Original Article

WM&R

Waste Management & Research
1–13

DOI: 10.1177/0734242X241237102
journals.sagepub.com/home/wmr
Sage

Environmental impacts of circularity strategies for social distancing plastic shields made of polymethyl methacrylate in the United States

Nathalia Silva de Souza Lima Cano[1], Md Uzzal Hossain[1] and Melissa M Bilec[1,2]

Abstract

One application of plastics that grew during the COVID-19 pandemic is for social distancing plastic shields, or protective barriers, made from polymethyl methacrylate (PMMA) such as transparent face guards. Although available for other applications, end-of-life impacts for barriers are currently lacking in the literature, and there is a need to fill in this gap to guide decisions. This study evaluated the end-of-life environmental impacts of PMMA barriers in the United States by using life cycle assessment. We evaluated five strategies including landfilling, waste-to-energy, mechanical recycling, chemical recycling and reuse. Data were sourced from literature and various life cycle inventory databases. The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) was used as the life cycle impact assessment method. Landfilling exhibited the highest impact in all indicators and reuse demonstrated optimal results for global warming potential. A scenario analysis was conducted to explore a combination of strategies, revealing that the most promising approach involved a mix of 40% reuse, 20% mechanical recycling and 40% chemical recycling. Circular economy recommendations are proposed for managing these sources of plastic waste in the United States.

Keywords

Plastics, life cycle assessment, waste, end-of-life, recycling, circular economy

Received 24th October 2023, accepted 8th February 2024 by Associate Editor David E. Ross.

Introduction

The global projection indicates an approximate 8% annual growth in the volume of plastics utilized in commerce (Gibb, 2019). The life-cycle stages of plastics, that is, production, use and end-of-life (EOL), lead to environmental and human health impacts from climate change to toxicity (Lau et al., 2020). Currently, plastic waste management is becoming one of the biggest challenges globally, since it is estimated that 79% of all plastics ever produced were discarded in landfills or the natural environment, 12% were incinerated and only 9% were recycled (OECD, 2022).

Assessments of waste management systems are needed to evaluate alternative scenarios and select the best solutions (Tunesi et al., 2016). In this sense, numerous studies have focused on quantifying the EOL plastics' environmental impacts either with life cycle assessment (LCA) or similar methods, detailed in Supplemental Table S1. Many studies were based in Europe, for example, Accorsi et al. (2015) compared landfilling, mechanical recycling and incineration of polyethylene terephthalate (PET) in Italy, whereas Jeswani et al. (2021) compared mechanical recycling, chemical recycling and waste-to-energy (WtE) of mixed plastic waste in Germany. Civancik-Uslu et al. (2021) compared the same EOL strategies for different plastics in Belgium and Salemdeeb et al. (2022) compared landfilling, incineration and mechanical recycling of PET, low-density polyethylene (LDPE), high-density polyethylene (HDPE) and polypropylene (PP) in Scotland. Aryan et al. (2021) and Schwarz et al. (2021) compared EOL environmental impacts in several countries within Europe, for polylactic acid (PLA) and 25 polymers, respectively.

Outside of Europe, Cosate de Andrade et al. (2016) compared chemical recycling, mechanical recycling and composting of PLA in Brazil, Neo et al. (2021) compared mechanical recycling, co-processing in cement kilns, WtE, landfill, open dumps and

[1]Department of Civil and Environmental Engineering, Swanson School of Engineering, University of Pittsburgh, Pittsburgh, PA, USA
[2]Mascaro Center for Sustainable Innovation, University of Pittsburgh, Pittsburgh, PA, USA

Corresponding author:
Melissa Marie Bilec, Department of Civil and Environmental Engineering, Swanson School of Engineering, University of Pittsburgh, Room 153, Benedum Hall, 3700 O'Hara Street, Pittsburgh, PA 15261, USA.
Email: mbilec@pitt.edu

Figure 1. Social distancing PMMA shields in hotel, office, school and reception.
Source: Adobe Stock Images (standard license).
The widely used face masks are not made of PMMA.

open burning of HDPE, LDPE, PP and PET in India and Indonesia, and Hossain et al. (2021) compared mechanical recycling, incineration, industrial incineration, construction and landfill of mixed plastics waste in Hong Kong. Most LCA studies based in the United States focused on the packaging sectors, especially polymers such as PET, LDPE, HDPE, PP (Chaudhari et al., 2021); HDPE (Gandhi et al., 2021; Zhao and You, 2021); PET, LDPE and PLA (Hottle et al., 2017). Depending on the context and the impact category, linear or circular EOL strategies might be recommended by researchers. For instance, Chaudhari et al. (2021) and Hottle et al. (2017) recommended that recycling strategies are better for plastics in the United States, whereas Hossain et al. (2021) find that industrial incineration is preferable to mechanical recycling of plastics in Hong Kong.

According to Heller et al. (2020), North America has the highest plastic consumption rate compared to other regions at 139 kg per capita per year. Specifically, the United States is both the greatest plastics producer (19% of global production) and consumer (21% of global consumption) (United Nations Environment Programme, 2018). Concerning the US plastic EOL management, 77% was landfilled, 14% was incinerated with energy recovery and 6% was collected as recyclable in 2015 (Di et al., 2021). The recycling system in the United States currently faces challenges such as 'confusion about what materials can be recycled, recycling infrastructure that has not kept pace with today's diverse and changing waste stream, reduced markets for recycled materials, and varying methodologies to measure recycling system performance' (US EPA, 2021). In late 2021, the US government set a new goal to increase recycling by 50% by 2030, creating the 2021 National Recycling Strategy to pursue that goal (US EPA, 2021). Circular economy strategies and business models have been proposed to enhance the circularity of plastics across spatial scales (Bocken et al., 2016). Discussing the EOL management of all types of plastics can be overwhelming in a country such as the United States (Di et al., 2021; Heller et al., 2020); therefore, selecting a specific case can be beneficial to understanding specific circular economy strategies.

The COVID-19 (Coronavirus disease 2019, the disease caused by a virus named SARS-CoV-2) pandemic caused an increase in plastic consumption globally (Patrício Silva et al., 2021; World Health Organization, 2022). Even though several types of plastics are used in various personal protective equipment, one application that has seen significant growth during the pandemic to reduce exposure to the virus is the use of 'protective shields made from polymethyl methacrylate (PMMA)', also called 'acrylic panels', 'plexiglass' or 'plastic glass' (Figure 1) (Grosso, 2022). Therefore, PMMA was chosen as the focus of this study. PMMA has better mechanical properties than common plastics such as abrasion resistance, hardness and stiffness; furthermore, it is one of the best plastics with optical clarity (Cao et al., 2020).

The global market for PMMA was estimated at 2.6 million tonnes in 2019 (ICIS, 2020), representing 0.4% of all plastics.

The United States was chosen for the case study because it represents one of the biggest PMMA markets in the world with a 15% share (Global Industry Analysis, 2022), and market revenue of approximately US$ 400,000,000.00 in 2015 (Statista, 2021). Signs and displays, automotive and construction industries represent together more than 60% of PMMA applications in the United States, but the healthcare equipment category presents a growing trend in the region (Grand View Research, 2022). While in general, plastics have a potential market growth rate of 4.5% (Grand View Research, 2021), PMMA presents a 5.3% potential market growth rate (Grand View Research, 2022), showing the importance of this type of resin in markets that use plastics. Little is known about the volume of PMMA protective barriers in use since COVID-19 and that may have been or be discarded in the future.

The World Health Organization only recommended the use of plastic shields for healthcare and airport contexts (World Health Organization, 2020); although, the efficacy of using these shields in preventing COVID-19 exposure has been questioned in the literature (Lessler et al., 2021; Li et al., 2022). However, plastic barriers were adopted by many establishments, such as schools, supermarkets, offices, stores, restaurants, etc. potentially creating a future waste problem. An estimation for the production quantity in tonnes of PMMA shields was performed based on the largest producer of PMMA barriers in the United States (see Supplemental Table S2 for calculation details), yielding a total of approximately 33,582 tonnes year^{-1}, which are assumed to become waste after the pandemic. While this quantity represents only 0.1% of all plastics generated in the municipal solid waste (MSW) stream in the United States, according to the US EPA (2020b), it is assumed this percentage will grow given the removal of the COVID-19 barriers.

Only two studies have evaluated the environmental impacts of PMMA resin (Kikuchi et al., 2014; Mahmud and Farjana, 2021). Mahmud and Farjana (2021) compared the environmental profiles of PET and PMMA but did not include EOL impacts. Kikuchi et al. (2014) performed an LCA using a Japanese database and life cycle impact assessment (LCIA) method, exploring different EOL scenarios using two case studies. They concluded that chemical recycling (i.e. methyl methacrylate (MMA) monomer recycling through pyrolysis) is a promising technology to manage EOL PMMA waste from not only automotive but also construction and packaging sectors, given the high efficiency of the process (70% mass-based recovery with 99.8% purity) and the high electricity demand for virgin MMA production.

Currently, there are no studies on quantifying the environmental impacts of different EOL strategies of PMMA protective barriers in the US region. In addition to the increase in the waste, if left untreated, the potential environmental threats of PMMA sheets are that with exposure to sunlight radiation, they can be photodegraded generating CO_2 emissions (Abouelezz, 1978; Li et al., 2020). Therefore, this study investigated the following research question: 'What PMMA end-of-life scenario would be less environmentally impactful in the U.S.?' We aimed to evaluate the environmental impacts of EOL strategies for PMMA barriers used during the COVID pandemic using the LCA approach. Five EOL strategies for PMMA were modelled and compared, including (i) reuse, (ii) landfilling, (iii) WtE, (iv) chemical and (v) mechanical recycling. Trade-offs between different impact categories were discussed, and a scenario analysis was conducted to compare the business-as-usual waste management scenario in the United States and other possibilities combining different EOL strategies. The results of this study will aid decision-makers such as manufacturers, government and waste managers and other relevant stakeholders such as commercial establishments and schools on how to treat their PMMA barriers when they become waste.

Methods

LCA approach, functional unit and system boundaries

LCA is a technique to assess potential environmental impacts related to a product's life cycle, from raw material extraction through processing, manufacturing, distribution, use and EOL. LCA's procedures are outlined in international standards ISO 14040:2006 and ISO 14044:2006 (International Organization for Standardization, 2006a, 2006b) and include (1) goal and scope definition – the finality of the study, approach, functional unit and system boundaries should be defined; (2) inventory analysis – a collection of data concerning material and energy flows (input and outputs) of the system; (3) impact assessment – inventory data is translated into quantified impact assessment, usually with several impact categories, including climate change and human health related categories for example and (4) interpretation – a critical review of results, data uncertainty and sensitivity. LCAs can also include various boundaries including cradle-to-gate, cradle-to-grave, gate-to-grave and cradle-to-cradle.

An anticipatory consequential LCA including one recycling cycle was adopted in this study. Anticipatory LCA does not treat uncertainty as a model reliability indicator, instead, it uses uncertainty to identify the possible futures in order to prepare for potential outcomes (Wender et al., 2014). Consequential LCA means that changes in the technology mix, production level and production method are going to be used to understand the change in environmental impact (Bamber et al., 2020; Neo et al., 2021).

The chosen functional unit was 1 MT of PMMA waste, following similar studies (Aryan et al., 2021; Chaudhari et al., 2021). We assumed a use-to-grave system boundary, including production (upstream) processes modelled in pertinent EOL strategies detailed in Supplemental Table S3 and Section 'Life cycle inventory: Assumptions and data sources'. Nevertheless, the upstream processes themselves as well as the use stage and the collection and sorting of PMMA waste are not included in this study.

Figure 2 shows the overall system and considerations for EOL of PMMA barriers with detailed descriptions of each strategy in

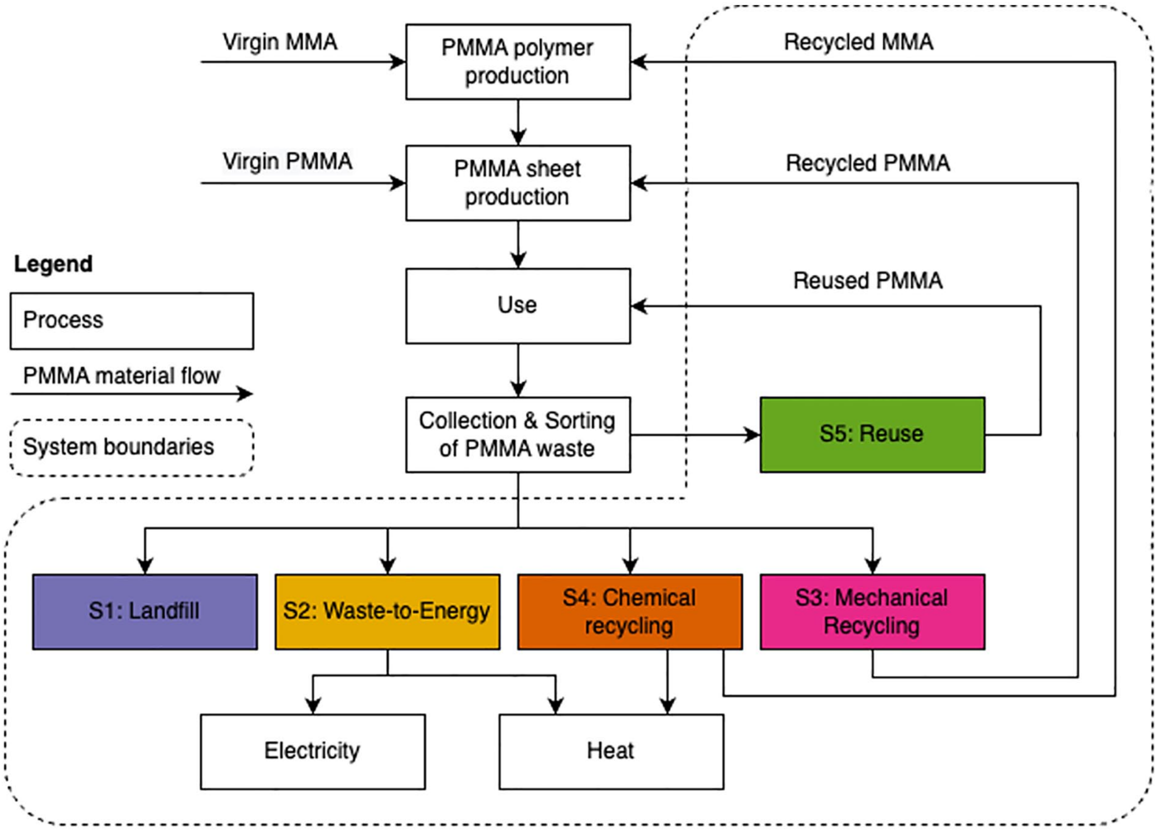

Figure 2. Overall process flow diagram of PMMA barriers.
PMMA: polymethyl methacrylate; MMA: methyl methacrylate; S: strategy; S1: landfill; S2: waste-to-energy; S3: mechanical recycling; S4: chemical recycling; S5: reuse.

Supplemental Figures S1–S5. The use phase was excluded since the data for the use of PMMA barriers in the whole United States is currently unavailable, and we assumed the use phase does not affect the LCA results of PMMA waste management with different EOL alternatives. Similarly, collection and sorting phases of PMMA waste were also excluded due to the unavailability of information on PMMA waste in the United States, and it would not affect LCA results in comparative analysis of different EOL alternatives, as it is assumed that the same fate will be incurred in all alternatives.

Life cycle inventory: Assumptions and data sources

For Strategy 1: Landfill (S1), we used the process for Landfill the Ecoinvent database for modelling Strategy 1 (landfilling) (see Supplemental Figure S1). For Strategy 2: Waste-to-Energy (S2), we modelled WtE based on the European reference Life Cycle Database (ELCD) database (see Supplemental Figure S2). Typical WtE plants for the thermal treatment of MSW include an incineration line with a grate and steam generator. The steam that is produced is utilized as process-steam and the balance generates electricity and heat. The electricity generated in the WtE process could avoid electricity generation from other sources, so we included the avoided impact using the US electricity mix from the US Life Cycle Inventory (USLCI) database. The heat generated was also included (from the Ecoinvent database). Based on Mukherjee et al. (2020), the United States has 86 WtE facilities, mainly in New York and Florida states.

Since there is no unit process available in databases that corresponds to the mechanical recycling of PMMA resin, we assumed it to be similar to the mechanical recycling of polystyrene based on Kikuchi et al. (2014) for Strategy 3: Mechanical recycling (S3). In this strategy, the plastic waste is shredded and then washed, leading to water usage; the plastics are assumed to be melted and pelletized. For every 1 tonne of PMMA waste, 611 kg of recycled plastic pellets are produced while 389 kg of non-recyclable waste is generated (Kikuchi et al., 2014). We assumed that the recycled pellets displaced the virgin PMMA pellets to be used to produce PMMA barriers at a substitution ratio of 1:1 because no blending would be necessary to achieve similar quality compared to virgin PMMA, which means that if 1 tonne of recycled PMMA pellets is used in the production of PMMA barriers, 1 tonne of virgin PMMA pellets will not be used. Thus, introducing recycled PMMA pellets into the production of PMMA barriers resulted in reductions in environmental impacts for S3 (see Supplemental Figure S3 for details of this process).

For Strategy 4: Chemical recycling (S4), we focused on chemical recycling which could include several different technologies depending on the polymer type, for example, depolymerization, hydrolysis, pyrolysis, etc. (Thiounn and Smith, 2020). We assumed that the technology for PMMA chemical recycling would be pyrolysis as described by Kikuchi et al. (2014). The pyrolysis process includes depolymerization, liquid recovery (treatment process for

Table 1. Scenarios combining EOL strategies (%).

Scenario	S1: Landfill	S2: WtE	S4: Chemical recycling	S3: Mechanical recycling	S5: Reuse
1 – Current US	75	16	–	9	-
2	100	–	–	–	–
3	–	100	–	–	–
4	50	50	–	–	–
5	25	25	–	50	–
6	25	25	25	25	–
7	20	20	20	40	–
8	20	20	40	20	–
9	20	20	20	20	20
10	10	20	30	20	20
11	10	20	20	30	20
12	–	10	30	30	30
13	–	–	40	20	40
14	–	–	25	50	25
15	–	–	–	–	100

effluent gas from the reactor), purification of the MMA monomer and heat recovery from the waste (Kikuchi et al., 2014). PMMA is decomposed by heat into MMA monomer and other secondary substances. The effluent gas, also called cracking gas, is separated from the liquid in the liquid recovery system with a temperature ranging from 350°C to 500°C. The crude MMA monomer is cooled and condensed before purification. In the purification, the first distillation column removes chemicals, and the second purifies the MMA monomer. All waste from both liquid recovery and purification is used as fuel in a heat recovery system (Kikuchi et al., 2014). The recycled MMA produced avoids the production of virgin MMA needed for PMMA production. The recovered monomer has a purity of more than 99% with a recovery ratio of 70% (the mass of the lost input is 30% and is recovered on-site and used as waste oil for heat utilization). To estimate how much heat is recovered, we used the energy content of PMMA (26.2 MJ kg^{-1}) (De Tommaso and Dubois, 2021). With the 70% recovery ratio and original input of 1 tonne PMMA, 300 kg of PMMA was lost input from pyrolysis, yielding 7860 MJ of heat. According to Hossain et al. (2016), the thermal conversion efficiency for coal is 90% output heat, for PMMA we assumed 90% as well. Therefore, heat recovered from pyrolysis of 1 tonne of PMMA was estimated to be 7074 MJ. Here, we modelled two options, heat from natural gas and from coal as avoided products. Supplemental Figure S4 presents the chemical recycling process model.

Finally, we also modelled, Strategy 5: Reuse (S5). According to Muranko et al. (2021), ‘as a circular economy strategy, reuse has the potential to reduce environmental impacts, such as waste accumulation and pollution to air, water and soil, which is caused by the intensive mining, manufacture, distribution, consumption, and disposal of materials’. Reuse as an EOL scenario has been included in LCA studies for beverage cups, diapers, menstrual products, plastic and glass bottles (Muranko et al., 2021). In this strategy, we assumed the PMMA sheets would be collected at a central location and then reused. For example, Construction Junction in Pittsburgh acts as a material bank as they receive and collect used building materials and repurpose them (Construction Junction, 2022). The distance between waste generation points and material banks was assumed to be within a 20-mi radius (for 1 tonne of PMMA). We assumed the cleaning process was similar to washing plastic bottles (Helmes et al., 2022). The reuse efficiency was assumed to be 90% and with 10% landfilled since there might be some cutting/reconfiguring to adapt to the next cycle. Avoided products included the PMMA sheets production in a substitution ratio of 1:1. See Supplemental Figure S5 for more details.

LCIA, uncertainty analysis and EOL scenario analysis

TRACI 2.1 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) was used to perform the LCIA (Bare, 2011), as it is widely used in LCA studies in the North American context (Adhikari et al., 2023; Li et al., 2020). The considered impact categories are global warming potential (GWP), eutrophication, ecotoxicity, acidification, ozone depletion, smog formation, carcinogens, non-carcinogens, respiratory effects and fossil fuel depletion.

Uncertainty in background LCI data was analysed via Monte Carlo simulations (Lloyd and Ries, 2007) by randomly sampling (1000 trials) from the underlying probability distributions obtained from the Ecoinvent background database. Results are shown with error bars representing 95% confidence intervals. Uncertainty concerning foreground data was not included.

Finally, an EOL scenario analysis was conducted, aiming to facilitate decision-making. Table 1 presents the scenarios used in this analysis. Scenario 1, the current US scenario comes from the EOL management of plastics in MSW from the US EPA (2020a, 2020b). The other 14 scenarios combine the five EOL strategies in incremental percentages, and the circularity of PMMA would increase as scenario numbers increase as well. Circularity here follows the definition from ‘The New Plastics Economy’ (Ellen MacArthur Foundation, 2016), where reusing is the most circular option, followed by mechanical recycling which keeps polymers intact, and chemical recycling which breaks down polymers.

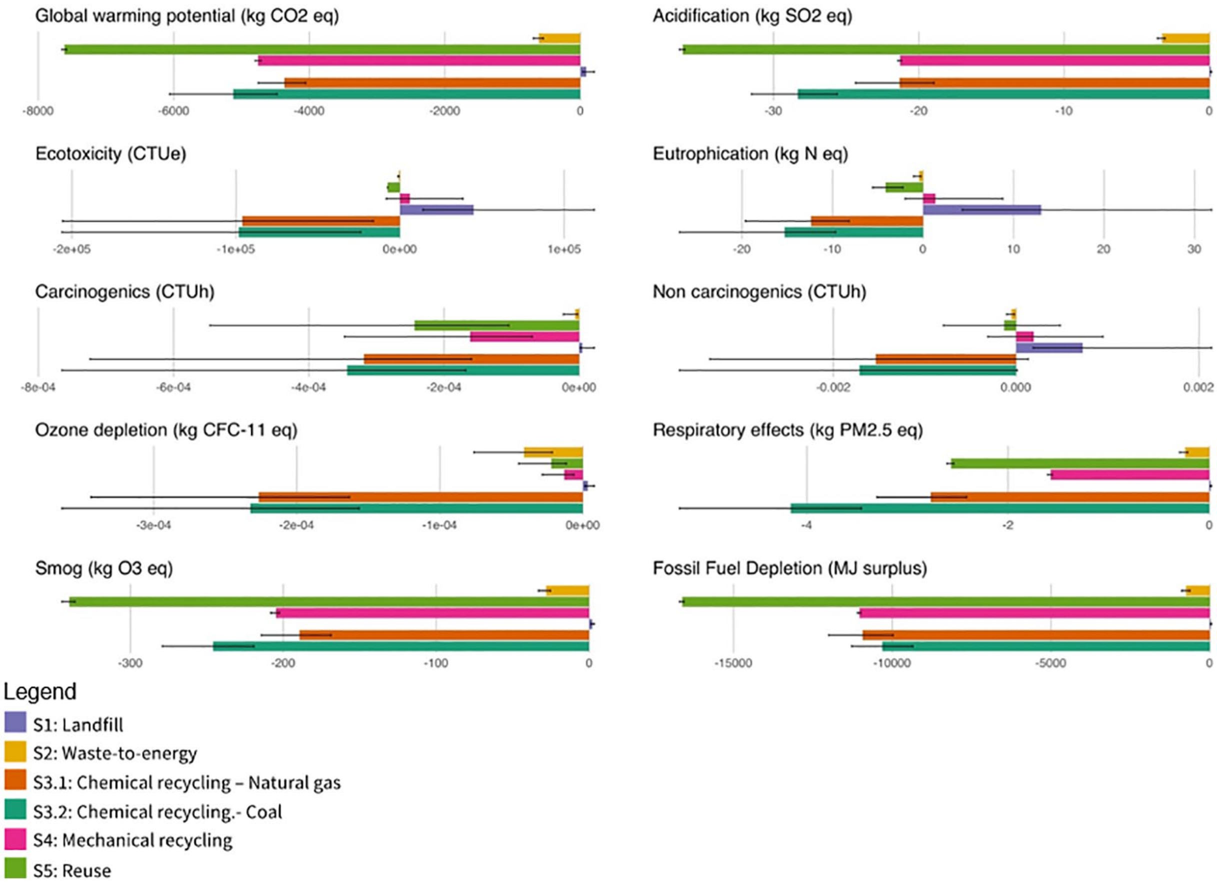

Figure 3. EOL strategies LCIA results for 1 tonne of PMMA waste. Chemical recycling is presented with natural gas or coal substitution for the heat production of the waste residue from the monomer pyrolysis process. Error bars represent 95% confidence intervals from the Monte Carlo simulations from Ecoinvent database.

Results and discussion

Environmental profile of PMMA EOL strategies

Figure 3 presents the LCIA of each EOL strategy for 1 tonne of PMMA waste, including the 95% confidence interval from the Monte Carlo simulations. For GWP, Reuse was the most promising, with impact savings of −7614 kg CO_2eq. Reuse demonstrated the greatest decreases in GWP, largely due to the assumption that no processing is needed, only transport to reuse material banks. The second most promising was chemical recycling with coal replacement, showing impact savings of −5123 kg CO_2eq. Landfilling was the only strategy with an increase in GWP at 88 kg CO_2eq. After landfilling, WtE presented the least savings compared to other strategies, at −615 kg of CO_2eq, followed by mechanical recycling, at −4760 kg of CO_2eq.

Although Reuse offers the most benefits concerning GWP and other impact categories such as acidification, smog and fossil fuel depletion, it is not the best option in terms of carcinogenics, non-carcinogenics, ecotoxicity, eutrophication, ozone depletion and respiratory effects. Chemical recycling (with coal substitution for heat production) presented the best results for these six categories mentioned.

Kikuchi et al. (2014) also found this for the Japanese case and explained that PMMA monomer recycling is highly effective because it recovers only one monomer (MMA) while other polymers (such as PET) might have more monomers in their compositions, making it a less energy-intensive process compared to these other polymers. Even so, uncertainty was also the highest for this strategy in all impact categories, probably because it involved more processes (electricity, heat, heat from waste), and these processes presented uncertainty in the background databases. This might point to the need for more specific decision-making concerning the location of the facilities and local context.

Landfilling showed the highest impacts across all categories, with an increase in impacts. Mechanical recycling also presented increased impacts in a few categories: ecotoxicity, non-carcinogenics and eutrophication. WtE had the second-highest impacts after landfill for some categories, including GWP, acidification, carcinogenics, respiratory effects, smog, ozone depletion and fossil fuel depletion.

Comparative analysis for GWP

The climate change-related impact category was chosen to be further investigated because it is the biggest threat to human health (US EPA, 2022). Of all the categories, GWP is the most studied, and most research has been done in most sectors (Quevedo-Cascante et al., 2023). Even though the comparison of LCA studies is not advised since different considerations, system boundaries, plastic types, geographical locations and LCIA methods are used, we discuss how the GWP for each EOL strategy found in literature compares to the results found in this study. A comparative analysis of GWP as an example with other studies is shown in Table 2.

For landfilling, the GWP results for plastics other than PMMA were similar. For WtE, Schwarz et al. (2021) employed a relatively low-efficiency process, resulting in a much higher induced impact compared to PMMA in our study. In India (Neo et al., 2021), the results for mixed plastics are more similar to our results; however, the electricity and heat outputs of those mixed plastics are much higher (electricity and heat in the order of 5–10 MJ kg^{-1}) than what was considered for PMMA in our study (electricity and heat in the order of 1–3 MJ kg^{-1}).

Also, concerning GWP, the savings are considerably higher for mechanical recycling due to the consideration of avoided products produced in the mechanical recycling process (about −4760 kg CO_2-eq). Compared to other plastics, such as polyethylene and PET (Hottle et al., 2017), the production of PMMA sheets is associated with higher energy consumption and greenhouse gas emissions (GHG) emissions than others (Mahmud and Farjana, 2021). In Schwarz et al. (2021), sorting is not included but energy recovery of 20% of the material is considered. Civancik-Uslu et al. (2021) included sorting for the Belgium case presenting around three times fewer savings for PP (−1000 kg CO_2-eq) than in our case study for PMMA (−4760 kg CO_2-eq). Including transport or sorting might explain why savings are less in these cases when compared to our study, which did not include those processes. The savings were substantially low for the mixed plastic wastes (e.g. Hossain et al., 2021; Neo et al., 2021), possibly due to the consideration of waste transportation, higher energy consumption for sorting, low energy content and contaminations for mixed ones.

Finally, the process modelling for chemical recycling varies significantly among studies. In our study, neither sorting nor transport was included, and all chemical recycling was assumed to be done in the same location. We assumed the production of MMA monomer as an avoided product at a ratio of 70% (Kikuchi et al., 2014). In addition, we included the heat produced from waste in the pyrolysis to either substitute coal or natural gas. The results show savings compared to other studies, −5123 (for coal substitution) and −4370 (for natural gas substitution) kg CO_2-eq. Jeswani et al. (2021) found 700 kg CO_2-eq of GWP impact considering pyrolysis for mixed plastics in Germany, including two by-products: char to substitute lignite in cement kilns and heavy vacuum residue that replaces fossil-based heavy vacuum residue. The study also included the transportation to a purification plant, which might explain the higher induced impact. Aryan et al. (2021) focused on PLA hydrolysis or alcoholysis by including transportation, washing agents and energy in the processes. The results are consistent with our study even though there is still a great difference in considerations. Civancik-Uslu et al. (2021) presented an impact of 100 kg CO_2-eq for the thermochemical recycling of PP, but they include sorting as well. For Schwarz et al. (2021), it is not clear whether they included the avoided product for all monomers produced.

Environmental impacts of PMMA EOL scenarios

This section describes the environmental benefits of PMMA EOL scenarios to implement circularities strategies. Therefore, a 15 set of potential alternative scenarios for PMMA management was developed and compared with the existing scenario. Figure 4 shows the results of the PMMA EOL scenario analysis (refer to Table 1 for details on each scenario). Upon analysing the results, two groups of impacts can be observed. Firstly, the six impact categories (acidification, carcinogenic, fossil fuel depletion, global warming, respiratory effects and smog formation) showed increasing benefits as the scenarios become more ‘circular’. Secondly, four categories (ecotoxicity, eutrophication, non-carcinogenic and ozone depletion) showed different patterns, including having fewer benefits with the 100% reuse scenario (e.g. ozone depletion in Scenario 15).

The current U.S. scenario (Scenario 1 – 75% landfill, 16% WtE and 9% mechanical recycling) showed benefits in the first group of categories while having an impact in the second group. It is only better than Scenario 2, which is landfilling all PMMA waste. However, Scenario 13 (40% reuse, 40% chemical recycling and 20% mechanical recycling) outperforms reusing all PMMA (Scenario 15), showing the highest impact savings across all categories. These results are consistent with the previous studies that apply LCA to plastics EOL, where recycling (chemical or mechanical) is a preferable EOL solution for reaching a circular economy because it avoids the impacts of producing new PMMA barriers from virgin resources (Chaudhari et al., 2021; Hottle et al., 2017; Kikuchi et al., 2014).

Implementing circular economy into the plastic sectors in the United States

The current plastics EOL practices should be improved to promote plastic circular economy strategies in the United States, and thus systemic changes are needed to reach an ideal scenario. Based on Figure 3, the least preferable options are Scenarios 1 through 5 (Scenario 1: 75% Landfill, 16% WtE, 9% Mechanical recycling; Scenario 2: 100% Landfill; Scenario 3: 100% WtE; Scenario 4: 50% Landfill, 50% WtE; Scenario 5: 25% Landfill, 25% WTE, 50% Mechanical recycling). The most preferable Scenarios are 13, 12, 14, 15 and 10 (Scenario 13: 40% Chemical recycling, 20% Mechanical recycling, 40% Reuse; Scenario 12: 10% WtE, 30% Chemical recycling, 30% Mechanical recycling, 30% Reuse; Scenario 14: 25% Chemical recycling, 50% Mechanical recycling, 25% Reuse; Scenario 15: 100% Reuse;

Table 2. Comparison of findings for GWP.

EOL strategy	Plastic type	GWP (kg CO_2-eq/ tonne of material)	Country/region	System boundaries	Source
Landfill	PMMA	88	US	Landfill process from Ecoinvent 3.8.	Our study
	PE	113	US	Landfill process from Ecoinvent 2.	Hottle et al. (2017)
	PET	80			
WtE	PMMA	−615	US	Electricity and heat in the order of 1–3 MJ kg^{-1}. No efficiency is considered.	Our study
	PMMA	8700	Europe	Efficiency of 0.2092 is used for electricity and 0.0603 for heat.	Schwarz et al., 2021
	Mixed plastics	1220	India	Electricity and heat in the order of 5–10 MJ kg^{-1}.	Neo et al., 2021
Mechanical recycling	PMMA	−4760	US	Production impacts of PMMA sheets is high. Substitution ratio 1:1. Neither sorting nor transport is included.	Our study
	PE	−1470	US	Production impacts of these polymer types are low. Substitution ratio 1:0.7. Neither sorting nor transport is included.	Hottle et al. (2017)
	PET	−2310			
	PET	2500	Europe	Sorting is not included. Substitution ratio 1:0.8. Leftover material (0.2) is assumed to be incinerated with energy recovery.	Schwarz et al. (2021)
	PMMA	5000	Europe		Schwarz et al. (2021)
	PP	−1000	Belgium	Sorting is included.	Civancik-Uslu et al. (2021)
	Mixed plastics	−750	Indonesia	Included transport of waste.	Neo et al., 2021
	Mixed plastics	−940	India		
	Mixed plastics	−634	Hong Kong	Included sorting and transportation.	Hossain et al. (2021)
Chemical recycling (pyrolysis)	PMMA	−5123 (coal) −4370 (natural gas)	US	Substitution of heat from waste in pyrolysis for heat produced from coal or natural gas. Neither sorting nor transport is included. All process is done in the same site location.	Our study
Chemical recycling (pyrolysis)	Mixed plastics	700	Germany	Char is a co-product that substitutes fuel (lignite) that goes in cement kilns. Another co-product, heavy vacuum residue, is used as an alternative fuel, it replaces fossil-based heavy vacuum residue. Pyrolysis oil transportation to purification plant is included.	Jeswani et al. (2021)
Hydrolysis	PLA	1670	Europe	Transport, washing agents and energy are included.	Aryan et al. (2021)
Alcoholysis – methanol	PLA	−1389		Transport, washing agents and energy are included.	
Alcoholysis – ethanol	PLA	−2910		Transport, washing agents and energy are included.	
Chemical recycling (pyrolysis)	PP LDPE HDPE PET PMMA	1300 1400 1300 2900 2700	Europe	For the pyrolysis to monomers the output product is assumed to be a mixture of hydrocarbon chemicals. These chemicals can be obtained and reused in chemical processes. The non-volatile material, the char, is used as feedstock for the recycling treatment step. This amount is therefore subtracted from the avoided materials.	Schwarz et al. (2021)
Thermochemical recycling	PP	100	Belgium	Sorting is included.	Civancik-Uslu et al. (2021)

HDPE: High Density Polyethelene; LDPE: Low Density Polyethelene; PET: Polyethylene terephthalate; PE: polyethylene; PLA: polylactic acid; PMMA: polymethyl methacrylate; PP: Polypropylene; US: United States.

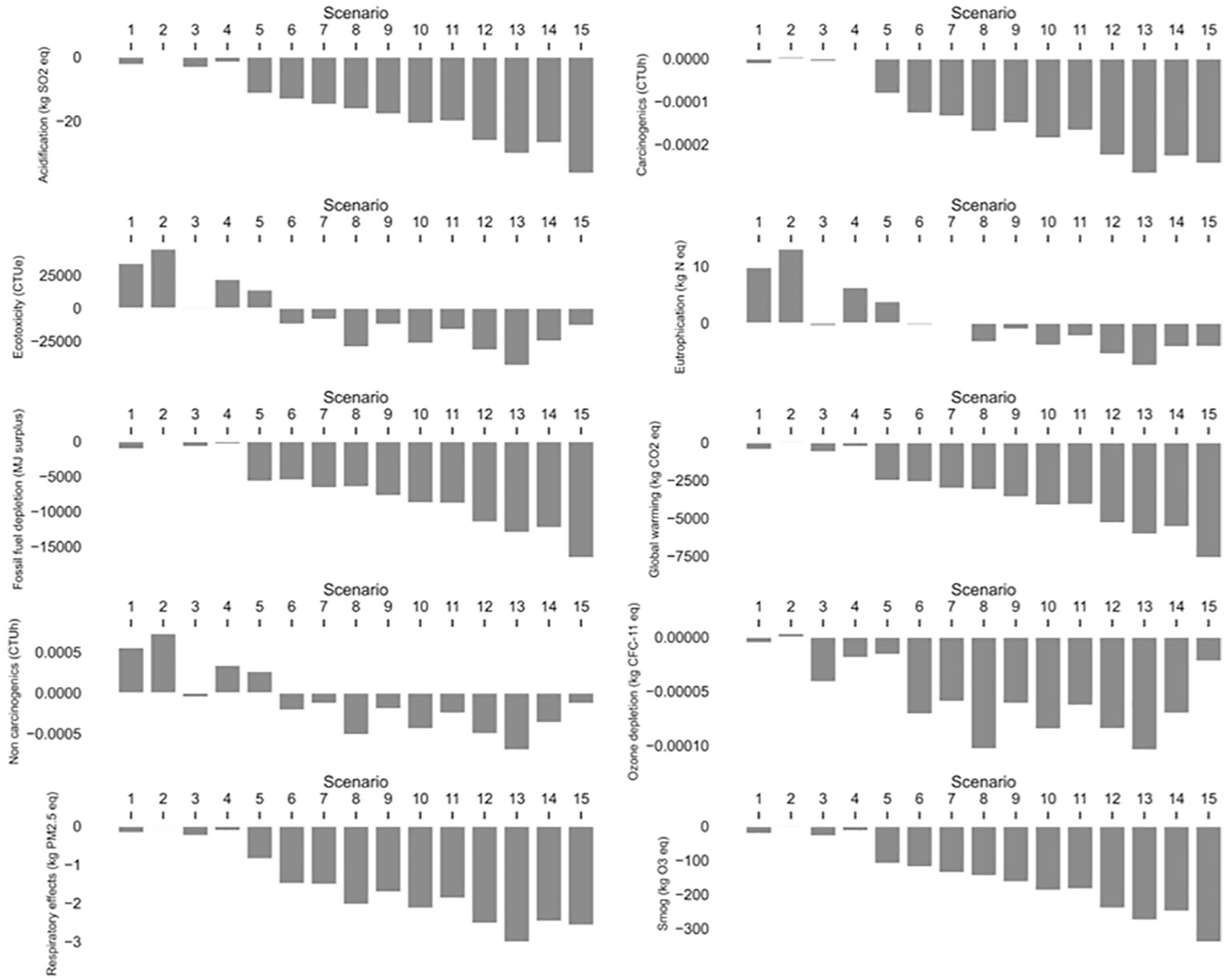

Figure 4. Environmental impacts of PMMA EOL scenarios.
See Table 1 for a description of the scenarios.

Scenario 10: 10% Landfill, 20% WtE, 30% Chemical recycling and 20% Mechanical recycling, 20% Reuse).

So far, practical directions for implementing circular economy in the plastic sector have been recommended by several studies (Di et al., 2021; Geyer et al., 2017; Raoul et al., 2021; Tsiamis et al., 2018; Wagner and Schlummer, 2020) and organizations (Ellen MacArthur Foundation, 2016; United Nations Environment Programme, 2014), including the Draft National Strategy to Prevent Plastic Pollution (US EPA, 2023). Thus, we have summarized and prioritized some specific directions for the plastic sector in the United States for the most preferable five scenarios of PMMA waste management which are shown in Table 3. The intensity of the measures for adopting circular economy strategies was based on expert opinions and a group discussion to achieve the aim of particular circular economy strategies towards sustainable management. The current scenario (Scenario 1) is shown as a reference.

There is a need to improve asset management and data for PMMA barriers and other plastics. Secondly, the existing infrastructure for the collection and sorting of PMMA barriers for reuse and recycling strategies should be improved at the national level including with the participation of the general population, commercial establishments that make use of PMMA barriers and recyclers. In this sense, the Japanese case presents a successful case because of their programme for collecting PMMA from the country's automotive, electronics and construction industries (Kikuchi et al., 2014). Concomitantly, the end markets for reused and recycled products should be expanded in the country, as pointed out by Heller et al. (2020). Finally, public policies have a major role to play in improving plastics EOL and for instance, taxing the production of virgin plastics feedstocks so that it becomes more expensive than circular strategies and/or tax exemptions to circular solutions such as innovative recycling technologies. Since December 2020, with the Save Our Seas 2.0 Act, the US EPA started coordinating solutions for plastic waste in the United States and in November 2021, with the Infrastructure Investment and Jobs Act, funding for the Circular Economy Strategy Series was secured, including a Plastics National strategic plan to be developed in the next few years (US EPA, 2022). According to Heiges and O'Neill (2022), there are an additional 19 bills concerning the circular economy for plastics to be evaluated by the US Congress, including, for example, the 'Zero Waste Act', 'Recycling Infrastructure and Accessibility Act' and 'Break Free From Plastic Pollution Act'.

Table 3. Relative impact of circular economy strategies by PMMA scenarios in the United States.

Circular economy strategies	Current Scenario: 75% land, 16% WtE, 9% mechanical recycling	Scenario 10: 10% land, 20% WtE, 30% chemical recycling, 20% mechanical recycling, 20% Reuse	Scenario 15: 100% reuse	Scenario 14: 25% chemical recycling, 50% mechanical recycling, 25% reuse	Scenario 12: 10% WtE, 30% chemical recycling, 30% mechanical recycling, 30% reuse	Scenario 13: 40% chemical recycling, 20% mechanical recycling, 40% reuse
1. Improve asset and data management throughout the supply chain, especially post-consumption						
2. Create a multiple-stream collection and sorting system, specific for reuse, chemical recycling or mechanical recycling						
3. Widen end markets for reused and recycled plastics products						
4. Tax the production of virgin plastics feedstocks						
5. Tax exemptions for circular businesses (reuse and recycling reclaimers)						
6. Scale up reuse and refill models, create reusable materials bank						
7. Establish resource recovery parks for plastic waste with sorting facilities, chemical and mechanical recycling facilities						

Green shades represent the intensity that these directions should be applied in each scenario. Grey is for reference.

Limitations

As LCA is a data-driven method, this study has several limitations. Firstly, due to the lack of plastics EOL data in the United States, including the use, collection and sorting phases of PMMA waste was shown to be complicated, and requires further investigation in future studies. In addition, foreground systems were modelled based on secondary data found in literature globally and do not always portray the reality of technologies used in the United States. Primary data concerning US-based companies and technologies for processing EOL plastics could be collected for future LCAs of PMMA barriers with a focus on the United States.

Secondly, uncertainty analysis included only background processes. Foreground systems used secondary data and sources did not report any variability or uncertainty in the data. Michiels and Geeraerd (2020) found that this is the case for most LCA studies that include uncertainty analysis and pointed out that future studies would consider each uncertain input parameter and its probability distributions during the inventory phase.

In addition, impurities in PMMA waste (e.g. nails made from metals, adhesives, paints, etc.) were not considered in this study. However, impurities in waste streams play a very important role in EOL processes. The more impurities there are, the less efficient circular strategies (reuse and recycling) will be, in terms of how much PMMA can be recovered. Future work should assess PMMA barriers impurities to investigate their effects on circular economy strategies. In theory, since their function is to protect against viruses, they should be disinfected (e.g. autoclaved) before sending to EOL streams. For this reason, PMMA barriers waste could be considered part of the healthcare sector waste stream. Therefore, sorting and cleaning along with transportation related to PMMA waste collection and recovered materials to reuse/reprocessing sites should be considered in the future LCA for completeness and comprehensiveness.

Conclusions

This LCA study was conducted to explore different circularity strategies for plastic shields used during the COVID-19 pandemic in the United States. The environmental impacts of five different EOL strategies of PMMA barriers were evaluated, including landfill, WtE, mechanical recycling, chemical recycling (i.e. monomer pyrolysis) and reuse through LCA and a sensitivity analysis via scenario analysis showed how adopting diverse combinations of the EOL strategies can change the LCA impact assessment. We conclude that landfilling is the least preferred EOL strategy for PMMA barriers, not only because it was the only EOL strategy that presented induced impacts, but mostly because there is no avoidance of new resource production in this linear paradigm. For GWP, Reuse was the most promising. When considering *all* impact categories, chemical recycling presented the highest savings when compared to the other four EOL strategies (landfill, WtE, mechanical recycling and reuse). The current plastics EOL practices should be improved to promote plastic circular economy strategies in the United States. To the best of our knowledge, this is the first LCA study that considers this set of EOL strategies focusing on PMMA in the United States. The limitations and future research directions highlighted in this study should be considered for a sustainable and circular fate for plastics in the future.

Acknowledgements

We would like to thank Dr. Vikas Khanna for his support and all colleagues who provided precious feedback for this project.

Author contributions

Nathalia Silva de Souza Lima Cano: Conceptualization, data curation, formal analysis, investigation, methodology, resources, validation, visualization, writing – original draft preparation. Md Uzzal Hossain: Formal analysis, supervision, validation, visualization, writing – review & editing. Melissa Marie Bilec: Conceptualization, methodology, project administration, software, supervision, validation, writing – review & editing.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This study was partially funded by Fulbright Commission (Fulbright-CAPES Scholarship, ME/CAPES N° 8/2020). This material is based upon work supported by the National Science Foundation under Grant No. 1934824.

ORCID iDs

Nathalia Silva de Souza Lima Cano https://orcid.org/0000-0003-3533-7992
Melissa Marie Bilec https://orcid.org/0000-0002-6101-6263

Research data

Most data used was based on literature. Confidential input data for LCA modelling of the mechanical and chemical recycling of PMMA was provided by personal communication.

Supplemental material

Supplemental material for this article is available online.

References

Accorsi R, Versari L and Manzini R (2015) Glass vs. plastic: Life cycle assessment of extra-virgin olive oil bottles across global supply chains. *Sustainability* 7: 2818–2840.

Adhikari B, Chowdhury NA, Diaz LA, et al. (2023) Electrochemical leaching of critical materials from lithium-ion batteries: A comparative life cycle assessment. *Resources, Conservation and Recycling* 193: 106973–106973.

Aryan V, Maga D, Majgaonkar P, et al. (2021) Valorisation of polylactic acid (PLA) waste: A comparative life cycle assessment of various solvent-based chemical recycling technologies. *Resources, Conservation and Recycling* 172: 105670.

Bamber N, Turner I, Arulnathan V, et al. (2020) Comparing sources and analysis of uncertainty in consequential and attributional life cycle assessment: Review of current practice and recommendations. *International Journal of Life Cycle Assessment* 25: 168–180.

Bare J (2011) TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0. *Clean Technologies and Environmental Policy* 13: 687–696.

Bocken NMP, de Pauw I, Bakker C, et al. (2016) Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering* 33: 308–320.

Cao D, Yang G, Bourham M, et al. (2020) Gamma radiation shielding properties of poly (methyl methacrylate)/Bi_2O_3 composites. *Nuclear Engineering and Technology* 52: 2613–2619.

Chaudhari US, Lin Y, Thompson VS, et al. (2021) Systems analysis approach to polyethylene terephthalate and olefin plastics supply chains in the circular economy: A review of data sets and models. *ACS Sustainable Chemistry and Engineering* 9: 7403–7421.

Civancik-Uslu D, Nhu TT, Van Gorp B, et al. (2021) Moving from linear to circular household plastic packaging in Belgium: Prospective life cycle assessment of mechanical and thermochemical recycling. *Resources, Conservation and Recycling* 171: 105633.

Construction Junction (2022) Construction junction. Available at: https://cjreuse.org (accessed 23 April 2023).

Cosate de Andrade MF, Souza PMS, Cavalett O, et al. (2016) Life cycle assessment of poly(lactic acid) (PLA): Comparison between chemical recycling, mechanical recycling and composting. *Journal of Polymers and the Environment* 24: 372–384.

De Tommaso J and Dubois JL (2021) Risk analysis on PMMA recycling economics. *Polymers* 13: 2724–2724.

Di J, Reck BK, Miatto A, et al. (2021) United States plastics: Large flows, short lifetimes, and negligible recycling. *Resources, Conservation and Recycling* 167: 105440.

Ellen MacArthur Foundation (2016) *The new plastics economy: Rethinking the future of plastics*. Ellen MacArthur Foundation.

Gandhi N, Farfaras N, Wang NHL, et al. (2021) Life cycle assessment of recycling high-density polyethylene plastic waste. *Journal of Renewable Materials* 9: 1463–1483.

Geyer R, Jambeck JR and Law KL (2017) Production, use, and fate of all plastics ever made. *Science Advances* 3: e1700782.

Gibb BC (2019) Plastics are forever. *Nature Chemistry* 11: 394–395.

Global Industry Analysis (2022) *Polymethyl Methacrylate Market (PMMA) – Global Industry Analysis 2029*. Pune: Maximize Market Research PVT. LTD. Available at: https://www.maximizemarketresearch.com/market-report/global-polymethyl-methacrylate-market/26389/ (accessed 9 June 2023).

Grand View Research (2021) Plastic resins market size, analysis & industry outlook – 2030. Available at: https://www.grandviewresearch.com/industry-analysis/plastic-resins-market (accessed 23 June 2023).

Grand View Research (2022) U.S. polymethyl methacrylate market size report, 2030. Available at: https://www.grandviewresearch.com/industry-analysis/us-polymethyl-methacrylate-market (accessed 23 June 2023).

Grosso M (2022) It's all about plastics. *Waste Management & Research* 40: 607–608.

Heiges J and O'Neill K (2022) A recycling reckoning: How operation national sword catalyzed a transition in the U.S. plastics recycling system. *Journal of Cleaner Production* 378: 134367–134367.

Heller MC, Mazor MH and Keoleian GA (2020) Plastics in the US: Toward a material flow characterization of production, markets and end of life. *Environmental Research Letters* 15: 094034.

Helmes RJK, Goglio P, Salomoni S, et al. (2022) Environmental impacts of end-of-life options of biobased and fossil-based polyethylene terephthalate and high-density polyethylene packaging. *Sustainability* 14: 11550–11550.

Hossain MU, Leu SY and Poon CS (2016) Sustainability analysis of pelletized bio-fuel derived from recycled wood product wastes in Hong Kong. *Journal of Cleaner Production* 113. Elsevier: 400–410.

Hossain MU, Ng ST, Dong Y, et al. (2021) Strategies for mitigating plastic wastes management problem: A lifecycle assessment study in Hong Kong. *Waste Management* 131: 412–422.

Hottle TA, Bilec MM and Landis AE (2017) Biopolymer production and end of life comparisons using life cycle assessment. *Resources, Conservation and Recycling* 122: 295–306.

ICIS (2020) PMMA faces long road to recovery. Available at: https://www.icis.com/explore/services/pmma-faces-long-road-to-recovery/ (accessed 9 May 2023).

International Organization for Standardization (2006a) ISO 14040: Environmental management – Life cycle assessment – Principles and framework.

International Organization for Standardization (2006b) ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines.

Jeswani H, Krüger C, Russ M, et al. (2021) Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. *Science of the Total Environment* 769: 144483.

Kikuchi Y, Hirao M, Sugiyama H, et al. (2014) Design of recycling system for poly(methyl methacrylate) (PMMA). Part 2: Process hazards and material flow analysis. *International Journal of Life Cycle Assessment* 19: 307–319.

Lau WWY, Shiran Y, Bailey RM, et al. (2020) Evaluating scenarios toward zero plastic pollution. *Science* 369:1455–1461.

Lessler J, Grabowski MK, Grantz KH, et al. (2021) Household COVID-19 risk and in-person schooling. *Science* 372: 1092–1097.

Li S, Qin Y, Subbiah J, et al. (2020) Life cycle assessment of the U.S. beef processing through integrated hybrid approach. *Journal of Cleaner Production* 265: 121813–121813.

Li W, Chong A, Lasternas B, et al. (2022) Quantifying the effectiveness of desk dividers in reducing droplet and airborne virus transmission. *Indoor Air* 32: e12950.

Lloyd SM and Ries R (2007) Characterizing, propagating, and analyzing uncertainty in life-cycle assessment: A survey of quantitative approaches. *Journal of Industrial Ecology* 11: 161–179.

Mahmud MAP and Farjana SH (2021) Comparative eco-profiles of polyethylene terephthalate (PET) and polymethyl methacrylate (PMMA) using life cycle assessment. *Journal of Polymers and the Environment* 29: 418–428.

Michiels F and Geeraerd A (2020) How to decide and visualize whether uncertainty or variability is dominating in life cycle assessment results: A systematic review. *Environmental Modelling and Software* 133: 104841.

Mukherjee C, Denney J, Mbonimpa EG, et al. (2020) A review on municipal solid waste-to-energy trends in the USA. *Renewable and Sustainable Energy Reviews* 119: 109512.

Muranko Ż, Tassell C, van der Laan AZ, et al. (2021) Characterisation and environmental value proposition of reuse models for fast-moving consumer goods: reusable packaging and products. *Sustainability* 13: 2609–2609.

Neo ERK, Soo GCY, Tan DZL, et al. (2021) Life cycle assessment of plastic waste end-of-life for India and Indonesia. *Resources, Conservation and Recycling* 174: 105774.

OECD (2022) Global plastics outlook. Available at: https://www.oecd-ilibrary.org/environment/global-plastics-outlook_aa1edf33-en (accessed 17 May 2023).

Patrício Silva AL, Prata JC, Walker TR, et al. (2021) Increased plastic pollution due to COVID-19 pandemic: Challenges and recommendations. *Chemical Engineering Journal* 405: 126683.

Quevedo-Cascante M, Mogensen L, Kongsted AG, et al. (2023) How does Life Cycle Assessment capture the environmental impacts of agroforestry? A systematic review. *Science of The Total Environment* 890: 164094.

Raoul M, Arne K, Marvin B, et al. (2021) Achieving net-zero greenhouse gas emission plastics by a circular carbon economy. *Science* 374: 71–76.

Salemdeeb R, Saint R, Pomponi F, et al. (2022) Beyond recycling: An LCA-based decision-support tool to accelerate Scotland's transition to a circular economy. *Resources, Conservation and Recycling Advances* 13: 200069.

Schwarz AE, Ligthart TN, Godoi Bizarro D, et al. (2021) Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. *Waste Management* 121: 331–342.

Statista (2021) *Market Revenue of PMMA in the US from 2014 to 2025, By Product*. New York: Statista Inc. Available at: https://www.statista.com/statistics/730988/pmma-market-revenue-in-the-united-states-by-product/ (accessed 5 June 2023).

Thiounn T and Smith RC (2020) Advances and approaches for chemical recycling of plastic waste. *Journal of Polymer Science* 58: 1347–1364.

Tsiamis DA, Torres M and Castaldi MJ (2018) Role of plastics in decoupling municipal solid waste and economic growth in the U.S. *Waste Management* 77: 147–155.

Tunesi S, Baroni S and Boarini S (2016) Waste flow analysis and life cycle assessment of integrated waste management systems as planning tools: Application to optimise the system of the City of Bologna. *Waste Management & Research* 34: 933–946.

United Nations Environment Programme (2014) Valuing plastic: The business case for measuring, managing and disclosing plastic use in the consumer goods industry. Available at: https://wedocs.unep.org/handle/20.500.11822/9238 (accessed 19 June 2023).

United Nations Environment Programme (2018) Mapping of global plastics value chain and plastics losses to the environment: With a particular focus on marine environment. Available at: https://www.unep.org/resources/report/mapping-global-plastics-value-chain-and-plastics-losses-environment-particular (accessed 7 July 2023).

US EPA (2020a) Advancing sustainable materials management: 2018 tables and figures. Available at: https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf (accessed 6 June 2023).

US EPA (2020b) National overview: Facts and figures on materials, wastes and recycling. Available at: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials (accessed 23 June 2023).

US EPA (2021) National recycling strategy: Part one of a series on building a circular economy for all. Available at: https://www.epa.gov/system/files/documents/2021-11/final-national-recycling-strategy.pdf (accessed 7 June 2023).

US EPA (2022) Building a circular economy for all: Progress toward transformative change. Available at: https://www.epa.gov/system/files/documents/2022-09/EPA_Circular_Economy_Progress_Report_Sept_2022.pdf (accessed 7 June 2023).

US EPA (2023) Draft national strategy to prevent plastic pollution. Available at: https://www.epa.gov/circulareconomy/draft-national-strategy-prevent-plastic-pollution (accessed 10 June 2023).

Wagner S and Schlummer M (2020) Legacy additives in a circular economy of plastics: Current dilemma, policy analysis, and emerging countermeasures. *Resources, Conservation and Recycling* 158: 104800.

Wender BA, Foley RW, Hottle TA, et al. (2014) Anticipatory life-cycle assessment for responsible research and innovation. *Journal of Resposible Innovations* 1: 200–207.

World Health Organization (2020) Rational use of personal protective equipment for COVID-19 and considerations during severe shortages: interim guidance. Available at: https://www.who.int/publications/i/item/rational-use-of-personal-protective-equipment-for-coronavirus-disease-(covid-19)-and-considerations-during-severe-shortages (accessed 15 June 2023).

World Health Organization (2022) Global analysis of health care waste in the context of COVID-19. Available at: https://www.who.int/publications/i/item/9789240039612 (accessed 15 June 2023).

Zhao X and You FQ (2021) Consequential life cycle assessment and optimization of high-density polyethylene plastic waste chemical recycling. *ACS Sustainable Chemistry & Engineering* 9: 12167–12184.