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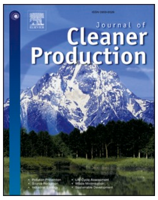

Human health effects of recycling and reusing food sector consumer plastics: A systematic review and meta-analysis of life cycle assessments

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ABSTRACT

Global transitions to circular economies of plastic could pose both risks and opportunities for human health. Life Cycle Assessment (LCA) can help to quantify possible health effects across plastic life cycles, syntheses of which could inform policy. This systematic review assessed LCA evidence for health effects of increased plastic recycling and reuse in the food sector. Scientific databases including Web of Science, Scopus, MEDLINE, Embase, Global Health, GreenFile and grey literature websites were searched for peer-reviewed LCA of consumer-level food sector plastics that compared virgin or single-use plastics with scenarios of increased recycling and reuse. Data on Human Health impacts and related midpoint impacts were extracted, converted to Disability-Adjusted Life Years (DALYs), and analysed using meta-regression. Forty-nine eligible LCAs were identified, only five of which related to low- and middle-income countries (China: $n = 1$ and Thailand: $n = 4$). Meta-regression showed strong evidence for a linear trend in reducing DALYs with increasing percentage recycled content compared to virgin plastic (Coefficient = −1.96E-5; 95% CI = −2.69E-5 to −1.24E-5; $p < 0.0001$) and increasing end-of-life recycling rate compared to landfill and/or incineration (Coefficient = −2.1E-5; 95% CI = −2.60E-5 to −1.63E-5; $p < 0.0001$), equating to almost a day of healthy life saved globally per tonne of plastic recycled. On average, reusable plastics reduced climate-related health impacts associated with single-use plastics after 30 uses. Global assessment was limited by data deficits, but meta-analyses suggested that health risks from linear economies of food sector plastics could be reduced by increasing recycling and reuse rates, though some reusable plastics would need to be used many more times than current norms. Encouraging greater geographical coverage in LCA, increasing uptake of health impact assessment methods, and incorporating emerging health data will strengthen future public health evaluations of circular economies.

1. Introduction

1.1. Background

The plastic linear economy is a resource-intensive and highly wasteful model of material management, driving unsustainable environmental damage and subsequent human health risks. By 2050, the plastics sector could be responsible for 20% of oil consumption if production remains dependent on virgin fossil feedstocks (World Economic Forum et al., 2016). Packaging is the largest market sector for primary polymer production (36%) and accounts for almost half of plastic waste produced (Geyer et al., 2017), most of which is likely to be generated by the food and beverage sectors where short-lifespan, single-use packaging proliferates (Cimpan et al., 2021). Around 390 million metric tonnes of plastic waste will be produced globally in 2023 alone, rising thereafter (OECD, 2023). Of this, 42% is likely to be mismanaged,

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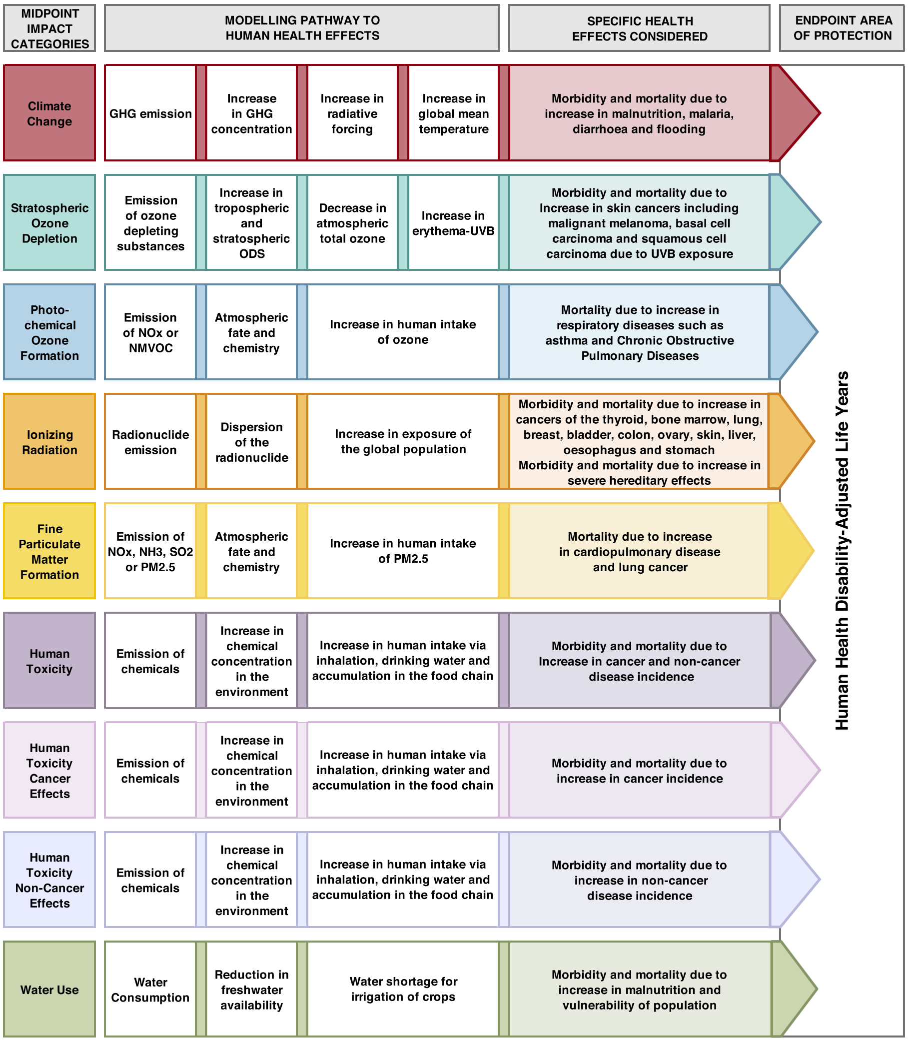
ending in unregulated dumpsites, open burning, and environmental pollution (Lau et al., 2020). Mismanaged waste has been suggested to cause between 400,000 and 1 million disease-related deaths a year in low- and middle-income countries (LMICs) (Tearfund et al., 2019).

The Sustainable Development Goals (SDGs) put responsible management of resources and waste reduction on the global agenda, highlighting circular economy approaches such as recycling and reuse as key alternatives to the linear economy (United Nations, 2015). A resolution for a legally binding Global Plastics Treaty to end plastic pollution was passed at the United Nations Environment Assembly in 2022 (United Nations Environment Programme, 2022a). Treaty negotiations will have to consider and compare the effectiveness of different waste reduction strategies, accounting for any benefits plastics provide society and balancing against any detrimental effects across environmental, social, and economic sustainability objectives (United Nations Environment Programme, 2022a). Research suggests that circular economy strategies could provide co-benefits for reducing climate change (Material Economics, 2016) and increasing employment (Green Alliance and WRAP, 2015). Yet, the potential opportunities and risks for human health remain poorly understood (World Health Organization, 2018).

Opportunities to improve health outcomes through circularity could be derived from reducing the impacts of the linear economy of plastics. For example, increased recycling and reuse would reduce the need for raw material extraction required by virgin plastic production and circumvent open burning at the end of life. These processes cause air pollution linked to respiratory diseases, and lead to greenhouse gas emissions which in turn increase heat-related morbidity and mortality due to climate change (Azoulay et al., 2019). Circular strategies could also pose health risks associated with occupational chemical exposure during remanufacturing processes, consumer exposure to unintentionally added chemicals in recycled plastics, or contaminants during reuse (World Health Organization, 2018). Whilst some evidence of these health effects exists, it is often limited by challenges of attribution or restricted to discrete stages of the packaging life cycle (Azoulay et al., 2019).

To comprehensively assess possible health co-benefits and trade-offs of circular strategies, methods based on systems thinking are required. Life Cycle Assessment (LCA) has been endorsed as the current most effective framework for assessing environmental impacts associated with products (European Commission, 2003), and as an effective tool for assessing the sustainability of the circular economy (Peña et al., 2021). LCA can also provide estimates of health effects, calculated in Disability-Adjusted Life Years (DALYs). This estimate is the sum of human morbidity and mortality resulting from environmental health



MIDPOINT IMPACT CATEGORIES	MODELLING PATHWAY TO HUMAN HEALTH EFFECTS				SPECIFIC HEALTH EFFECTS CONSIDERED	ENDPOINT AREA OF PROTECTION
Climate Change	GHG emission	Increase in GHG concentration	Increase in radiative forcing	Increase in global mean temperature	Morbidity and mortality due to increase in malnutrition, malaria, diarrhoea and flooding	Human Health Disability-Adjusted Life Years
Stratospheric Ozone Depletion	Emission of ozone depleting substances	Increase in tropospheric and stratospheric ODS	Decrease in atmospheric total ozone	Increase in erythema-UVB	Morbidity and mortality due to Increase in skin cancers including malignant melanoma, basal cell carcinoma and squamous cell carcinoma due to UVB exposure	
Photo-chemical Ozone Formation	Emission of NOx or NMVOC	Atmospheric fate and chemistry	Increase in human intake of ozone		Mortality due to increase in respiratory diseases such as asthma and Chronic Obstructive Pulmonary Diseases	
Ionizing Radiation	Radionuclide emission	Dispersion of the radionuclide	Increase in exposure of the global population		Morbidity and mortality due to increase in cancers of the thyroid, bone marrow, lung, breast, bladder, colon, ovary, skin, liver, oesophagus and stomach Morbidity and mortality due to increase in severe hereditary effects	
Fine Particulate Matter Formation	Emission of NOx, NH3, SO2 or PM2.5	Atmospheric fate and chemistry	Increase in human intake of PM2.5		Mortality due to increase in cardiopulmonary disease and lung cancer	
Human Toxicity	Emission of chemicals	Increase in chemical concentration in the environment	Increase in human intake via inhalation, drinking water and accumulation in the food chain		Morbidity and mortality due to Increase in cancer and non-cancer disease incidence	
Human Toxicity Cancer Effects	Emission of chemicals	Increase in chemical concentration in the environment	Increase in human intake via inhalation, drinking water and accumulation in the food chain		Morbidity and mortality due to increase in cancer incidence	
Human Toxicity Non-Cancer Effects	Emission of chemicals	Increase in chemical concentration in the environment	Increase in human intake via inhalation, drinking water and accumulation in the food chain		Morbidity and mortality due to increase in non-cancer disease incidence	
Water Use	Water Consumption	Reduction in freshwater availability	Water shortage for irrigation of crops		Morbidity and mortality due to increase in malnutrition and vulnerability of population	

Fig. 1. Modelling human health effects in Life Cycle Assessments. Life Cycle Assessment (LCA) conceptual modelling process of health impact pathways from midpoint health-related categories to endpoint Human Health Disability-Adjusted Life Years (DALYs), according to ReCiPe 2016 LCA impact assessment method. Authors' own: Adapted from ReCiPe 2016 v1.1 Report 1: Characterization. 2017 (Huijbregts et al., 2017).

pathways (Fig. 1), calculated by applying conversion factors based on the latest scientific evidence to a complete inventory of the resources used and emissions generated by a product and its life cycle processes (Verones et al., 2017). This unique perspective allows circular versus linear economy health impacts to be analysed across plastic production, transport, consumer use and disposal.

1.2. Syntheses of life cycle assessments and research gaps

Systematic reviews and meta-analyses are considered to be the most robust form of evidence in many disciplines, particularly in medicine and public health (OCEBM Levels of Evidence Working Group, 2011). These approaches are used to summarise and synthesise existing evidence, compare methodological approaches, identify trends, gaps, and sources of uncertainty in the evidence, and to pool effect estimates for greater statistical power or to answer new questions, which in turn can better support decision making (Zumsteg et al., 2012). LCA as a discipline is proliferating, with rapidly increasing numbers of publications on similar products and processes but with varied data inputs, methodological approaches, impact estimates and even differences in conclusions. Recent reviews of LCA of food sector plastics have provided important insights: (1) significant variability exists in the methodological approaches used in LCA to model plastic recycling, which may lead to differences in impacts (Kousemaker et al., 2021), (2) packaging produced with recycled material tends to show lower environmental impacts than the same virgin material but end-of-life recycling of packaging is not consistently favourable over alternatives (Vendries et al., 2020), and (3) that reusable plastic products including bags (United Nations Environment Programme, 2020), cups (United Nations Environment Programme, 2021), and supermarket packaging (United Nations Environment Programme, 2022b) can be superior to single-use but this depends on a number of factors such as material and mass, electricity mix, washing rates, and impact assessment indicators. These reviews were comprehensive but not systematic and do not provide a statistical meta-analysis of data across studies, nor were they designed to review or extend LCA data to consider human health. Statistical meta-analyses of LCA, harmonising data across studies in pooled analyses, can support a greater understanding of the possible magnitude of impacts and their methodological drivers (Brandão et al., 2012). This insight is critical to estimating the scale of possible health impacts associated with waste reduction strategies and to quantitatively assessing the importance of co-benefits or trade-offs.

This systematic review and meta-analysis of evidence from LCA studies aimed to assess how health impacts have been considered in existing LCA of selected food sector consumer plastics and to provide a quantitative analysis of possible human health risks and opportunities associated with recycling and reuse across the life cycle of plastic products. The two primary objectives of this paper were:

Objective 1: To identify trends and gaps in the use of health-related indicators in LCA of plastic primary food and drink packaging, food service ware and grocery bags that compare virgin and single-use plastics to recycling and reuse options.

Objective 2: To quantitatively meta-analyse LCA data to assess the human health effects of increasing recycling and reuse of plastic primary food and drink packaging, food service ware and grocery bags.

2. Materials and methods

This review was conducted according to the standardised technique for assessing and reporting reviews of LCA (STARR-LCA) checklist (Zumsteg et al., 2012), and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) reporting guidelines (Moher et al., 2009) (Table S1). A study protocol was prospectively registered (Deeney et al., 2020).

2.1. Search strategy

A systematic search was conducted in Web of Science, Scopus, MEDLINE, Embase, Global Health and GreenFile databases on July 29, 2020 and the search was updated on July 22, 2021 with no limits on geographical location, language, or publication date. Key search terms for LCA, food sector consumer plastics, and recycling and reuse were combined. All database search strings are provided in Tables S2–S7, this example was run in Scopus:

TITLE-ABS-KEY ((lca OR lcas OR lcia OR lcias OR {life cycle} OR {life-cycle}) AND (packag* OR pack OR packs OR packet OR packets OR container* OR casing OR casings OR pouch OR pouches OR pot OR pots OR punnet OR punnets OR carton OR cartons OR box OR boxes OR tray* OR film OR films OR wrap OR wraps OR wrapping OR wrappings OR wrapper OR wrappers OR bottle* OR cup OR cups OR bag OR bags OR cap OR caps OR clamshell* OR tableware OR {food service ware} OR cutlery OR crockery OR spoon OR spoons OR fork OR forks OR knife OR knives) AND (food* OR beverage* OR drink* OR water OR waste OR plastic OR plastics OR polyolefin OR polyolefins OR polyethylene OR polythene OR pe OR pet OR hdpe OR mdpe OR ldpe OR lldpe OR {polyvinyl chloride} OR pvc OR polypropylene OR pp OR polystyrene OR ps OR acrylic OR polycarbonate OR pc OR polylactide OR {polylactic acid} OR pla OR styrofoam OR styrene OR {acrylonitrile butadiene} OR nylon OR pa OR fibreglass OR fiberglass OR tetrapak OR {tetra pak} OR {single-use} OR {single-use} OR {one-way} OR {one way} OR disposable OR vacuum OR aseptic OR multilayer* OR recycl* OR reuse OR reusing OR reused OR reusable OR multi-use OR multiuse))

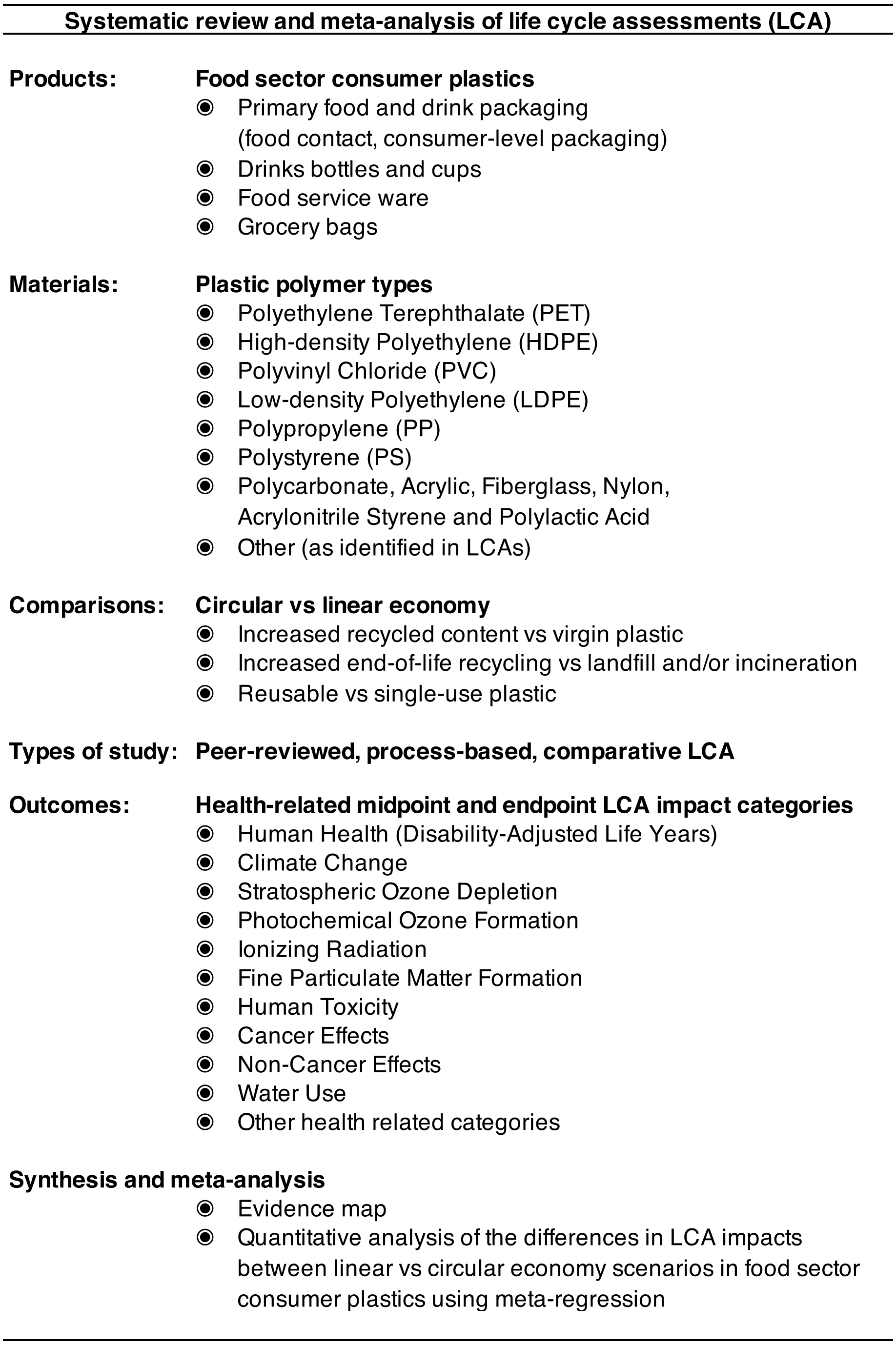
Websites of relevant organisations and select government agencies were searched for grey literature (Table S8), reference lists of included LCAs were screened, and authors were contacted where necessary to retrieve studies.

2.2. Eligibility criteria

Studies were included if they were peer-reviewed, process-based, comparative LCA of plastic food and drink primary packaging (defined as consumer-level, food contact packaging), food and drink service ware and grocery bags that compare virgin and single-use plastics with recycling and reuse options. These plastic products are collectively referred to as '*food sector consumer plastics*' in this review. Eligible functional units included those based on a specific number of plastic products (e.g. 1000 cups), a measure of plastic mass (e.g. 1000 kg of plastic food packaging) or the provision of a service (e.g. the bags required for 1000 shopping trips). Eligible studies considered the whole packaging life cycle, at a minimum including both plastic production and end-of-life stages in the system boundaries of the assessment. All plastic polymer types were eligible, including those listed in the Resin Identification Codes that informed the search strategy (ASTM International, 2020), and any other types of plastic identified in the literature, including bio-based plastics (Fig. 2).

Only comparative LCAs were included, focusing on the differences between linear and circular scenarios as identified within studies, rather than across studies, to reduce confounding by varying methodological choices and assumptions in different LCAs (Zumsteg et al., 2012). Three groups of LCA comparisons were eligible:

1) Recycled content of food sector consumer plastics: LCAs comparing a unit of plastic product made entirely of virgin plastic, or lower recycled content, compared to the same product made of any higher level of recycled plastic content. For example, a 100% virgin polyethylene terephthalate (PET) bottle compared with a 20% recycled content PET bottle
2) End-of-life recycling of food sector consumer plastics: LCAs comparing incineration and/or landfill of plastic products with any higher rates of recycling. For example, a PET bottle with 100% incineration at the end of its life cycle compared to 100% recycling



Systematic review and meta-analysis of life cycle assessments (LCA)

Products: **Food sector consumer plastics**
- Primary food and drink packaging (food contact, consumer-level packaging)
- Drinks bottles and cups
- Food service ware
- Grocery bags

Materials: **Plastic polymer types**
- Polyethylene Terephthalate (PET)
- High-density Polyethylene (HDPE)
- Polyvinyl Chloride (PVC)
- Low-density Polyethylene (LDPE)
- Polypropylene (PP)
- Polystyrene (PS)
- Polycarbonate, Acrylic, Fiberglass, Nylon, Acrylonitrile Styrene and Polylactic Acid
- Other (as identified in LCAs)

Comparisons: **Circular vs linear economy**
- Increased recycled content vs virgin plastic
- Increased end-of-life recycling vs landfill and/or incineration
- Reusable vs single-use plastic

Types of study: **Peer-reviewed, process-based, comparative LCA**

Outcomes: **Health-related midpoint and endpoint LCA impact categories**
- Human Health (Disability-Adjusted Life Years)
- Climate Change
- Stratospheric Ozone Depletion
- Photochemical Ozone Formation
- Ionizing Radiation
- Fine Particulate Matter Formation
- Human Toxicity
- Cancer Effects
- Non-Cancer Effects
- Water Use
- Other health related categories

Synthesis and meta-analysis
- Evidence map
- Quantitative analysis of the differences in LCA impacts between linear vs circular economy scenarios in food sector consumer plastics using meta-regression

Fig. 2. Summary of systematic review eligibility criteria and meta-analysis strategy. Life cycle assessments (LCAs) were systematically screened against pre-defined eligibility criteria. Studies were required to meet at least one of the inclusion criteria under each of the sub-headings. Strategy for synthesis and meta-analysis of data extracted from LCAs included an evidence map, summary statistics and regression.

3) Reusable food sector consumer plastics: LCAs comparing plastic products designed for single-use compared to plastic products designed to be reused for the same purpose. Eligible studies could compare any number of uses of the reusable product. For example, a PET bottle designed for single-use, and used once, compared with a PET bottle that is designed to be reused, and is used 20 times

LCA methodology offers a range of possible impact categories that can be modelled. To be eligible for this review, each LCA was required to model at least one of the available health-related impact categories including: the endpoint modelling category “Human Health” (calculated in DALYs) and/or contributing midpoint impact categories including “Climate Change”, “Stratospheric Ozone Depletion”, “Particulate Matter Formation”, “Photochemical Ozone Formation”, “Ionizing Radiation”, “Human Toxicity” and “Water Use” (Verones et al., 2017). This specific terminology is taken from the ReCiPe 2016 methodology; in which DALYs are based on estimated morbidity and mortality from respiratory diseases, cancers, malnutrition, malaria, diarrhoea, and flooding (Fig. 1) (Huijbregts et al., 2017). Studies using other LCA impact assessment methodologies were also eligible for this review.

Studies that only reported inventory data, purely economic input-output or social LCAs and all other study designs were excluded. LCAs that only compared plastic with another type of material (e.g., glass or paper) and those in which the product was a composite of plastic and other materials such as paperboard, were excluded. Plastic used in other parts of the food system (e.g., in agriculture or secondary and tertiary packaging for bulk transport) was excluded, as were studies in which plastic packaging was only part of the inventory list for a food product functional unit. Studies that only reported environmental, non-health related impact indicators according to LCA methods (Verones et al., 2017) were excluded.

2.3. Data screening and extraction

Records were exported from database searches into Eppi Reviewer software. Screening was conducted in two stages, by title and abstract and then by full text, with 10% checks completed by a second researcher at both stages. Agreement rates were 98% at title and abstract stage and 94% on full text, discrepancies were discussed and resolved by consensus. The data extraction form was developed in Eppi Reviewer and captured key aspects of LCA including the goal and scope definition, data inventory sources and modelling assumptions, impact assessment methods and impact data. Data extraction was carried out with 10% checks completed by a second researcher. Study authors were contacted directly to request additional information and data where necessary. Full data extraction tables are available in **Data S1, S4 and S9.**

2.4. Reporting quality and suitability for meta-analysis

Only LCAs that were peer-reviewed or subject to critical review were included. A tool proposed by Price and Kendall (2012) was adapted to assess the reporting transparency of included articles and their suitability for the purpose of the meta-analysis, based on (1) the completeness of life-cycle modelling, (2) methodological focus and input data transparency, and (3) the granularity of impact assessment. This was not an appraisal of overall study quality, and lower scores may indicate that individual studies, whilst relevant, were designed to meet different objectives from those of this review. This assessment was carried out on all studies with 10% checks completed by a second researcher. The full tool is provided in Fig. S1.

2.5. Analysis

2.5.1. Evidence map

An interactive evidence and gap map was created using Eppi Reviewer software to visualise the frequencies of LCA studies by their circular economy comparisons, cross-tabulated by LCA impact categories. The map is segmented by product type and can be further filtered by plastic material types and geographical location.

2.5.2. Quantitative meta-analysis

Each included study provided quantitative LCA impact assessment data for a reference linear economy food sector consumer plastic product and comparative impact data for the same product under scenario(s) of increased circularity including: (1) increased recycled content, (2) increased end-of-life recycling, and/or (3) design for reuse and increased reuse. Impact assessment data was extracted for all health-relevant indicators and results were tabulated in Excel.

Binary comparisons of extracted impact data were created in Excel to quantitatively compare linear versus circular economy scenarios *within* studies, calculating the absolute difference in LCA impacts (e.g. number of kg CO_2 equivalents) (**Equation 1**) and the percent difference (e.g. relative percent change in kg CO_2 equivalents) (**Equation 2**) between scenarios.

Equation 1. Absolute difference in Life Cycle Assessment impacts

$$\textit{Absolute difference} = I_R - I_{VS}$$

Equation 2. Percent difference in Life Cycle Assessment impacts

$$\textit{Relative percent change} = \frac{I_R - I_{VS}}{I_{VS}}$$

where:

I_{VS} = The impact of the reference virgin plastic or single-use plastic product
I_R = The impact of the recycling or reuse comparison

For studies of recycling, these calculations were only conducted for comparisons based on the same polymer type so that differences in LCA impacts were derived purely from increased recycled content or increased end-of-life recycling, rather than a result of different polymer compositions. Reuse comparisons where the single-use product was a different polymer to the reusable product were included to acknowledge differences in product design. The values calculated from within studies for the absolute and relative differences in LCA impacts between linear and circular scenarios, are subsequently referred to as *data points (dps)* in this review. These data are available in full in **Data S2, S5 and S10.**

Comparisons *between* studies were considered by calculating the *average* percent difference in LCA impacts for common linear and circular economy scenarios across the studies, summarised using the median and interquartile range of percent differences taken from individual studies. These data are available in **Data S2, S5, S6 and S10**. For consistency, ReCiPe 2016 terminology was used to describe the impact categories, but these groups also include data from studies using other methods, which were grouped based on conceptual similarity.

2.5.2.1. Meta-analysis using mixed-effects linear regression. Mixed-effects linear regression was conducted in Stata 17.0 with the *xtmixed* command, specifying random effects for individual studies to account for multiple comparisons of linear versus circular economy scenarios within each study. The range of values was used for percentage recycled content, percentage end-of-life recycling and number of uses for reusable products as identified across studies as predictor variables. Including only studies that used 0% recycled content, 0% recycling or a single-use item used once as the reference baseline allowed the response variable to be meaningful as the absolute or relative difference in LCA health-related impacts. In line with Cochrane advice, meta-regressions were restricted to LCA impact categories for which there was minimum of 10 studies (Deeks et al., 2021), and that had at least 5 variations in the predictor variable.

To compare both the effects of increasing recycled content, and increasing end-of-life recycling, across studies, functional units and impact data were standardised to 1 metric tonne of plastic. Reference flow data provided in each study was used to calculate the plastic mass equivalent to the functional unit described, then impact assessment data was scaled to 1 metric tonne. Detailed documentation of each calculation is provided in **S1.3 and 2.4**. A fixed intercept at 0 was included to facilitate interpretation of the co-efficient and because 0% recycled content or 0% end-of-life recycling is equivalent to the reference baseline therefore there is no difference in impacts. All midpoint impacts were standardised to ReCiPe 2016 Hierarchic perspective midpoint indicators, and subsequently converted to DALYs using the same method (Huijbregts et al., 2017). The only exceptions were for some midpoint Human Toxicity indicators for which 2016 conversions were not available. Comparative Toxic Units for human toxicity (CTUh) were converted to DALYs using factors for Cancer Effects and Non-Cancer Effects from the International Resource Panel (International Resource Panel, 2019). Where Human Toxicity was not disaggregated by Cancer and Non-Cancer Effects, ReCiPe 2008 conversion factors (Goedkoop et al., 2009) were used. Where converting impact indicators was not possible or meaningful, data were excluded from the meta-analysis, as highlighted in **Data S3 and S7**. Studies reported different numbers of health-related midpoint indicators. The Total DALYs is based on the sum of DALYs from all provided midpoint indicators within each study. This means that for some studies, DALY estimates are based on one pathway only, whereas estimates from other studies were based on multiple pathways depending on data provided. A detailed description of all conversions and the number of midpoint indicators contributing to each DALY estimate is provided in **Data S3, S7 and S8.**

For comparisons of reuse, standardisation of functional units was not possible because of the variability in definitions between studies and because of the comparisons based on different polymers within studies, so the unitless percent difference values were used in regressions. The number of uses required to ensure the reusable product had lower or equal health related impacts compared to the single-use product was estimated using the regression formula to calculate x (number of uses) when y = 0 (relative percent change in impacts). This is referred to as the *break-even point*.

The Stata do file is available in **Data S12** and all Stata regression outputs are available in Figs. S11–S13.

3. Results

Initial database searches retrieved 10,499 unique records. After screening by title and abstract, 532 records were eligible for full text screening, of which 30 were included in this review. Searching reference lists of included studies and contact with the authors resulted in eight additional studies for inclusion. The updated database search, on the July 22, 2021, produced seven new eligible studies and grey literature searches returned four, resulting in a total of 49 LCA studies included in this review (Fig. 3).

3.1. Characteristics of included life cycle assessments: trends and gaps in evidence

All included studies were published in the last 20 years, with the highest number of annual publications in 2020–2021. Evidence from high-income countries in Europe and the United States of America predominated (n = 44 studies), with four from Thailand and one from China. Only one study calculated Human Health impacts in DALYs, all studies assessed Climate Change (n = 49), but fewer calculated other health-related midpoint indicators, such as Cancer and Non-Cancer Effects (n = 6 and n = 4) (Fig. 4). These studies can be explored in the interactive, online evidence map and filtered by product and polymer type, publication date and location. Complete data extraction and meta-analysis calculations are available in **Data S1-11.**

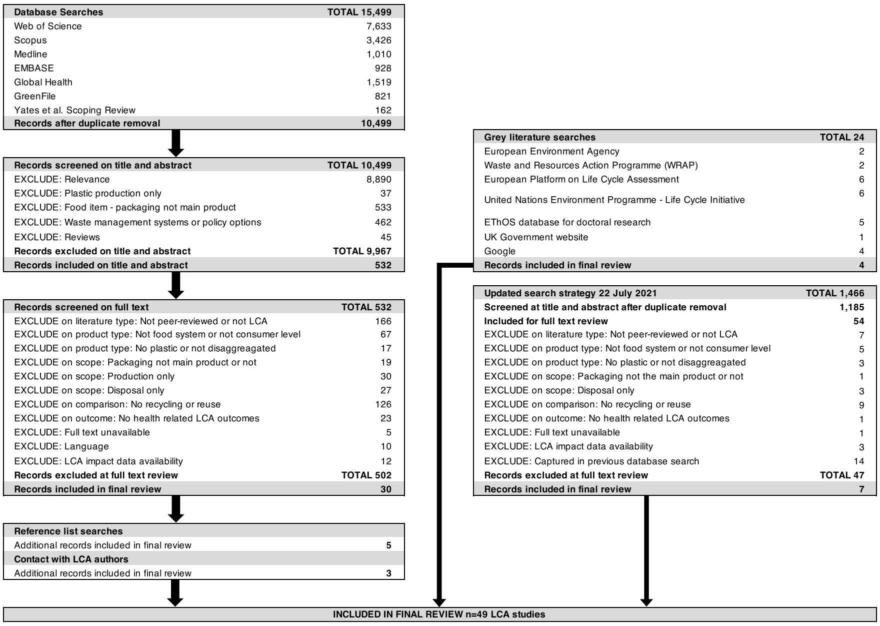
3.2. Reporting quality and suitability for meta-analysis

None of the LCAs explicitly sought to determine health impacts of recycling and reuse in their goal definition though many calculated relevant midpoint categories. Most LCAs provided a detailed description of the functional units with weight measurements (88%) and modelled the plastic life cycle comprehensively (Fig. S2), though the consumer use phase was rarely included in recycling comparisons, most authors stating assumed negligible or equal impacts during this phase. Two thirds of studies provided evidence of sufficient data for all modelled life cycle stages, either by publishing the data, or detailing and referencing sources. The specific method for accounting for recycling and reuse was not explicit in 29% of studies and 8% did not provide the specific impact assessment method used. Total life cycle impacts were reported in 47 studies, the other two presented impact data by life cycle stage under multiple scenarios. Half the included studies presented disaggregated results for at least some of the life cycle stages modelled.

The quality of reporting through provision of comprehensive information on data inputs, methodological choices, and granular analysis of impacts was inconsistent in included LCAs, which limited understanding of the differences and drivers of impact results. Given the small number of studies, the resulting scores were not used to exclude studies from meta-analysis but to aid discussion of the literature.

3.3. Meta-analysis of the health effects of increasing recycled content of food sector consumer plastics

This review identified 15 LCAs that assessed increasing the recycled content of food sector consumer plastics (Camps-Posino et al., 2021;



Database Searches	**TOTAL 15,499**
Web of Science	7,633
Scopus	3,426
Medline	1,010
EMBASE	928
Global Health	1,519
GreenFile	821
Yates et al. Scoping Review	162
Records after duplicate removal	**10,499**

Records screened on title and abstract	**TOTAL 10,499**
EXCLUDE: Relevance	8,890
EXCLUDE: Plastic production only	37
EXCLUDE: Food item - packaging not main product	533
EXCLUDE: Waste management systems or policy options	462
EXCLUDE: Reviews	45
Records excluded on title and abstract	**TOTAL 9,967**
Records included on title and abstract	**532**

Records screened on full text	**TOTAL 532**
EXCLUDE on literature type: Not peer-reviewed or not LCA	166
EXCLUDE on product type: Not food system or not consumer level	67
EXCLUDE on product type: No plastic or not disaggreagated	17
EXCLUDE on scope: Packaging not main product or not	19
EXCLUDE on scope: Production only	30
EXCLUDE on scope: Disposal only	27
EXCLUDE on comparison: No recycling or reuse	126
EXCLUDE on outcome: No health related LCA outcomes	23
EXCLUDE: Full text unavailable	5
EXCLUDE: Language	10
EXCLUDE: LCA impact data availability	12
Records excluded at full text review	**TOTAL 502**
Records included in final review	**30**

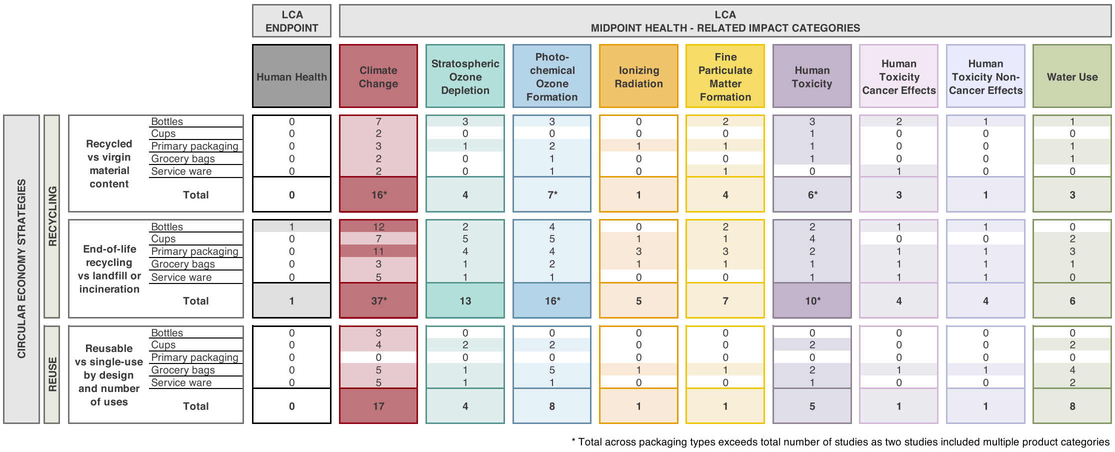
Reference list searches	
Additional records included in final review	**5**
Contact with LCA authors	
Additional records included in final review	**3**

Grey literature searches	**TOTAL 24**
European Environment Agency	2
Waste and Resources Action Programme (WRAP)	2
European Platform on Life Cycle Assessment	6
United Nations Environment Programme - Life Cycle Initiative	6
EThOS database for doctoral research	5
UK Government website	1
Google	4
Records included in final review	**4**

Updated search strategy 22 July 2021	**TOTAL 1,466**
Screened at title and abstract after duplicate removal	**1,185**
Included for full text review	**54**
EXCLUDE on literature type: Not peer-reviewed or not LCA	7
EXCLUDE on product type: Not food system or not consumer level	5
EXCLUDE on product type: No plastic or not disaggreagated	3
EXCLUDE on scope: Packaging not the main product or not	1
EXCLUDE on scope: Disposal only	3
EXCLUDE on comparison: No recycling or reuse	9
EXCLUDE on outcome: No health related LCA outcomes	1
EXCLUDE: Full text unavailable	1
EXCLUDE: LCA impact data availability	3
EXCLUDE: Captured in previous database search	14
Records excluded at full text review	**TOTAL 47**
Records included in final review	**7**

INCLUDED IN FINAL REVIEW n=49 LCA studies

Fig. 3. PRISMA flow chart. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow chart showing the study selection process for inclusion of Life Cycle Assessments in the systematic review according to pre-defined eligibility criteria.



CIRCULAR ECONOMY STRATEGIES			LCA ENDPOINT	LCA MIDPOINT HEALTH - RELATED IMPACT CATEGORIES								
			Human Health	Climate Change	Stratospheric Ozone Depletion	Photo-chemical Ozone Formation	Ionizing Radiation	Fine Particulate Matter Formation	Human Toxicity	Human Toxicity Cancer Effects	Human Toxicity Non-Cancer Effects	Water Use
RECYCLING	Recycled vs virgin material content	Bottles	0	7	3	3	0	2	3	2	1	1
		Cups	0	2	0	0	0	0	1	0	0	0
		Primary packaging	0	3	1	2	1	1	1	0	0	1
		Grocery bags	0	2	0	1	0	0	1	0	0	1
		Service ware	0	2	0	1	0	1	0	1	0	0
		Total	**0**	**16***	**4**	**7***	**1**	**4**	**6***	**3**	**1**	**3**
	End-of-life recycling vs landfill or incineration	Bottles	1	12	2	4	0	2	2	1	1	0
		Cups	0	7	5	5	1	1	4	0	0	2
		Primary packaging	0	11	4	4	3	3	2	1	1	3
		Grocery bags	0	3	1	2	1	1	1	1	1	1
		Service ware	0	5	1	1	0	0	1	1	1	0
		Total	**1**	**37***	**13**	**16***	**5**	**7**	**10***	**4**	**4**	**6**
REUSE	Reusable vs single-use by design and number of uses	Bottles	0	3	0	0	0	0	0	0	0	0
		Cups	0	4	2	2	0	0	2	0	0	2
		Primary packaging	0	0	0	0	0	0	0	0	0	0
		Grocery bags	0	5	1	5	1	1	2	1	1	4
		Service ware	0	5	1	1	0	0	1	0	0	2
		Total	**0**	**17**	**4**	**8**	**1**	**1**	**5**	**1**	**1**	**8**

* Total across packaging types exceeds total number of studies as two studies included multiple product categories

Fig. 4. Static map of Life Cycle Assessment studies on food sector consumer plastics recycling and reuse. Frequency of Life Cycle Assessment (LCA) studies included in the systematic review, cross tabulated by: (1) the specific circular economy comparison categories considered in each study: recycled versus virgin material content, end-of-life recycling versus landfill or incineration, reusable versus single-use by design and number of uses; (2) the product type: bottles, cups, primary food packaging, grocery bags or service ware and (3) the health-related LCA impact categories calculated in each study. Full data extraction is provided in Data S1, S4 and S9.

Changwichan and Gheewala, 2020; Dormer et al., 2013; Hekkert et al., 2000; Horowitz et al., 2018; Kimmel, 2014; Kouloumpis et al., 2020; Kruger et al., 2009; Maga et al., 2019; Mattila et al., 2011; Nessi et al., 2012; Rybaczewska-Blazejowska and Mena-Nieto, 2020; Stefanini et al., 2021; van der Harst et al., 2016; WRAP, 2010), two of which related to LMICs (Camps-Posino et al., 2021; Changwichan and Gheewala, 2020). To examine the level of agreement between LCAs in assessing health-related impacts based on the same scenario, studies that compared 100% recycled plastic products to the same products made of virgin plastic were analysed (Fig. 5). All studies showed that recycled products had lower impacts in Climate Change, Ozone Depletion, Photochemical Ozone Formation, Ionizing Radiation, Particulate Matter Formation, Human Toxicity and Cancer Effects, relative to their virgin plastic counterparts. These data demonstrate general agreement between studies in terms of the direction of effect, though LMIC LCAs did not assess this scenario. On average, 100% recycled plastics had as little as half the impacts of virgin plastics, but estimates ranged considerably between studies. One study estimated a very small increase in Non-Cancer Effects from 100% recycled plastic, and Water Use was the only impact for which the direction of the relationship was unclear: on average across studies there was a 7.03% increase in Water Use for 100% recycled plastic, but one study estimated a 20% reduction (dps = 3; Median = 7.03%; IQR = −21.52% to 9.50%). The mean and standard deviations are available in Fig. S3.

Meta-regression was used to analyse the absolute impacts of increasing recycled content on health-related outcomes. Relative to baseline 0% recycled plastic, increasing percentage recycled content showed strong evidence for a linear relationship with decreasing

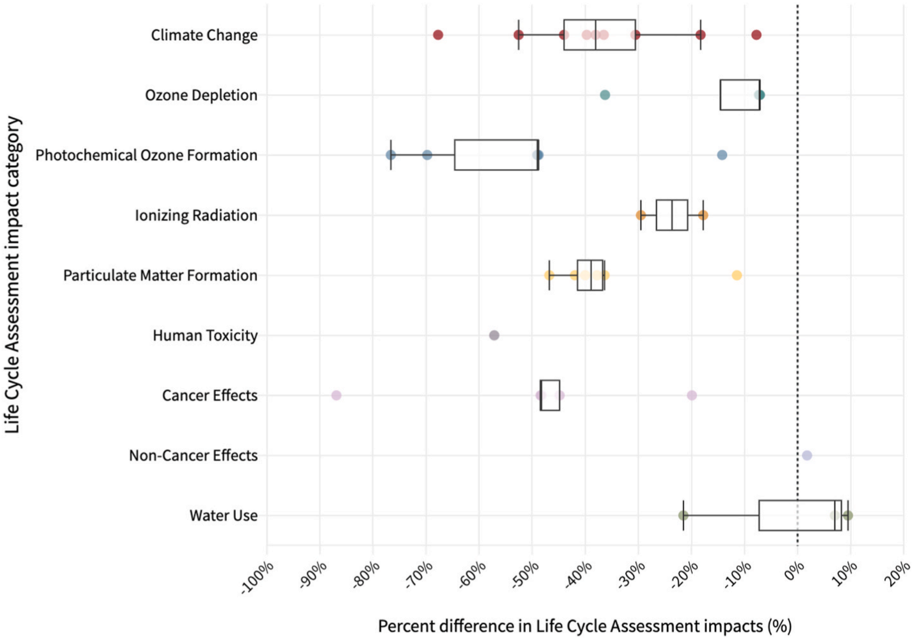


Fig. 5. Relative health-related impacts of 100% recycled plastic content. Percent difference in health-related Life Cycle Assessment (LCA) impacts, comparing 100% recycled food sector consumer plastics to virgin plastics. Values calculated for each comparison identified within LCA studies are represented with dots and summarised using box plots of the median and interquartile range (IQR) with Tukey fences (1.5 x IQR). All data are provided in Data S2.

Climate Change impacts and Total DALYs based on 41 comparisons extracted from 13 studies (three comparisons from one LMIC study) (Fig. 6a). Of these comparisons of increased recycled content, 21 related to bottles, six to service ware, five to cups, five to grocery bags and four to food packaging. On average, relative to virgin plastic, there was an additional 161 kg decrease in Climate Change impacts (kg CO_2 equivalents), for every 10% increase in recycled content in 1 metric tonne of food sector consumer plastics (Coefficient $= -16.10$; 95% CI $= -20.64$ to -11.55; $p < 0.0001$).

There was insufficient data on other midpoint impact categories to create separate regression models, but the Total DALYs resulting from combined midpoint indicators within each study were calculated **(Data S3).** The trend for Total DALYs remained in favour of increasing recycled content. On average, relative to virgin plastic, there was an additional 0.00020 decrease in Total DALYs for every 10% increase in recycled content in 1 metric tonne of food sector consumer plastics (Coefficient -0.000020; 95% CI $= -0.000027$ to -0.000012; $p < 0.0001$) (Fig. 6b). This equates to nearly a day of healthy life gained for every tonne made from 100% recycled plastic as opposed to virgin plastic (0.72 days). Stata outputs are available in Fig. S4.

Reductions in Total DALYs were largely due to reductions in Climate Change impacts, though in some cases Climate Change effects contributed to increasing DALYs (Fig. S5). Particulate Matter Formation contributed to reductions in Total DALYs more than the Climate Change effects in six comparisons, and Human Toxicity mostly supported reductions in DALYs though increased them in three cases. Two studies could not be included in quantitative meta-analysis because the recycled content comparison was part of a mixed strategy scenario, but both showed decreased impacts relative to other scenarios (Camps-Posino et al., 2021; Hekkert et al., 2000).

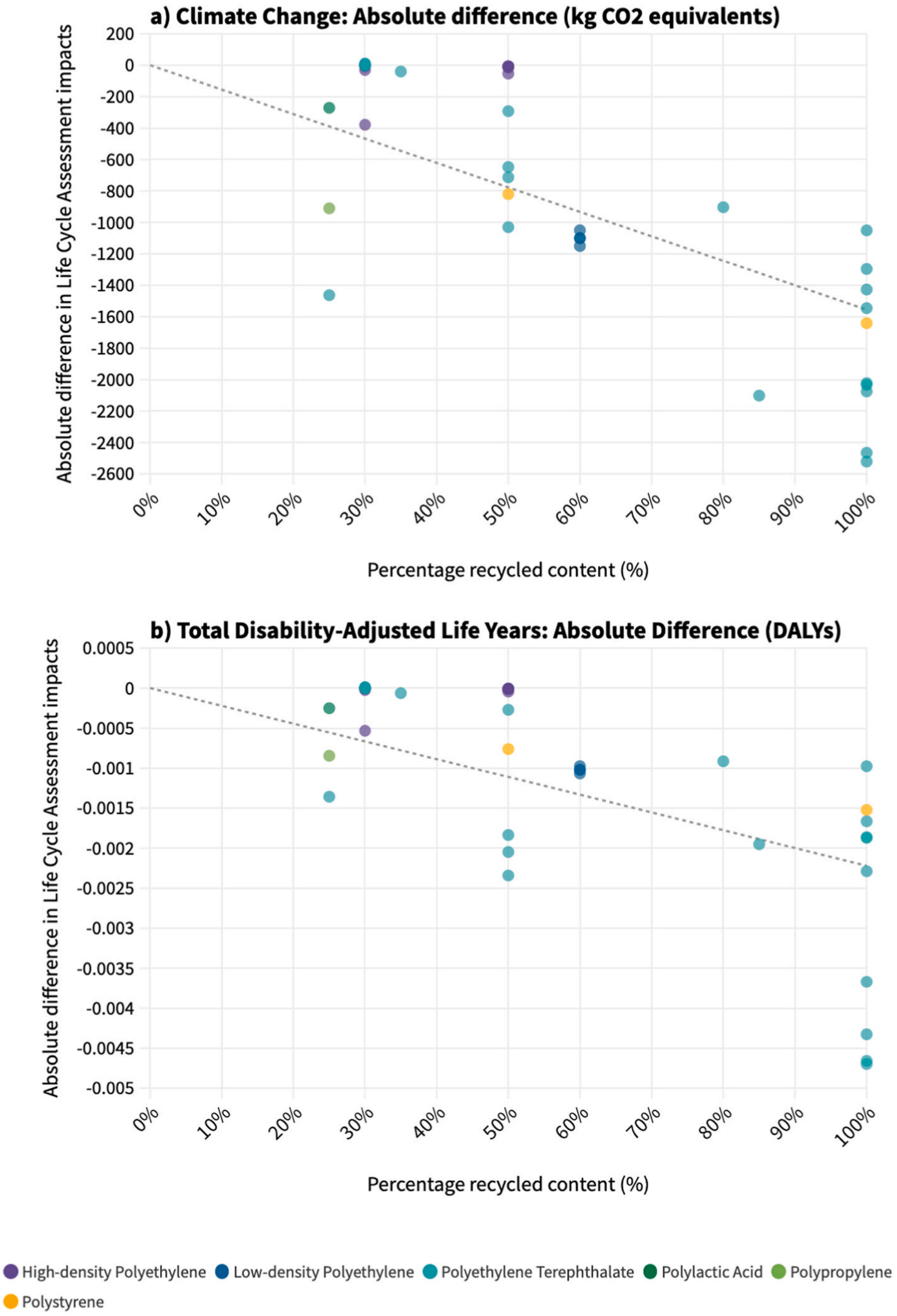


Fig. 6. Meta-regression of the effects of increasing recycled plastic content in one metric tonne of food sector consumer plastics on Climate Change and Total DALYs. Illustrative scatter plot for mixed-effects linear regression with percentage recycled content as the predictor variable and the response variables: **(a)** absolute difference in Climate Change impacts (kg CO_2 equivalents) relative to virgin plastic packaging and **(b)** absolute difference in Total Disability-Adjusted Life Years (DALYs) based on multiple health-related Life Cycle Assessment midpoint impacts, relative to virgin plastic. All data are provided in Data S3.

3.4. *Meta-analysis of the health effects of increasing end-of-life recycling of food sector consumer plastics*

End-of-life recycling was compared to incineration and/or landfill in 36 studies (Amienyo et al., 2013; Camps-Posino et al., 2021; Changwichan et al., 2018; Changwichan and Gheewala, 2020; Cottafava et al., 2021; Dormer et al., 2013; Environment Agency, 2011; Fangmongkol and Gheewala, 2020; Ferrara and de Feo, 2020; Gallego-Schmid et al., 2019; Ghenai, 2012; Hekkert et al., 2000; Herberz et al., 2020; Hermansson et al., 2016; Horowitz et al., 2018; Ingarao et al., 2017; Kouloumpis et al., 2020; Kuczenski and Geyer, 2013; Ligthart and Ansems, 2007; Madival et al., 2009; Maga et al., 2019; Meneses et al., 2012; Moretti et al., 2021; Pasqualino et al., 2011; Rattana and Gheewala, 2019; Rossi et al., 2015; Šerešová and Kočí, 2020; Simon et al., 2016; The Danish Environmental Protection Agency, 2018; Toniolo et al., 2013; van der Harst et al., 2016, 2014; van der Harst and Potting, 2014; Wikstrom et al., 2016, 2014; WRAP, 2010), five of which were from LMICs (Camps-Posino et al., 2021; Changwichan et al., 2018; Changwichan and Gheewala, 2020; Fangmongkol and Gheewala, 2020; Rattana and Gheewala, 2019). The only study to estimate Human Health DALYs calculated a 28% reduction in global DALYs (an absolute reduction of 0.9 μDALYs, equivalent to roughly 30 s) for 100% recycling of four PET wine bottles compared to a scenario of equal landfill and incineration (Ferrara and de Feo, 2020). The recycling rate was extracted from studies as the percentage of plastic product(s) modelled as being sent to recycling processes, as opposed to other end-of-life scenarios, after which point some studies included estimates of losses during reprocessing and others did not **(Data S4)**.

To assess agreement between studies, the percent difference in health-related impacts based on scenarios of 100% recycling versus 100% landfill and 100% incineration was analysed. Identified data included 52 comparisons from 12 studies of 100% recycling versus 100% landfill (including three comparisons from two LMIC studies), and 92 comparisons from 19 studies of 100% recycling versus 100% incineration (including nine comparisons from four LMIC studies), across different food sector consumer plastics, with highly heterogenous results for the differences in impacts between scenarios (Fig. 7). All studies comparing 100% recycling to 100% landfill reported lower impacts for recycling in Climate Change, Ozone Depletion, Ionizing Radiation, Particulate Matter Formation, Cancer Effects and Water Use though results were mixed for Photochemical Ozone Formation, Human Toxicity and Non-Cancer Effects.

Results were more heterogenous in studies that compared 100% recycling to 100% incineration. Studies consistently showed that 100% recycling reduced Climate Change and Non-Cancer Effects but increased Ionizing Radiation. Mixed results were found for all other indicators, with 100% recycling resulting in average increases in Ozone Depletion (dps = 17; Median = 27%; IQR = 7%–378%), Particulate Matter Formation (dps = 11; Median = 86%; IQR = −29%–91%) and Water Use (dps = 17; Median = 16%; IQR = −13%–81%). The mean and standard deviations are available in Figs. S6–S7.

To examine absolute health-related impacts, meta-regression was used to analyse the effects of increasing end-of-life recycling compared to a baseline of 100% landfill and/or incineration. Data included 179 comparisons of increased end-of-life recycling from 27 studies (16 comparisons from five LMIC studies); 65 of which were based on food packaging, 61 on bottles, 23 on service ware, 15 on cups and 15 on grocery bags. Relative to landfill and/or incineration, there was an average 227 kg decrease in Climate Change impacts (kg CO_2 equivalents) for every 10% increase in end-of-life recycling rate of 1 metric tonne of food sector consumer plastics (Coefficient = −22.70; 95% CI = −27.22 to −18.17; $p < 0.0001$) (Fig. 8).

Calculations of Total DALYs remained in favour of increasing recycling. On average, relative to 0% recycling there was an additional 0.000211 decrease in Total DALYs for every 10% increase in recycling of 1 metric tonne of food sector consumer plastics (Coefficient −0.0000211; 95% CI = −0.000026 to −0.0000163; $p < 0.0001$). This equates to nearly a day of healthy life gained for every tonne of plastic recycled instead of incinerated and landfilled (0.77 days). Stata outputs are available in Fig. S8.

Climate Change impacts consistently supported overall reductions in DALYs though contributions from Human Toxicity measures, Particulate

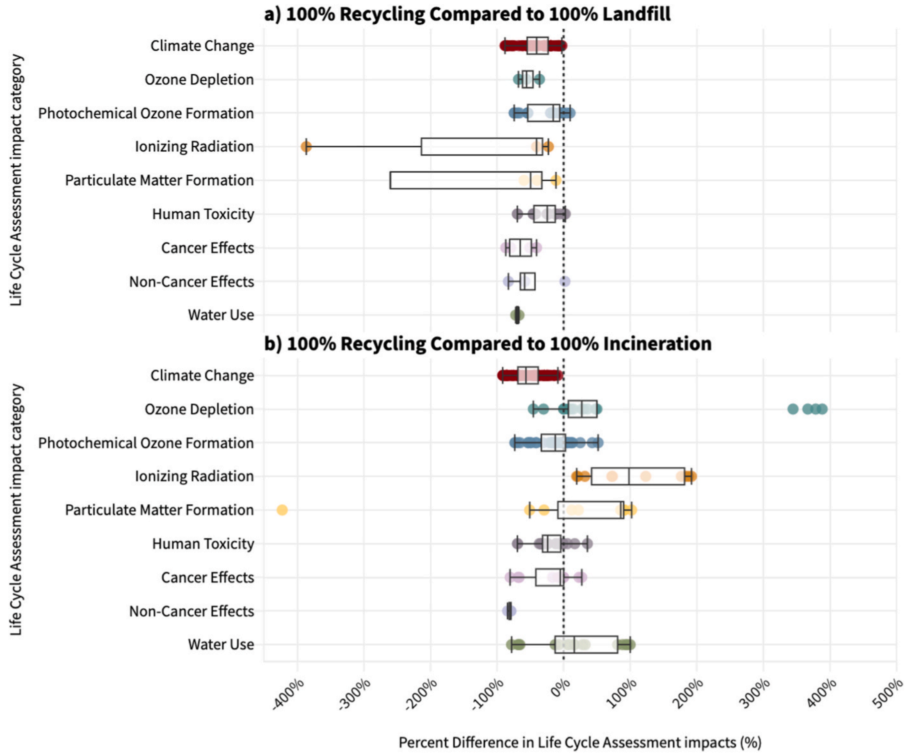


Fig. 7. Relative health-related impacts of 100% end-of-life plastic recycling of food sector consumer plastics. Percent change in health-related Life Cycle Assessment (LCA) impacts, comparing 100% recycling to **(a)** 100% landfill and **(b)** 100% incineration. Values calculated for each comparison identified within LCA studies are represented with dots and summarised using box plots of the median and interquartile range (IQR) with Tukey fences (1.5 x IQR). All data are provided in Data S5–S6.

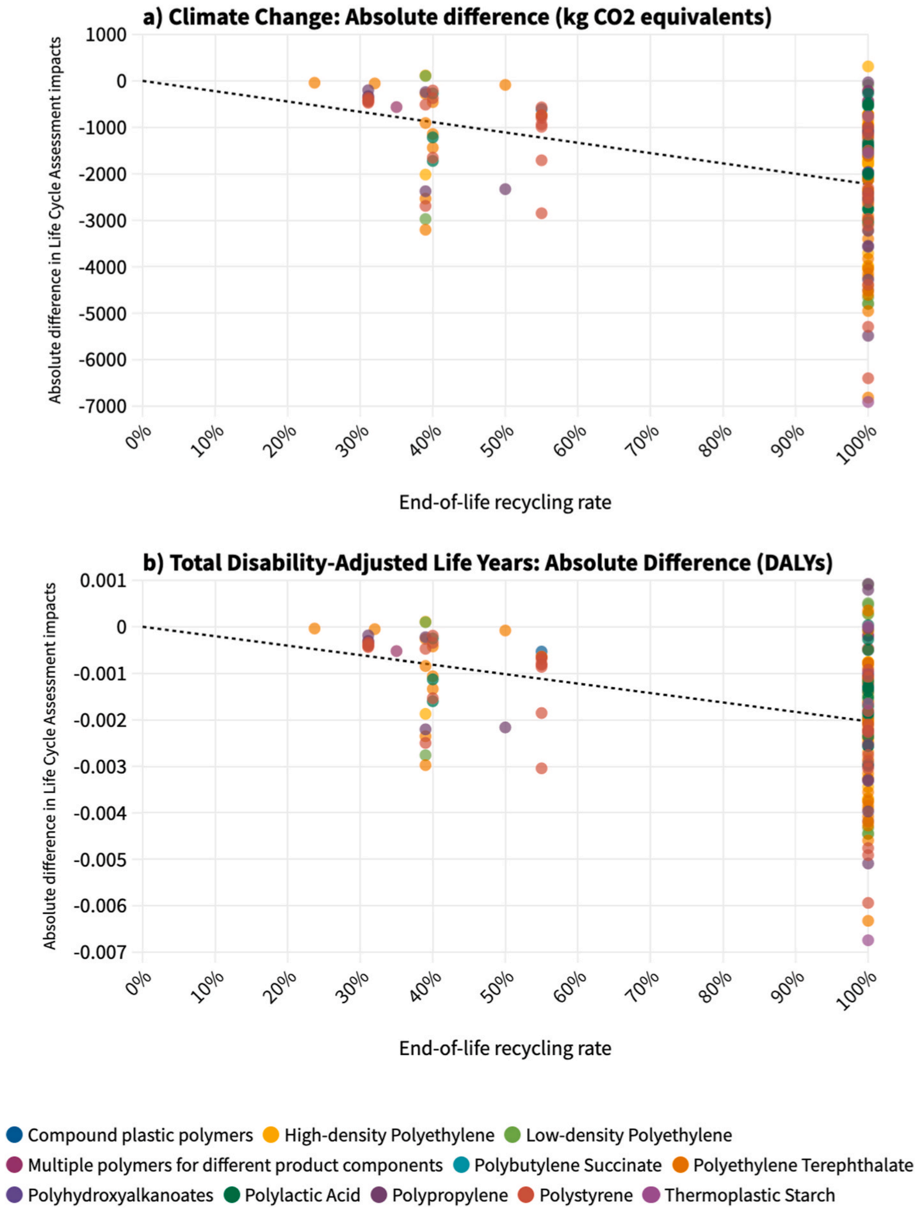


Fig. 8. Meta-regression of the effects of increasing end-of-life recycling of food sector consumer plastics on Climate Change and Total DALYs. Illustrative scatter plot for mixed-effects linear regression with end-of-life recycling rate (the proportion of material sent for recycling as opposed to landfill or incineration) as the predictor variable and the response variables: **(a)** absolute difference in Climate Change impacts (kg CO_2 equivalents) relative to 0% recycling and **(b)** absolute difference in Total Disability-Adjusted Life Years (DALYs) based on multiple health-related Life Cycle Assessment midpoint impacts, relative to 0% recycling. All data are provided in Data S7–S8.

Matter Formation and Water Use were mixed, and in some cases increased DALYs in recycling scenarios (Fig. S9). Eight LCAs could not be included in meta-regression because of challenges with comparability of data and scenarios. The specific reasons are listed in **Data S4.** These studies also predominantly reflected that increasing recycling could reduce health-related impacts relative to landfill and incineration.

Differences in impacts for recycled content and end-of-life recycling comparison points were generated almost entirely from emitting processes and credits awarded for avoided virgin material at the production and waste management stages of the packaging life cycle. Where studies provided disaggregated data by life-cycle stage, some calculated differences in transport stages, as a result of different collection systems, but this only accounted for 1–12% of the total difference in impacts. Systematic reporting of contribution analyses based on specific activities and elementary flows was rare but one example of this showed that eletricity use and fuel combustion were the key drivers of impacts at several stages of the PLA life-cycle (Moretti et al., 2021). Increasing this form of reporting would facilitate greater understanding of the causes of health-related impacts and the differences between study estimates.

3.5. *Meta-analysis of the health effects of reusable food sector consumer plastics*

Reusable food sector consumer plastics were compared to single-use counterparts in 17 LCAs (Camps-Posino et al., 2021; Civancik-Uslu et al., 2019; Copeland et al., 2013; Cottafava et al., 2021; Ecobilan, 2004; Environment Agency, 2011; Fetner and Miller, 2021; Gallego-Schmid et al., 2019; Greenwood et al., 2021; Hekkert et al., 2000; Hutner et al., 2018; Kimmel, 2014; Ligthart and Ansems, 2007; Nessi et al., 2012; Pladerer et al., 2008; Simon et al., 2016; The Danish Environmental Protection Agency, 2018), one of which related to an LMIC (Camps-Posino et al., 2021). To consider baseline variability between studies, comparisons of plastics designed to be reused with plastics designed for single-use were analysed, based on both products being used just once (n = 6 studies; 32 comparisons; no LMIC data). Studies estimated almost universal and on average large relative increases in all health-related impacts for reusable plastics (between 448% and 4689% greater impacts compared to single-use) (Fig. S10). Data are available in Fig. S11.

To estimate an average health-related impact break-even point between reusable plastics and their single-use counterparts a mixed-effects regression model was applied to data on the percent change in impacts from 97 comparisons identified in 13 studies (one comparison from one LMIC study); 45 based on grocery bags, 32 on cups, 13 on bottles and 7 on service ware. Compared to the impact of single-use plastics used once, the percent change in Climate Change emissions for reusable plastics decreased on average by 15.05 percentage points for every additional use (Coefficient = −0.15; 95% CI = −0.31 to −0.01; p = 0.07). These results show that on average whilst the impact of reusable plastics was initially relatively higher than single-use counterparts, the relative difference becomes smaller with each additional use until equivalent and eventually smaller impacts were generated. The average break-even point for Climate Change impacts, (where percent change = 0) occurred at 30 uses, meaning that on average reusable plastics must be used at least this many times to equal or reduce Climate Change impacts and climate associated DALYs, compared to single-use counterparts. Stata outputs are available in Fig. S12.

Due to the limited number of studies, formal sub-group analysis by product and material type was not possible, though no visible patterns were identified (Fig. 9a and b). Other impact categories did not meet the threshold of ten studies needed for formal regression analysis but scatter plots with a line of best fit are shown in Fig. S13 and suggest linear relationships between increased reuse and reduced Ozone Depletion, Ozone Formation, Human Toxicity and Water Use impacts relative to single-use plastics.

Five studies in this review were not included in the quantitative reuse meta-analysis; two had no single-use baseline and three had no absolute impact data but provided their own break-even points. For Climate Change impacts, these were four times for reusable plastic cutlery (Fetner and Miller, 2021), between two and four times for takeaway food containers (Greenwood et al., 2021), and less than three to seven times for drinks cups (Pladerer et al., 2008).

4. Discussion

Meta-regressions indicated that increasing recycling and reuse could reduce the health impacts of linear economies of food sector consumer plastics. Strong evidence was found for a linear trend between both increasing recycled plastic content and increasing end-of life recycling with decreasing DALYs relative to virgin plastic and incineration or landfill waste management, resulting in around a day of healthy life gained per tonne of plastic recycled. Despite overall health benefits, some studies reported increased risks with increased recycling from Human Toxicity, Particulate Matter Formation and Water Use, suggesting possible trade-offs that have been underexplored. Reusable plastics needed to be used an average of 30 times to reduce climate change-related health effects of single-use plastics. These meta-analysis results predominantly reflected high-income, industrial settings and the health impacts of climate change based on the data available from included LCAs. By systematically reviewing LCA studies in this context, key trends and gaps in the literature were revealed that include a critical lack of uptake of human health impact assessment methods, inconsistent modelling of health-related midpoint impacts and a concerning scarcity of studies addressing LMIC settings.

4.1. *Meta-analysis results in the research context*

This is the first meta-regression of LCA data to specifically analyse human health impacts in any sector. This approach facilitated analysis of multiple environmental health pathways that may mediate the risks and benefits of circular economies of plastics. A rapid review of all research evidence on circular economies and health similarly found that circularity in the food, healthcare and financial sectors could provide significant benefits by reducing the health effects of climate change, air pollution and toxicity, though it highlighted the lack of quantification of these effects (World Health Organization, 2018). Comparing quantitative estimates of total DALYs, the health benefits identified in this meta-regression for increasing recycling of food sector consumer plastics were of the same order of magnitude as an LCA study of similar scenarios of recycling in healthcare-related plastics, where single-use plastics also pose a significant challenge (Rizan et al., 2021) but smaller than those found for other types of sustainability strategies such as making changes in dietary choices, perhaps due to a more direct impact of diet on health but also more established methods of accounting for these effects (Stylianou et al., 2021).

Most LCAs in this review focused on climate change impacts, with an average 38% reduction in climate impacts in studies comparing 100% recycled plastics to virgin plastic, which was comparable with another LCA meta-analysis using similar approaches in the context of remanufactured mechanical products (Peng et al., 2022). The present meta-regression indicated average reductions of $2.3tCO_2$ equivalents per tonne of food sector consumer plastics recycled at the end-of-life, which is similar though slightly higher than the $1.9tCO_2$ equivalents estimated by a stochastic modelling study (PEW Charitable Trusts and SYSTEMIQ, 2020). This difference is likely due to different baseline comparisons and methods for calculating emissions. For other health-related midpoint indicators, a meta-analysis of various packaging materials similarly found trends towards reduced impacts with increased recycled content (Vendries et al., 2020) and a systematic review of solid waste management LCA corroborated findings that health-related midpoints have been underutilised (Mulya et al., 2022).

For reusable packaging, the present meta-analysis suggested a break-even point of 30 uses, higher than reported in another review of

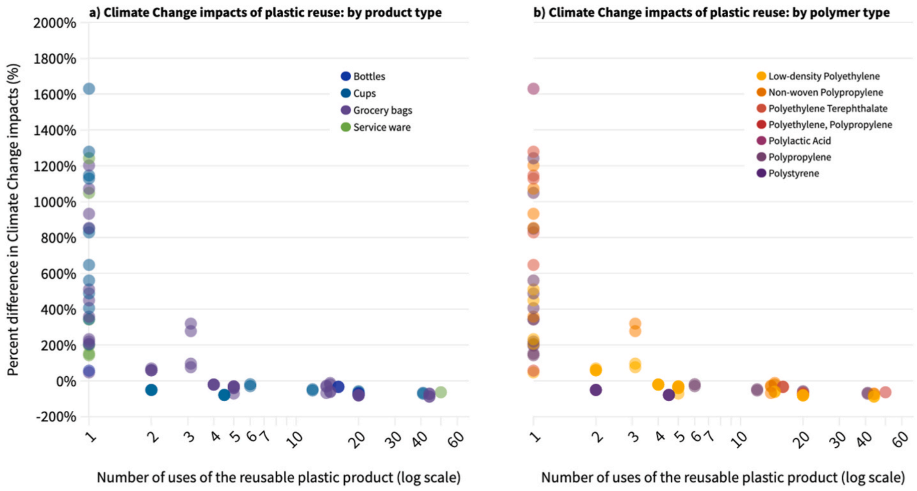


Fig. 9. Meta-regression of increasing uses of reusable plastics compared to single-use plastics used once. Illustrative scatter plot for mixed-effects linear regression with number of uses of the reusable plastic as the predictor variable and the percent change in Climate Change impacts relative to the single-use counterpart plastic: **(a)** by plastic product type and **(b)** by plastic polymer type. For ease of viewing a log scale was applied to the x axis and the y axis was capped at 2000% but there were six data points above this point, all were based on one use of reusable plastic cups, 5 referred to reusable Polylactic Acid cups and had between 1631% and 7450% higher Climate Change impacts than the respective single-use cup and one reusable Polyethylene Terephthalate cup had 2238% higher Climate Change impacts than the single-use alternative. All data are provided in Data S11.

packaging materials (Zero Waste Europe: Reloop, 2020) and in a review of alternatives to single-use plastic carrier bags (United Nations Environment Programme, 2020), which found break-even points of between two and 20 uses. Differences may be due to (1) specification in the present analysis of single-use plastic as the baseline for all comparisons; whilst highly pollutive, single-use plastic can perform relatively well in other environmental categories so the break-even point for reusables will be higher; and (2) averaging results across product types that include very durable items such as Tupperware that will require higher levels of reuse. Overall conclusions concur that the comparative impacts of reusable products will reduce with each usage, and the break-even point against single-use counterparts is relatively high. This means that products need to be sufficiently durable, and that consumer behaviour reflects the required level of reuse.

4.2. *Meta-analysis results in practice*

Included LCAs often modelled impacts based on hypothetical scenarios, such as 100% recycling, rather than real-life recycling systems. This is useful in indicating trends for increasing circularity but does not always align with technological and economic possibilities so estimates of associated health effects may not reflect the reality of health opportunities, or the risks, associated with recycling. For example, stochastic modelling has estimated that mechanical recycling could be scaled up by 2040 to process a maximum of only 33% of global total plastic municipal solid waste, limited by the projected capacity for waste collection, the economics of recycling and material losses (PEW Charitable Trusts and SYSTEMIQ, 2020), so limiting potential health benefits estimated in the meta-analysis. All LCAs included in this review modelled recycling as if it took place in an industrial, high-income setting, which does not account for factors such as the greater health risks experienced in the informal recycling sector in LMICs (Cook et al., 2022), nor international trade directing waste from high-income countries to LMICs (Brooks et al., 2018).

Modelling reuse does not necessarily consider the variability in consumer behaviour, which will also affect the accuracy of health estimates. Nationally representative surveys in nine European countries, including the UK, indicated that consumer reuse may be significantly lower than that required to break-even or reduce impacts compared to single-use packaging (Tame, 2020). Heavy and lightweight plastic carrier bags were reused once by 27% of consumers and not at all by 40% (Tame, 2020). Well-intentioned redesign for reuse and national policies may be having the unintended effect of increasing environmental and health risks if consumer behaviour does not correspond with the necessary level of reuse.

Recycling and reuse systems have been affected by the COVID-19 pandemic. Due to hygiene and safety concerns, reusable takeaway services have not been available and recycling capacity has been restricted by lockdowns and worker illness (Duer, 2020). The fact that these circular strategies are subject to external shocks that can limit implementation and introduce new risks and opportunities for human health cannot be ignored.

4.3. *Evidence gaps in life cycle assessments for estimating global health impacts*

The most important gaps for informing questions of global health in this body of literature are the relatively small number of LCAs on this topic and the narrow geographical coverage, the inconsistent use of available health-related indicators and the current limitations of LCA methods for health research.

Given the surge of policy action to increase recycling and reuse, surprisingly few LCAs were identified that assessed these actions in food sector consumer plastics. Many assessments were conducted several years ago and may be relying on data that has subsequently changed. Endorsement by the European Commission (European Commission, 2003) and the evolution of circular economy policy may help to fuel a larger evidence base over the coming years. Investments should be made to ensure LCA is more inclusive of LMICs given that these countries will experience the greatest growth in plastic consumption (Lebreton and Andrady, 2019) and suffer greater health risks from waste (Tearfund et al., 2019).

LCAs predominantly focused on Climate Change impacts, whilst critical in the context of the climate crisis, restricting modelling to a single impact category offers a one-dimensional view of the effects of circular economies, possibly belying trade-offs in other impacts such as Particulate Matter Formation and Human Toxicity, for which some evidence of increased risk was found (Schweitzer et al., 2018). The lack of estimates of DALYs may be due to the high level of inherent uncertainty in these calculations (Hauschild and Huijbregts, 2015) but represents an overlooked opportunity to further understanding circular economy risks and opportunities for health.

LCA is a holistic approach to assessing the health effects of circular economies, but emerging evidence indicates pathways for health effects that are not yet captured by LCA studies. For example, epigenetic health risks from direct consumer contact with chemicals leaching from recycled plastics has been suggested (World Health Organization, 2018) but the use phase was excluded in all included LCA models of recycling. The respiratory effects of open burning were not considered, despite projections that 144 million metric tonnes of plastic will be burned annually by 2040 (PEW Charitable Trusts and SYSTEMIQ, 2020). Similarly, occupational hazards of the informal recycling sector including waste pickers, and the health effects of environmental plastic pollution were not modelled (Cook et al., 2022). As more data becomes available, it will be critical to develop methods of accounting for such health pathways in LCA, to improve estimates and evaluations of regionally representative and global health effects.

4.4. *Strengths and limitations*

4.4.1. *Research approach: systematic review and meta-analysis of Life Cycle Assessments*

By systematically reviewing LCA of recycling and reuse of food sector consumer plastics, conclusions could be drawn on trends and critical gaps in the current evidence base for health impacts that can be used to direct future LCA. Meta-analyses of the percent differences in impacts within given scenarios of increased recycling and reuse were useful for assessing overall trends and discordance between LCA studies. This form of meta-analysis has been used in other LCA reviews, it is relatively time-efficient and could be applied to research for other sectors but requires that studies model the same scenarios and does not quantify the absolute differences in impacts. The latter is critical to demonstrating the contribution of specific strategies to a given outcome, in this case the overall impacts on health. In meta-regressions of recycling, absolute impact data were harmonised across studies to assess the impacts of increasing recycled content and end-of-life recycling. This approach allowed for percentage recycled content and end-of-life recycling rates, that varied between identified LCA studies, to be incorporated as continuous variables, providing the capacity estimate impacts at certain levels of recycling in the absence of data. This approach has not been widely used in meta-analyses of LCA, likely because of the challenges and time-intensity of harmonising functional units and impact assessment data across LCA studies. Meta-regression has the potential to offer robust statistical insight into absolute impacts, drivers of impacts and sources of uncertainty across LCA studies, in any sector. The ultimate quality and power of this form of meta-analysis is highly dependent on the availability and quality of individual LCA studies, requiring greater standardisation of methods and transparency in reporting.

4.4.2. *Analytic approach: systematic review and meta-analysis processes*

This systematic review was conducted and reported in accordance with standardised LCA review (Zumsteg et al., 2012) and systematic review guidance (Moher et al., 2009) but was not designed to capture studies in languages other than English, though studies in French and Spanish were reviewed where identified, nor was it designed to cover LCA conducted by the private sector, which are often proprietary.

Midpoint impact data taken from studies using different impact assessment methodologies was used in meta-regression. This was necessary to analyse average differences in impacts across studies but may be the source of some of the variability in impacts between LCAs. Whilst many impact assessment methodologies use the same or similar indicators, the assumptions behind these calculations are slightly different. The limited number of studies prevented sub-group analysis by methodology but would be useful in future analyses. An internationally recognised LCA impact assessment method (ReCiPe 2016) (Huijbregts et al., 2017) was used as the basis for standardising impact data across methodologies and to convert midpoint health-related indicators to DALYs. It is important to acknowledge that other recognised methods exist and may influence results though a sensitivity analysis was not feasible. To convert aggregate midpoint Human Toxicity impacts it was necessary to apply ReCiPe 2008 (Goedkoop et al., 2009) factors, as a single conversion factor is not available in the updated methodology, providing a more conservative estimate of DALYs in these studies.

Converting all provided midpoint impacts to a single summed estimate of Human Health DALYs within each study provided sufficient data on linear versus circular economy comparisons for us to perform a unique meta-regression analysing the health effects of increased recycling. The key limitation of this approach is that different studies modelled different numbers of contributing health-related midpoint indicators. Whilst each estimate of Total DALYs includes the Climate Change pathway to health, other pathways are not consistently accounted for and this likely contributes to the variability in DALY estimates between studies. This meta-analysis provides an indication of the average direction and magnitude of global health effects associated with increased recycling in food sector consumer plastics, as identified in LCA. Results should not be interpreted as predictive of health effects but used to support further investigation of these pathways.

The limited number of studies that met the eligibility criteria for this review meant that statistical sub-group analysis could not be performed for other key factors that could influence the estimates of health effects. For example, sub-group analyses by product and polymer type would be informative, and methodological choices such as inclusion of specific life cycle stages in the system boundary, the inclusion of secondary packaging in the inventory, whether credits are given for energy recovery from incineration and landfill comparisons, the method of allocating benefits from recycling and the specific impact assessment method used. As the body of LCA literature on circular economies in plastics grows, these considerations should be included in future analyses.

4.4.3. *Limitations of included life cycle assessments*

This review responds to calls for quantification of human health effects associated with circular economies (World Health Organization, 2018). Given the highly cross-disciplinary objectives of this research, the analysis relies on studies that were not explicitly designed to examine health effects. The limitations of included studies are partly due to this divergence of aims, rather than the quality of the studies, which were required to have been previously peer-reviewed or subject to critical appraisal and a subsequent reporting quality assessment was conducted within this review. Most studies reported following the International Organization for Standardisation LCA guidelines (International Organization for Standardization, 2006a; The International Organization for Standardization, 2006b) but were nevertheless highly heterogenous in methodological approaches and reporting quality. A common limitation of the evidence was insufficient granularity in the reporting of data inputs and impact assessment results that would support interpretation of the drivers of impacts, in terms of the contributing plastic life cycle processes, and the specific substances and emissions that are causing the greatest damage. This black box of effects must be explicitly unpacked in future studies to ensure sufficient analysis of environmental and health damages that will lead to more efficient and appropriate solutions.

4.5. *Conclusion and recommendations*

This systematic review and meta-analysis indicated that health risks from linear economies of food sector consumer plastics could be reduced by increasing recycled content, increasing end-of-life recycling rates, and increasing reuse, though certain reusable plastics would need to be used many more times than current norms. Whilst the LCA evidence base on circular economies of food sector consumer plastics is growing, this analysis of the literature highlighted a strong bias towards high-income, industrial settings exists, and showed that health impacts have been largely underexplored. Results presented in this review and meta-analysis provide (1) an illustrative quantification of health effects of aspects of plastic circular economies, (2) a demonstrated method of synthesising LCA data for global health research, that once more LCA studies are available, could be used to generate more robust estimates and to analyse specific drivers of health effects (e.g. the relative importance of different environmental mediators for health outcomes, or the influence of LCA methodological choices on quantitative estimates), and (3) a systematic analysis of trends and gaps in evidence that highlights critical priorities for future LCA on food sector consumer plastics, circular economies and global health, that in turn would support future meta-analyses to inform policy.

Based on the findings of this review, there is a critical need for continued research and investments for LCA of circular economies in food sector consumer plastics, ensuring that analyses reflect current technologies, using the latest data and LCA methodological developments in impact assessment. Methods for accounting for circularity need to be harmonised so that waste reduction strategies can be directly compared. Recommendations from this review include conducting studies with broader international scope and investment in the use of LCA in LMIC settings. Greater transparency in reporting data inputs and methodological choices is needed in studies and more comprehensive modelling of available impact indicators including Particulate Matter Formation, Human Toxicity, and Human Health DALYs. To further enhance the capacity of LCA for health research, development of impact assessment methods accounting for a greater spectrum of health impacts as scientific evidence emerges would be beneficial, such as those mediated through occupational exposure, consumer use and end-of-life open burning, open dumps, and macro and micro-plastic pollution.

Further consensus and guidance for conducting meta-analyses of LCAs is needed, including tools and advice for harmonising differences in LCA methodological choices and appraising studies. Ongoing developments in circular economy policy should be based on analysing strategies for co-benefits and trade-offs across multiple economic, environmental, health and social indicators, informed by LCA, to ensure simultaneous progress towards multiple objectives within the Sustainable Development Goals.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data is available in supplementary files

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Appendix A. Supplementary data

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