are aggregated into a single score for the compared alternatives (ISO 2006). Before LCA results can be weighted and aggregated, they must be normalized to a common unit or to a unitless measure (e.g., it is not possible to directly add kg CO_2 eq. to kg $PM_{2.5}$ eq.). All

[4] Assuming that cheaper bags have a higher probability of being abandoned in the environment than more expensive ones.

steps required in weighting "*are based on value-choices and are not scientifically based. Different individuals, organizations and societies may have different preferences and values; therefore, it is possible that different parties will reach different weighting results based on the same indicator results or normalized indicator results*." (ISO 2006). For this reason, the ISO LCA standard does not allow an LCA practitioner to apply weighting to product comparisons that are disclosed publicly; that is, weighting is left to the user of LCA results and should not be influenced by the personal view of the practitioner. The ISO standard also recommends that where weighting is applied, sensitivity analyses be conducted "*to assess the consequences […] of different value-choices and weighting methods*."

Normalization

In this study, NCASI normalized indicator scores for the various impact categories by dividing by the maximum of the scores of plastic or paper (internal normalization). Justification and discussion of this method can be found in the appendix.

While there are no data that would allow applying external normalization to all impact categories (see appendix), external normalization data are easily obtainable for the climate change impact category and help provide a degree of broader context to the results obtained. Hence, using results of LCA studies specific to the US and assuming these to be accurate, NCASI compared the climate change emission reduction that would occur if all paper bags produced in the US in a given year were replaced by plastic bags. In 2017, 1100 thousand short tons (998 thousand metric tonnes) of bags and sacks were produced in the US (USEPA 2019). The change that would have occurred in total US GHG emissions in 2017 as a result of this substitution was expressed as a percentage change compared to the total.

Weighting

The studies by Civancik-Uslu et al. (2019) and CIRAIG (2017) presented numerical scores for a series of impact categories, including their proposed littering impact category. This allowed NCASI to apply various weighting schemes to evaluate the potential implications of differences in preferences expressed by a decisionmaker for various environmental issues. The weighting schemes tested are listed in Table 4.

Table 4. Weighting Schemes Tested

Weighting Scheme	Description
W1	All impact categories receive the same weighting factor (WF). For example, if a study includes five impact categories, each gets a WF of 0.20.
W2	Global warming is considered the most significant environmental issue and gets a WF of 0.50. All other impact categories, including littering, get an equal WF for which the sum is equal to 0.50 (1 – 0.50). For example, if a study includes five impact categories, global warming gets a WF of 0.50 and the four other impact categories each get a WF of 0.125 [(1 – 0.50)/(5 – 1)].
W3a	Global warming and littering are considered equally significant and each get a WF of 0.25. All other impact categories get an equal WF for which the sum is equal to 0.50 [1 – (2 x 0.25)]. For example, if the study includes five impact categories, global warming gets a WF of 0.25, littering gets a WF of 0.25, and the three other impact categories each get a WF of 0.167 [(1 – 0.50)/(5 – 2)].
W3b	Global warming and littering are considered equally significant and get each a WF of 0.50. All other impact categories are considered relatively insignificant compared to global warming and littering and get a WF of 0.
W4	Littering is considered the most significant environmental issue and gets a WF of 0.50. All other impact categories get an equal WF for which the sum is equal to 0.50 (1 – 0.50). For example, if a study includes five impact categories, littering gets a WF of 0.50 and the four other impact categories each get a WF of 0.125 [(1 – 0.50)/(5 – 1)].
W5	This weighting scheme was used to calculate the littering indicator WF needed for the paper alternative to perform at least as well as the plastic alternative, assuming all other impact categories receive equal weights. This 'break point' WF provides additional context.

4.2.2 Results

Normalization

Results in Table 5 show that replacing 998 million kg of paper bags with a functionally equivalent amount of plastic bags would decrease US GHG emissions by 0.01 to 0.05% if applying results of LCA studies by Chaffee and Yaros (2007) and Kimmel (2014). This potentially overestimates the significance of the substitution because the data used by Chaffee and Yaros (2007) and Kimmel (2014) are very old. Improvements in the environmental performance of paper mills in the last 15 or 20 years are not reflected in the results. For example, based upon information from EPA's GHG Reporting Program (USEPA 2020a, 2020b), EIA Manufacturing Energy Consumption Surveys (USEIA 2005, 2009, 2013, 2017), and the FAO (2019), NCASI estimated that there was a decrease of approximately 30% in direct GHG emission intensity for the US pulp and paper industry between 2002 and 2017. However, facilities producing plastic have probably also improved their performance in that period, making it difficult to assess the effect of old data on the relative environmental performances of paper and plastic.

Table 5. Significance of Potential Change in US Greenhouse Gas Releases from Full Substitution of Plastic Bags for Paper Bags based on Different Life Cycle Assessment Studies

Author	Change in GHG from Substitution (tonne CO_2 eq./yr)	2018 US Total GHGs (tonne CO_2 eq./yr)	Change in Total US GHGs
Chaffee and Yaros 2007; 1:1 plastic to paper bag ratio, sequestration in landfills	-898,239	6,488,200,000* (USEPA 2020a, 2020b)	-0.014%
Chaffee and Yaros 2007; 1.5:1 plastic to paper bag ratio, sequestration in landfills	-598,826		-0.009%
Kimmel 2014; plastic bags recycled content 30%, paper bags recycled content 40%	-1,469,059		-0.023%
Kimmel 2014; plastic bags recycled content 30%, paper bags recycled content 100%	-1,224,580		-0.019%
Kimmel 2014; plastic bags recycled content 0%, paper bags recycled content 40%	-1,418,854		-0.022%
Kimmel 2014; plastic bags recycled content 0%, paper bags recycled content 100%	-3,088,739		-0.048%

*Excludes biomass CO_2

Weighting

Table 6 presents aggregated environmental scores obtained by applying the different weighting schemes in Table 4 (with a lower score indicating an environmentally "better" result). A trade-off occurs when establishing the relative significance of various impact categories. When assuming that all impact categories are of equal importance, global warming is the most significant issue, or global warming and litter are the two most significant environmental issues for decision-making, plastic bags are the preferred option. When assuming that global warming and littering are equally important and all other environmental issues are of relatively low significance, paper is the preferred option (although not by far). When assuming that littering is the most significant environmental issues, paper is always the preferred option. Substitution of plastic bags for paper bags is likely to be of little significance in the context of US total GHGs. Coupled with the likelihood that reductions in environmental effects from littering could be significant when substituting paper for plastic, this may justify application of a lower weighting factor to the global warming impact category and a higher weighting factor to the littering impact category when considering the potential implications of the use of paper versus plastic bags. Even though climate change is generally considered to be a highly important environmental indicator by decisionmakers, an understanding of potential implications for non-climate change indicators is critical during the decision-making process. This indicates the need develop reliable external normalization values for all relevant environmental indicators.

Table 6. Results of Applying Various Weighting Schemes

Study	Number of impact categories	W1: All equal		W2: GW most significant issue		W3a: GW and LIT equally significant		W3b: GW and LIT equally significant, other categories relatively insignificant		W4: LIT most significant issue		W5[a]
		Plastic Score	Paper Score	Plastic Score	Paper Score	Plastic Score	Paper Score	Plastic Score	Paper Score	Plastic Score	Paper Score	
Civancik-Uslu et al. 2019: paper bags vs HDPE bags	9	0.43	0.89	0.38	0.94	0.51	0.75	0.79	0.50	0.68	0.50	≈0.39
CIRAIG 2017[b]: paper bags vs HDPE (thin) bags, endpoint indicators[c]	4	0.32	0.75	N/A (no global warming indicator)		N/A (no global warming indicator)		N/A (no global warming indicator)		0.54	0.50	≈0.48
CIRAIG 2017[b]: paper bags vs HDPE (thin) bags, midpoint indicators[d]	18	0.07	0.30	0.06	0.63	0.27	0.39	0.52	0.50	0.51	0.16	≈0.23
CIRAIG 2017[b]: paper bags vs LDPE (thick) bags, endpoint indicators[c]	4	0.61	0.75	N/A (no global warming indicator)		N/A (no global warming indicator)		N/A (no global warming indicator)		0.73	0.50	≈0.35
CIRAIG 2017[b]: paper bags vs LDPE (thick) bags, midpoint indicators[d]	18	0.19	0.83	0.12	0.91	0.34	0.69	0.52	0.50	0.57	0.44	≈0.43

HDPE: high density polyethylene; LDPE: low density polyethylene; IC: impact category; WF: weighting factor; GW global warming; LIT: littering

[a] WF applied to littering indicator for paper alternative to perform at least as well as plastic alternative, considering all other impact categories as equally important/significant

[b] average of "small shopping" and "big shopping" scenarios

[c] CIRAIG (2017) considered endpoint indicators of human health, ecosystem quality, and use of fossil resources, contrasted with midpoint indicator for littering potential

[d] because midpoint-to-midpoint indicator weighting might be more appropriate, NCASI obtained midpoint results directly from CIRAIG because they were not published in original report

5.0 CONCLUSIONS

The current body of LCA literature on paper versus plastic bags is often used to support claims that plastic has a lower environmental footprint than paper on several impact categories. However, NCASI's study found that this assumption: (1) depends on a variety of factors and cannot necessarily be extended to other products where paper can be used as a replacement for plastic, such as cups and plates for food packaging applications; and (2) typically does not include consideration of the implications of material littering.

Factors that influence the relative environmental performance of paper versus plastic bags were shown to include the product weight and various LCA methodological choices. More specifically, WR of the compared alternatives was one of the most important drivers for the impact categories of global warming, fossil fuel usage, particulate releases, and water consumption. Other impact categories showed less correlation with WR, indicating that other factors such as the assessment method employed and the actual paper and plastic types compared are probably more important drivers of relative environmental performance. It is not possible to extend findings of LCA studies concluding that plastic shopping bags score better than paper shopping bags to other products where paper can be used as a replacement for plastic, such as cups and plates or food packaging applications. For example, when examining cups and plates/food packaging applications at WRs up to 1.5 to 2, paper products showed environmental performance at least comparable to plastic for several impact categories. Paper-based beverage containers also showed better LCA results than plastic beverage containers for WR <1.

With few exceptions, the body of existing LCA studies generally does not include consideration of material littering in the environment. The few studies that included a quantitative or qualitative indicator for littering all found that low-weight disposable plastic bags pose significantly more littering risk than paper bags. Moreover, the primary attribute–low bag weight–that led to favorable scores for plastic bags on several indicators, such as climate change, also significantly increased their risk of abandonment into the environment. Furthermore, because of the absence of a reliable indicator, studies that looked at littering did not go as far as to assess the effect on health and ecosystems of paper and plastic materials left in the environment, but instead limited analyses to the risk that a material would end up in the environment and not be biodegraded. No assessment was made of the actual effects of various materials abandoned in the environment on human health and ecosystems. This suggests a need for further research to more fully account for trade-offs in material choices.

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APPENDIX

JUSTIFICATION OF THE NORMALIZATION METHOD

There are two main categories of normalization in LCA: internal methods and external methods (Norris 2001). Internal methods use the score of one of the compared alternatives as the basis for normalization. They address primarily the problem of non-commensurate units. Using internal methods, normalization is seen only as an operational pre-requisite to weighting. In contrast, external methods have the objective of assessing the relative environmental relevance of the results across impact categories. This is done by dividing the score obtained for each impact category by an estimate of the total score for that same impact category for a chosen reference system (e.g., total score for a country). External normalization requires that reliable reference impact scores be available for all impact categories considered. NCASI did not have access to external normalization scores for all impact categories. Hence, internal normalization has been used in this analysis.

There are limitations to internal normalization. First, normalized results are insensitive to the significance of the magnitude of the results of a given study. For instance, the studied plastic bag might perform 5 or 10 times better than the paper bag for the climate change indicator, but if neither the production of the plastic bag nor of the paper bag was an important contributor to the climate change issue, this context would not be reflected. Thus, in defining weightings using internal normalization, a decisionmaker may wish to consider the relative environmental relevance of the different impact categories. Second, rankings derived through internal normalization can change simply by virtue of including or removing one of the alternatives. This limitation is not an issue when comparing only two alternatives, but it could become important if several alternatives are considered. For this reason, NCASI performed only pairwise comparisons in its weighting analysis.

There are a few different internal normalization approaches: “division by the maximum” score in each impact category across alternatives; “division by the sum” of scores in each impact category; “division by a baseline,” where one alternative is used as the reference system; and “division by the average” score in each impact category. “Division by the maximum” and “division by a baseline” are often used for the purpose of weighting (Norris 2001). Here, NCASI chose “division by the maximum” to avoid the issues associated with “division by a baseline,” which would require arbitrarily selecting between paper and plastic as the baseline, a choice that would affect the results of weighting and might involve division by zero.

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