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EXAMINING MATERIAL EVIDENCE THE CARBON FINGERPRINT

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HIGHLIGHTS

If all plastic bottles used globally were made from glass instead, the additional carbon emissions would be equivalent to 22 large coal-fired power plants producing enough electricity for a third of the UK.

If all plastic were recycled this could result in mean annual savings of 30 to 150 million tonnes of CO_2, equivalent to shutting between 8 and 40 coal-fired power plants globally.

KEY WORDS

Circular Economy
Climate Change
Net Zero
Sustainable Packaging
Plastics
Life-cycle Assessment

Executive Summary

Only 2% of British people consider plastic, compared to other materials used in packaging, to contribute the least greenhouse gases to the environment from its production, use, and post use treatment. Whilst in absolute numbers it is a fact the least impactful. Plastics do have a large carbon impact - accounting for 3.8% of global greenhouse gases emissions - but it is wrong to assume that alternative packaging materials would perform better, and it is important to consider the carbon benefits that arise from plastics use.

When considering the production and manufacturing of the main alternatives to plastic for a 500ml bottle, other packaging types (fibre, glass, steel and aluminium) emit more greenhouse gases than plastic bottles, with glass bottles being the highest emitter overall. By way of example, if all plastic bottles used globally were made from glass instead, the additional carbon emissions would be equivalent to powering around 22 large coal-fired power plants. This is equivalent to the electricity consumed by a third of the UK.

Life-cycle assessment (LCA) is a useful tool which should be more widely used to evaluate environmental impacts of packaging alternatives over their life-time, from the extraction of raw material to the disposal or recycling of packaging at the end of its life. Undertaking LCAs to compare the environmental performance of alternative materials for different packaging applications is essential if we want to take into account the environmental impacts associated with the whole life-cycle of packaging (mining, manufacturing process, logistics, usage and end-of-life route).

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Results can vary significantly from one study to another, depending on key parameters and assumptions. For example, the risk of producing more food waste because of the packaging design and shelf life is not always considered in LCAs while this can have a large impact on the packaging carbon contribution.

In this study, a total of 73 publications on LCAs comparing different types of packaging were identified and reviewed. By assessing many different studies we can draw some general conclusions about the range of results and what the majority of analysis determined. Findings indicate that in the applications it is used, most of the time, plastic packaging performs better than its alternatives, and mainly due to its very lightweight properties.

Transport distance and method, sources of electricity generation, packaging shape and weight, all significantly influence the LCA results and should be considered on a case by case basis. It is also important to consider the full life cycle of the material, such as, for plastic the prospecting and mining stages.

The waste management route in place to treat packaging at its end of life, is also shown to be a critical factor explaining variations of LCA results for the same packaging. Recycling always wins over virgin production on all environmental indicators. For plastics, there seems to be consensus that recycling saves between 30% and 80% of the carbon emissions that virgin plastic processing and manufacturing generate.

If all plastic were recycled this could result in mean annual savings of 30 to 150 million tonnes of CO_2, equivalent to stopping between 8 and 40 coal-fired power plants globally.

The findings of this study demonstrate that if we really want to tackle the environmental issues we face with plastics today then removing, reducing, reusing or recycling the plastic packaging placed on the market is the way forward. This approach is more certain and reaps better results than waiting and hoping for solutions not yet commercialised or switching to alternative available materials respectively.

Considering that only around 9% of plastics are currently being recycled worldwide, there is a lot that can be done to improve things. We can see that where the right policy drivers are in place, this is already happening, with regulatory statutes that themself deliver fiscal actions on business. In the UK, the various measures planned in the UK Waste and Resources Strategy planned by DEFRA, such as the extended producer responsibility scheme, the deposit return scheme and the harmonisation of waste collection associated with a clear labelling system, as well as HM Treasury proposals for a plastic packaging tax are all good steps for creating a fully functioning circular and sustainable system for packaging.

In concert with the widespread application of renewable energy and demand-management strategies, increasing the recycling of plastics have the potential for both curbing the growing life-cycle GHG emissions from plastics, and also preventing them from entering the marine environment.

If all plastic were recycled this could result in mean annual savings of 30 to 150 million tonnes of CO_2, equivalent to stopping between 8 and 40 coal-fired power plants globally.

Introduction

Plastic production, use, and disposal all emit significant amounts of greenhouse gases, but the situation is complex and one would be wrong to assume that reducing plastic use or switching to alternative materials would automatically result in curbing emissions.

In a paper published in 2019 in the journal Nature Climate Change[1], the global assessment of the life cycle of greenhouse gas emissions from all plastics was presented. The overwhelming majority of plastic resins come from petroleum, which requires extraction and distillation. Then the resins are formed into products and transported to market. All of these processes emit greenhouse gases, either directly or via the energy required to undertake them. The carbon footprint of plastics continues after their end of life, since landfilling, incinerating, recycling and composting (for certain plastics) all release carbon dioxide either directly or via the energy and consumables used to undertake the treatment (in the case of landfill for example). Emissions from plastics in 2015 were equivalent to nearly 1.8 billion metric tonnes of CO_2[2]. Across their lifecycle, plastics account for 3.8% of global greenhouse gas emissions[3]. Plastics production has risen from 2 million tonnes per annum in 1950 to 381 million tonnes per annum in 2015, with an estimated 9% of plastic discarded since 1950 considered to have been recycled[4]. Rising plastic production will exacerbate both problems with pollution and climate change. Production is set to increase. If current trend continues, by 2050, it is estimated that total plastics ever produced will reach 34,000 million tonnes[5]. By then, if the production and recycling systems for plastics do not change, the accumulation of greenhouse gas emissions from plastic could reach 15% of the amount of global carbon emissions permissible to keep temperature rise under 1.5°C[6] . With around 8 million tonnes of plastic ending up in the oceans every year, and 3,000 pieces of plastic litter found in every square kilometre of seawater, this not only represents a significant hazard to marine species and human health, but considerable wastage of resources and inefficiency[7].

Looking at the entire life cycle of fossil fuel-based plastics today, nearly two thirds of its greenhouse gas emissions are produced in the early stages from fossil fuel extractions to the production of resin, while converting resin to pipes, bottles, bags and other products generates just under one third of its emissions, with the remainder coming from the disposal phase. This indicates there are high carbon benefits of recycling plastics, avoiding those 61% of greenhouse gases emissions from the extraction and resin production process, discussed further throughout this paper. Despite the large impact of plastics on the environment, their application for packaging offers some environmental benefits. Reducing its usage or switching to different materials may have unintended negative consequences.

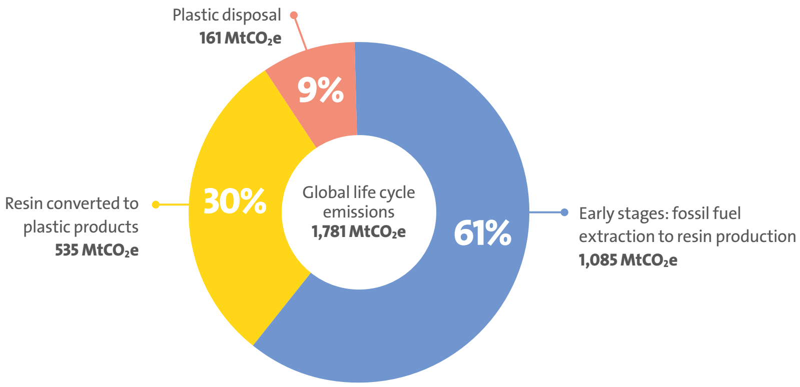

Figure 1. Life cycle emissions of fossil fuel-based plastics in metric tons of CO_2 equivalent, 2015[1]

"If we recycle plastics we avoid the 61% contribution of plastics emissions"

[1] J. Zheng and S. Suh, 'Strategies to reduce the global carbon footprint of plastics', Nature Climate Change , 9/5 (2019), 374–78.

[2] Zheng and Suh, 'Strategies to reduce the global carbon footprint of plastics'.

[3] J. G. J. Olivier, K. M. Schure, and J. A. H. W. Peters, 'TRENDS IN GLOBAL CO_2 AND TOTAL GREENHOUSE GAS EMISSIONS Summary of the 2017 report', 2983 (2017).

[4] S. Cheriyedath, 'What Counts as Plastic Waste?', (2019).

[5] J. M. Simon, Zero Waste Europe, F. Rosa, C. Allen, M. Wilson, and D. Moon, 'Changing trends in plastic waste trade: Plastic waste shipments report', November (2018).

[6] J. Y. S. Leung, B. D. Russell, and S. D. Connell, 'Adaptive Responses of Marine Gastropods to Heatwaves', One Earth , 1/3 (2019), 374–81.

[7] IUCN, 'Marine Plastics: What is the issue? Why is this important? What can be done?', International Union for Conservation of Nature Issues Brief , (2018), 1–2.

[8] Center for International Environmental Law, Fueling Plastics. Fossils, Plastics, & Petrochemical Feedstocks. , (2017).

[9] B. Brandt and Harald Pilz, 'The impact of plastic packaging on life cycle energy consumption and greenhouse gas emissions in Europe. Executive Summary', July (2011), 1–7.

[10] Bright Blue, 'lastics and climate change: unwrapping the evidence', (2018).

[11] STATISTA, 'Production of polyethylene terephthalate bottles worldwide from 2004 to 2021', (2020).

The benefits of plastic

Plastic is a versatile material which can easily be made thin and lightweight. It is durable and provides protection from contaminants and the elements. It reduces food waste by preserving food and increasing its shelf life. It protects food against pests, pathogens and humidity. Plastic packaging is more flexible and lighter than alternatives such as glass and card, which reduces transportation costs and the carbon emissions that come with them.

Without packaging, food is more likely to get damaged and become unusable. Since food waste contributes to climate change, water and energy consumption, deforestation and biodiversity loss, every effort we make to mitigate those effects makes a big difference, and plastic packaging helps make that possible. Plastic packaging is useful for keeping products fresh and insulated. Removing plastic entirely from our food supply may not be the best solution when it comes to protecting the environment and conserving valuable resources. Plastic packaging is used in the food supply chain because it supports the safe distribution of food over long distances and minimises food waste by keeping food fresh for longer.

A lot of food is air freighted, so prolonging its shelf life has important benefits for the environment. Plastic minimises food waste and conserves all valuable resources involved from farm to shelf. A 2016 review of studies on food waste found that 88m tonnes of food is wasted every year in the EU – that's 173kg per person and equals about 20% of food produced[12]. Minimising this wastage is crucial for environmental protection, as well as food security. Several factors must be considered when determining how useful plastic packaging is in the food supply chain, as it has the potential to preserve food and prevent its wastage. For example, the use of just 1.5g of plastic film for wrapping a cucumber can extend its shelf life from three days to 14 days and selling grapes in plastic bags or trays has reduced in-store wastage of grapes by 20%[13]. Recent estimates from Zero Waste Scotland suggest that the carbon footprint of food waste generated can be higher than that of plastic, with 456,000 tonnes of food waste produced in Scottish households contributing to around 1.9m tonnes of CO_2, three times higher than that of the 224,000 tonnes of plastic waste generated[14].

[12] M. Dora and E. Iacovidou, 'Why some plastic packaging is necessary to prevent food waste and protect the environment', (2019).

[13] Dora and Iacovidou, 'Why some plastic packaging is necessary to prevent food waste and protect the environment'.

[14] BBC, 'Scotland's food waste causing more greenhouse gas than plastic', (2019).

The carbon impact of plastic bottles compared to other material type containers

All food and drink packaging, whether plastic or another material, has an environmental impact. There is a lot of emphasis on plastic waste and pollution, but other impacts such as carbon emissions must also be considered when determining which materials are most suitable for different packaging applications. When considering reductions in the use of plastics, it is therefore important to consider the carbon footprint of things that could replace plastic — materials such as paper, aluminium, or glass.

It is also worth noting that aluminium cans and carton containers, despite often being explicitly depicted as alternatives to plastic bottles, still contain considerable amounts of plastic. Aluminium cans often have a complex plastic closure weighing around 4g (nearly half the weight of a single use plastic bottle); glass containers usually include a relatively heavy plastic lid – 14g (meaning they weigh more than a lightweight plastic water bottle); and multilayer cartons usually include nearly 10g of plastic (roughly the weight of a plastic water bottle)[15]. In addition, virtually all metal cans used for food and beverage products are also lined on the inside with a coating that uses Bisphenol A (BPA) as a base protective material, while most plastic bottles are made from polyethylene terephthalate (PET) plastic, which does not contain BPA.

To illustrate the difference of carbon impacts from the production of bottles from plastics and alternative materials, we calculated carbon emissions that would have been incurred in 2016 if every 500ml PET bottle produced worldwide was replaced by alternative material. The results are shown in Table 1 and Figure 2.

Carbon emissions from the production of plastic bottles are lower than all other materials equivalent: glass, aluminium and steel in particular, glass bottle being the worst alternative from a carbon perspective. If all plastic bottles used globally were made from glass instead, the additional carbon emissions (87.4Mtonnes of CO_2eq annually) would be equivalent to powering 22 coal-fired plants[16]. Although plastic bottles perform similarly to liquid fibreboard packaging in terms of carbon impact during the production process, they are much easier to recycle and thus should have a lower carbon impact if we were considering their end of life.

The necessity to capture all environmental impacts of a packaging full life (including its end of life), and to capture the complexity of each specific packaging design produced in a specific supply chain and disposed in a specific waste management system, advocates to use a more detailed life cycle approach to assess the environmental impact of one particular packaging.

Note: It is important to note that there will be examples when alternative materials still make sense, for example the widely cited reusable milk glass bottles case where it is evident that emissions can be lower when the farm is local, bottles are filled and distributed by electric milk floats (running on low carbon electricity) in a locality close to the milk distribution centre, and are then cleaned and reused (not forgiving the detergent and water required for the cleaning)[17].

Therefore, every case must be assessed in its own merits, since there will be examples of Liquid Fibre Board, Metals and Glass presenting better packaging solutions on a carbon basis.

[15] Green Alliance, 'Losing the bottle: why we don't need single use containers for water'.

[16] EPA Greenhouse Gas Equivalencies Calculator (March 2020 update)

[17] WRAP, Life cycle assessment of example packaging systems for milk, (2010)

Table 1. Calculating greenhouse gases emissions for producing all 500ml containers in 2016 from alternative materials

Container type (500ml bottle or can)	Composition	Weight per bottle (grams)	Tonnes in 2016 (485 billion bottles)	Tonnes CO_2-e per tonne of 500ml bottles/cans produced*	Million tonnes of CO_2 in 2016 from production if all plastic bottles were replaced by this format and material*
Plastic bottle (baseline)	Plastic (PET)	12.7	6,159,500	4.053	25.0
Liquid fiberboard packaging	Plastics (50% PET closure and 50% PE layer)	8	3,880,000	3.585	25.5 (+0.5)
	Aluminium	1	485,000	12.874	
	Carton	13	6,305,000	0.844	
Steel can	Steel	30	14,550,000	3.004	43.7 (+18.7)
Aluminium can	Plastics (PE layer)	4	1,940,000	3.116	105.9 (+80.9)
	Aluminium	16	7,760,000	12.874	
Glass bottle	Glass	259	125,615,000	0.895	112.4 (+87.4)

*Emissions have been calculated using the 2019 Conversion Factors from Defra that covers the extraction, primary processing, manufacturing and transporting materials to the point of sale[18]

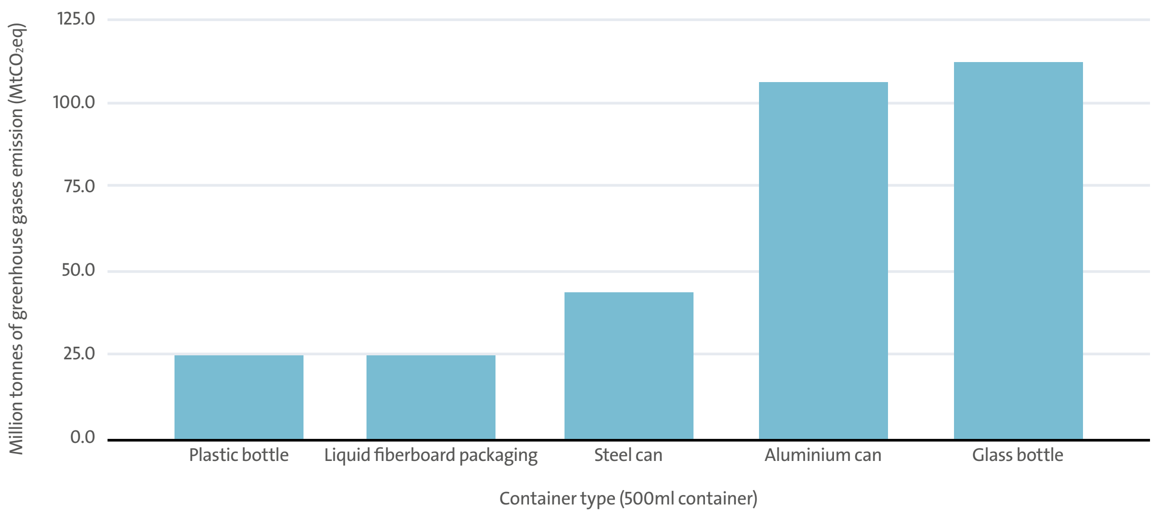

Figure 2 - Greenhouse gases emissions for producing all 500ml containers in 2016 from alternative materials

[18]Defra, 'Greenhouse gas reporting: conversion factors 2019', (2019).

Life cycle assessment (LCA)

Life cycle thinking is increasingly seen as a key concept for ensuring the sustainability of resources production and consumption. Over the years, life cycle assessment has been used extensively to assess products from "cradle to grave" - from extraction of resources to end of life management. The assessment has been formalized by the International Standard Organization (ISO) (Geneva, Switzerland). LCA is based on an iterative process with four steps, i.e., goal and scope definition, inventory analysis, impact assessment, and interpretation.

In January 2018, when the European Commission adopted the European Strategy for Plastics in a Circular Economy, they proposed a vision in which alternative materials and feedstocks should only be developed and used where evidence clearly shows that they are more sustainable compared to the non-renewable alternatives[19]. In particular, they promoted specified specific actions aiming at better understanding the life-cycle impacts of alternative feedstock for plastics production.

LCA provides a quantified methodology to assess the environmental performance of goods and processes. The cradle-to-gate LCA study usually starts with raw material extraction and ends with the final products leaving the factory gate[20]. A cradle-to-grave study starts with raw material extraction and ends with the disposal of product in landfill, incineration or recycling. A cradle-to-cradle study starts with the same process and considers not only the final disposal but also the energy recovery from incineration or the raw material replacement due to recycling of the studied products[21]. In the assessment, the burdens imposed on the environment by plastic packaging is ascertained by accounting for the resources and energy (inputs) consumed at each stage of the system and the resulting pollutants and wastes (outputs) emitted.

Unlike issues such as energy, water, and material use, which can be measured during the production process, "impact of plastic litter on the environment" is not easy to express in figures. Plastic crumbles into smaller and smaller pieces that enter the food chain, resulting in unknown effects on our health. Despite the increasing concerns regarding the impacts of plastic in the marine environment, including the long-term impacts associated with their durability under marine conditions of cold and dark which inhibit degradation, there is a stark lack of literature on the LCA end-of-life impact in the marine environment. Woods et al. (2016) examined the use of LCA for marine ecological impacts, and singled out key stressors such as ocean acidification, over exploitation and invasive species in order to examine approaches to quantifying their effects on the biodiversity of the marine environment[22]. However, for marine plastic debris they concluded that no methods have yet been proposed to quantify the effect of plastic waste on biodiversity at any scale greater than the individual organism. The Medellin Declaration in 2017 has addressed this need but it remains unmet[23].

Keeping this limitation in mind, LCA still remains the best existing assessment tool to compare the environmental impact of packaging alternatives. In the following section, we review existing LCAstudies on plastic packaging and its alternatives and discuss the main factors driving its environmental impact.

Comparing packaging alternatives - a review of existing life cycle assessments

A total of 73 LCAs (see Annex 1) were identified, and information on LCA procedures including scope and boundary, functional units and analysed life cycle impacts were reviewed and summarized. Most LCA undertaken for various plastic uses show plastic performing better than the alternatives from a carbon perspective. Even if, ounce for ounce, some kinds of plastic have a higher carbon footprint than other kinds of packaging, less quantity is used reducing overall impact, as plastic is light. Plastic performs better most of the time (for example heavier-duty plastics, such as low density polyethylene or woven polypropylene bags, do have a bigger climate and energy impact than paper, but they're more durable and you get more use out of them). Several studies have shown many materials used as alternatives to plastic in packaging, such as cotton, glass, metal or bioplastics, to have significantly higher CO_2 impact or water usage compared to plastic packaging. On average over current food packaging, replacing plastic packaging with alternatives, would increase the weight of the packaging by 3.6 times, the energy use by 2.2 times, and the carbon dioxide emissions by 2.7% but these can vary significantly for different cases[24]. Some examples are 23 highlighted in Figure 3.

[19] European Commission, 'A European Strategy for Plastics', European Comission , (2018).

[20] S. Madival, R. Auras, S. P. Singh, and R. Narayan, 'Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology', Journal of Cleaner Production , 17/13 (2009), 1183–94.

[21] Madival, Auras, Singh, and Narayan, 'Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology'.

[22] J. S. Woods, K. Veltman, M. A. J. Huijbregts, F. Verones, and E. G. Hertwich, 'Towards a meaningful assessment of marine ecological impacts in life cycle assessment (LCA)', Environment International , 89–90 (2016), 48–61.

[23] G. Sonnemann, S. Valdivia, M. Prox, P. Wiche, C. Hasenstab, M. Diaz, C. Peña, N. Suppe, I. Vázquez-Rowe, I. Quispe, C. Ugaya, A. Barona, E. Cadena, J. R. Vieira, A. Moeller, H. Harris, S. Humbert, N. Duque-Ciceri, M. Goedkoop, J. R. Pons, and C. Naranjo, 'Medellin Declaration on Marine Litter in Life Cycle Assessment and Management', 2017.

[24] Committee for the Environment Food and Rural Affairs, Plastic food and drink packaging , (2019).

Plastic versus glass

Humbert et al. (2009) showed that plastics perform better than glass packaging in terms of production and waste treatment processes based on global warming scores [24]. The steam consumption with ultra-high temperature process used in plastic packaging system is lower that those with retort process in glass packaging systems. Though Accorsi et al. (2015) showed than PET bottling line compromising many automated working stations is more energy consuming compared to glass bottling lines, but also more efficient when dealing with input materials [25]. Plastic packaging is lighter, and this leads to a significant reduction in packaging transportation. Glass packaging performs worse for impact categories such as primary energy demand, abiotic depletion, acidification potential, human toxicity potential, terrestrial toxicity potential and photochemical oxidant creation potentia [26]. A 2L PET soft drink packaging in the same study was shown to perform best across most of the impact categories.

Plastic versus aluminium

According to El CA studies on beverage packaging, plastic bottles perform better than aluminium cans. Amienyo et al (2013) Pointed that aluminium can production causes higher global warning potential than PET bottle production [26]. Due to high emissions of PAH and hydrogen fluoride during aluminium can production, the human and marine toxicity are disproportionately higher for aluminium cans than PET bottles compared with their market share in the study area. Pasqualino et al. (2011) as well as Simon et al. (2016) had similar findings with the aluminium cans intensive thermal production performing worse for the environment [27,28]. Plastic product saved 57% more energy and 61% more GHGs emissions compared to alternatives.

Plastic versus paper

Comparing plastic to paper bags, the global warming potential of paper bag production was shown to be much higher due to the need for fertiliser during the tree farming and plantation [30]. Moreover, cardboard production, as a common stage of paper packaging production, has significant water depletion potential. Paper packaging production is also responsible for greater ecosystem quality damage due to the land use required for wood pulp as a paperboard production input [31].

Figure 3. Comparing packaging alternatives [25, 26, 27]

[25] S. Humbert, V. Rossi, M. Margni, O. Jolliet, and Y. Loerincik, 'Life cycle assessment of two baby food packaging alternatives: Glass jars vs. plastic pots', International Journal of Life Cycle Assessment , 14/2 (2009), 95–106.

[26] R. Accorsi, L. Versari, and R. Manzini, 'Glass vs. plastic: Life cycle assessment of extra-virgin olive oil bottles across global supply chains', Sustainability (Switzerland) , 7/3 (2015), 2818–40.

[27] D. Amienyo, H. Gujba, H. Stichnothe, and A. Azapagic, 'Life cycle environmental impacts of carbonated soft drinks', The International Journal of Life Cycle Assessment , 18/1 (2013), 77–92.

[28] J. Pasqualino, M. Meneses, and F. Castells, 'The carbon footprint and energy consumption of beverage packaging selection and disposal', Journal of Food Engineering , 103/4 (2011), 357–65.

[29] B. Simon, M. Ben Amor, and R. Földényi, 'Life cycle impact assessment of beverage packaging systems: Focus on the collection of post-consumer bottles', Journal of Cleaner Production , 112 (2016), 238–48.

[30] Brandt and Harald Pilz, 'The impact of plastic packaging on life cycle energy consumption and greenhouse gas emissions in Europe. Executive Summary'.

[31] J. B. M. M. Biona, J. A. Gonzaga, A. T. Ubando, and H. C. Tan, 'A comparative life cycle analysis of plastic and paper packaging bags in the Philippines', 2015 International Conference on Humanoid, Nanotechnology, Information Technology,Communication and Control, Environment and Management (HNICEM), (2015), 1–6.

[32] J. Cleary, 'Life cycle assessments of wine and spirit packaging at the product and the municipal scale: A Toronto, Canada case study', Journal of Cleaner Production , 44 (2013), 143–51.

Important factors impacting a packaging LCA

While LCAs are widely used to inform discussions on packaging, the inherent complexity in capturing the environmental impacts of packaging means that results will vary based on the details of the methodology used. For example, food waste can or not be taken into account in a food packaging LCA via shelf-life extension or via other drivers linked to the packaging design (e.g. trimming and multipack). The shape of the packaging container also influences the overall environmental performance of the system since the amount of resin used per container varies in different shapes. The stackable container consumes more resin for enabling distribution without any crates, resulting in high greenhouse gases emission and energy consumption associated with the production process. Containers with different plastic materials also have various scores in impact categories due to the container mass. PET strawberry packaging with higher container weight is worse for the environment compared with similar PLA or PS packaging[33].

Though some LCA studies claimed that transport-induced environmental impacts are much smaller than the environmental impacts of packaging production[34] most pieces of literature have considered transportation within the life cycle impacts. The results of the country-scale LCA study in the United States also suggest that railway transportation has a better environmental performance than the truck one[35]. Different weight of packaging material types also influences the transporting related impacts. The heavier the packaging type is, the higher impact is generated within the transportation phase[36]. Another LCA study on olive oil packaging suggested that the preferable packaging changed with distribution distance. Glass bottles were more suitable for local transportation while tinplate cans were chosen for long-distance distribution. Besides, a reduction in the average distance travelled to market can improve the overall environmental performances of heavier packaging containers[38]. In summary, transport-efficient packaging depends on several factors including food ingredient, type and amount of used packaging materials, and more importantly, travel distance between producer and retail as well as transportation mode[39].

Technological advances and changes can also alter LCA results, as materials improve over time. Over the past years the gram weight of the 16.9 ounce "single serve" bottled water container has dropped by 32.6%[40]. The average PET bottled water container weighed 18.9 grams in 2000 and by 2008, the average amount of PET resin in each bottle has declined to 12.7 grams[41]. The amount of aluminium and steel used to produce cans has also been reduced by around 50% in the past 40 years: a 500ml aluminium can now weighs around 16 grams, while a steel can weighs around 30 grams[42]. Transport costs are a function of weight, so this further reduces outgoings and also CO_2 emissions. Another important factor in the LCAs is the source of electricity and the type of energy supplied during the whole product life which can dramatically influence the total environmental impacts[43].

[33] Madival, Auras, Singh, and Narayan, 'Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology'.

[34] Amienyo, Gujba, Stichnothe, and Azapagic, 'Life cycle environmental impacts of carbonated soft drinks'; H. H. Khoo, R. B. H. Tan, and K. W. L. Chng, 'Environmental impacts of conventional plastic and bio-Based carrier bags', International Journal of Life Cycle Assessment , 15/3 (2010), 284–93.

[35] Madival, Auras, Singh, and Narayan, 'Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology'.

[36] Pasqualino, Meneses, and Castells, 'The carbon footprint and energy consumption of beverage packaging selection and disposal'.

[37] A. Guiso, A. Parenti, P. Masella, L. Guerrini, F. Baldi, and P. Spugnoli, 'Environmental impact assessment of three packages for high-quality extra-virgin olive oil', Journal of Agricultural Engineering , 47/4 (2016), 191–96.

[38] Cleary, 'Life cycle assessments of wine and spirit packaging at the product and the municipal scale: A Toronto, Canada case study'.

[39] Katrin, M.-B., 'Prioritization guidelines for green food packaging development', British Food Journal, 118/10 (2016), 2512–33

[40] H. Forcinio, 'RPET OK in Canada, SPC Metrics, Concentrated Detergent', Sustainability Times , 4/2.

[41] Forcinio, 'RPET OK in Canada, SPC Metrics, Concentrated Detergent'.

[42] Metal Packaging Europe, 'Can logistics: lighter, greener and more efficient', (2020).

[43] Khoo, Tan, and Chng, 'Environmental impacts of conventional plastic and bio-Based carrier bags'.

Importance of recycling

Finally, considering the waste management capabilities of locations/countries where waste is collected at the end of its life is essential to have a full and accurate LCA. Many environmental impacts, such as environmental leakage and chemical migration, are not captured well by LCA when real-life waste scenarios are not considered. Changing waste management practices for food waste, including increasing redistribution, or separate collection of organic waste for composting and anaerobic digestion, for example has the potential to reduce the impact of waste and LCAs could be used to explore the waste reduction potential of these activities.

Some LCAs maintain the assumption that all products are collected, recycled, and reused in the end-of-life phase. The reality, however, is not that simple; and often depends on recycling rate in a particular study/country/city. End of life scenario has a great impact on the LCA results and on what can be done to reduce impacts, as currently 79% of plastic worldwide ends up in landfills or the environment[44]. Similarly, in some studies [26], where plastics perform better, it is assumed that the PET material recycling systems are operated with a high share of high-grade recycled PET in a closed loop. Assuming a high proportion of recycled PET in bottle production might not be a realistic assumption in some countries on one hand, on the other it shows the importance of closed loop recycling in improving the environmental performance of plastics. Amienyo et al. (2013) showed that increasing recycling rate to 60% of PET bottles would save approximately half of the emissions, equivalent to 445,000 tonnes of CO_2 eq. every year in that study[45].

Recycling wins over virgin production on all environmental measurements, especially when it comes to carbon emissions. Estimates vary with the type of recycling process used, but researchers agree that recycling and remanufacturing plastic saves between 30% and 80% of the carbon emissions that original processing and manufacturing produces. That could mean annual savings of 30 to 150 million tons of CO_2, given our previous calculations of carbon emissions from plastics production. An LCA study showed that the environmental impact of PET bottle-to-fibre recycling compared to virgin PET fibre and other commodity fibre products, i.e. cotton, viscose, PP (polypropylene) and PLA (polylactic acid) offer important environmental benefits[46]. Depending on the allocation methods applied for open-loop-recycling, non-renewable energy use savings of 40–85% and global warming potential savings of 25–75% can be achieved[47]. Recycled PET fibres produced by mechanical recycling performed better than virgin PET in at least eight out of a total of nine categories used in the study, with recycled fibres produced from chemical recycling performing better in six to seven out of nine categories compared to virgin PET fibres.

[44] D. Maga, M. Hiebel, and V. Aryan, 'A comparative life cycle assessment of meat trays made of various packaging materials', Sustainability (Switzerland) , 11/19 (2019); R. Geyer, J. R. Jambeck, and K. L. Law, 'Production, use, and fate of all plastics ever made', Science Advances , 3/7 (2017), 25–29.

[45] Amienyo, Gujba, Stichnothe, and Azapagic, 'Life cycle environmental impacts of carbonated soft drinks'.

[46] L. Shen, E. Worrell, and M. K. Patel, 'Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling', Resources, Conservation and Recycling , 55/1 (2010), 34–52.

[47] Shen, Worrell, and Patel, 'Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling'.

Discussion

According to a recent YouGov poll[49], only 2% of British people consider plastic, compared to other materials used in packaging, to contribute the least greenhouse gases to the environment from its production, use, and post use. The survey findings prompted a better understanding of the issues amongst the wider public to help them make "informed" decisions. Indeed, as reviewed in this work, in terms of carbon emissions, plastic is often the packaging material that is least damaging to the environment from a whole life cycle perspective, particularly when used in closed loop recycling, and most alternative packaging are actually not plastic free.

It should not be dismissed that plastics have a large and unacceptable impact on the marine environment and potentially impacts to human and ecosystem health that are not yet well understood and which cannot be easily expressed in figures and incorporated into life-cycle assessments. This complicates the choice made between carbon emissions versus marine pollution, environmental and health impacts in terms of deciding what to choose for packaging.

However, we believe this dilemma must be pragmatically managed. Environmental bodies and industry are already supporting the view that climate is one of the most serious threats to the ocean, certainly in the long term, which indirectly restricts most of the options for replacing plastics. On the other hand, global demand for plastics is expected to increase by some 22% over the next five years, with GHG emissions from plastics reaching 15% of the global carbon budget by 2050[50]. This anticipated growth of plastic production is of real concern, but we need to recognise that production is growing in response to increasing global demand for lightweight automotive parts, building insulation, and product packaging—all of which will play an important role in reducing greenhouse gas emissions and helping people live more sustainably around the world. We must be mindful to not fix a problem by removing one of the solutions.

What is clear is that we need to **reduce** plastics production while ensuring that any alternatives do not contribute more to climate change, and this is **where recycling comes in**. The emissions reductions from eliminating the need for new plastic outweigh the slightly higher emissions that come from processing wastes to recover plastics.

The findings of this study indicate that if we really want to tackle the environmental issues we face with plastics today, removing, reducing, reusing or recycling the plastic packaging placed on the market is an important part of the way forward, and a better option to replacing it with current alternative materials or waiting and hoping for solutions not yet available. Considering that only around 9% of plastics are currently being recycled worldwide, there is a lot that can be done to improve on this. We can see that when the right policy drivers are in place, this is happening already, with regulatory statutes that themself deliver fiscal actions on business. In the UK, the various measures planned in the UK Waste and Resources Strategy planned by DEFRA, such as the extended producer responsibility scheme, the deposit return scheme and the harmonisation of waste collection associated with a clear labelling system, as well as HM Treasury's proposed plastic packaging tax are all good steps for creating a fully functioning circular and sustainable system for packaging. Increasing the levels of recycled content in plastic packaging can reduce both the need for manufacturing plastics and the amount of plastic wastes produced[51]. As recycled plastic is more expensive than virgin plastic, the future plastic packaging tax announced by the UK government will be a key initiative to drive the market, increasing the recycling infrastructure and ultimately improving plastics recycling rate.

Widespread application of renewable energy, recycling and demand-management strategies in concert, have the potential to curb the growing life-cycle GHG emissions from plastics. Recycling can also play a key role in stopping plastics entering the marine environment, as once collected the chances of plastic waste entering the environment are reduced or at least there is clear accountability in what ultimately happens to plastic waste. Whilst it is not the only way to address the packaging conundrum, we can - at least in part - **recycle our way out of this problem**.

Building a sustainable system for packaging and all the products we use every day is achievable, but only if we accept to continue using plastic when it is the most carbon efficient option, supporting any material choice with scientific facts and not led by popular beliefs. Still, heightened public awareness of the growing and unsustainable plastics production provides policy makers with a unique mandate for change and businesses with opportunities for using packaging that can be easily recycled and reused. Making the transition to a sustainable circular economy is an important goal for society, yet, the complexity and interdependencies of such an undertaking mean that ecosystem-wide orchestration is necessary. Strong regulations and policies have a clear role to play in supporting recycling if we are ever to reach as a society a truly circular sustainable state.

[49] YouGov, 'Most Brits support ban on harmful plastic packaging', (2019).

[50] Zheng and Suh, 'Strategies to reduce the global carbon footprint of plastics'.

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Annex 1 - The 73 Life Cycle Studies of plastics reviewed in this study.

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