Research Topics

The sustainability series: The plastics problem - pathways towards sustainable solutions against plastic pollution

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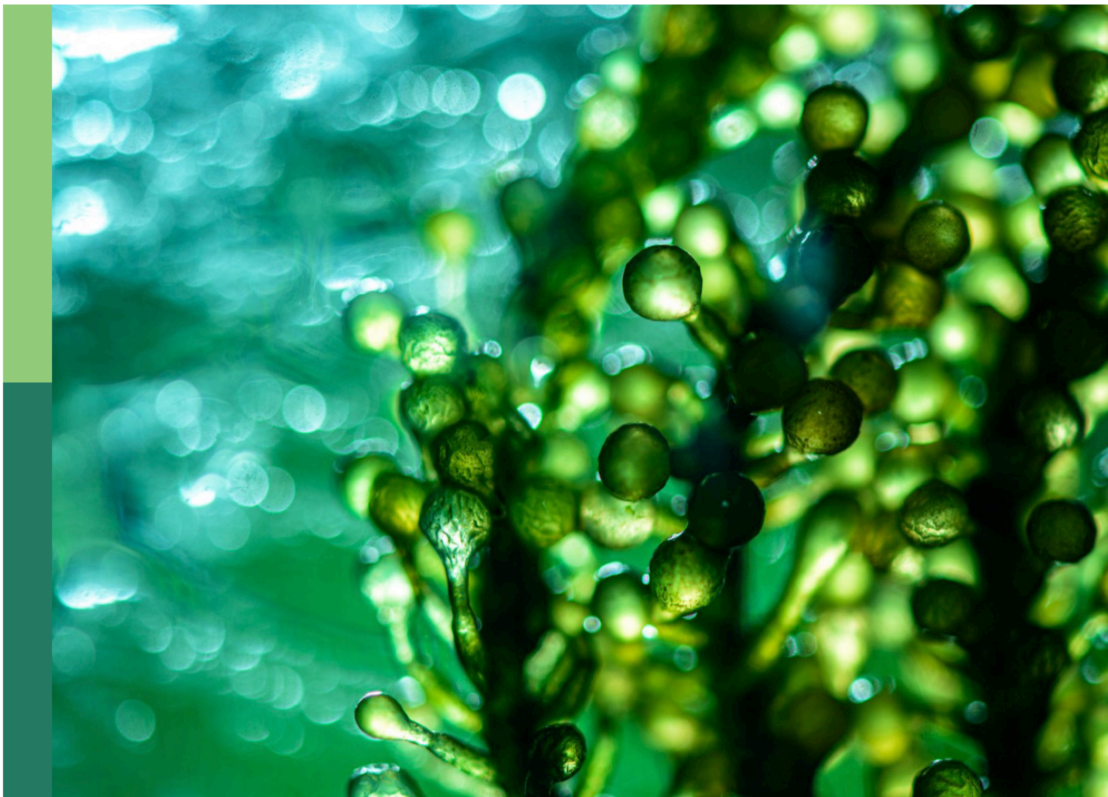

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The sustainability series: The plastics problem - pathways towards sustainable solutions against plastic pollution

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Editorial: *The sustainability series:* the plastics problem - pathways towards sustainable solutions against plastic pollution

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Editorial on the Research Topic
The sustainability series: the plastics problem - pathways towards sustainable solutions against plastic pollution

Plastic is acknowledged as a topic of growing international concern with impacts on people, communities, livelihoods and ecosystems (Worm et al., 2017). This has sparked a global response that has resulted in the creation of numerous national and international laws. An important step was reached when the United Nations Environment Programme (UNEP) agreed to be given the responsibility of negotiating a legally binding international convention to address the comprehensive effects of plastics (Treaty to End Plastic Pollution by 2024) (Mofokeng et al., 2023).

Over the past decade, most of the attention on the plastic problem has been centered around the issue of plastic pollution in the environment. However, this represents only a fraction of the overall impact of plastic. Plastic manufacturing, trading, and consumption heavily rely on fossil fuels, resulting in adverse consequences for people, communities, and the environment and contributing to climate change (Ford et al., 2022). Many initiatives to combat plastic pollution have focused on improving waste management (see OECD, 2018), cleaning existing pollution (e.g., https://theoceancleanup.com/), and redesigning eco-friendly products (e.g., https://zerowasteeurope.eu/). Some have also concentrated on implementing bans and encouraging reductions in plastic consumption. However, none of these measures can succeed in isolation. It is crucial to prioritize reevaluating the materials entering the supply chain and enhancing our ability to recycle and reuse plastic. We can fundamentally transform the situation by treating plastic as a valuable resource rather than mere waste.

In this Research Topic, we present new research, in the form of 12 articles, that addresses multiple areas to consider to reduce the challenges posed by this problem. Geographically, contributions span from the Galapagos and Brazil to South Africa and the Seychelles, Europe, Australia and New Zealand. Topics range from measurement and mapping of plastic losses in the environment, alternative materials to fossil-based plastic, management solutions and the associated challenges, to policies that are likely to be effective in mitigating plastic losses to the environment and actions that can help improve plastics circularity (Figure 1).

Muñoz-Pérez et al. quantified and mapped plastic pollution's magnitude and biological effects in the Galapagos islands (Pacific Ocean), and they found that no sampled coast was plastic debris-free. By working closely with citizen scientists, the authors documented 52 species exposed to plastic pollution through entanglement and ingestion, including the iconic marine iguana (*Amblyrhynchus cristatus*) and four Critically Endangered species. Ballerini et al. also applied a citizen-science approach to quantify macrolitter along the Durance riverbank and Lake Serre-Ponçon's beach (France), finding that 82% of mismanaged waste was plastic. The information shared from both of these studies can be used to support the development of targeted policies in litter prevention, mitigation, and reduction of most abundant litter items, as well as to test whether implemented measures to reduce plastic pollution are effective.

Data availability is crucial to decision and policy-makers and to encourage a more sustainable science regarding financial and natural resource use. de Ramos et al. analyzed open data repositories to identify the presence of datasets related to marine litter in Brazil, and they concluded that more data still needs to be published. This work highlights the utility of data sharing, which supports resource optimization, complementarity, and data-driven management decision-making.

Plastic has impacts that go unnoticed, which are related to the whole life-cycle, from the extraction of the raw materials to the creation of the pellets until the end of life of plastic products. Thus, a life cycle management (LCM) approach for plastic products is needed, as declared in the Medellin Declaration on Marine Litter in Life Cycle Assessment and Management (Sonnemann and Valdivia, 2017). Chitaka et al. explored how enhanced knowledge of plastic leakage has influenced approaches to plastic product LCM in South Africa. The authors found that the drivers for developing strategies to address plastic pollution mirror those for adopting LCM-based concepts, including maintaining a competitive advantage, compliance with regulations and legislation, and meeting investor and consumer expectations.

Among the various tools in LCM is life cycle assessment (LCA), which is a method for identifying and evaluating the environmental impacts of a product over its entire life cycle. LCA can broaden our understanding of the ecological impacts of a product beyond what is the most visible. In this Research Topic, Miller provided an overview of the LCA process and described the benefits and limitations of LCA methods as they pertain to plastic waste. The paper summarized major trends observed in prior LCA studies and discussed how LCA could best help resolve the plastics problem

FIGURE 1
Word cloud generated from keywords from the papers included in this Research Topic (generated through WordArt.com).

without causing other unintended issues. The author concluded that reduced consumption of the underlying need for plastic is the only way to ensure reduced environmental impacts.

Alternatives to fossil-based plastics exist, including compostable and biodegradable plastic. However, the damage caused by incorrect waste management may offset them, and currently, different products are confusing to consumers, as we still lack a consistent labeling system. Mismanagement of compostable plastic may derive from contamination in recycling, the inability of waste streams to separate compostable from traditional plastic due to a lack of technologies that automatically detect and divide it, or both. Allison et al. developed a program to improve compostable plastic disposal in the United Kingdom focused on improving citizens' behavior. The resulting intervention was a disposal instruction label for compostable packaging comprising instructions and a logo. However, the authors pointed out that introducing a disposal instruction label is unlikely sufficient as an intervention strategy until products that are not compostable—but claim to be—are banned from the market. Taneepanichskul et al. developed classification models for automatically identifying and classifying compostable plastics using a hyperspectral imaging camera and chemometric techniques. Indeed, the advantages of compostable packaging are realized when they do not enter the environment or pollute other waste streams or the soil. The system can accurately sort and differentiate compostable plastics from identical-looking conventional plastic items.

Recycling may be essential to reducing waste and developing a plastics circular economy. Circularity also includes the application of smart logistics to maximize the potential discarded plastic and the development of new business models. The European Commission has taken a circular economy-focused approach to the problem of End-Of-Life (EOL) fishing gear and abandoned, lost, or otherwise discarded fishing gear (ALDFG), encouraging their separate collection, transit, and circular treatment (Basurko et al., 2023). Andrés et al. propose a new circular business model for tuna purse seine nets. Tropical tuna purse seiners are one of the world's most significant contributors to EOL fishing gears, and these fishing nets can become a promising secondary raw material. Innovation and logistics play a fundamental role in making the business sustainable.

However, recycling is not the best option for all kinds of products. Whilst an increasing share of post-consumer plastic waste in OECD countries is collected for recycling (Bishop et al., 2020), globally, only 9% of plastic waste is recycled, while 22% is mismanaged (OECD, 2022). Plastic waste export has been a common waste management practice, and importing countries increasingly receive unrecyclable plastic waste designated as "recyclable". Unfortunately, nearly all nations that receive significant amounts of plastic waste also have some of the world's highest rates of waste mismanagement (Jambeck et al., 2015). In response, the Basel Convention, an international treaty designed to reduce the movements of hazardous wastes, adopted the Plastic Waste Amendments clarifying which types of plastic waste are subject to the control procedure for exports, transit and imports. Nevertheless, severe weaknesses still exist regarding the actual implementation of the convention, as reported by Farrelly and Chitaka by drawing on a plastic waste material flow analysis conducted in Palmerston North (New Zealand). According to the authors, weaknesses could be resolved with clarity and harmonization of key definitions, improved data collection, and greater transparency in the monitoring and reporting of plastic waste flows.

An important strategy to address plastic pollution is creating and supporting the model of replacing disposable items with reusable products and preventing waste generation in the first place. Moss et al. described the Global Landscape of Reusable Solutions,[1] a regularly updated, open and free-to-everyone dataset created to understand the evolution, current state, and potential environmental benefits of reuse and refill solutions. Reusable item material and assortment problems, expanding and integrating reuse infrastructure, businesses' willingness to adopt reuse solutions, customers' acceptance, and, in some places, policies that restrict reusing and refilling containers are some of the barriers to growth for reuse solutions identified by the authors. The acceptance and scalability of reuse solutions can be improved through behavioral campaigns, better and more easily accessible data, sharing examples of successful systems, and growing knowledge and understanding of reuse system design.

The policy environment is critical in reducing plastic pollution (Vince and Hardesty, 2017). National and international policy changes tend to redefine how plastics are designed, produced and used to lay the foundations for a new circular plastic economy. Hardesty et al. focused on Australia's National Plastics Plan as a case study of a national approach to addressing this transboundary issue. The Plan was considered in regard to supply chains, best practices and standards, and guidelines for a successful circular plastic economy. Recognizing that plastic leakage into the environment is a social equality issue, the authors encourage place-based solutions that are culturally relevant, commercially viable, and environmentally appropriate.

Plastic pollution is a problem that begins long before it reaches the environment, and so it must be the solution. García-Hermosa and Woodall suggested a multidisciplinary approach to effectively address the marine plastic litter problem, minimizing plastic production and consumption and reducing waste leakage through better waste management. The authors also encouraged the creation of a shared user-friendly tool designed to facilitate transparency and democratization of methodologies by gathering pertinent information from diverse sources. This tool would present the current problem and a list of possible interventions, serving as a valuable mechanism to help choose, prioritize and optimize interventions.

Overall, the papers included here highlight important areas of consideration and opportunities to reduce waste losses to the environment. These span improved data collection and management, methods harmonization and data sharing, to increased circularity via design and better waste management practices. While plastic production continues to grow, we are seeing an increase in more holistic understanding and integrated approaches to change

1 www.reuselandscape.org/database

our relationship with plastic at all steps along the plastics life cycle.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Where are Brazil's marine litter scientific data?

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The environmental sciences work with datasets every day. Recently, data sharing has become a more familiar activity for academic researchers. Records of marine litter are scarce and generally difficult to find worldwide, especially in databases. This work reviews and analyzes data repositories to identify the existence of datasets related to marine litter in Brazil. Only one global repository specializing in marine litter was found, and it is in the early stages of operation. Only two datasets about marine litter in Brazil were found in the generalist repository Figshare that do not follow all the FAIR principles (Findable, Accessible, Interoperable, and Reusable) for data sharing. A few initiatives are being developed aiming to collect and share marine litter data, but only one of them (Our Blue Hands) is already in place and uses a standardized, replicable method, and aims to share the data by design. Our work identified interoperability as the main point to be tackled within our context. In the UN Decade of Ocean Science for Sustainable Development (2021–2030), it is essential that repositories are created, improved, and encouraged to address the specific needs of marine litter data-sharing and researchers' behavioral shift to start sharing the data already collected. Data sharing not only allows for the integrated vision of the academic community but can also contribute to public policies, helping decision-makers and encouraging a more sustainable science regarding financial and natural resource use.

KEYWORDS

FAIR principles in open education, interoperability among databases, dataset, repositories in science and technology, sustainability, predictable ocean, GPML, cooperation (with civil society organizations)

Introduction

The environmental sciences work with data every day. Recently, data sharing has become a more familiar activity for academic researchers (Goben and Sandusky, 2020). Available data can support new research and can be used by decision-makers. Technological advances, including the internet and easy access to information, help advance science. Despite the technology available, more data are produced every year that needs to be organized and accessible. Data accessibility brings advantages to science and society and links different study areas (Barreto et al., 2019). It would be possible to carry out many studies with already existing data. An example is that in the

COVID-19 pandemic scenario, some reviews and reanalysis used previously available data. This shows that the available data is important to guide our next works more consciously (Saadat et al., 2020). During COVID-19, the universities were closed in Brazil and most parts of the world to contain the spread of the virus. Due to the global lockdown, researchers had no access to their laboratories, and fieldwork was canceled. Since scientists are "rated" by their number of publications, they had to find some way to keep publishing during this time. Some options were review articles and analysis using data that were previously collected and/or available in repositories.

However, it is not only in a pandemic scenario that data should be shared; if not shared, data remain unused. Hence, sustainable initiatives for resources and/or biological samples are used for data collection and processing, which can be optimized by sharing and reusing the data.

Marine litter is an important theme worldwide, presented in the Sustainable Development Goals (SDGs) target 14.1, "By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution" (United Nations, 2022). Among a wide range of pollutants, marine litter and nutrients were prioritized. Also, marine litter is listed as an Essential Ocean Variable (EOV) by the Global Ocean Observing System (GOOS), highlighting the relevance of marine litter impacts on marine conservation and the importance to collect and provide such data. In the scenario of the UN Decade of Ocean Science for Sustainable Development (2021–2030), marine litter datasets following FAIR principles can help to achieve a clean and predictable ocean.

Depending on research areas, data sharing can be in its early stages or better developed. In some study areas, it is possible to choose a suitable repository, organize the data, prepare the metadata, accessory documents, copyright, consent, and permissions, and deposit the dataset (EDCTP, 2022) more easily than in other fields. Data regarding marine litter could help better understand the current scenario and support decision-making. In this work, we bring a review of previously used and potential scientific marine litter data and databases focusing on Brazil.

Brazil is the fifth largest country in the world in terms of land area (8,547,403 km^2) (IBGE, 2021). The Brazilian economy has components based on coastal and marine activities, for example, oil and gas exploitation, harbor and industrial activities, fishing, leisure, and tourism. Also, almost 30% of the population lives in the coastal zone (IBGE, 2011). Besides being a large and developing country with diverse and complex environmental and socio-economic issues, Brazil is the fourth largest plastic waste producer in the world (Zamora et al., 2020). This can cause a loss of 5.7 billion Real (Brazilian currency) a year for not dealing with this problem (Zamora et al., 2020), and also increase marine litter pollution. In this context, the number of papers about marine litter in Brazil is increasing (Castro et al., 2018; da Silva Videla and de Araujo, 2021). However, there are few datasets available related to these publications for further development of possible solutions to marine litter problem based on data.

This work aims to review and analyze data repositories to identify the existence of datasets related to marine litter in Brazil, bringing a global point of view of marine litter data sharing. In addition, we aim to highlight the importance of FAIR principles and data sharing as key points for improving and encouraging sustainable science of natural resource use and conservation.

Data, databases, and related repositories

It is common sense that data is the primary building block for both information and knowledge (Zins, 2007b). Data, information, and knowledge are the major components of information science (Zins, 2007a). Although there are some divergences in the definitions of what really involves this area (e.g., the subtypes of knowledge), for the purpose of this work, we are going to consider data, information, and knowledge as parts of sequential order. Therefore, data will be the precursor of information, which will serve as the base for knowledge. Data for this work is any set of records from observation or measurement arranged comprehensively.

The use of data is important for different areas, including environmental sciences. The use of natural resources and the ecological footprint for data collection in the environmental sciences can be optimized if more studies are carried out with the same dataset. Oceanographic cruises that collect a large amount of data also have polluting potential, for example, due to the use of fossil fuel. Using data already collected can better justify the polluting activity and allow more people to use, discuss and compare data. In addition, data availability can support better understanding or even the integration of ideas, allowing the detection of temporal and spatial patterns, such as physical oceanography data that can indicate patterns of accumulation and disposal of marine litter (Van Sebille et al., 2020). Thus, places to store and share data are becoming more common in the scientific community. Data storage requires infrastructure and energy. To make this more sustainable, it is recommended to optimize existing data repositories and resources to improve interoperability and reusability (Tanhua et al., 2019).

In agreement with this, some government and funding agencies require that researchers make their data available to receive financial support (Michener, 2015; Brainard, 2021), which plays an important role in the open science and open data movement. In 2022, the Brazilian government launched the National Consortium for Open Science (ConCIenciA in Portuguese), an initiative that aims to encourage open data repositories for research data in the national territory and support their governance with international acceptance and visibility. An action of ConCIencia was the launching of

LattesData platform (https://lattesdata.cnpq.br/) from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), a funding agency from Brazilian government. The repository was created to reunite, storage and share scientific data from funded CNPq researchers, in the future it can be open for every researcher. It highlights the role of universities in facilitating pathways to address environmental problems (Gardner et al., 2021) by providing FAIR (Findable, Accessible, Interoperable, and Reusable) data.

There are several repositories where scientists from different areas are able to share their data. Data repositories can be generalists or specialists. Generalists do not require specific formatting and/or topic of research, while specialists accept only data referring to a research area and/or certain formatting for the database (De Pooter et al., 2017). Most of the time, scientists do not know where to publish, which leads to unavailable and scattered data (Park and Wolfram, 2017). Nevertheless, the importance of sharing has been overcoming the difficulties, allowing the sharing culture to grow despite the adversities (Pendleton et al., 2019).

The open scientific data approach is proposed to help increase the speed of science, allow the comparison and cross information, increase the reproducibility of scientific work as well as mitigate data manipulation (Hampton et al., 2013; Pendleton et al., 2019). In addition, it is a strategy to optimize resources and produce a more sustainable scientific outcome, including transparency of public funds used in data acquisition.

The goal of Open Science is to make scientific research and its dissemination accessible to all levels of society. Also encompassed in the concept of Open Science are open access, open educational resources, open-source software, and citizen science, all of which are grounded in equity, diversity, and inclusion (European Commission, 2019).

In addition to online repositories, many countries have a Spatial Data Infrastructure (SDI) that includes technology, policy, standards, and human resources and encompasses activities, such as data acquisition, processing, distribution, use, maintenance, and preservation. In other words, an SDI goes far beyond an online repository. Some examples are the British Oceanographic Data Center (BODC), the Centro Argentino de Datos Oceanográficos, the Australian Ocean Data Network (AODN), the North American National Centers for Environmental Information (NCEI), and the Infrastructure for Spatial Information in Europe (INSPIRE). However, the SDI might not have data on marine litter; an exception is EMODnet, which is an EU SDI including marine litter data.

In Brazil, the National Spatial Data Infrastructure (NSDI) was launched in 2010, aiming at the integration between systems of different institutions. Its purpose is to catalog, integrate, and harmonize existing geospatial data in Brazilian government institutions. It has good documentation and defined standards for data and metadata (Gandra et al., 2018). However, in general and globally, there is still a lack of national and international collaboration for SDIs (Gandra et al., 2018); in addition, it is necessary to increase the scope to cover timely themes such as marine litter. An example is the vanguard work that is done in EMODnet, an SDI that covers most of the Essential Ocean Variables (EOVs) and keeps updated on new themes such as marine litter.

Sharing is not a problem

Despite the importance of sharing data, this is still a trend for most researchers all over the world that used to keep their data under personal control and now are dealing with the data sharing process (Reichman et al., 2011). Therefore, the first big challenge is the cultural change shift (Pendleton et al., 2019). Some of the factors that do not collaborate to this change are time and effort to find suitable repositories to upload the data, write appropriate metadata, and format the data in templates that do not always fit the type of data sampled (Park and Wolfram, 2017). Since it is still a new field, there is not much information on what to do in terms of standardized procedures and guidelines for the authors. In this regard, an example is a step-by-step guide developed by Soranno (2019) to facilitate this decision process. There are other examples such as the EMODnet ingestion portal (EMODnet, 2022a) and the EDCTP Knowledge Hub (EDCTP, 2022) guidelines.

Another factor contributing to the resistance to sharing data is data authorship/ownership (Costello, 2009; Reichman et al., 2011), which concerns about data misinterpretation and misuse (Campbell et al., 2002; Borgman, 2012). Both of these are related since many times authors start viewing this data as a product that was created by them and not only as a result/output of their work (Broom et al., 2009). There are laws about intellectual property and initiatives as the Creative Commons license, which guarantee the authors the credit for the data. However, the problem seems to be more related to the work put into collecting the data and the need to overprotect it rather than the actual ownership (Broom et al., 2009; Perrier et al., 2020). On the other hand, researchers understand that collected and processed data should be accessible to contribute to science and assure transparency, especially in the case of government funding bodies (Broom et al., 2009).

Despite some governmental and funding agencies moving toward implementing data sharing, there is still lack of specific incentives for researchers to share the data (Costello, 2009; Reichman et al., 2011), such as clear rules, training, and planned financial support. Additionally, there is resistance from some spheres of the scientific community to make data available in an organized and open manner (Perrier et al., 2020). So, there is an urgent need to change this culture and work together in a less-competitive way making cooperation the mainstream science model (Figure 1).

In an attempt to mitigate some of the problems related to data sharing, various societal sectors worldwide—academia,

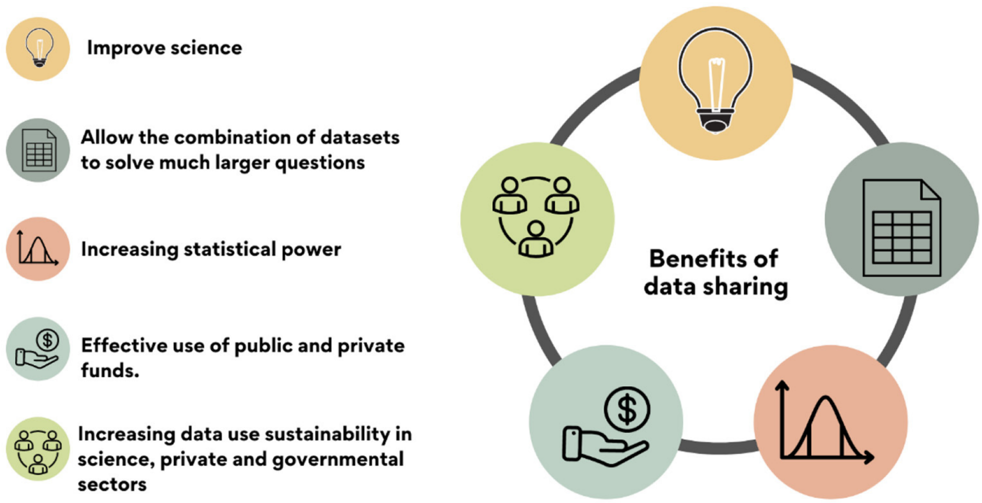

FIGURE 1
Benefits of data sharing under FAIR principle, based on Perrier et al. (2020).

industry, funding agencies, and publishers—have agreed to use the FAIR principle (Findable, Accessible, Interoperable, and Reusable). In this context, data must be Findable, having a unique identifier for the data file and the data content. Accessibility: the sampling/data collection protocol and datasets are open and free. Interoperable: data representation is done with language that follows the FAIR principle, and different repositories can access and provide datasets. Reusable: the data are made available with detailed metadata that allows more than one use/study (Wilkinson et al., 2016; Tanhua et al., 2019).

The FAIR principle allows data to be easily used by other researchers, decision-makers, and machines (Wilkinson et al., 2016). The FAIR principle help to mitigate the problems raised related to data integrity, quality, and adequate amount of details that allow the reuse of the data (Perrier et al., 2020). Quality check and control performed by humans and/or machines is an important practice to keep repositories reliable.

The publication of articles with supplementary material containing the data used does not characterize a data repository since it does not meet the FAIR principles, has no specific identifier for the dataset (e.g., DOI) (not Findable), and rarely presents metadata or standardization (not Accessible and Reusable). Also, journal publishers do not have a repository structure to store and make available datasets submitted as Supplementary material. There are papers being published with Supplementary material that could also be datasets to be placed in repositories.

Metadata are data that provides basic information about the main dataset, such as the time zone of collection, details about equipment, method used, etc. Some publishers and journals encourage data sharing in repositories, such as Data in Brief and Mendeley Data, that have started the process of publishing data papers and/or dataset. In this case, the data present a detailed metadata in agreement with the FAIR principle. However, the publication process is costly.

Methodology

This review analyzed open data repositories to identify the presence of datasets related to marine litter in Brazil. Google's Dataset search (https://datasetsearch.research.google.com/) was used on the first search to find datasets and their host repositories. Google's Dataset is a platform that compiles all datasets available online being a powerful tool for global searches. The main goal is to organize the information that exists in the world and make it accessible and useful.

In Google's Dataset website, a search was performed using the terms: "marine litter," "marine debris," "lixo marinho," "lixo no mar," "Brasil," "Brazil," "plástico," "plastic," "microplástico," "microplastic." The searches were conducted until April 2022, with no restrictions on the start date. The datasets found in the searches were assessed and checked for the rules of FAIR principles (Wilkinson et al., 2016; Tanhua et al., 2019).

Although, Google's Dataset search is not considered a repository since it is a search tool that redirects users to the repositories. It was not possible to find data papers through Google's Dataset search, indicating that this type of publication is in an intermediate area between data publication and a scientific article. Second, an active search was conducted to

TABLE 1 A summary of data repositories and potential of data related to marine litter in Brazil.

Coverage	Type	Repository	Marine litter data for Brazil	Notes
National	Specialist	BNDO	None	Distribution of data through an e-mail request. Difficult to search for available data. Incomplete metadata. Brazilian Navy is responsible for keeping the repository.
	Specialist	GOOS	None	Each project associated has its own website and criteria for uploading and downloading the data. Difficult to search for available data.
International	Specialist	OBIS	None	Depends on the cooperation of institutions to feed the database. Specialist repository. Darwin Core format
	Generalist	Figshare	2	No data audit/curation Incomplete metadata Provide metrics (view, downloads and citations)
	Generalist	PANGAEA	None	With data audit/curation
	Generalist	KNB	None	With data audit/curation
	Specialist	GPML	None	Gathers data from partners

identify other repositories. In each repository, there was a search using the same keywords used in Google's Dataset. Active searches have a controlled level of uncertainty. However, by overlapping different search methods, it is possible to keep it to an acceptable minimum.

Regional repositories, e.g., focused on the EU Member States, Artic region, Indonesia, or other region outside the analyzed area, were not considered in the analysis because they were not related to the main goal of the study. However, Brazilian and global repositories that did not present marine litter's data in Brazil accounted for a better understanding of the possibilities of future data hubs focusing on marine litter in the region.

Results and discussion

Marine Litter is a pressing environmental problem in the 21st century; many scientific papers are published in Brazil annually involving macro and/or microlitter, especially in coastal zones (Castro et al., 2018; da Silva Videla and de Araujo, 2021). The complex nature of litter data and the lack of standardization regarding the use of the already existing guidelines (e.g., GESAMP, UNEP, and NOAA) for collection and nomenclatures are often detrimental in the process of making litter databases available, as well as entailing management and conservation challenges (Hartmann et al., 2019). Marine litter encompasses a wide range of materials from various sources, including Abandoned Lost or otherwise Discarded Fishing Gear (ALDFG), sanitary materials, and construction waste; there are a lot of litter typologies, glass objects, anthropic wood, plastic fragments, microplastics. Different types of litter have different measurable parameters, e.g., size, weight, color, malleability, material, brand, possible source, among others.

Marine litter data

Seven data repositories related to environmental science with the potential to present a Brazilian marine litter dataset were identified (Table 1). Two repositories had national coverage: Banco Nacional de Dados Oceanográficos in Portuguese (BNDO) and the Brazilian node of Global Ocean Observing System (GOOS). Five repositories had international coverage: Ocean Biogeographic Information System (OBIS), which is integrated with the Brazilian Biodiversity Information System (SiBBr), Figshare, Pangaea, KNB, and Global Partnership for Marine Litter (GPML).

One specialist repository for marine litter was found: the Global Partnership on Marine Litter (GPML) Data Hub. However, in 2022, the platform is in its early stages of operation and there are no clear guidelines on how the data curation and/or auditing process will work. GPML works as a hub that puts together data from different data partners, such as Florida State University, University of Leeds, Alliance to End Plastic Waste, GRID Arendal, and EMODNet Chemistry. The platform also proposes to be a place to deposit best practices and experiences to tackle marine litter worldwide. There is no dataset from Brazil available in GPML yet.

Regarding national repositories, one possible database for marine litter data could be the National Oceanographic Database (BNDO) (https://www.marinha.mil.br/chm/dados-do-bndo/acesso-dados-e-produtos), which is managed by the Brazilian Navy. The aim of the institution is to promote and coordinate the participation of Brazil in the activities of the Intergovernmental Oceanographic Commission of UNESCO (IOC - UNESCO) related to Ocean Services and Ocean Mapping. However, the data are focused on physical and geological oceanography, and for some access data, it is necessary to contact by e-mail to request access, which in many cases can delay the research and/or decision-making process. Also, besides its difficult user interface and incomplete metadata, it does not meet the accessibility and reusability of the FAIR principles and has no data on marine litter listed in its available variables.

The Global Ocean Observing System (GOOS) is led by the Intergovernmental Oceanographic Commission (IOC) of UNESCO and co-sponsored by the World Meteorological Organization (WMO), the United Nations Environment Programme (UNEP), and the International Science Council (ISC). The Brazilian node (https://www.marinha.mil.br/secirm/psrm/goos) is led by the Brazilian Navy and is focused on physical oceanographic measurements from 10 projects, such as Prediction and Research Moored Array in the Tropical Atlantic (PIRATA). A weak point is that each project associated with the Brazilian GOOS node has its own website and criteria for uploading and downloading the data, making it difficult to search for available data, especially regarding format files and time series. It also does not present marine litter data listed in its available variables.

Regarding international coverage repositories, the Ocean Biogeographic Information System (OBIS) is a specialist repository focusing on marine biodiversity. The repository compiles data from various national nodes. One of these nodes and also Brazil's first initiative for sharing environmental data is the Brazilian Biodiversity Information System (SiBBr—Sistema de Informação Sobre a Biodiversidade Brasileira in Portuguese), an online platform that integrates data on biodiversity and ecosystems from various sources in Brazil and abroad. The platform is easy to use and has a user-friendly interface. Strengths include data curation and the use of the Darwin Core (DwC) format to write and publish data. It is one of the platforms with better adherence to the FAIR principle. Additionally, OBIS has packages in R that make it easy to import data for exploratory and statistical analysis; the data is accessible and interoperable. The dependence on partner institutions to feed the platform can be a weakness. However, the scientific community is very active and presents acceptance of the idea of data sharing, and the platform is kept updated. It has no data for marine litter, not even related to interactions with the fauna globally. It happens because OBIS accepts data in Darwin Core (DwC) format, which is not applicable to marine litter data.

Figshare is a generalist repository (https://figshare.com/). The biggest weakness is the lack of auditing and curation of the published datasets, which makes searching difficult. It also allows datasets in several data formats; hence, it does not meet the FAIR principle. However, Figshare was the only database that had Brazilian marine litter data. Only two datasets were found in Brazil, one regarding microplastic (Zanetti and Leonel, 2019) and one on macro litter (Ramos et al., 2020). Both datasets have complete metadata, data identification keys, and meet the FAIR principles. Also, both datasets are relatively recent, highlighting that Brazil is only starting the process of sharing marine litter data. In Brazil, there is one case of marine litter dataset publication in a repository (Ramos et al., 2020) and its related article (de Ramos et al., 2021). For the other dataset (Zanetti and Leonel, 2019) located during our search, there is no published paper associated yet. It shows that data publication can happen in different phases of paper publication (pre, during, or post); licenses and temporary data embargoes help scientists decide when they will make data available. However, the growing number of publications on the topic (Castro et al., 2018; da Silva Videla and de Araujo, 2021) suggests that Brazilian researchers have a fair amount of data kept under personal control while it could be published, giving a better picture of the marine litter situation and even helping decision-makers address this problem. PANGAEA is an open access data hosting system aiming to archive, publish, and distribute georeferenced data from environmental surveys; it is a generalist repository. The data goes through an auditing process, which ensures integrity and authenticity, as well as high usability. Also, PANGAEA is hosted by the Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research (AWI) and the Center for Marine Environmental Sciences, University of Bremen (MARUM). The repository does not present marine litter datasets for Brazil despite presenting these data for other locations, thus emerging as a viable option regarding marine litter data sharing for Brazilian researchers. In addition, the repository meets all FAIR principle.

Knowledge Network for Biocomplexity (KNB) is an international repository aiming to facilitate ecological and environmental research. It is similar to PANGAEA; it also has data auditing and curation and adheres to the FAIR principle. The platform is focused on data management, and the metadata pass through a quality check, following the guidelines proposed by Borer et al. (2009). It has no datasets of marine litter for Brazil, but it does have marine litter data for other places. Again, being a possible option for datasets on the topic.

The BNDO and SiBBr (OBIS) databases are examples that Brazil has specific databases. In the case of BNDO, it still could improve some features, but it shows potential to share data in other areas (e.g., physical and geological oceanography). On the matter of marine litter, there is no specialist database in the world or in Brazil to host a marine litter dataset.

Direct observations, remote sensing, and numerical modeling can be integrated to compose a specialized marine litter repository and a global Integrated Marine Debris Observing System (IMDOS), as proposed by Maximenko et al. (2019). Data regarding marine litter can have different sources and formats; it will be important

TABLE 2 FAIR principle according to repositories with marine litter data fitness for the Brazilian context.

	Figshare	PANGAEA	KNB
Findable	Datasets are not easy to find. It is necessary to know dataset details or its DOI.	The interface is user-friendly, and it is easy subset regions, time ranges, or themes to find datasets. It is possible to search using DOI.	
Accessible	Metadata is not mandatory. Metadata is not always explaining all the necessary things to understand the dataset. There is no curation process	All data and metadata are quality checked. There is a tutorial in how to prepare data and metadata. Experienced data curators are available to help with each dataset submission.	There are guidelines for submissions. It uses MetaDig program to evaluate metadata quality (https://github.com/NCEAS/metadig-engine).
Interoperable	Datasets from different sources or publishers.	Data processed for machine readability. Some web portals connected (e.g., OBIS, Google Dataset Search)	Some connected portals [The State of Alaska's Salmon and People (SASAP)].
Reusable	Since metadata sometimes is poor, it can impair data reusability. It is free without a review process.	Data is verified to be readable for machines, which allows efficient and reliable data re-usage. Quality data and metadata allows people to reuse the data. Python (pangaeapy) and R (pangaear) packages It is free.	Quality data and metadata allows people to reuse the data. R package (rdataone) There are available tools to help manage data such as Metacat (https://knb.ecoinformatics.org/knb/docs/). It is free.

and facilitate the researcher or decision-maker usage if they can see, subset, and download the data in a unique portal that is integrated with other data repositories enhancing the interoperability.

However, GPML is being developed and will soon make great progress for the scientific community. A database specific for this topic have to take into consideration all the characteristics and peculiarities of litter data, highlighting the quality of the data and increasing the chance of reuse, facilitating a sustainable scientific approach to minimize financial resources use and allow best management decisions. Despite not having a local database focused on marine litter, Brazilian researchers need to start sharing data on the topic in favor of the benefits this can cause. In this case, generalist databases can be the temporary solution, at least while the GPML is not fully operational to deposit data directly.

Three generalist repositories (Figshare, PANGAEA, and KNB) present the potential to receive marine litter data. Only Figshare presents it for Brazil, although it is important to pay attention to the FAIR principle on these repositories (Table 2). The FAIR principle was analyzed following Tanhua et al. (2019) approach.

Analyzing the FAIR principle regarding the generalist repositories Figshare, PANGAEA, and KNB, it is possible to observe that Figshare is the repository that worst fits in FAIR principle, especially related to data and metadata quality checks. The two datasets found for marine litter in Brazil are placed on Figshare. Despite having some weaknesses related to the FAIR principles, from a scientific point of view, this characteristic can allow that not well-standardized data to be published.

An important initiative from PAGAEA and KNB is using open-source programming languages (Python and R) to spread data usability, which can save resources from research institutions and environmental agencies and expand the analysis. In addition, connections between different data portals optimize resources since the maintenance costs can be distributed. Interoperability and reusability are factors related to sustainability since it is possible to optimize resources (natural and/or financial) and analyze data with greater consistency, allowing more developed environmental monitoring that results in practical actions in society. Marine litter data in emerging economies should be a key topic to be addressed by repositories due to its importance in local, regional, and international spheres. GPML is a starting repository that should be integrated into other repositories, such as Figshare, PANGAEA, and KNB, to optimize computational efforts and encourage interoperability.

The increasing number of research papers on marine litter topic suggests that the data is being collected. The reason why it is not being shared remains unclear but can possibly rely on the same fears/problems most of the researchers that do not publish data, have. However, the benefits of sharing should overcome insecurities and fears.

Marine litter data sharing around the world

A successful legislative framework involving the standardization of marine litter data and the construction of data baselines was the European initiative within the Marine Strategy Framework Directive (MSFD) that created the first world's beach litter database. This consultation included 22 European countries, and 3,063 surveys were conducted on 389 beaches between 2012 and 2016. In addition, data from non-European countries that have coastlines facing Europe were also included (European Commission, 2013; Addamo et al., 2018).

The biggest challenges encountered by Addamo et al. (2018) in building the European baseline were related to the compilation of data with different formats, quality, and protocols used for litter sampling. Europe is the most advanced territory regarding marine litter sharing data; there are more than 15,000 dataset results for marine litter search on data.europa website (search done on December 2021).

The European Environment Agency has developed a Marine LitterWatch mobile app to collect information on marine litter. It is a citizen science initiative that aims to help fill data gaps in beach litter monitoring. All data is available on an online platform, and it is possible to visualize and download all data easily. Despite being an European platform, there is a record of Copacabana beach in Brazil. It is possible to observe that it was a top-down initiative but included citizen science approach. Different stakeholders should work together to achieve the best data sharing and availability.

Also, in Europe, European Marine Observation and Data Network (EMODnet) in the chemistry hub developed the first pan European Marine Litter Database (MLDB). It expresses a collective effort involving specially the EU-Technical Group on Marine Litter and EMODnet Chemistry structure; they developed guidelines focused on harmonizing marine litter data, vocabulary, and quality controls (EMODnet, 2022b,c). Hanke et al. (2019) devolved an analysis of a pan-European 2012–2016 beach litter dataset, including data availability, spatial and temporal data coverage, data treatment, and results (Hanke at al., 2019). This report is important to understand gaps and priorities. In the near future, with repositories about marine litter worldwide, it will be possible to have a global picture following Hanke et al. (2019) data treatment and analysis.

EMODnet marine litter data hub contains data on beach and sea floor litter from a variety of sources, including existing International and Regional Sea Conventions, and data submitted by the EU Member States, EMODnet partners, and external research or monitoring projects. Most datasets have come from existing monitoring projects that have published their data in project-specific databases (e.g., OSPAR, ICES DATRAS, even in the PAGAEA repository). These databases may hold more and differently formatted information, so direct comparison with these sources is not always possible, although it is possible to download harmonized datasets where data are formatted following Guidelines regarding vocabulary and values accepted in EMODnet marine litter data hub (EMODnet, 2022b,c). Also, the interoperability between repositories appears to be working well and FAIR principles were considered and are being applied to marine litter in Europe in the context of EMODnet chemistry, improving released data sets quality (Partescano et al., 2021).

A global initiative is the G20 Implementation Framework for Actions on Marine Plastic Litter (MOEJ, 2019). It aims to put in place the Action Plan on Marine Litter, based on each country's national policies, approaches, and circumstances. Brazil presented advances related to the National Plan to Combat Marine Litter (MMA, 2019). For efficient information sharing and updating, as well as for outreach to wider international communities, a network was created; the idea was the same as that proposed by IMDOS stakeholders (Maximenko et al., 2019).

Data usability

The importance of shared data spreads to different areas of society through academic, educational, and management purposes. Data from satellites, autonomous underwater vehicles, and other platforms are coming together and producing emerging data streams from social media, smartphones, and low-cost distributed sensors to create a "data tsunami" (Jucan and Jucan, 2014). More data have been collected about the oceans in 2018 alone than in the entire 20th century. Citizen science is becoming a major player in this change and how we make data available. It is necessary that data from automatic systems and citizen science pass through a quality check process that verify its usability, metadata quality, and reliability. There are some frameworks being developed to access the quality control of oceanographic data; an example is an open-source package on Python called CoTeDe, which aims to provide an adaptive and automatic quality check that combines different quality control standards according to the equipment (CBT, Argo, and CTD) and the researchers' own needs (Castelao, 2020). In addition, data quality check procedures on ocean wave data, which include automatic and manual check procedures, are well described by Doong et al. (2007).

Regarding citizen science data, there are also some ways of accessing data quality. Successful projects have characteristics such as volunteer training and testing, expert validation, replication across volunteers, and statistical modeling of systematic error (Kosmala et al., 2016). Wiggins et al. (2011) created a framework of mechanisms (e.g., rating participant performance, expert review, paper data sheets submitted in addition to online entry, and data mining). These mechanisms can be used in citizen science projects before, during, and/or after their execution for ensuring data quality. They mapped two sources of errors (protocols and participants).

Data and metadata quality, data curation, and check are important to obtain meaningful information, and for the accomplishment of the FAIR principle, otherwise there is the risk to extrapolate data and information not well linked to the real situation, especially when it was measured by automatic systems and citizen science without a data quality check process.

However, ocean data management has not kept pace with the growth of data production, which limits the ability to use both new and old data in marine science (Serrat, 2008; Pendleton et al., 2020). A substantial time and geographical data series may help to identify and understand anomalies and their frequency, strength, and duration. In a climate-changing scenario, it can be helpful to develop management strategies in cases of oil spills, floods, coastal erosion, among others. It is important to inform and engage stakeholders about the importance of ocean observing systems to society, decision-making, academia, and secure financial support to improve data infrastructure (Sales et al., 2020; Teixeira, 2022).

Marine litter is a theme to explore the potentialities of the free and open-source software (FOSS); R and Python are programming languages that have packages available to PANGAEA, KNB, and OBIS. A study in Brazil developed an open-source geospatial framework for beach litter monitoring using R and QGIS (Schattschneider et al., 2020); initiatives in this context can grow, improve, and/or can be easily used if there are marine litter data available to perform tests, thus improving sampling methods or base some management decisions. The available marine litter data in repositories can enhance the usability of open-source tools and framework analysis, such as proposed by Schattschneider et al. (2020).

There are some initiatives about marine litter in Brazil with potential regarding data sharing. An example is the Blue Flag program, which suggests a marine litter monitoring program on accredited beaches. With the monitoring program, beaches with Blue Flag in Brazil should have data in their annual reports, but it is not publicly available. Tombo beach in São Paulo, Brazil has Blue Flag certification for 12 years in a row in 2022, which means that probably there are many of marine litter data about this beach, although it is not yet possible to find/access it.

The challenges of working with data on marine litter are great; however, ocean management is often hampered by a lack of available and clear data on human activity and how it affects the ocean. To solve this type of problem, a "National Plan to combat marine litter" (PNCLM) (Plano Nacional de Combate ao Lixo no Mar in Portuguese) was launched in 2019 (MMA, 2019). The PNCLM encourages the development of a virtual platform to organize and share National marine litter data aiming for continuous improvement of prevention actions of pollution and environmental recovery (MMA, 2019). A virtual dashboard (https://app.powerbi.com/view?r=eyJrIjoiNDY2OTU3NmMtOGVmZS00NDEwLTlhNzItYjI2Y2FjNTYxOWE5IiwidCI6IjM5NTdhMzY3LTZkMzgtNGMxZi1hNGJhLTMzZThmM2M1NTBlNyJ9) with clean-up actions data is already being developed and is available online. However, there are some concerns about the type of data. Most of the information on the dashboard is from NGOs and may lack data curation, metadata, common vocabulary, and unit measure. Another problem is that sometimes litter was not classified, and when they are, the categories used can be overlapping. For example, two categories are "Plastic" and "Fishing materials"; however, most of the fishing materials are made of some sort of plastic. Data sharing should follow guidelines (e.g., UNEP, GESAMP, and EMODnet vocabulary) with adequate vocabulary and hierarchy for layers of terms. In addition, the data cannot be downloaded to perform other analyses. Although it is an interesting initiative to begin data sharing, it still needs improvement. Initiatives regarding the scientific community can also be developed to fulfill the actions established by the PNCLM. In addition, a sub-national scale (Federation states) is developing and launching its own plans to combat marine litter; this can spread and scatter actions and data regarding marine litter in Brazil.

In this context, it is important to have data curation and well-detailed metadata. To agree with the FAIR principle. In the future, it could be possible to integrate different platforms with different kinds of data that can improve environmental analysis. For example, marine litter data can be influenced by meteo-oceanographic factors, such as wind, tide, currents, among others, and an integrated platform with data can allow a much deeper understanding. This integration is one of the aims of the Spatial Data Infrastructure (SDI). Marine litter data available following the FAIR principle can also contribute to model inland waste management initiatives, mainly those ones that use a mathematical model to optimize management actions (Barma et al., 2022).

Another initiative in Brazil involving citizen science is "Our Blue Hands" (https://www.ourbluehands.com.br/), which was implemented for the first time in Brazil on Itamambuca beach and now is spreading to more cities in Brazil through volunteers and a citizen-science approach. The focus of this initiative is microplastic pollution with the aim of data sharing in a developing partnership with the OBIS repository. The strengths of this initiative is that the methodology applied is standardized, following the Monitoring Strategy for microplastic in the European Union in the context of the Marine Strategy Framework Directive (Hanke, 2013). This allows data comparison worldwide, especially in Europe. Also, Our Blue Hands aims to share the data following FAIR principles by design.

The data-sharing culture is only in its infancy. There are other initiatives focused on other environmental areas in Brazil aiming for data sharing and its public availability (Table 3), but they lack some aspects of the FAIR principle, mainly the interoperability and accessibility. In some cases, there is a bureaucratic process to access data, or it is possible to only see processed data in a dashboard (e.g., PNCLM and NOAA), nearer to NGO's (e.g., Ocean Conservancy) model to make information available.

Since data are the building blocks for information and knowledge, the scientific community is responsible for the collection and quality of this data. It is important to highlight

TABLE 3 Some initiatives to share environmental/marine data in Brazil.

Name	Summary	Year	Website
National Bank of Biological Samples of Albatrosses and Petrels—BAAP	It maintains biological samples of albatrosses and petrels from bycatch in commercial fisheries. A collaborative network.	2013	https://baap.org.br/
Open Access Atlantic and Eastern Pacific Reef Fish Database	A dataset of 2,200 species of reef fish from the Atlantic Ocean and the east side of the Pacific. Easy download in.csv format.	2021	https://zenodo.org/record/4455016#.YnOnrdrMLIW
Oceanographic buoy data from PELD ILOC (Long-Term Monitoring of the Brazilian Oceanic Islands)	The buoys provide near real-time surface (1 m) and bottom (23 m) water temperature data, wind direction and intensity and wave height at 6-h intervals. Download is only possible for temperature data.	2022	https://aqualink.org/sites/1186

that some initiatives are starting in Brazil, bringing scientists together to discuss the marine litter issue. Brazilian Marine Litter Science Patch is an initiative that is being created in a collaborative and transversal way to integrate research projects and researchers on this topic. Another is "Polimera: a scientific network about marine litter" (https://polimera.org/). This initiative was created by universities in south Brazil. Despite being in their initial stages, they can bring a new paradigm to marine litter studies. Collaborative work among researchers is extremely important for the growth of the scientific community and enables standardized data, quality work, integrated views, findings, and the training of more researchers on the topic.

Future perspectives

Despite the various possible uses, the importance of sharing data and the great number of publications about marine litter in Brazil, there are still very little data published in databases. Some initiatives have already started, but there is still a long path ahead. More funding for environmental science, associated with incentives from funding agencies, should encourage scientists to share their data.

Brazil has numerous institutions and researchers that collect, analyze, and publish data on marine litter derived from specific projects in the form of scientific papers, thesis, dissertations, and reports. However, there are only a few frameworks to facilitate and encourage the availability and harmonization of these data. Ways need to be found to collect ocean data with quality and share following the FAIR principle; if data will be shared, resources can be optimized, and possible environmental impacts can be minimized since it will not be necessary to replicate sampling processes. Also, studies and decision-making will be based on more extended time series, improving science quality, which can support better management decisions in the context of SDG (Sustainable Development Goals) and beyond. The benefits are not only related to marine litter but also the information is the base of successful management actions regarding society and the environment.

In the management sphere, there are still gaps related to curbing marine litter. It is difficult to establish management strategies to combat marine litter if there is no accessible and standardized data baseline. It is urgent to seize the scenario of the UN Decade of Ocean Science for Sustainable Development (2021–2030) to build new relationships and alliances with stakeholders inside and outside academia. Especially regarding the objective of a predictable ocean in the Ocean Decade where society has the capacity to understand current and future ocean conditions. All societal sectors should enter the era of innovation, data sharing, and scientific co-creation. In this context, initiatives such as Our Blue Hands and clean-up actions may bring society closer to academia. Public spheres should encourage and support this initiative so it can be improved.

Soon, repositories such as GPML (entering in operational phase) and OBIS (through a partnership with Our Blue Hands) are some options to share marine litter data. Since OBIS follows the FAIR principle, it gives more credibility to datasets published in their repository. However, at present, the only option for marine litter datasets is generalist repositories, such as Figshare, PANGAEA, and KNB; since GPML is not fully operational, OBIS only accepts datasets on Ocean Biodiversity and uses Darwin Core (DwC) format. Partnership with new platforms, such as Global Ghost Gear Initiative (GGGI) data portal (https://globalghostgearportal.net/login.php), should be encouraged to gather together efforts and computational infrastructure.

The FAIR principles remain unknown and need promotion and compliance in the scientific community. In this context, sharing data should be encouraged, and not participating will lead to isolation in or outside academia. Scientists should also be encouraged to use available data worldwide in their field to give these data new analysis interpretations, and even more integrative uses, thus highlighting the international cooperation approach. Organization for sampling and protocols are well developed in marine sciences and even in marine litter sampling (Cheshire et al., 2009; GESAMP, 2019). So, it is necessary to use this expertise to incorporate data management and publication in the sampling protocols process.

Finally, FAIR data sharing can also be a question of environmental justice. Developed territories with resources to maintain data centers and their infrastructure should be made available worldwide to encourage data sharing and its use by worldwide researchers. Also, different places may benefit from shared data interpretation when considering similar environmental settings to elaborate their own management strategies, thus saving resources and speeding up ocean conservation and restoration actions.

Author contributions

BR contributed to the conception and design of the review and wrote the first draft of the manuscript. TL and MC contributed with new insights and wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

MC is a Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) fellow.
The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Plastic pollution on Durance riverbank: First quantification and possible environmental measures to reduce it

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Plastic pollution is one of the most pressing issues of our time, with negative impacts on natural ecosystems, human health, and the climate system. The identification of top litter items discarded in the environment is essential to prioritize environmental policies to prevent plastic leakage and promote a circular economy. Here, we present the first quantification of macrolitter on three sites along Durance riverbank and one site on Lake Serre-Ponçon's beach, in the Région SUD–Provence-Alpes-Côte d'Azur, southeastern France. Data were collected through citizen science between 2019 and 2020 in three sampling occasions (autumn, winter, spring) on Durance riverbank and in 22 occasions on Lake Serre-Ponçon. A total of 25'423 litter items were categorized, of which 82% were plastics. Single-use plastic items correspond to 8.13% of total, while single-use plastic bottles are among the top 10 litter items at each site. Median litter abundance across all samples is 2,081 items/100 m survey, two orders of magnitude higher than European precautionary threshold value for marine litter (20 items/100 m survey). The majority of items (74.83%) were small and non-identifiable. Pieces of polystyrene, soft plastics and rigid plastics represented the majority of litter items in total (56.63%) and at S1 (89.28%), S2 (58.95%) and S3 (79.60%). Glass pieces corresponded to 15.83% of total litter items. Soft plastic pieces are the most abundant litter category overall and correspond to 58.85% of litter items at sampling site along Durance riverbank located in an agricultural zone, suggesting their source from agricultural plastic mulch films. Among the identifiable items, the most abundant were plastic biomedia used in waste water treatment plants and single-use beverage bottles in plastic and in glass. The development of extended producer responsibility schemes for plastic mulch films and plastic biomedia and of deposit return schemes for single-use beverage bottles is suggested as a way to prevent leakage in the environment.

This work confirms the opportunity to use citizen science to gather relevant data on macrolitter items and to monitor the effectiveness of environmental regulations to reduce plastic pollution.

KEYWORDS

plastic pollution, marine litter, extended producer responsibility (EPR), plastic policy development, single-use packaging, citizen science, deposit return systems (DRS), circular economy

Introduction

Plastic waste accumulation in the natural environment is one of the most pressing issues of our time with wide-reaching consequences on natural ecosystems, impacts on human health, contribution to climate change (United Nations Environment Programme, 2021b). From 9 to 23 million metrics tons of plastic waste are emitted yearly on rivers, lakes, and the ocean, while from 13 to 25 million metrics tons per year are emitted on terrestrial ecosystems (Borrelle et al., 2020; Lau et al., 2020). According to several authors, plastic pollution can be considered a planetary boundary threat (Galloway and Lewis, 2016; Jahnke et al., 2017; Villarrubia-Gómez et al., 2018; Arp et al., 2021; MacLeod et al., 2021; Persson et al., 2022). Rillig et al. (2021) have suggested that we are already living through a period of "toxicity debt," related to longer-term consequences of plastic degradation such as the release of toxic additives associated with plastics and the fragmentation to nanoplastics, which can themselves give rise to toxic effects.

Plastic waste enter the natural environment mainly as the result of mismanaged municipal solid waste (Lebreton and Andrady, 2019) and several initiatives have been taken at the international and national level to reduce plastic emissions and associated chemicals (United Nations Environment Programme, 2021b). In order to estimate the effectiveness of interventions to reduce marine plastic pollution, Lau et al. (2020) modeled stocks and flows of municipal solid waste and four sources of microplastics through the global plastic system for five scenarios between 2016 and 2040. They found that under a business-as-usual (BAU) scenario, mismanaged plastic waste leaking to the environment would increase by almost 3-fold by 2040 and that if all current major industry and government commitments were met, the world would see a reduction in annual rates of plastic pollution flowing into the ocean of only 7 per cent in respect to BAU. If all countries worldwide implemented the EU Single-Single Use Plastics Directive (SUPD, 2019/904/EU), one of the most ambitious regulations to tackle marine litter and plastic pollution, plastic waste emissions would be reduced by only 15 percent in respect to BAU (Lau et al., 2020). Further regulatory action is clearly needed and in March 2022 the Fifth United Nations Environment Assembly (UNEA-5.2) adopted a resolution for a mandate for an internationally legally binding agreement by 2024 to end plastic pollution both in the marine and in the terrestrial environment considering the whole life cycle of plastics.

Initially, most of the attention has been given to plastic waste in the marine environment (Blettler et al., 2018). Rivers were recognized for their role as a major source of macroplastic litter to the ocean (Wagner et al., 2014; Jambeck et al., 2015; Blettler et al., 2018; van Emmerik and Schwarz, 2020) and riverine inputs to the global ocean are estimated to range between 0.8 million and 2.7 million MT (Meijer et al., 2021), while at the European level they range between 1,600 and 5,000 tons per year (González-Fernández et al., 2021). However, recent studies suggest that the majority of macroplastic pollution never leaves rivers (Meijer et al., 2021; Tramoy et al., 2022; van Emmerik et al., 2022). These long residence times of plastic litter in rivers increase the negative effects that plastic waste has on the riverine environment.

Studies on macrolitter on rivers have increased in recent years. In Europe, plastic items were predominant in sub-surface garbage on River Thames in UK (Morritt et al., 2014) as well as in floating macrolitter on the Seine (Gasperi et al., 2014; Tramoy et al., 2020) and the Rhône (Castro-Jiménez et al., 2019) in France, on the Tiber in Italy (Crosti et al., 2018), and the Rhine in the Netherlands (Vriend et al., 2020b). A study of 42 rivers and streams in 11 EU and non-EU countries confirmed that plastic litter items are the major fraction (82%) of floating macrolitter and showed the importance of smaller streams in contributing plastic litter items from the whole catchment of a river to the sea (González-Fernández et al., 2021). Measurements on riverbanks showed that plastic litter items represent 94% of macrolitter on the Adour River in France (Bruge et al., 2018), 81% on the Rhine-Meuse River delta in the Netherlands (van Emmerik et al., 2020a), between 87.5 and 100% on the Ems, Weser and Elbe rivers (Schöneich-Argent et al., 2020), 31% on many large and small rivers in Germany (Kiessling et al., 2019) and 81% in 8 rivers in central Italy (Cesarini and Scalici, 2022). Plastic debris were 150% heavier in mass than organic debris on Seine riverbank, in France (Tramoy et al., 2019). Outside of Europe, plastics were the prevailing macrolitter items on riverbanks in Chile (Rech et al., 2014), were found in all sampled sites on the Selenga River system in Mongolia (Battulga et al., 2019) and the Lower Citarum River in Indonesia (Hidayat et al., 2022), represented 88.4% or more of macrolitter on the Tukad Badung River, in Bali, Indonesia, and 80.7% of riverbank macrolitter in the Karamana River, Kerala, India (Owens and Kamil, 2020).

The identification of top litter items discarded in the environment is essential to understand what needs most attention and to prioritize specific measures to prevent further inputs and reduce their abundance in natural ecosystems (Joint Research Centre, Institute for Environment and Sustainability, 2014; Addamo et al., 2017). In France, alongside the reception of EU SUPD and the national action plan "Zero Plastic Waste at Sea" (French Ministry for the Ecological Transition, 2020), several other initiatives have been proposed to reduce plastic waste, such as the "Chart for plastic free beaches" by the Ministry of the Environment, the "Zero Plastic Chart" by the Region SUD Provence-Alpes-Côte d'Azur (https://www.arbe-regionsud.org/1375-2-chartes-pour-zero-dechet-plastique.html), and the "Charter of Plastic Free Rivers," presented to France city majors in November 2021 (https://www.fleuve-sans-plastique.fr/). Despite these initiatives, baseline data on litter items are missing for most rivers.

Here, we present for first time results on macrolitter occurrence, with focus on macroplastics, from the Durance riverbank and the Lake Serre-Ponçon beach gathered through the citizen science project "Stop plastiques in the Mediterranée". The project was developed and carried out under the supervision of NGO Expédition MED and FNE PACA and involved volunteers from several environmental NGOs that are active in the Durance watershed.

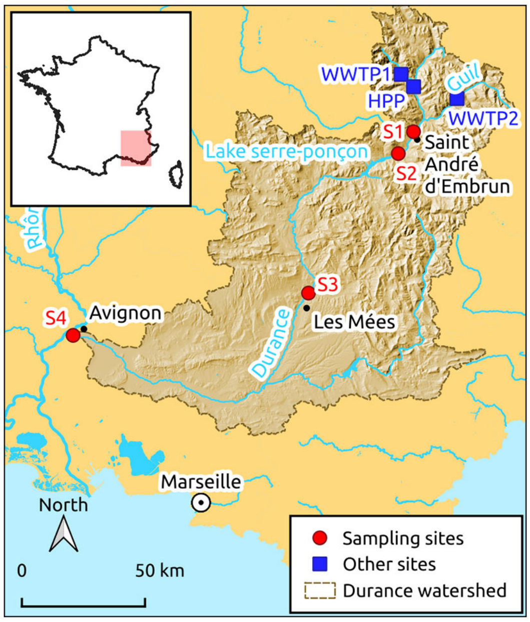

FIGURE 1
Map of Durance watershed, study sites, and other sites mentioned in the study.

Materials and methods

Study sites

The Durance is the largest watershed in the Région SUD–Provence-Alpes-Côte d'Azur, south-eastern France, with a length of 324 km and drainage basin of 14,472 km (Figure 1). It crosses several departments including a population larger than 1 million inhabitants and it is the second longest and third largest in terms of flow of the Rhône tributaries. The Rhône River has the largest watershed of rivers in the Northwestern Mediterranean, where it delivers 2–10 Mt of sediments and ~50 × $10^9 m^3$ of freshwater annually (Sempéré et al., 2000; Eyrolle et al., 2012). It also delivers mismanaged plastic waste, estimated at ~0.7 t per year as floating plastic debris (Castro-Jiménez et al., 2019) and 900 tons, considering both floating and non-floating debris (Boucher and Billard, 2020). The Mediterranean Sea, in turn, is one of the most affected seas by marine litter and plastic pollution (Eriksen et al., 2014; Cózar et al., 2015; Suaria et al., 2016; Boucher and Billard, 2020).

The study sites in the SPEM project were selected based on three criteria: at all sites there is a stretch of riverbank or beach that can be submerged with high water levels; the sites are legally accessible by the volunteers; the sites are representative of land uses along the river (Figure 1 and Table 1). From upstream to downstream they are: Site 1 (S1), located close to the village of Saint André d'Embrun in a scarcely populated region, close to one national park and two regional parks, at 272 km from the river mouth, where the Durance flows into the Rhône River: Site 2 (S2), located on the beach of Lake Serre-Ponçon, an artificial lake and a touristic site situated at 259 km from the river mouth. The lake is closed by a dam that is operated to make electricity. Dams and other stream infrastructures are known to retain macrolitter items (van Emmerik et al., 2022); Site 3 (S3), located in a flat area where the Durance forms meanders and borders an agricultural zone close to the village of Les Mées, at 154 km from the river mouth. The width of the study area being large and characterized by different vegetation types, the site was divided into two distinct areas, a river-side area (S3 river, S3R) with no vegetation or only small bushes and a forest-side area (S3 forest, S3F) with trees; Site 4 (S4) is located in an isolated spot near the Avignon high speed train station under the bridge of national road 1,007, not far from the city of Avignon at 4 km from the river mouth and 87 km from the Mediterranean Sea.

TABLE 1 Survey sites along the Durance River and on Lake Serre-Ponçon, with number of surveys conducted and a description of the site.

Site	Surveys	Description of the sampling site
S1	3	High course of the Durance River, at 15 minutes' walk from the car road, not much visited close to the village of Saint André d'Embrun. The Écrins National Park starts on the banks of the other side of the river in respect to the sampling site. Length of the transect 100 m. Width of the transect 20 m. Estimated surface of the sampling area: 2000 m^2.
S2	22	On the beach of Lake Serre-Ponçon beach, an artificial lake with important changes in water volume throughout the year. Collection of litter items on average every 10 days. Length of the transect 100 m. Width of the transect 67 m. Estimated surface of the sampling area: 6700 m^2.
S3	3	Flat area along the Durance River close to the village of Les Mées. Agriculture is the main productive activity. The sampling site was divided in two portions, based on the relative abundance of vegetation. The zone closer to the river (Les Mées River, S3R) with scarce or null vegetation, the zone further apart (Les Mées Forest, S3F) with intense shrubby and trees vegetation. Length of the transect 100 m. Width of the transect ranging from 70 to 160 m. Estimated surface of the sampling area: 7200 m^2.
S4	3	At 4 km from where the Durance River merges with Rhône River. On a white road parallel to the river, isolated, not much traffic. Close to the high-speed train station of Avignon. Length of the transect 50 m. Width of the transect 53 m. Estimated surface of the sampling area: 2650 m^2.

Sampling protocol

Macrolitter items were collected on 100 m long stretches parallel to the waterline and considering the band from the waterline to the high-water line similarly to what is done in the Beach-OSPAR method (OSPAR Commission, 2014), but differently than in the River-OSPAR method where the width of the transect from the waterline cannot exceed 25 m (van Emmerik et al., 2020c). At S4 the stretch over the riverbank was reduced to 50 m because of high density of vegetation and high density of litter items. The surface of the sampling area was estimated for each site during the first survey (Table 1).

The Beach-OSPAR method distinguishes 121 identification item categories, grouped by 11 material types (OSPAR Commission, 2014). We modified the Beach-OSPAR list of items to include litter items that were not present in the original list (ID 122 Fishing bait; ID 123 Filter media; ID 124 Twine and pieces of twine) and separated rigid plastic items from polystyrene items (ID 46 Piece of plastic/polystyrene 2.5–50 cm became ID 46 Rigid piece of plastic 2.5–50 cm; ID 47 Piece of plastic/polystyrene> 50 cm became Piece of plastic> 50 cm; ID 48 Other plastic/polystyrene object became ID 48 Other plastic object; and ID 117 Piece of plastic/polystyrene 0–2.5 became ID 117 Rigid piece of plastic 0–2.5 cm). We changed category ID 112 plastic bag end to ID 112 soft plastic pieces for a total of initial 128 litter items (see Supplementary Table 1).

The detection of litter items was carried out by visual observations and in each transect all visible litter items were collected and counted. The surveys were conducted without disturbing the upper layer of the sampling unit, i.e., without digging to release litter buried in the soil/sand, but litter items that were half under the soil/sand were retrieved.

The selection of sampling sites was done by the scientific personnel of Expédition MED and France Nature Environnement together with personnel from local NGOs, that were trained during the first survey. One or two people per site were appointed as responsible of data collection, categorization, and reporting. In addition to the authors, 36 volunteers took part in sampling and categorization of litter items. At each site, the data were validated by the trained personnel and in case of litter items difficult to classify, pictures were taken and a discussion followed up with Expédition MED scientific personnel.

At the sites on the Durance riverbank (S1, S3, S4) surveys were carried out in autumn (September–October 2019), winter (February–March 2020) and spring (June 2020). On the Lake Serre-Ponçon (S2), volunteers of the Ligue de Protection des Oiseaux (LPO–League for the Protection of Birds) carry out regular beach clean ups since January 2017. At S2 a total of 22 surveys were carried out from May 2019 to July 2020 roughly every 2 weeks distance apart following the schedule of beach clean-up activities carried out by LPO (see all the sampling dates in the Data Sheet 1 in Supplementary material).

Data analysis

Data were reported as number of litter items/100 m survey. Survey data for S3 were collected separately for the two vegetation bands and were summed up to provide a unique value of total abundance. Survey data for S4, that were collected over 50 m transect, were normalized to 100 m transect. Litter median densities at all sites were calculated as the litter median abundance over the surface of the sampling area and expressed as number of litter items/10 m^2.

The modified Beach-OSPAR list of categories was matched to the Joint List of Litter Items (Fleet et al., 2021) for harmonized comparison with other studies. In particular, the sub categories cigarette butts and cotton bud sticks, considered respectively in the material categories Paper and Sanitary items in the

OSPAR method (OSPAR Commission, 2014), where considered as Plastic and the items corresponding to Single-Use Plastic Items (SUP) were identified for subsequent analyses.

The aggregation of data at different temporal/spatial scales requires the averaging of data. The median is the calculation method that is suggested to be used to aggregate data at different temporal /spatial scales to asses EU marine beach litter baselines (Hanke et al., 2019). In this work, we have three values for S1, S3 and S4 and 22 values for S2. For each site we report the range of values (min and max) over the different surveys. We report the median value of the Durance across the 31 surveys to compare with other studies.

The top 10 most abundant litter items for each site were identified by lumping together the items over the different measurements and presenting the top 10 as fraction of the total. The top 20 litter items for the Durance were identified by lumping together the litter items over all the measurements and presented as fraction of total litter items.

The analyses were performed using R Statistical Software [v4.1.1; (R Core Team, 2021)] while the map of Figure 1 was created using QGIS (QGIS Development Team, 2021).

Results

First survey of macrolitter along Durance riverbank

Between May 2019 and July 2020, a total of 25'423 litter items were sampled at S1 ($n = 6{,}425$), S2 ($n = 8{,}984$), S3 ($n = 3{,}142$) and S4 ($n = 6{,}872$) (Figure 2) for a median litter abundance for all measurements of 2,081 items/ 100 m survey.

Of the initial 128 litter item categories considered, only 99 were found during the SPEM study. The majority of items (74.83%) were degraded to small, non-identifiable items. Pieces of polystyrene, pieces of soft plastics, and pieces of rigid plastics represented the majority of litter items both in total (56.63%) and at S1 (89.28%), S2 (58.95%) and S3 (79.60%). Glass pieces corresponded to 15.83% of total litter items and where the most abundant litter items at S4 (57.95%).

The specific litter items featuring in the top 20 for all measurement combined (93.33% of total) are plastic biomedia (small plastic cylinders used as bacterial biofilm carriers in the wastewater treatment process, also known as filter media), crisps/sweet packets and lolly sticks, glass bottles, plastic caps/lids, plastic drinks bottles, metal bottle cups, cotton bud sticks, plastic food containers, plastic cups, cigarette butts (Figure 3).

When aggregated to the 11 material categories of the OSPAR protocol, plastic items correspond to 74.76% of the total litter items, followed by glass (18.28%), paper/cardboard (1.90%), metal (1.74%) and manufactured wood items (1.22%) (Figure 4).

SUP items [*sensu* (Fleet et al., 2021)] correspond to 8.13% of the total litter items and 7 of them figure in the top 20: crisps/sweet packets and lolly sticks, plastic caps/lids, plastic drinks bottles, cotton bud sticks, food and fast-food containers, plastic cups, cigarette butts (Figure 3). Considering also glass bottles, single-use items correspond to 10.58% of total litter items.

Abundance and distribution of litter types in the four sampling sites

The highest abundance of litter items was found at S4 (range: 4,278–4,894 litter items/100 m survey), followed by S1 (range: 1,172–2,572 litter items/100 m survey), S3 (range: 460–1,092 litter items/100 m survey), and S2 (range: 8–1,798 litter items/100 m survey) (Figure 2). Data are available in Data Sheet 1 in Supplementary material.

At S1, the top 10 litter items (96.22% of the total) included polystyrene pieces, rigid plastic pieces, other wood, soft plastic pieces, metal corks and plastic drinks bottles (Figure 5). Plastic items represented 94.38% of the total. Despite their removal during sampling, pieces of polystyrene were found at each survey. At the first survey, polystyrene pieces smaller than 2.5 cm ($n = 1{,}222$) contributed to 58.72% of total litter items, while polystyrene pieces larger than 2.5 cm ($n = 459$) contributed to 22.06%; in the second survey, polystyrene pieces smaller than 2.5 cm ($n = 1300$) contributed to 73.36% of the total litter items while polystyrene pieces larger than 2.5 cm ($n = 279$) represented 15.74% of the total; at the third survey, polystyrene pieces smaller than 2.5 cm (1546) were 60.11% of the total, while pieces larger than 2.5 cm ($n = 590$) were 22.94% of the total litter items. SUP items were found at each sampling occasion, and in particular plastic drinks bottles were always present.

At S2, the top 10 litter items (90.27% of total), include soft plastic pieces, plastic biomedia, plastic pieces and polystyrene pieces, and four SUP items (crisps/sweets packets, plastic caps and lids, cotton bud sticks and plastic drinks bottles) (Figure 5). Plastic biomedia were recorded in 21 surveys over 22. The biggest occurrence was at time 19 with 121 items, time 20 with 860 items and time 21 with 147 items. Overall, 1,461 plastic biomedia were collected at S2 in the 22 surveys and they were of two types: white flat disks known as "biochips" and black cylinders in the shape of a helix known as Gamme Hel-X [numbers 13 and 16 in the categorization of (Bailly et al., 2018), respectively]. The overall abundance of litter items varied greatly, also as a function of river discharge. For example, from survey S2-time 17 (14/05/2020) and S2- time 18 (25/05/2020) the total number of litter items went from 8 to 330 (Figure 6).

At S3 the top 10 litter items (88.19% of total) include soft plastic pieces, rigid plastic pieces, textiles, construction material, polystyrene pieces, plastic drinks bottles, pieces of metal. The soft plastic pieces are 58.85% of the total. Litter items in the denser vegetation band farther from the river were almost twice

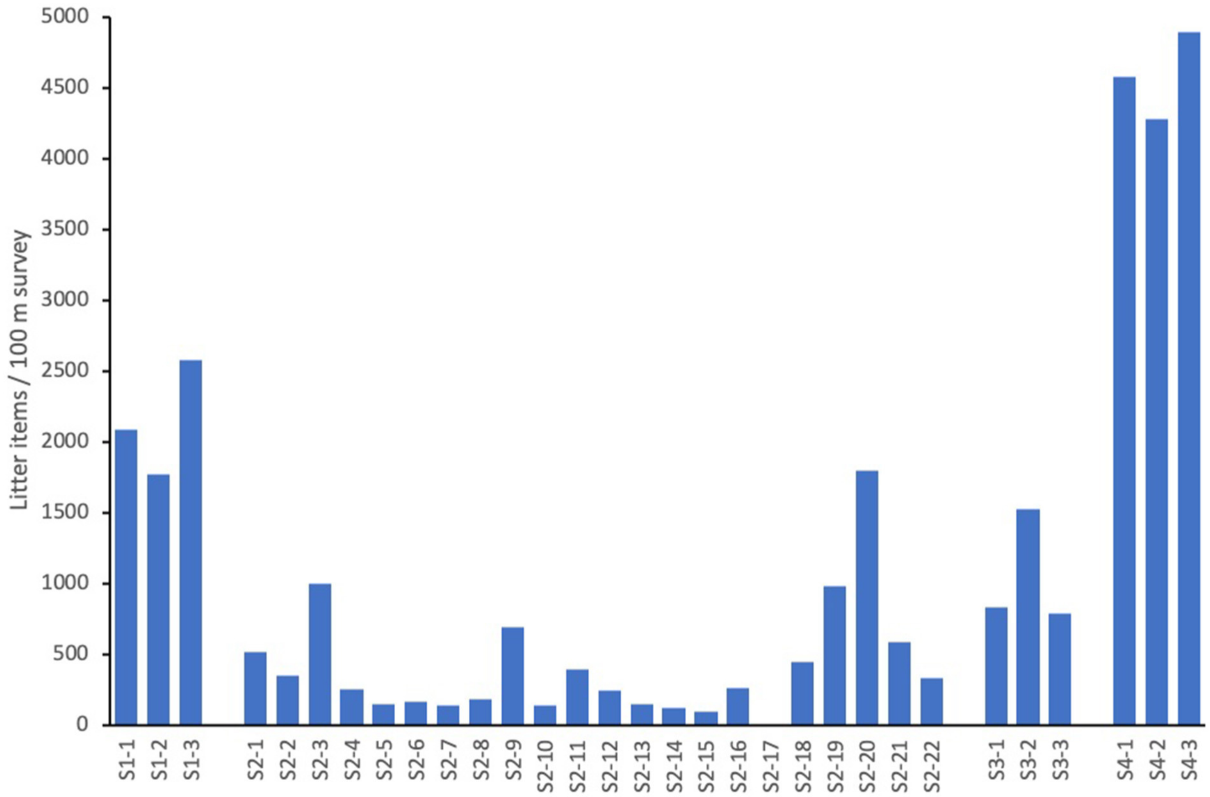

FIGURE 2
Abundance of litter items at each site and for each sampling occasion. Data for S4 were collected over a 50 m transect and here were standardized to 100 m transect.

more abundant (range: 460–1,092 litter items/ 100 m survey) than litter items in the sparser vegetation band closer to the river (range: 279–436 litter items/100 m survey) and soft plastic pieces were the most abundant litter type at each sampling occasion in both vegetation bands (ranging from 29.62 to 75.64% of the total litter items). SUP items such as plastic drinks bottles were in the top 10 in all three sampling occasions in the denser vegetation band. A full plastic film was found at the second sampling occasion (10/02/2020), as well as other pipes used in agriculture.

At S4, the top 10 litter items (90.69% of the total) include glass pieces, rigid plastic pieces, glass bottles, paper items, metal bottle caps, rigid and soft plastic pieces, plastic drinks bottles, cigarette butts, plastic cups (Figure 5). Of the 10 top litter items, three were SUP items. Glass bottles were found at each survey. At the first survey, a total of 440 bottles were found, of which 374 green bottles of 25 cl of Heineken beer brand and 66 other glass bottles; at survey 2, a total of 72 bottles, all of the type green bottles of 25 cl Heineken beer; at survey 3, a total of 58 glass bottles, of which 51 green bottles of 25 cl Heineken beer. Overall, Heineken beer bottles represented 87.06 % of all glass bottles. Green pieces of glass were found at each of the three surveys (619, 1,490, and 1,973 items, respectively).

Discussion

Abundance of litter items higher than the EU marine litter threshold at all sites

The Marine Strategy Framework Directive (MSFD, 2008/56/EC), requires that European threshold values (TVs) for marine litter (descriptor 10) be defined in order to achieve or maintain Good Environmental Status (GES). The MSFD Technical Group on Marine Litter set the TV at 20 litter items /100 m beach length, estimating that this value will be able to reduce harm from beach litter to a sufficiently precautionary level (van Loon et al., 2020). While TVs for litter have not been set specifically for rivers, the data gathered in this study show that median total abundance of litter items on Durance riverbank and Lake Serre-Ponçon beach (2,081 items/ 100 m survey) is two orders of magnitude higher than the precautionary value set by the MSFD. This threshold value was surpassed in all sampling sites, also at the S1 which is situated in a relatively isolated location, close to a national park and two regional parks.

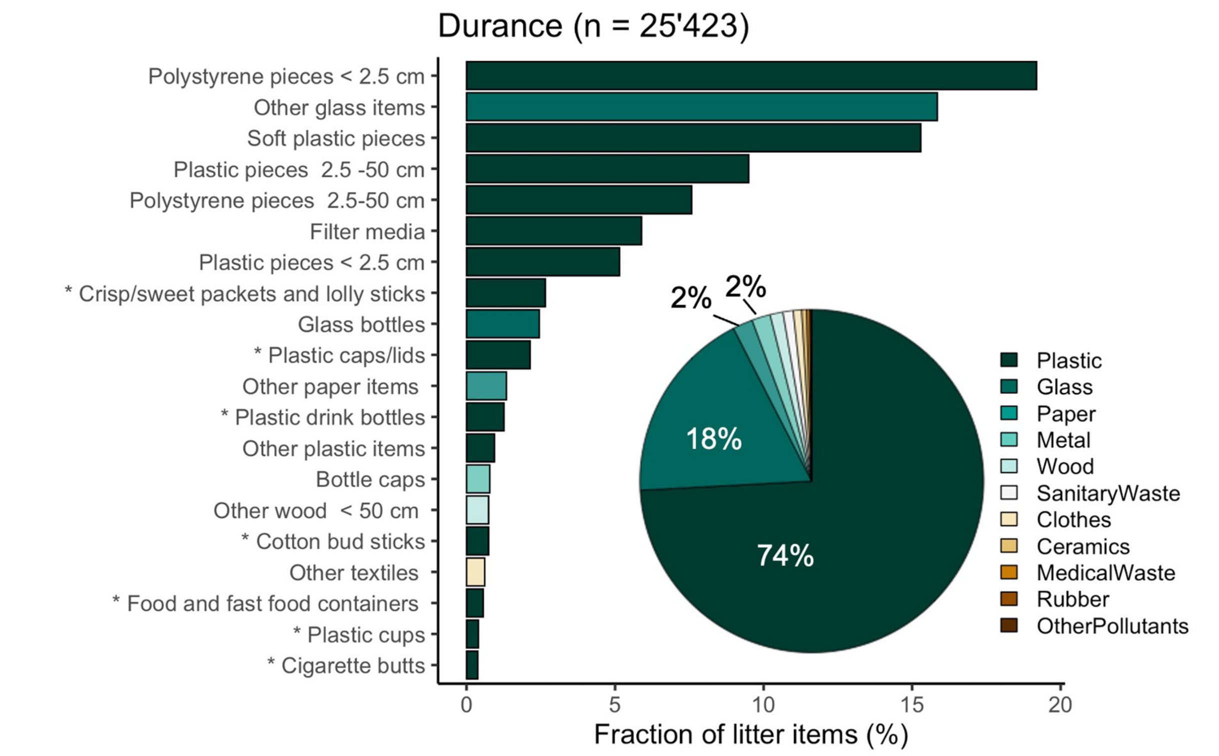

FIGURE 3
Top litter items and materials on Durance's riverbank and on Lake Serre-Ponçon's beach. Top 20 litter items are shown as fraction of the total. Percentages <2% are not shown.

Although quantitative direct comparison of abundance of litter data from other riverbanks is complicated by the fact that existing riverbank measurement methods vary greatly [see reviews in van Emmerik et al. (2020c) and in Vriend et al. (2020a)], the overall median total abundance (TA) of litter items found on the Durance in the SPEM project is higher than on riverbanks in the Dutch Rhine-Meuse delta (206 items/100 m; van Emmerik et al., 2020a), which also surpass the threshold value to achieve the GES. Median total abundance on the Durance is also higher than on beaches on the French Mediterranean coastline (214 items/100 m survey), on beaches at the level of the Western Mediterranean Sea (196 and 255 items/100 m survey in 2015 and 2016, respectively) and at the level of the whole Mediterranean basin (306 and 323 items/100 m survey, in 2015 and 2016, respectively) (Hanke et al., 2019).

The proportion of plastic litter items on Durance riverbank and on Lake Serre-Ponçon beach (82%) is comparable to riverbanks in the Netherlands (81.5 %, van Emmerik et al., 2020a) and Germany (between 87.5% and 100%, Schöneich-Argent et al., 2020), as well as to the amount of plastic litter floating at the surface of the Rhône River (Castro-Jiménez et al., 2019), at the surface of 41 rivers in Europe (82%; González-Fernández et al., 2021), and stranded on beaches in Europe (∼80%; EU, 2019).

During transport on rivers, plastic litter is broken and degraded (Tramoy et al., 2019; van Emmerik et al., 2020a). As a result, plastics in river systems are commonly fragments of soft and hard plastics or foam (Castro-Jiménez et al., 2019; Tramoy et al., 2019; van Emmerik et al., 2020a, 2022). This is true also in this study, where they represented 56.63% of total litter items. SUP items (bottles and other packaging) are usually the most abundant specific litter items in rivers in Europe (González-Fernández et al., 2021; Tramoy et al., 2022). SUP items are among the most abundant specific litter items also in this study, but here the most abundant specific litter items are plastic biomedia.

Deposits on riverbanks can be the results of different processes: they can be left intentionally such as illegal dumping, be the result of recreational activities (Kiessling et al., 2019), be transported by the wind, or be the consequence of the dynamic processes that occur in the water body (Tramoy et al., 2021). Hydrometeorology plays a role in explaining variability in macrolitter abundance on riverbanks, but a substantial part of the variability is caused by unaccounted (and often

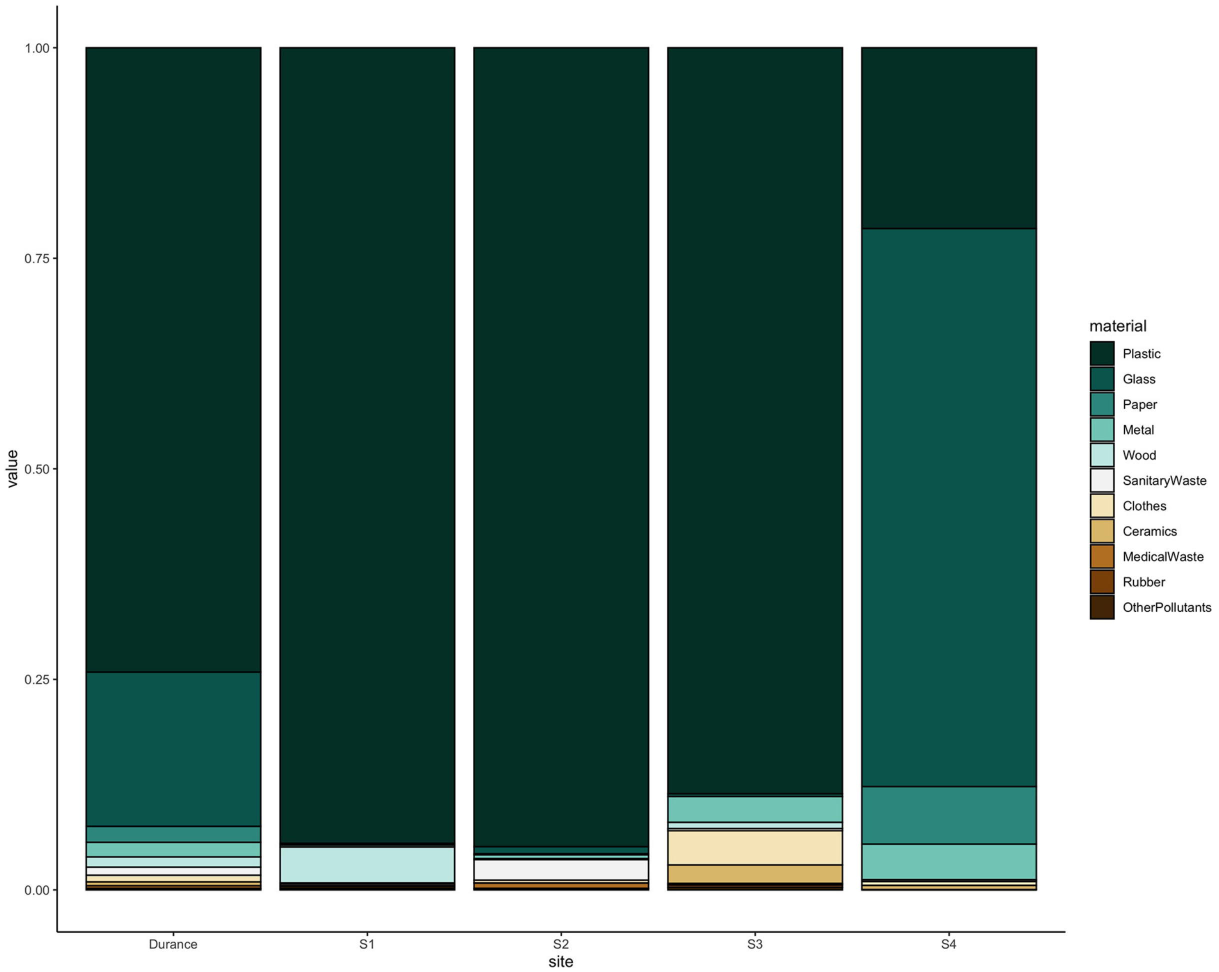

FIGURE 4
Percentage composition of materials of litter items.

fundamentally unknowable) stochastic processes, rather than being driven by the deterministic processes (Roebroek et al., 2021). Liro et al. (2021) developed a conceptual model that divides the macroplastic route into (1) input, (2) transport, (3) storage, (4) remobilization and (5) output phases. According to their model, phase 1 is mainly controlled by humans, phases 2–4 by fluvial processes, and phase 5 by both types of controls.

In the following sections we focus on three litter item categories for which we identified the possible source mechanism and for each we discuss possible environmental policies to reduce their dispersion in the environment: soft plastic pieces at S3, we supposed derived from plastic mulch films used in agriculture and the result of wind transport; plastic biomedia at S2 on Lake Serre-Ponçon beach, transported by the Durance River and accumulated by the lake; and single-use plastic and glass beverage containers at S4 and S2, caused by direct input by humans.

Plastic mulch films used in agriculture as the possible source of soft plastic pieces at S3

Unidentified soft plastic pieces represent 58.85% of total litter items at S3. While part of them might have originated from fragmentation of plastic bags or other packaging due to transport in the river and abrasion by sediments (van Emmerik et al., 2020a), we think that the high quantity of soft plastic pieces at S3 derives from plastic mulch films used in agriculture, the principal land-use type at Les Mées and have probably derived by short-distance transport by wind (Lau et al., 2020).

Statistical reporting of agriculture plastics data in Europe is still relatively underdeveloped and the proportion of conventional plastic mulch films that typically are left remaining on the soil is not known (Hann et al., 2021). In

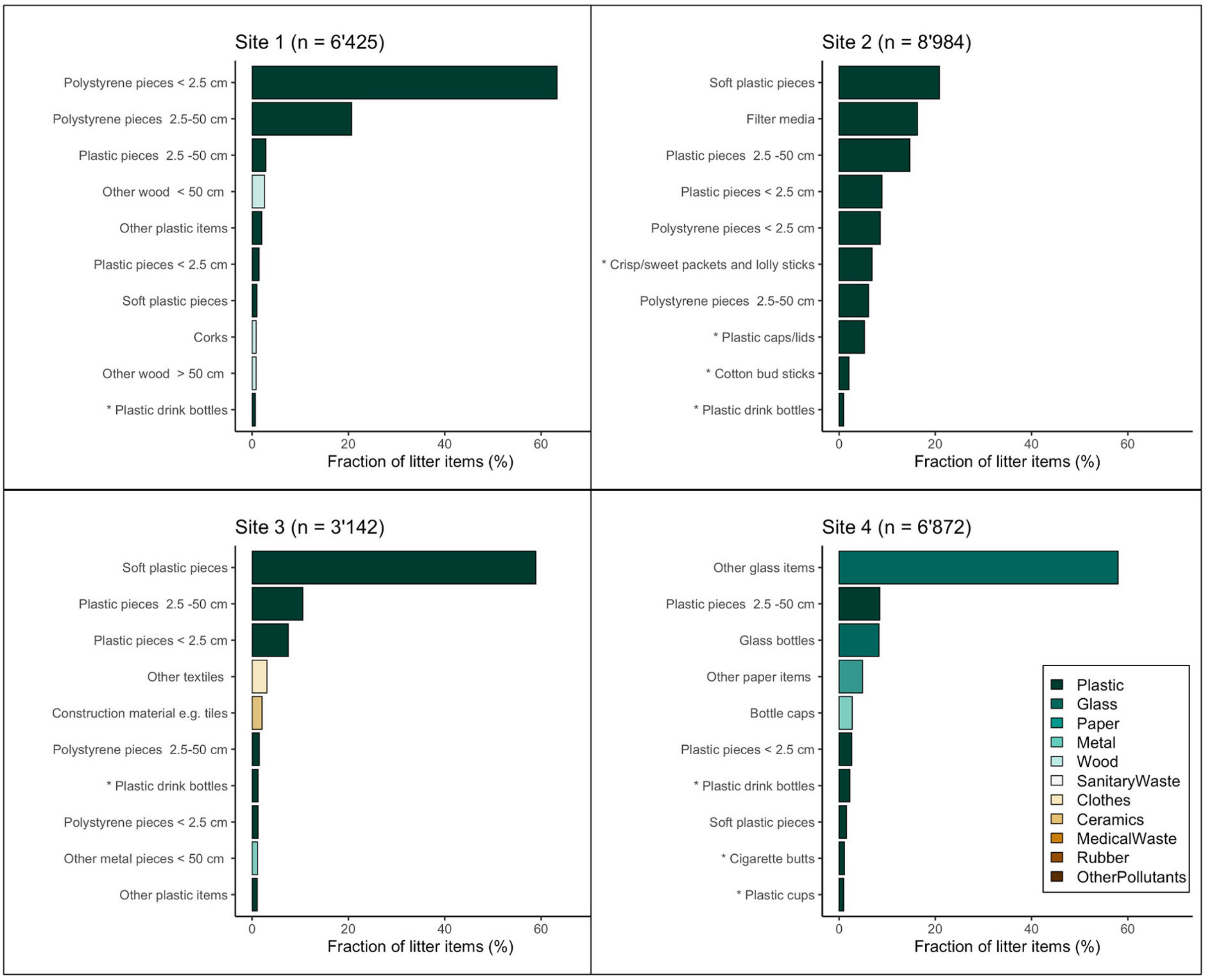

FIGURE 5
Top litter items and materials at the four sampling sites. Top 10 litter items are shown as fraction of the total. SUP items are indicated (*).

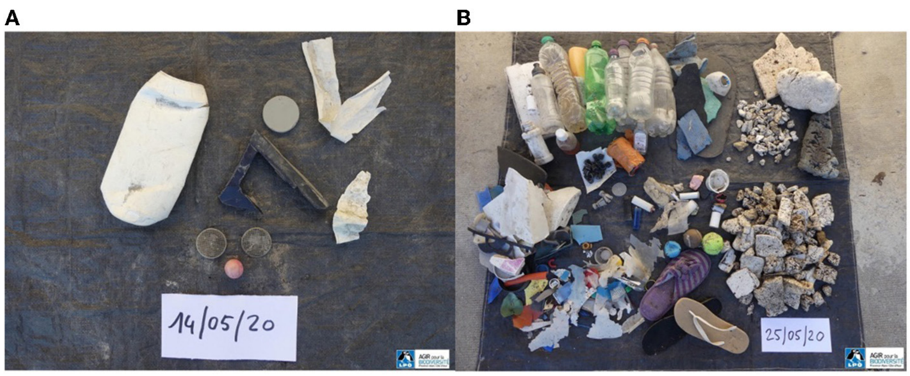

FIGURE 6
Items collected on the 100 m survey band at S2 before **(A)** and after **(B)** of a big river discharge.

France, (non-packaging) agricultural plastic waste is managed through a voluntary collection scheme operated by the producer responsibility organization (PRO) ADIVALOR and by other private companies. Using data provided by ADIVALOR, Hann et al. (2021) estimated that approximately 70,000 tons of agricultural plastic waste from mulch films were generated in France in 2019 and of these around 50% were recycled. The significant difference between the volume put on the market and the volume collected and recycled is probably due to high contamination, which is up to 50% for plastic mulch films (Hann et al., 2021).

The amount of plastic waste accumulated in world's agricultural soils is likely larger than on the ocean's surface (Hurley and Nizzetto, 2018; Galafassi et al., 2019), it is poorly reversible and can lead to long-term changes in soil properties and potentially irreversible degradation (Steinmetz et al., 2016; Bandopadhyay et al., 2018). Plastic waste accumulation in soils can have negative impacts on plant performance and diversity (de Souza Machado et al., 2019), while pathogen organisms for humans can concentrate on it (Gkoutselis et al., 2021) and plastic pieces can be transferred along the terrestrial food chain (Huerta-Lwanga et al., 2017).

The FAO identified several alternative interventions for the problem of plastic mulch films, including: adopting mulching practices that avoid the use of plastic; redesign mulching films to be biodegradable, reusable over time, and improve retrievability and reduce leakage to the environment; implementing mandatory EPR collection schemes; and redesign business models to provide agricultural plastic as a service, including retrieval and end-of life management (FAO, 2021).

In addressing the different types of plastic pollution, attention must be carried out not to shift from a source of pollution to another. While the long-term impact on soils of the use of different types of biodegradable mulch films need to be assessed (FAO, 2021), a comparison of conventional plastic mulch films and biodegradable mulch (BDM) films (i.e., plastics that passed the new EU standard EN 17033 that specifies necessary requirements and test methods for BDM to be used in agriculture and horticulture) concluded that currently there is a trade-off between plastic pollution in the environment vs. greenhouse gas emissions (as well as most other environmental impact categories) for the use of conventional vs. BDM films (Hann et al., 2021). As part of the new Circular Economy Action Plan, the EU Commission will develop a policy framework on the use of biodegradable plastics, based on an assessment of the applications where such use can be beneficial to the environment and criteria for these uses.

Litter density at S3 was higher in the zone with trees and shrubs farther from the river. This is in accordance to other riverbanks and on tidal zones were macroplastic abundance on the surface of vegetated areas is higher in comparison to the adjacent unvegetated areas (Cozzolino et al., 2020; Cesarini and Scalici, 2022). Macroplastic debris stored on the surface of alluvium, in riparian vegetation, and in river sediments can fragment and constitute the main source of secondary microplastics in river (see review in Liro et al., 2021). Taking into account the long preservation of macroplastic debris in the natural environment, the storage–remobilization cycles of macroplastic debris in fluvial systems may last for decades or centuries and this implies that the presence of riverine macroplastic and related environmental risk may continue in the future, even when the input of new plastic debris to the fluvial systems is decreased (Liro et al., 2021).

Plastic biomedia

Plastic biomedia are the most abundant specific litter item collected in this study (1,461 items) and most of them were retrieved at S2, on Lake Serre-Ponçon beach. Dams and other stream infrastructure increase the retention of litter items by removing them from the river flow (González-Fernández et al., 2021; Poletti and Landberg, 2021) and are key controls of microplastic storage and remobilization in rivers (Liro et al., 2021). Plastics on lakes may either come from local activities (e.g., littering, fishing gear, direct wastewater drainage from a nearby urban area or direct surface runoff) or have been conveyed by rivers that discharge into the lake (van Emmerik et al., 2022). This is the case for the plastic biomedia. The Serre-Ponçon dam interrupts the course of the Durance River and during normal operations the only possible exit of water and objects from the lake is situated in correspondence of the water intake for the turbines, situated at 100 meters deep. Every floating object, therefore, remains at the surface and is accumulated by the wind and the currents on the beach at north-eastern side of the lake. In addition to the plastic biomedia collected at S2 during the SPEM project, more than 60'000 black Gamme Hel-X plastic biomedia (corresponding to about 0.3 m^3) were collected by LPO in 2021 stranded on the beaches of Lake Serre-Ponçon (Ligue Pour la Protection des Oiseaux, 2021). According to an investigation by the Direction Départmental des Territoires des Hautes-Alpes (DDT 05) these plastic biomedia were accidentally released from the waste water treatment plant (WWTP) of Vallouise, the only WWTP in the Durance watershed upstream of Lake Serre-Ponçon to use the black Gamme Hel-X type. The Vallouise WWTP said to have lost 2 m^3 of plastic biomedia in the accident and currently it remains unknown where the majority of lost biomedia went, if they have been retained along Durance riverbank or if they made it to sea. The white biochips found in the SPEM project are instead probably derived from the WWTP of Molines-en-Queyras and Saint-Veran, the only WWTP upstream of the lake to use this type of plastic biomedia.

Large numbers of plastic biomedia have been found washed-up along European coasts since 2007 and since then they have been found on coastlines worldwide (Bencivengo et al., 2018). The latest reported incidents in Europe are in Denmark (2021), France (2020), and Italy (2018). Here, the public WWTP of the municipality of Capaccio Paestum, Salerno, had two consecutive accidents during which 126 million plastic biomedia of the type biochips (white disks) were released on the Sele River and arrived in the Tyrrhenian Sea. Currently, only 5.5 million of the lost biochips have been retrieved on Italian and French beaches and eight people are under criminal proceedings in to what is, according to our knowledge, the first legal process for plastic pollution at sea. Plastic biomedia are mainly made of polyethylene (PE) or high-density polyethylene (HDPE) and vary in shape and size according to the industrial application for which they are used (Bencivengo et al., 2018). Although they have been identified as a source of unintentionally released microplastics to the environment (Hann et al., 2018), currently they are not included in the EU legislation. To close this legislative hole, Surfrider Foundation and other NGOs asked for the inclusion of plastic biomedia as a source of pollution in the revised EU Urban Waste Water Treatment Directive (UWWTD, 91/271/ EEC) (Surfrider Foundation, 2020). The development of EPR schemes, the obligation for the waste water treatment industry to declare which types of biological treatment they use detailing the biomedia and models used, and the implementation of prevention measure and protocols would help to prevent losses to the environment and facilitate the identification of the source of pollution if pollution occurs (Surfrider Foundation, 2020).

Single-use litter items

Single-use plastic (SUP) items were found at all sites and seven specific items figure in the top 20 at the level on Durance riverbank (crisp/sweet packets and lolly sticks, cap lids, drinks bottles, cotton bud sticks, food and fast-food containers, cups, cigarette butts) alongside unidentified plastic pieces, similarly to what happens in other studies on rivers across Europe (González-Fernández et al., 2021). SUP items were more abundant at S2, a touristic location, and at S4, an isolated spot close to the city of Avignon. At S4 there was also a large amount of single-use glass bottles and pieces of glass bottles, abandoned in clusters alongside paper and plastic packaging related to fast food restoration and cigarette butts. These litter items derive from visitors that use the river as a leisure area and are responsible of local pollution, similarly to the case of rivers in Germany where high abundance of paper and plastic packaging related to fast food restauration, single-use glass bottles, and cigarette butts where also found (Kiessling et al., 2019).

France has transposed the EU SUPD into the Anti-waste and circular economy law (Law N. 2020-105 of 10 February 2020) and anticipated it by banning the sale of disposable tableware in batches (glass, cups, plates) and plastic cotton but sticks from January 1, 2020, 6 months prior to EU deadline and 7 months before the last litter collection and categorization in the SPEM project. Litter data collected in this study after January 1st 2020 still contain SUP items, but the time from the start of the adoption of the new law might be too short to see a difference.

The SUPD also sets targets for separate collection of single-use plastic beverage bottles (77% by 2025 and 90% by 2029) and says that to achieve these goals, Member States may establish deposit return systems (DRS) or establish separate collection targets for relevant EPR schemes. A DRS place a small deposit on beverage purchases, which is refunded to the consumer when the empty container is returned for recycling (DRS for recycling) or for reuse (DRS for reuse). In 2011 the European Parliament proposed the implementation of an EU-wide DRS for reuse/recycling of beverage packaging with the goal to reduce the environmental impacts of packaging systems and increase resource efficiency (European Parliament, 2011). DRS are an effective way of reducing the littering of the packaging items that they target (European Commission, Directorate-General for Environment, 2018; Grant et al., 2021) and are one way to implement the EPR. The establishment of EU-wide DRS for beverage packaging would have helped the producers to optimize production and the logistics of their products, and the free movement of goods would not be restricted (Leal Filho et al., 2019). This idea was not taken further, and as June 2022 there are 13 independent DRS schemes across Europe, the ones implemented for more than 2 years all achieving collection rates higher than 80% and up to 94% (Global Deposit Book, 2020). DRS have been suggested as a tool to achieve the collection rates of the SUPD by the European Court of Auditors (ECA, 2020). The Anti-waste and circular economy law has not set a DRS in France, but says that one or more DRS for recycling and reuse will be implemented starting in 2023 if the collection rates set by the SUPD have not been achieved through the separate collection of municipal waste. European NGOs and European beverage producers also support a DRS for recycling for plastic beverage bottles (https://zerowasteeurope.eu/wp-content/uploads/2022/05/27-04-2022_Collection_Closed-Loop-recycling_Access-to-recycled-content_FINAL-Statement.pdf).

The large abundance of single-use glass bottles for beer found at S4 are also due to illicit disposal and abandonment by users, i.e., by the same littering behavior that causes dispersal of single-use plastic items, showing that the problem is single-use packaging (United Nations Environment Programme, 2021a). This suggests that the development of an "all-in" DRS which includes containers of any material (plastic, glass, metal, tetrapack) and for all kinds of drinks, so to avoid material substitutions or changes in the composition of the beverage to elude the law, would be the best strategy to reduce littering (United Nations Environment Programme, 2021a).

Municipalities can significantly limit plastic pollution on their territory through the development of integrated strategies that include public procurement and exemplarity as well as territorial animation (WWF France, 2020; Azzurro et al., 2021). For instance, they can ban the use of SUP products in public buildings and events as well as on natural tourist places (similarly to what done on the so-called "plastic free beaches"), while promoting business that voluntarily decide to reduce the use of single-use packaging (Azzurro et al., 2021).

Plastic pollution reduction strategies that can be put in place by municipalities also include the prevention of plastic waste generation and promotion of reuse; the promotion of the consumption of tap water in their territory; the improvement of wastewater and stormwater management infrastructure to preserve the water cycle from plastic pollution; the improvement of the collection and recycling of plastic wastes; the reduction of plastic pollution locally through clean ups, that event thought are not a solution to plastic pollution as they act downstream from the problem, nevertheless have the advantage of making people aware of the issues raised by plastic waste and allow collecting data useful for steering local strategy against plastic pollution (WWF France, 2020).

Citizen science and the evaluation of the effectiveness of environmental regulations

Temporal series on macrolitter abundance are important to evaluate through time the effectiveness of the implementation of existing environmental regulations such as the EU Marine Strategy Framework Directive (MSFD, 2008/56/EC) and the EU SUPD at French national level and to promote further local actions to reduce litter items dispersed in the environment. The EU MSFD requires a reduction of marine litter and the European Plastic strategy (COM/2018/028 final) has set an aspirational reduction target of 30%. In order to gather baseline value estimates with adequate precision to be able to detect changes in time, abundance of litter items shall be gathered for time periods varying from 3 to 5 years, according to the precision required (Schulz et al., 2019).

The data collected in this study represent the first available data on quantity and types of litter items for the Durance River and can be used to support the development of targeted policies in litter prevention, mitigation and reduction of most abundant litter items, as well as be used to test whether implemented measures to reduce plastic pollution are effective (van Emmerik et al., 2019; Vriend et al., 2020a; González-Fernández et al., 2021). Additional surveys on the Durance could assess if SUP items targeted by the EU SUPD and French Anti-waste and circular economy law are less prevalent after a few years of restriction from the market and the obligation of collection targets. Future studies could include a higher spatial/temporal resolution and take into consideration hydrological variations, so to account for extreme events such as floods (Tramoy et al., 2022; van Emmerik et al., 2022) and provide data useful for quantifying emission of litter items from the Durance to the Rhône River and the Mediterranean Sea.

Collecting data on macrolitter is resource-intensive and citizen science can provide a cost-effective way to do it. Citizen science has been very valuable for carrying out large scale survey of marine litter on sea beaches (Hidalgo-Ruz and Thiel, 2015; Syberg et al., 2020; Vlachogianni et al., 2020; Zorzo et al., 2021) and riverbanks (Rech et al., 2015; Kiessling et al., 2019; van Emmerik et al., 2020a,b). In the Danish Realm, it was used to carry out the first scientific survey of plastic litter to cover an entire country (Syberg et al., 2020). Comparison of data collected by citizen scientists vs. trained professionals shows that citizen scientists report a higher fraction of non-categorized items (Rech et al., 2015) and find less small or "dirty" items (Roebroek et al., 2021). However, most litter items do now show any significant bias of volunteers (Roebroek et al., 2021) and the similar values of total abundance of litter items reported by citizen scientists and professional researchers show the value of citizen science (Rech et al., 2015; Zorzo et al., 2021), especially where monitoring programs are scarce or not in place (Smail et al., 2020). As noted by van Emmerik et al. (2022), the use of citizen science mobile applications can facilitate upscaling of data collection of plastic pollution on land (Ballatore et al., 2022) in river systems (van Emmerik et al., 2020b) and in urban environments (Tasseron et al., 2020). Data collected through citizen science can assist local decision-making (Hidalgo-Ruz and Thiel, 2015; United Nations Environment Programme, 2021b).

Data collected in the SPEM project cover smaller spatial and temporal scales in comparison to other citizen science projects developed throughout Europe (Rech et al., 2015; Kiessling et al., 2019; Syberg et al., 2020; van Emmerik et al., 2020a,b; Vlachogianni et al., 2020; Zorzo et al., 2021) and in Chile (Hidalgo-Ruz and Thiel, 2015; Rech et al., 2015), that have been running for longer times and on wider spatial scales. However, even limited amount of data can be useful when no data at all is available (Owens and Kamil, 2020). Indeed, the data on litter items collected in the SPEM project allowed to suggest environmental regulations that could be put in place at EU and French level and immediate action that can be taken at municipal level to reduce plastic pollution.

Conclusions

In this study we have quantified and characterized for the first-time macrolitter items on Durance riverbank and Lake Serre-Ponçon beach using citizen science. Plastic litter items correspond to 82% of total litter items and the overall abundance of litter items is two orders of magnitude higher than the European threshold value for marine litter to achieve or maintain the Good Environmental Status.

Unidentified soft plastic films probably derived from plastic mulch films used in agriculture, plastic biomedia used in waste water treatment plants, and single-use beverage bottles in plastic and glass were among the most abundant litter items. We discussed policies that could reduce these sources of pollution. These include the expansion of extended producer responsibility (EPR) schemes for plastic mulch films, the development of new EPR schemes for plastic biomedia, and the introduction of deposit return systems (DRS) for single-use beverage bottles.

We suggest that complementary to EU and French national laws, municipalities can start immediately to address the issue of plastic pollution targeting the most abundant litter items found on Durance riverbank through green public procurement and territorial animation. The same measures can be taken by other municipalities in the whole Region SUD Provence-Alpes-Côte d'Azur. Future surveys carried out with citizen science could be carried out as a cost-effective way to monitor litter items and assess the effectiveness of environmental regulations in reducing plastic pollution.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

BD, MF, and TB contributed to conception and design of the study. MF and TB contributed to the methodology and training of citizen scientists. EM, JP, J-PC, MF, NC, and TB contributed to investigation. BD and NC contributed to resources, project administration, and funding acquisition. TB performed the formal analysis and wrote the manuscript. All authors read the manuscript, contributed to discussion, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2022.866982/full#supplementary-material

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Nuts and bolts of tropical tuna purse seine nets recycling: A circular business model

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Tropical tuna purse seiners are one of the most important contributors to end-of-life (EoL) fishing gears in the world, and these fishing nets can become a promising secondary raw material. Thus, tuna companies are looking for possibilities to valorize them by applying circular economy (CE). This contribution aims at assessing the viability of creating a circular business model out of recycled tropical tuna purse seine EoL nets. The yearly contribution of the Spanish tuna freezer purse seine companies to EoL fishing nets was estimated at 900 tons. Three pilot projects were implemented (involving 80 tons of EoL tuna nets) to learn about the monetary and material flows, supply chain, stakeholders' perception, and the environmental impacts of upcycling polyamide nets into four marketable products (i.e., conditioned fishing nets, backpacks, fishers' dungarees, and sunglasses). The results indicate that recycled regrinds/flakes and pellets were 37 and 50%, respectively, more expensive than virgin counterparts, but the yarn may achieve competitive production costs in the textile industry, with an additional environmental benefit close to 69% per kg of virgin–origin yarn. The challenges faced when recycling EoL polyamide fishing nets were discussed. Innovation and logistics appear to play a fundamental role in making the business sustainable. Besides, the circular business model methodology to assess the value proposition was also discussed in its empirical application.

KEYWORDS

end of life fishing gear, circular business model, value chain, textile industry, plastics recycling, circular economy

Introduction

Circular economy (CE) has become a cornerstone of the quest of finding solutions to the marine plastic pollution. The three theoretical strategies under the CE paradigm fit with the desired solution for marine plastic: (i) minimize inputs of raw material and outputs of waste, (ii) keep the resource as long as possible within the system, and (iii) reintegrate products into the system when they reach the end of life (Suárez-Eiroa et al., 2019). Public administrations have echoed this challenge by developing a regulatory framework (Vollmer et al., 2020; Williams and Rangel-Buitrago, 2022). The

European Strategy for Plastics in a CE and related action plans (European Commission, 2021) foster the adoption of sustainability criteria along the entire plastic supply chain from primary producers to converters, brand owners and retailers, waste collectors, and recyclers (Foschi and Bonoli, 2019). Particularly, the entry into force of policies designed to limit the use of single-use plastic products as a way to reduce the contribution of marine plastic [Directive (EU) 2019/904] together with the will of entrepreneurs for new opportunities has led to the creation of new initiatives from emerging market niches and business models on recovery of marine plastic (Dijkstra et al., 2021). In parallel, the textile and fashion industries have started to shift their focus toward sustainable fashion-making recycled marine plastic textiles (Khandual and Pradhan, 2019). Some examples are Adidas-Parley Ocean Plastic(R), Prada, Converse (Luo and Deng, 2021), Ecoalf's Upcycling the Ocean, Ternua Group (Peña-Rodriguez et al., 2021), Inditex, H&M, Hérmes (Ramos et al., 2020), and Patagonia (Leal Filho et al., 2019). This increasing number of initiatives indicates not only a new production model but also a consumption change in society.

Among marine plastics, end-of-life (EoL) fishing gears are particularly gaining attention within the CE paradigm (Bishop et al., 2020). Despite that the available regulations promote the sustainable management of recovered marine plastic [Directive (EU) 2019/883, Directive EC 2018/251], knowledge of the amount of EoL fishing gear generation is limited (Basurko et al., 2022). Likewise, the management of EoL fishing gear, today, is yet to be consistent with the waste hierarchy (Argüello, 2020), due to fishing gear waste is often dispensed in the "cheapest container," i.e., the sea (Sherrington et al., 2016; Richardson et al., 2021), or it is sent to landfill or abroad because of the non-existence of recovery and valorization industry nearby the ports they are discarded. This latter point was highlighted by two studies analyzing the management of fishing gear in Spain and Norway. Basurko et al. (2022) studied the EoL fishing gear management practices by Spanish fishing fleets and ports and concluded that EoL fishing gear management is heterogeneous across the country, and the type of management depends on the location, nature of the ports, and whose responsibility it falls (i.e., regionally or nationally managed). Deshpande et al. (2020), in contrast, estimated that of the 4,000 tons of annually discarded fishing gears, 55% were sent abroad for recycling; they also underpinned the need to improve the recycling capabilities of the country to deal with discarded fishing gears.

Among all fisheries, tropical tuna purse seiners stand out as one of the most important contributors to EoL fishing gears in the world. The nets employed by this fishery are made mainly of high-quality polyamide (PA6) and can reach dimensions of up to 2,000 m long in perimeter and about 300 m in depth (Zudaire et al., 2020). The net size can vary depending on vessel characteristics, e.g., power or target species (ICCAT, 2006–2016). This leaves tropical purse seine shipowners with a high quality but large quantity of material (currently unquantified) in their base ports where they normally are deposited. This circumstance has been triggered, in part, by the prohibition of net reuse in the construction of drifting fish aggregating devices (dFADs) in the Indian Ocean (IOTC-2021-WGFAD02-INF02, 2021). Thus, the amount of tropical tuna purse seiners' EoL fishing gears (hereafter "EoL tuna nets") stored in their fishing ports (an example is shown in Figure 1) calls for actions to foster their valorization.

Fishing gear valorization is feasible by establishing proper management, collection, conditioning, and recycling scheme; in turn, this can prevent fishing gears from becoming marine litter by being dumped at sea (Brodbeck, 2016). However, recovered fishing gears are often dirty and very degraded. Thus, the conditioning, recycling, and transport of such raw materials tend to be costly both in time and resources (Madricardo et al., 2020). In general terms, EoL fishing gears can be recycled mechanically (Mondragon et al., 2020) or chemically, or they can be incinerated (Arandes et al., 2004). The knowledge regarding the recyclability of polyamide-based fishing gears has particularly increased in recent years (Klun and Kržan, 2000; Brodbeck, 2016; Kamimura et al., 2019; Bertelsen et al., 2020; Feary et al., 2020; Garrido et al., 2020; Mondragon et al., 2020; Peña-Rodriguez et al., 2021), identifying the limitations of mechanical recycling (Madricardo et al., 2020). Despite the logistic chains derived from the recycling being studied (van Giezen and Wiegmans, 2020), there are still few examples of real implementation quantifying the cost-benefit along the value chain (from the fishing gear collection to the final product development) (Boldrini and Antheaume, 2021) together with the environmental impacts. Those who have succeeded omit to discuss the challenges encountered along the entire value chain producing valuable information that could help others achieve a competitive product made of marine plastic when developing a circular business model.

In line with the European strategies, business models in this field should be framed within the perspective of the CE. Circular business models (CBMs) stand as enablers for the implementation of the CE (Kirchherr et al., 2017). CBMs are rising as a more comprehensive version to define new business models within a CE perspective than traditional or linear business models (Nußholz, 2018), which only describe the rationale of how an organization creates, delivers, and captures value (Osterwalder and Pigneur, 2010). CBM aims to reconcile the creation of commercial value with the adoption of circular strategies that can prolong the useful life of products and parts and close material loops (Nußholz, 2017). CBMs are considered a class of sustainable business models (Geissdoerfer et al., 2018); they assess the environmental, economic, and social viability of the real implementation of a business (de Kwant et al., 2021) and envisage the environmental status while creating a business model. The scientific literature on CBM has increased in recent years providing several CBM definitions (Bocken et al., 2013;

FIGURE 1
View of the storage of EoL tuna nets in Seychelles.

Nußholz, 2017; Manninen et al., 2018; Geissdoerfer et al., 2020) and theoretical reviews on its concept (Pieroni et al., 2018, 2019; Bocken et al., 2019; Lüdeke-Freund et al., 2019; Reim et al., 2019; Rosa et al., 2019; Centobelli et al., 2020; Geissdoerfer et al., 2020). The most general definition is the one proposed by Geissdoerfer et al. (2020) where CBM is defined as a "*business model that are cycling, extending, intensifying, and/or dematerialising material and energy loops to reduce the resource inputs into and the waste and emission leakage our of an organizational system. This comprises recycling measures (cycling), use phase extension (extending), a more intense use phase (intensifying), and the substitution of products by service and software solution (dematerialising)*." Some authors have also proposed different conceptual frameworks and tools to build CBMs (Joyce and Paquin, 2016; Nußholz, 2017; Manninen et al., 2018; Bocken et al., 2019; Lüdeke-Freund et al., 2019; Donati et al., 2020; Geissdoerfer et al., 2020; Boldrini and Antheaume, 2021); others have already discussed the implementation of CBM, barriers, and limitations (Núñez-Cacho et al., 2018; Dijkstra et al., 2020; Guldmann and Huulgaard, 2020; Liu et al., 2021). No contribution was found, however, on studies quantifying monetary and material flows and also environmental benefits of an empirical application of CBM of recycling EoL fishing nets, including also the stakeholders' knowledge of the whole value chain.

The recovery and recycling of EoL tuna nets emerge as a promising business opportunity that can profit from CE approaches, fitting in the CBM archetype "creating value from waste" (Bocken et al., 2014). Within this context, this study aims to (1) provide the first estimate on the amount of EoL tuna nets created by the Spanish tropical tuna freezer purse seine fleet, (2) assess the potential of building new CBM based on recycled EoL tropical tuna nets, and (3) identify the constraints and strengths of applying CBM models. For the first, the Spanish tropical tuna freezer purse seine shipowners were interviewed, and the annual amount of EoL fishing net was estimated, detailing the contribution of net component, material, current management, and discarding reason. To have enough stock to guaranteeing a cost effective production and a continuation of the new business is identified as a constraint, so are the low recycling capabilities of certain polymers and gears (Feary et al., 2020). For the second and third objectives, three case studies were carried out involving the real recovery, recycling, and upcycling of 80 tons of EoL tuna nets of Seychelles into four textile products marketed in Europe. Material balances, transport needs, and costs of each valorization stage (i.e., recovery, conditioning, recycling, and product creation) were measured empirically. The technical, economic, and environmental data obtained from each valorization stage of the value chain served to design a CBM for tuna purse seine net recycling. The CBM was built and contrasted with the stakeholders involved along the entire value chain. The results helped to identify the phase of the value chain that needs to be improved to achieve a competitive commercial product derived from the recycled fishing nets. Challenges faced by private companies when recycling EoL tuna nets were also assessed in the three levels of CE: micro, meso, and macro levels (Suárez-Eiroa et al., 2019).

Theoretical framework

According to the European Green Deal, the CE will create sustainable growth in Europe. This statement is supported by other authors that recommend CE as an approach for reconciling economic growth with sustainable environment and economic development (George et al., 2015; Korhonen et al., 2018a; Busu and Trica, 2019; Androniceanu et al., 2021). The acquiring importance of the CE concept is reflected in the growing number of studies on the subject. There are several literature reviews on the definition of the CE (Geissdoerfer et al., 2017; Kirchherr et al., 2017), one of the more complete definitions being the one by Geissdoerfer et al. (2017): "*a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling*". However, a lack of theoretical analysis of the CE was identified (Corvellec et al., 2022), arguing that it has been mainly developed by practitioners and because a single generally accepted definition is still lacking. Thus, it has been claimed that CE is not a theory but an emerging approach to industrial production and consumption (Korhonen et al., 2018b).

Following the premise that CE is an approach and not a theory, several authors (George et al., 2015; Geissdoerfer et al., 2017; Gao et al., 2020) attribute the embryonic idea of CE to Boulding (1966) and the introduction of CE concept to Pearce et al. (1989). The theoretical background of the CE has been slightly studied in the last few years (George et al., 2015; Ghisellini et al., 2016; Korhonen et al., 2018b), relating CE with economic growth theories, based on CE aims to create sustainable growth. Several authors affirm that CE operates around the neoclassical exogenous growth theory (Ghisellini et al., 2016; Bimpizas-Pinis et al., 2021; Donaghy, 2022), but this theory does not consider the limitation of natural resources availability as a constraint (Meadows et al., 1972; Kornafel and Telega, 2020), which is one of the main ideas underlying the concept of the CE. This limitation (Ghisellini et al., 2016) is contemplated in the steady-state economy theory (Daly, 1977), which aligns it with the CE philosophy. However, it lacks tools for dealing with environmental and ecological problems (Pin and Hutao, 2007). In contrast, the endogenous theory of growth, and in particular, the endogenous innovation in the theory of growth (Grossman and Helpman, 1994) states that "*the best way to sustain the economic growth in the long run is by the improvements in technology by discovering ways to produce output while conserving those inputs that cannot be accumulated or regenerated*." Although the endogenous growth theory is not exempt from critics, for example, due to its operationality (Dinopoulos and Thompson, 1996), the CE could be a way to produce output while conserving inputs for at least a longer period and can be just one of many paths to be taken for the sustainable economic growth. The linkages between Industrial Ecology and CE have also been studied, concepts that although have different shades, should feed each other to enable and catalyze sustainable management of natural capital (Ghisellini et al., 2016; Saidani et al., 2020). In line with this idea, the European Commission remarks that the EU's economic prosperity and wellbeing are underpinned by its natural capital. Similarly, in 2021, the United Nations adopted a new statistical framework to complement the economic accounts with the natural capital accounts (Edens et al., 2022).

The positive aspect of CE is that the CBMs are considered enablers for CE implementation (Kirchherr et al., 2017). CBM is a class of generic sustainable business models (Bocken et al., 2013) suitable for CE application. The authors (Pieroni et al., 2019; Andreini et al., 2021) also looked into business model innovation (BMI), defined as "*the design process for giving birth to a fairly new business model on the market, which is accompanied by an adjustment of the value proposition and/or the value constellation and aims at generation or securing sustainable competitive advantage,*" for CE and sustainability. Both models still show constraints that are further discussed in the present study. Either CBM or BMI, tools to implement the CE to prompt a sustainable economic growth, should be accompanied by a circular supply chain management (CSCM) playing a crucial role in the transformation of a business model for the CE (Geissdoerfer et al., 2018).

Methods and data

This section is structured as follows: first, the EoL tuna net data collection is explained; second, empirical case studies are described, and finally, the selected methodology for the CBM application is defined.

EoL tuna net data collection

The estimation of the EoL tuna nets production by the tropical tuna purse seine fisheries focused on the Spanish tuna freezer companies operating in the Indian, Atlantic, and Pacific oceans. This study is focused on the Spanish tuna freezer sector because the need to valorize networks arose from the sector itself. Data for the estimation were collected by means of a survey process using a questionnaire (Appendix 1) where the companies were asked about the components (nets, thread, floating lines, eyebolts, etc.) of the fishing gears (quantitative and qualitative), the life span, and discarding frequency and fate of the nets (Zudaire et al., 2020). All Spanish companies were contacted, but not all of them responded at the time of writing this paper. The results of the questionnaire were extrapolated to the whole Spanish tuna freezer fishing fleet companies according to the number of vessels of each company.

TABLE 1 Value chain stages of the EoL tuna net recycling, data collected from each stage, and data availability of each case study.

Stages	Data collected	Data available from case studies
Raw material	Origin and type of raw material, quantity, storage time, and requirements	CS1, CS2, CS3
Dismantling	Dismantling costs and requirements, companies involved, and their location	CS1, CS2, CS3
Transport	Transport type, distance, trajectories performed	CS1, CS2, CS3
Conditioning	Net conditioning and transport costs, company location	CS1, CS2
Chemical recycling	Recycling and transport cost, technical performance	CS1, CS2
Yarn production	Production and transport cost, technical performance	CS1, CS2
Textile manufacturing	Production and transport cost, technical performance	CS1, CS2
Final product production	Production and transport cost, technical performance	CS1: backpacks CS2: sunglasses and fishing dungarees CS3: conditioned fishing nets

CS, case study.

Case studies

Three real implementation experiences or case studies (CS1, CS2, and CS3) were performed in collaboration with several stakeholders (ship owners, recyclers, textiles companies, fashion brands, and researchers) because the value creation processes for BMI involve actors across a wide variety of level spanning boundaries including not only organizational but also external actors (Andreini et al., 2021). Data were gathered during 2020–2021 to collect information on material flow, production costs, quality of the products, and logistic needs for the different value chain stages of the recovery and recycling of EoL tuna nets (Table 1). This information was then used to build the CBM of recycling EoL tuna nets of tropical tuna purse seine fleet that operated in the Indian Ocean.

Not all the case studies went through the entire value chain. CS1 (involved 46 tons of EoL tuna nets) completed the entire value chain from the fishing nets collection, net conditioning for its transportation, transport, net dismantling for the recycling process, recycling process, yarn production, textile production, and final product for fishing sectors (backpacks and hats); CS2 (involved 2.5 tons of EoL tuna nets) developed same steps as CS1, but with different companies and different final products (dungarees for fishers and sunglasses); and CS3 (involved 32.6 tons of EoL tuna nets) stopped in the sale of conditioned fishing nets, and it was performed to verify some figures in dismantling process (Figure 2). The case studies (Figure 2) were only focused on the fleet operating in the Indian Ocean, whose nets have arrived at their end of life and are stored in Seychelles. Cost-related data are in relative terms based on a kilogram of recycled yarn. Costs in absolute terms are not presented due to confidentiality issues. The design of the case studies was performed together with the stakeholders (fishing companies, recyclers, textiles companies, and fashion brands) to cover all the stages. The CS2 and CS3 were developed to achieve data from different sources to calibrate data for each stage.

Circular business model

Recycling EoL tuna nets is especially focused on the value creation process of the sustainable BMI processes (Andreini et al., 2021). EoL tuna nets of PA6 used to be stored in ports, and in the presented business model, this secondary raw material provides higher environmental and economic value (Geissdoerfer et al., 2018). This business model aims to create value from waste (Bocken et al., 2014). Thus, the suitability of EoL tuna net recycling was assessed by applying a CBM approach based on Manninen et al. (2018) and considering the beginning of life (BoL: fishing nets), middle of life (MoL: lifespan of fishing nets in fisheries), and EoL (recycling tuna nets) (Figure 3). The description of the CBM followed the approach of five steps:

STEP 1: **Environmental value proposition (EVP) definition**: In line with the EVP given by Manninen (Manninen et al., 2018), the EVP considered the environmental value improvement of the EoL tuna net recycling process compared to the use of virgin material.

STEP 2: **Stakeholder identification**: The relevant stakeholders of the CBM in the whole value chain were defined, and their roles were determined.

STEP 3: **Reference system and assessment of environmental impacts definition:** The reference system is currently in the market. This reference system is the unit by which the proposed circular model is compared to different stages of the value chain. Depending on the stage of the value chain, the reference system is related to the non-recycled pellets or substitutive products for recycled yarn.

STEP 4: **EVP verification:** In this step, the environmental benefits related to different stakeholders were identified based on Step 3 and compared with the EVP defined in Step 1. To introduce circularity to the EoL fishing gears, the recycling process was quantitatively assessed. The material flow and the costs of each process were assessed. The life cycle phases of the raw material (EoL tuna nets) acquisition, transportation, and transformation were identified and quantified. To estimate the environmental benefits of this CBM, the benefit of preventing the creation of marine litter thanks to the recycling process and the benefit due to the reduction of CO_2 were considered. The functional unit for the assessment was 1 kg of yarn.

STEP 5: Identification of improvement proposals: Possible improvement measures were proposed for the value chain of the business model to meet the EVP.

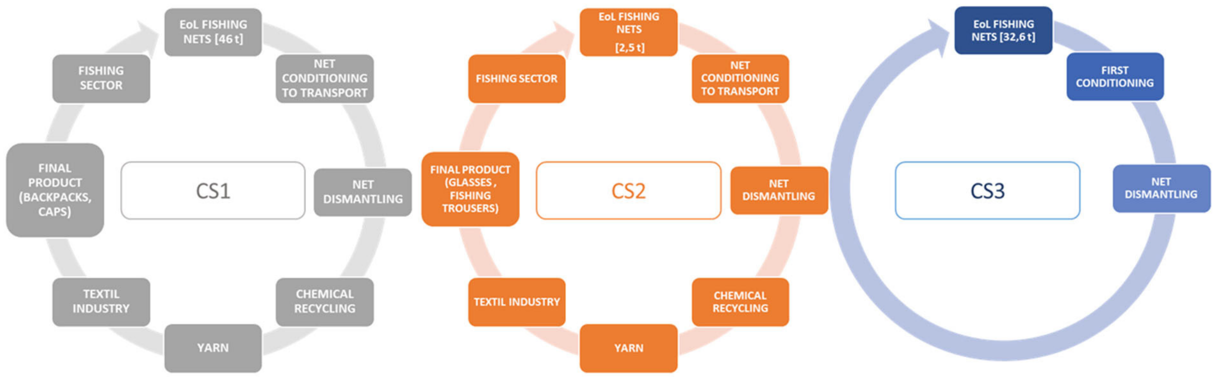

FIGURE 2
Flowchart of the three case studies (CS) that were focused on the chemical recycling of EoL tuna nets. Each colored rectangle represents the production stages achieved in each CS. The final stages of each CS are CS1: production of backpacks; CS2: production of glasses and fishing dungarees; CS3: selling fishing nets. CS1 and CS2 undertook the same production phases, but by different companies; in CS3, only the first three phases were analyzed.

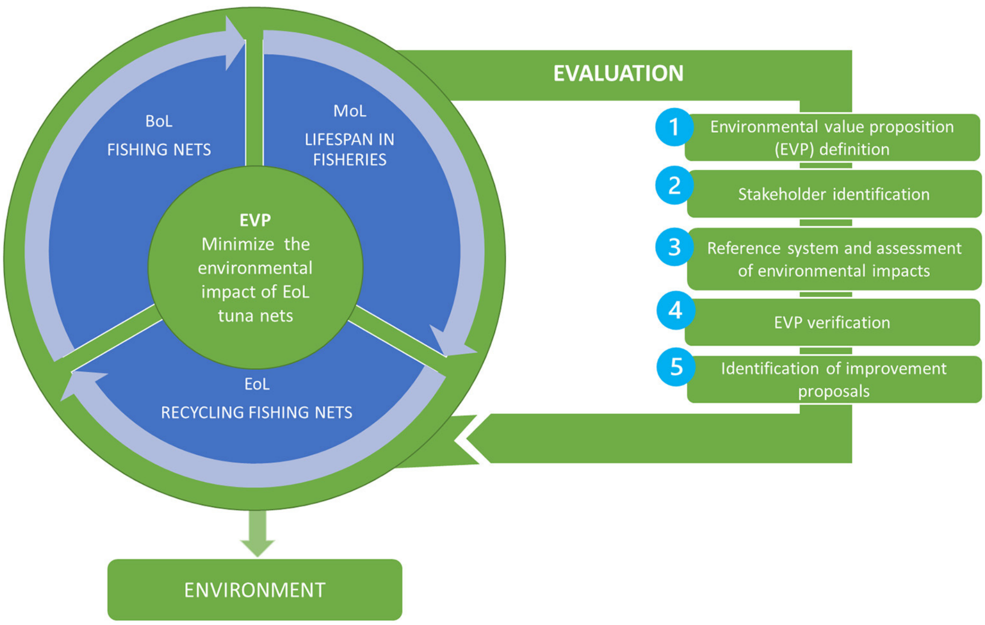

FIGURE 3
Environmental value proposition framework [adapted from Manninen et al., 2018]. The stages of the life cycle (BoL, beginning of life; MoL, middle of life; EoL, end of life) are in blue. The environmental value proposition (EVP) that impacts the environment is in green. This model is evaluated by the five steps defined on the right side of the figure.

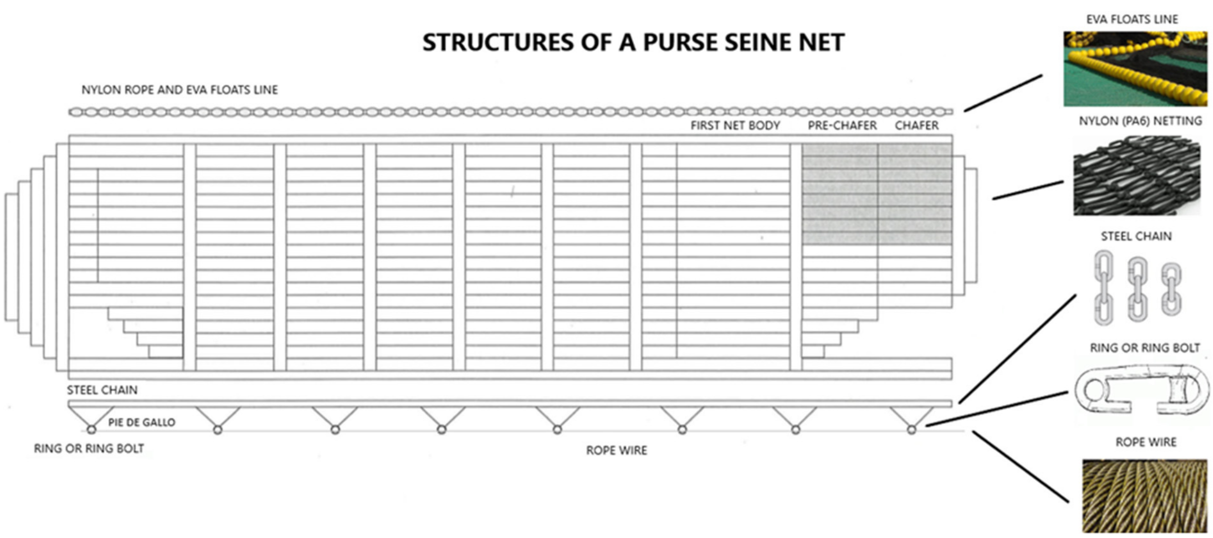

FIGURE 4
Tuna purse seine fishing net design including the different elements of which it is composed. On the right side of the figure, there are pictures of the main elements of the fishing gear.

Results

EoL tuna net data collection

At the time of this analysis in Spain were 10 tropical tuna purse seiner companies, all of them were surveyed, and five of them answered the questionnaire. The responses represented 63% of the Spanish tropical purse seiner vessels. According to the results, the weight of a tropical tuna purse seine net (Figure 4) is on average 93.2 tons with a standard deviation (SD) of ±16.2 tons. The net is made of nine components (Table 2). The netting, ropes, and flotation headlines are made of PA6, and the total mean weight of this material is around 64.2% of the total weight. The ethylene-vinyl acetate (EVA) floats are used in the upper part of the flotation headline and constitute 9.7% of the total mean net weight. The metallic components (chain, crowfoot, and ring bolts) are built of steel and correspond to 26.1% of the total mean weight of the whole fishing gear.

The results showed high variability in the estimated life span of net components, with an average value of 3.2 and SD of ± 0.8 years for nets. According to the companies, one net is operative for at least 2 years, but it can also be used for up to 4 years. All components are susceptible to replacement or repair, which depends on the number of sets, life span, or observation of significant deterioration. For example, the netting is repaired in case of breakage and/or replaced after 12–14 months of use. These replaced net components are usually stored in Port of Victoria (Seychelles), Abidjan (Costa Marfil), Mindelo (Cabo Verde), and Posorja (Ecuador). According to the companies, some of the elements of the net (i.e., net, ropes, and chain) can be reused in new nets or as replacements and in the construction of dFAD. Despite these uses, significant amounts of nets can remain stored for years in these ports.

TABLE 2 Components and materials of a typical tropical tuna purse seine net (average 93.1 tons).

Gear component	Material	Weight (average ± SD) per net (in tons)
Netting	PA6	58.9 ± 11.1
Ropes	PA6	0.9 ± 2.0
Flotation line	PA6	0.9 ± 0.6
Ropes	PA	2.1 ± 1.1
Floats	EVA	8.3 ± 1.0
Rope wire	Steel	7.4 ± 4.2
Chain	Steel	13.3 ± 2.2
Ring bolts	Steel	0.6 ± 0.4
Crow foot	Steel	0.7 ± 1.6

SD, standard deviation.

Case studies

The stages of the different case studies are described below, and Table 3 summarizes them.

STAGE 1. Raw material: The raw material considered for CS1, CS2, and CS3 was PA6 of the EoL tuna netting of the Spanish freezer tuna vessels. These EoL tuna nets were sold to recycling companies for 3.2–4.9% of the cost of one kg of recycled yarn. However, according to the interviewed

TABLE 3 Description of the phases of the case studies.

Objective		Case study 1 Production of backpacks from EoL fishing net recycled	Case study2 Production of sunglasses and fishing dungarees from EoL fishing net recycled	Case study 3 Selling of tuna nets
Raw material	Type	PA6 EoL tuna net	PA6 EoL tuna nets	PA6 EoL tuna nets
	Quantity (t)	46	2.5	32.6
Dismantling	Location	Seychelles	Seychelles	Seychelles
	Quantity (t)	46	2.5	32.6
Transportation	Origin	Seychelles	Seychelles	Seychelles
	Destination	Lithuania	Spain	Lithuania
Conditioning	Conditioning by	Company 1[*1]	Company 2[*2]	
	Quantity (t)	32.2	2.3	
Chemical recycling	By	Company 3[*3]	Company 4[*4]	
	Quantity (t)	58 (recycled material is mixed with other materials)	1.7	
Yarn production	By	Company 3[*3]	Company 5[*5]	
	Quantity (t)	52	1.17	
Textile manufacturing	By	Company 6[*6]	Company 6[*6]	
	Quantity (t)	47	*(1 eEstimated value)*	
Final products	By	Company 7[*7]	Company 7[*7] Company 8[*8]	
	Quantity (units)	*472 000 (estimated data)*	*370 fisher's dungarees (estimated value)* *3 150 glasses (estimated value)*	

In the rows, there are the value chain stages, and in the column, the case studies with the most relevant information are described.
[*1]Company 1; Activity: Conditioning fishing gears. Location: Lithuania.
[*2]Company 2; Activity: Conditioning fishing gears. Location: Spain.
[*3]Company 3; Activity: Chemical recycling. Location: Turkey.
[*4]Company 4; Activity: Chemical recycling. Location: Portugal.
[*5]Company 5; Activity: Yarn production. Location: Spain.
[*6]Company 6; Activity: Textile manufacturing. Location: Spain.
[*7]Company 7; Activity: Fashion industry. Location: Spain.
[*8]Company 8; Activity: Glasses manufacturing. Location: Italy.

stakeholders, not all the materials can be absorbed by this industry. Additionally, shipowners pay a fee (3.4–3.9% of the cost of 1 kg of recycled yarn) to rent the space for storing the fishing nets in port.

STAGE 2. Fishing net dismantling: Nets needed to be dismantled and then fitted into containers to be shipped to the conditioning plant. The dismantling was done by a local company (CS1) or by the tuna companies' own staff (CS2 and CS3). The cost of dismantling ranged from around 0.13–3.38% over the cost of 1 kg of recycled yarn.

STAGE 3. Secondary raw material transport: The transportation of containers from Seychelles to the dismantling company in Europe was done by ship for ocean transport and then by truck for road transport. In CS1, the nets were transported to a North European company, and in CS2, the nets were transported to a company located in the south of Europe. The transportation costs ranged from 2.6 to 5.1% over the cost of 1 kg of recycled yarn.

STAGE 4. Fishing net conditioning: In this process, the tuna nets were cleaned and prepared for its recycling. The conditioning process was undertaken by a North European company in CS1 and CS3. To contrast data obtained from this company, this stage was done with another company (South European) in the case study CS2. The estimated costs of net conditioning range between 2.5 and 9.9% over the total cost of 1 kg of recycled yarn. The CS3 traceability was finished at this stage.

STAGE 5. Net chemical recycling: Conditioned nets were chemically recycled. In CS1, the dismantling and recycling processes were done by North European companies, and the traceability of these processes was missing. In CS2, the net was recycled by a Portuguese company. The obtained recycled pellets were 100% made of EoL tuna nets. No additives were used in the process. The costs of chemical recycling ranged from 32.9 to 48.3% over the cost of 1 kg of recycled yarn. This cost included the transport from the dismantling company to the recycling company.

STAGE 6. Yarn production: In CS2, the recycled pellets were used for the yarn production, which was carried out in Spain. The cost of the yarn production phase was estimated from 27 to 51.5% over the total costs of recycled yarn.

STAGE 7. Textile manufacturing: The yarn was transported to the textile company located in Spain (CS1 and CS2) where the fabric was produced. The fabric production cost depends on the typology of the fabric. In CS2, the fabric was mixed with certain components such as elastomers to meet the requirements the final product had to present.

STAGE 8. Final products: The textile final products were backpacks and trucker caps (CS1) and dungarees for fishers (CS2), all produced by a Basque company. Additionally, in CS2, with the recycled pellet, sunglasses were produced in Italy.

Collected data and results were validated with stakeholders that are currently a part of this value chain, and who are coauthors of this contribution.

Circular bussines model

A CBM focuses on resources to check whether the model contributes to slowing, closing, or narrowing resource loops (Bocken et al., 2018). Using the EoL tuna nets instead of leaving them abandoned as a waste material means a circular economy solution (D'Amato and Korhonen, 2021), and accordingly, a circular business model. Figure 4 shows the scheme of the CBM for recycling EoL tuna nets.

STEP 1. Environmental value proposition (EVP) definition: The EVP is the result of three variables: first, the reduction of environmental impact caused by abandoned, lost, or otherwise discarded fishing gears (ALDFG) on the environment, especially if the recovering and recycling of EoL nets work as marine litter prevention mechanism; second, the reduction of petrol-based material extracted from the environment derived from recycling existing material; and third, the generation of a new business from the already existing and discarded raw material.

STEP 2. Stakeholder identification: For the recovery and recycling of EoL tuna nets, several are targeted as key stakeholders: (1) the public administration because the regulation is one of the main drivers for these types of business; (2) fishing companies as providers of raw material; (3) depending on the way nets are managed once they arrive to their EoL, the cost of the net recycling may vary; hence, net managers are also key for the cost efficiency of the process. For the transformation process, fishing net dismantling companies, recycling companies, textile companies and clothing or fashion companies have been identified and contacted. (4) Logistics and related stakeholders become pivotal, and several transport companies are involved along the whole value chain. Finally (5), research institutions also play a key role to improve the recycling process because currently chemical recycling of the PA6 EoL tuna nets is still costly and the price of the recycled PA6 pellet is still high compared to the virgin PA6 or other PA6 pellets from other recycled materials.

STEP 3. Reference system and assessment of environmental impact: In the case of raw material (PA6) and pellets, the reference system are the substitutive products existing in the market whose data are provided by the identified stakeholders. The reference system for the yarn was one that can be considered a substitutive product due to similar technical and market characteristics. Additionally, in the reference system, EoL tuna nets that are not collected, remain in the environment damaging it. In Figure 5, the values of the reference system compared to the CBM are represented.

STEP 4. Verification of the environmental value proposition (EVP): As Figure 5 shows, although the regrinds and pellets from virgin raw material (reference system) are 1.5 times less costly than pellets made of recycled material from EoL tuna nets, the recycled yarn can achieve a competitive value in the market. Additionally, the environmental benefit (15–140% over the market price of the recycled yarn) was estimated as a result of the recycling process.

STEP 5. Improvement proposals: Several improvement proposals were identified. First, the chemical recycling of the PA6 EoL tuna net was not optimal because difficulties were encountered during the yarn production. The recycling of nets needed to be improved, with one option being the use of additives to improve the viscosity of the materials during yarn production. Second, the EoL of the final products (textile final products) needed further assessment in order to establish the best use for this material at the end of its life because, for a more circular model, the final product needs to be done using a recycled material and it should be a recyclable material. For example, the recycled yarn used to manufacture the fabric of fisher dungarees had to be mixed with elastomer to improve the properties of the final product. This addition hampers the recycling of recycled fabric. Third, logistics and transportation are an issue in the tropical tuna purse seine nets recycling. The diverse locations of the agents involved in the value chain (Figure 6) from Seychelles to the dismantling plant (Lithuania or Spain), recycling plant (Turkey or Portugal), yarn production plant (Spain or Turkey), textile production (Spain), and finally the fashion company (Spain) can jeopardize the whole business model. Centralizing the processes would decrease the transport costs and CO_2 emissions, improving the sustainability of the CBM. But for developing the whole value chain in just one region, the amount of recycling nets should be enough to justify the investment in the conditioning and recycling plants and facilities.

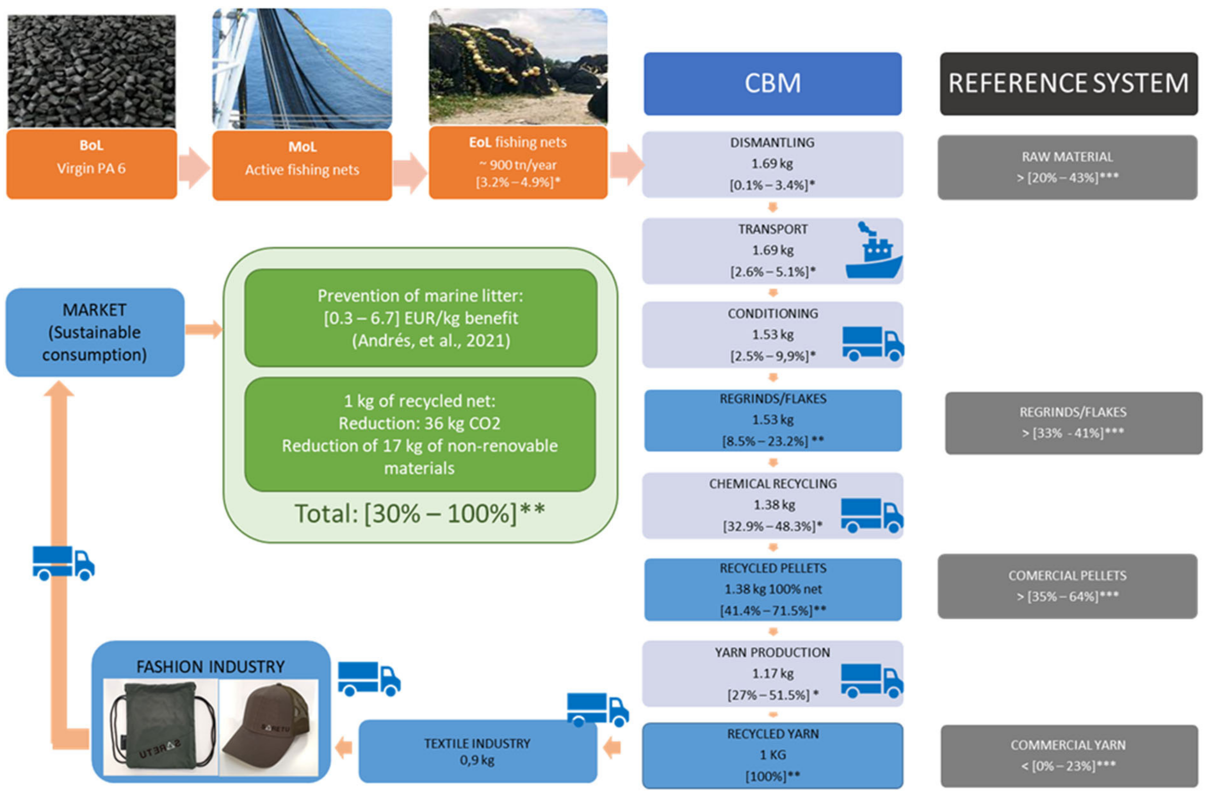

FIGURE 5
Value chain related to 1 kg of PA6 recycled yarn. Data [material flow in kilograms (kg) and costs in percentages] related to July 2021. The material flow is in orange, the CBM is in blue, the reference system is in gray, and the environmental value proposition of the CBM is in green. The subscript "*" represents the % of cost of the process (light blue) over the total costs of yarn production. Subscript "**" represents the total cost of production of intermediate products (dark blue) over the total costs of recycled yarn production. Subscript "***" represents the variation percentage of the CBM intermediate products compared to the products existing in the market (reference system).

Discussion

The recovery and revalorization of marine plastic within a CE are an attractive paradigm to increase global welfare while minimizing the environmental impacts of economic activities (Donati et al., 2020). This study has estimated, for the first time, the yearly contribution of Spanish tuna freezer purse seine companies to EoL fishing nets and assessed the viability of creating a CBM out of recycled tropical tuna purse seine EoL nets. This study allowed us to learn about the monetary and material flows, supply chains, stakeholders' perceptions, and the environmental impacts of upcycling polyamide nets. However, although the assessment and quantification of EoL tuna nets recycling CBM supported promising results, limitations in the business itself and in the methodology to assess the CBM have also been identified.

The first limitation when applying a CBM is to define the level of CE that needs to be analyzed. The high investment for recycling fishing nets should be addressed with a holistic perspective on a European-level basis by optimizing the location of the recycling plants according to the EoL fishing nets generation and logistic issues (i.e., macro level). This case study demonstrates the implementation of the circular economy of EoL tuna nets needs to implement the three levels of circular economy (Suárez-Eiroa et al., 2019): (i) micro level (recycling company), (ii) meso level (fisheries + recycling company + textile industries), and (iii) macro level (holistic perspective and European Regulation). While the CBM has been applied at the micro level, the meso and macro levels are affecting the CBM directly. Therefore, isolated CBM at the micro level should be accompanied by its related meso and macro CBMs. There is a need for innovative multi-level solutions (Madricardo et al., 2020), and how to relate these several CBMs at different levels needs further research.

Innovation seems to be a requirement along the whole value chain. EoL tuna nets are an important source of secondary raw material for its revalorization, even more, if this revalorization implies an environmental improvement. These nets are subjected to be recycled, although the process is more costly and requires adjustments in almost all stages of

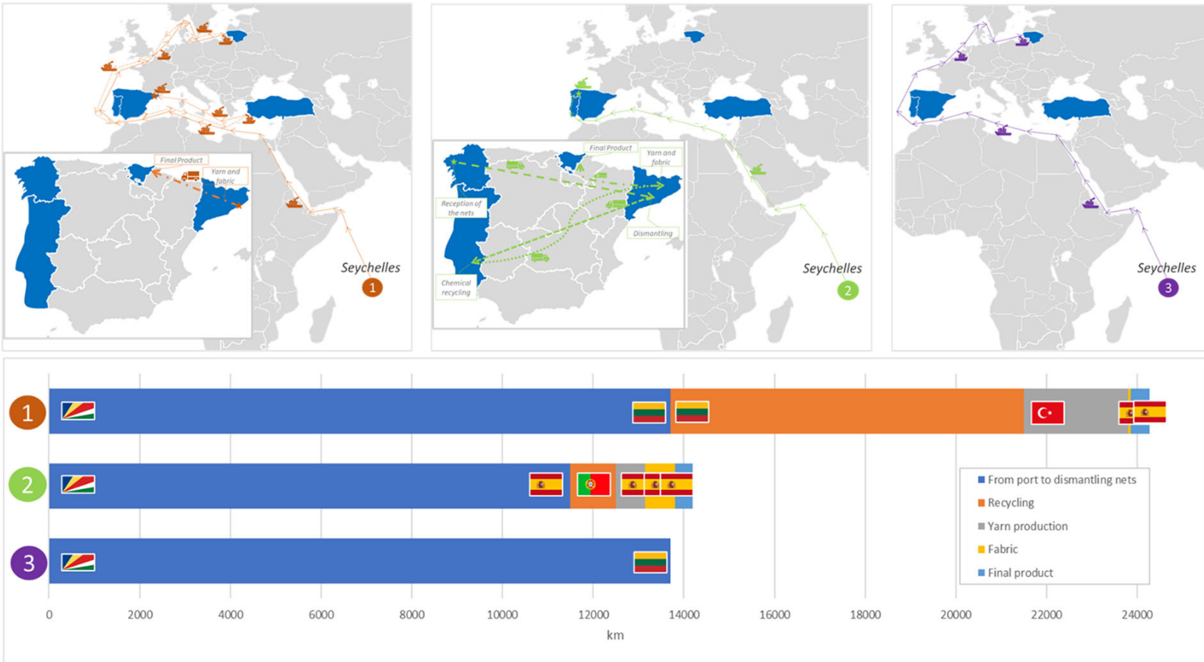

FIGURE 6
Transport required in the case studies to recycle EoL tuna nets, with a base port in Mahe, Seychelles. In the maps at the top of the figure the trajectories traveled by the EoL tuna nets from the country of origin to the final product processing are represented, and their transport methods (by vessel or by truck) are described with icons. The map in the top left (in orange) describes the CS1, the map in the top center (in green) represents the CS2, and the map in the top right (in purple) represents the CS3. In the graph below, the number of kilometers to reach the destination of each production phase for CS1, CS2, and CS3 is represented. The flag represents the country where the production phase indicated in the legend is performed.

the process up to yarn production. This cost overrun can be balanced when high-value final products are produced (e.g., textile garments). The recycling of EoL tuna nets business cannot be understood without the BMI process. The processes of BMI (Andreini et al., 2021) linked to the recycling of EoL tuna nets are: (i) cognition processes of the stakeholder linked to the whole value chain, from fisher to textile and final consumers, developing a strategic sensitivity; (ii) understanding of the new way to produce and consume yarn in the textile industry considering the new technologies and innovations related to nets recycling; (iii) knowledge-shaping processes looking for a more sustainable solution for the EoL tuna nets; and (iv) value creation process with stakeholders' cooperation. The assessment and quantification of CBM shed light on the innovation requirement along the value chain. CE cannot, therefore, be understood without applying the BMI processes (Andreini et al., 2021).

Clothing production is associated with myriad environmental damages (Menke et al., 2021), and more sustainable production is required to minimize environmental impacts. The reduction of clothing consumption can be a part of the solution, but there could be attitudinal obstacles regarding clothing consumption (Kleinhückelkotten and Neitzke, 2019; Roba et al., 2021). Thus, sustainable clothes are the meanwhile solution. Circular supply chains contribute holistically to sustainable development, and they also have immediate effects in the ecological dimension that then spill over into the economic and social dimensions (Montag et al., 2021). Therefore, CE has emerged as a potential strategy for developing business practices based on sustainability concerns, especially in the fashion industry (Binet et al., 2021; Ostermann et al., 2021). Recycling fishing nets can also allow advancing in this direction and address both problems, the fashion industry and the marine litter driving the economy toward a sustainable growth.

The textile and fashion industries have adopted different strategies to make the use of marine plastic profitable. Consequently, the percentage of recycled marine plastic added to the final textile products is diverse. The presence of recycled marine litter products is increasing on the market, but there are some doubts about consumers' understanding of sustainability in the clothing industry. It is not the same as a fabric done with monofilament 100% recycled materials or with a lower percentage of recycled material. This sometimes generates confusing messages among consumers. The chemical recycling of mixed plastic waste has a 50% lower climate change impact and life cycle energy user than the energy recovery option, but chemical recycling has other higher impacts than mechanical recycling (Jeswani et al., 2021). Obtaining PA6 from EoL tuna nets seems to be valid for mechanical recycling, as they can be processed for different potential industrial applications without any remarkable loss of main properties (Mondragon et al., 2020). However, the experiences developed in this study showed chemical recycling of EoL tuna nets is more appropriate for the objective of the specific clothing design.

The production costs of the first stages of the value chain (raw material, regrinds/flakes, and pellet) could not be as competitive as the reference system, unless the regulatory framework will drive this kind of CBMs or demand change. Additionally, in terms of costs, the environmental benefits of recycled pellets could also offset the over-cost in comparison to the virgin material. In this sense, the conceptual framework of CBM has been widely studied (Geissdoerfer et al., 2020), but the quantification and comparison of the costs and benefits at economic, social, and environmental levels have not been still addressed. There is a need to create multidimensional indicators to measure the circularity of a business model in its totality, addressing all the components, including economic, social, and environmental dimensions (Rossi et al., 2020; Boldrini and Antheaume, 2021; Walzberg et al., 2021). The circularity needs to be assessed not only considering the whole life of the fishing nets: from the BoL, i.e. its design and construction, to the EoL, i.e. final products such as fisher trousers. But also the life cycle of the final products need to be assessed to determine the circularity. In line with this, textile recycling is also perceived as one of the key directions needed for a sustainable transition of the sector (Leal Filho et al., 2019), facilitating the manufacturing of recyclable textiles. In this paper, only a window of the CBM has been assessed, from the EoL tuna nets to the final product made by recycled nets. Nonetheless, the ‘real circularity will be assessed only by analysing the successive transformations of the raw material, that is, assessing the primary, secondary, tertiary and so on transformations of the raw materials. Considering the second law of thermodynamics, entropy (Georgescu-Roegen, 1971), every circular transformation or process should be analyzed for its (global) net environmental sustainability contribution (Korhonen et al., 2018a). As the material is neither created nor destroyed, it is only transformed, the circularity may be infinite, which makes difficult the assessment of the global net environmental contribution. The cyclic flow should be assessed in each loop. These loops should be supported only when they are socially desirable and eficient (Suárez-Eiroa et al., 2019), along all consecutive loops, because this is precisely the essence of the CE, the law of thermodynamics (Ghisellini et al., 2016). While perpetual loops may be desirable, there are several limitations (D'Amato and Korhonen, 2021). According to the entropy law, it seems unlikely that a fully circular economic system exists with product and energy turning back to raw material forever (Daly, 1977). Therefore, the CBM should be able to capture the value proposition of all consecutive loops, which could be a complex issue when the reuse of the final product done by recycled pellet has not been assessed, and so on. Existing models are not able to assess quantitatively the whole process of circularity, and this lack could entail biased estimation of the CBM outcomes. In this sense, further research is needed for addressing adequately (Nußholz, 2018).

Another important issue detected in the case studies is the large number of kilometers that the material travels from the collection to the final product is achieved. An alternative logistics chain to accommodate abandoned, lost, or otherwise discarded fishing gear recycling would improve the costs and environmental impacts (van Giezen and Wiegmans, 2020), optimizing the location of the different stages at the meso level of the CE. From a simplified point of view, these business models depend on oil (natural resource) which is found in its different transformation products in the whole cycle, from fuel to transformed product. Furthermore, in a globalized economic system such as the one we have, kilometers are equally important and costly regardless of the business model, so the option to make them more local (micro or meso level) is important to minimize environmental impacts.

Regarding the environmental impacts, measuring the environmental value proposition (Das et al., 2022) is difficult in any CBM, but this study has taken one step forward by analyzing not only the reduction of CO_2 emission but also the benefit of marine litter prevention. However, those are only a part of the ecosystem services that the environment can provide. Here arises one of the limitations of CBM when quantifying the environmental aspect of the value proposition. It is true that progress is currently being made in this direction in developing a Valuation for Natural Capital and Ecosystem Accounting (Badura et al., 2017), and this methodology should be coupled with the CBMs for the correct environmental value proposition evaluation.

The EoL tuna net CBM sustainability trade-off has been quantified using both, economic and environmental indicators. Regarding the social indicators, there is still a need for further research because in this study the social indicators were not addressed, and indeed social aspects were mentioned only in a third of CBM case studies in the literature (Dijkstra et al., 2020). How to quantify the social dimension of the CBM is another issue to be addressed in the future for a complete evaluation of the sustainability of the model. Note that differences between sustainability and CE were identified (Geissdoerfer et al., 2017), as CE prioritizes financial advantages for companies and less resource consumption and pollution for the environment. But monetarizing the environmental impacts, i.e., valuation of ecosystem services and its associated social welfare, may allow these dimensions into the model affecting directly to the financial performance of the business. In any case, CBM currently considers the three dimensions of sustainability, although the way of quantifying the impact on each dimension is still lacking general agreement. Thus, recycling fishing nets and textile garments seem to be a circular solution. But in the case of a textile garment recycling, it can lead to wrong incentives, because if a company or the society is able to recycle the textile products, consumers may be not interested in reducing the amount of waste (Gwehenberger et al., 2003). To mitigate trade-offs between raw material needs and other ecosystem services, solutions envisioned should include sustainable management practices (D'Amato and Korhonen, 2021), that need to be designed along the entire value chain.

There are more barriers identified when applying CBMs: high investment, complexity of the system, low consumer awareness or inherent irrationality of consumer behavior (Planing, 2015), lock-in supply chain agents, technological bottlenecks, reluctance within the organizations, and sustainability trade-offs were also identified as barriers of CBMs (Bishop et al., 2020). In this study, the pilot projects and the involvement of the stakeholders shed light on those barriers. From the third dimension of sustainability (society), consumer awareness seems to be already perceived by the fashion brands that are increasingly using recycled raw materials (Khandual and Pradhan, 2019). The supply chain is guaranteed due to the amount of EoL tuna nets generated by the Spanish tuna freezer fleet that has been quantified for the first time in this study. Regarding the technological bottlenecks, this study proved that the recycling process is possible, although some improvement in cleaning and sorting is needed (Vollmer et al., 2020). Regarding the reluctance within the organization, the regulation in force is driving this issue. BMI seems to be the process to follow for the CE.

In addition, currently, the profitability of the business presented in this study depends directly on the supply and demand of oil and the price that is imposed on it (Moutinho et al., 2017; Ghosh et al., 2021; Guo et al., 2021). There may be times when products derived directly from oil are cheaper, making the recycling processes unprofitable, as an example of what has happened because of the global pandemic of COVID. However, in the event of a variation in the price of oil, changes in the price of intermediate products could be estimated, making the price of the final product derived from oil and recycled products competitively priced. That is why it is important to focus on the environmental impact that both processes generate. Among these impacts, transportation could be assumed to be quite similar in both, deducing that the process dependent on natural resources has a greater impact than the recycling processes.

As a final remark, we can conclude that circular strategies are one option among others for sustainable economic growth (Geissdoerfer et al., 2017). Recycling EoL tuna nets seems to be a suitable strategy, although still need an efficiency improvements along the whole value chain. These improvements would have to be driven by BMI processes. But recycled materials for the fashion industry may lead to wrong incentives. This industry could be advocated for creative destruction (Scafidi, 2020) following the Schumpeterian theory. The way of production and consumption of clothes in first world countries is unsustainable. Thus a novel and most sustainable business model, driven by technological innovation, is required to substitute the current model. The innovation in the bussiness model will be a keystone to achieve sustainable fashion industry succeed commercially (Teece, 2010).

Conclusion

The CE is a suitable framework for the solution of EoL tuna nets. The valorization of EoL fishing nets involves not only a prevention measure for the marine litter but also a solution, at least a temporal solution, for the fashion industry. The empirical CBM was developed and quantified, production costs of each stage of the value chain and material flow, to recycle the EoL tuna nets into textile products. The Spanish tuna freezer companies yearly produce ∼900 tons of tuna nets, and this waste material can transform into a secondary raw material for the textile industry. The production costs of the first stages of the value chain (raw material, regrind/flakes, and pellets) are higher than the reference system (which are those substitutive products in the market), but the cost of yarn may be competitive compared to the substitutive products. Even more so, if we consider that at the time of writing this paper the market price of polyamide is reaching its historical maximum. Logistics issues should be improved to build a more sustainable business model; thus, a local CBM seems to be an improvement in sustainable terms.

However, the CBM tool to evaluate the EoL tuna nets recycling leads to several limitations. First, there is a lack of methodologies to relate or integrate the three levels of the CE when designing the CBM. Although the micro level seems to be the most direct application, the meso and macro levels are implicitly involved in the micro level, and in a CBM, the micro level is difficult to be evaluated without considering the rest of the levels of the CE. Second, measuring the three levels of sustainability is not an easy issue since there are no explicit indicators for all dimensions; although there are advances in quantifying the natural capital, the application of CBM could be very case-specific making it more difficult for the measurement of the environmental dimension. Third, the EoL tuna net recycling for the textile industry can lead to wrong incentives for the fashion industry because society may not be interested in reducing the amount of waste. Thus, the CBM should be considered the consecutive loops of the material and business models to address real sustainability.

The CE paradigm could contribute to sustainable economic growth or at least can slow down the depletion of natural capital. Although this paradigm has the CBM as an enabler, social and environmental dimensions need to be further addressed to be implemented in the consecutive loops of the CBMs. If not, it will be difficult to assert that a CBM contributes to sustainable economic growth in the long term.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statement

Ethics review and approval/written informed consent was not required as per local legislation and institutional requirements.

Author contributions

MA, IZ, OB, and JL conceived of the presented idea. MA developed the theoretical formalism, performed the analytic calculations, and performed the numerical analysis. MA, OB, JL, and IZ wrote the manuscript with the support of AA and NG. MM, EU, NG, and AA provided data and revised the manuscript. All authors provided critical feedback and helped shape the research, analysis, and manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Authors MM and NG was employed by Antex and Edu Uribesalgo by Ternua Group.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2022.929902/full#supplementary-material

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Improving compostable plastic disposal: An application of the Behaviour Change Wheel intervention development method

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Compostable plastics have great potential environmental benefits, however, the damage caused by incorrect waste management offsets them. This study aims to develop a behavior change intervention aimed at improving compostable plastic disposal. We illustrate application of the Behaviour Change Wheel framework to design an intervention in this context. First, the target behavior was understood by specifying it and identifying potential behavioral influences. Second, behavioral influences were systematically linked to potential intervention strategies and refined by evaluating the likely affordability, practicability, effectiveness, acceptability, equity and potential for side-effects (APEASE criteria) in a UK implementation context. Finally, intervention content and implementation options were selected by systematically selecting specific Behavior Change Techniques and refining them by evaluating them against APEASE criteria. The target behavior was identified as UK citizens disposing of compostable plastic waste in the food waste bin meant for collection by local authorities. Influences on compostable plastic disposal were identified as "psychological capability" (i.e., attention and knowledge), "reflective motivation" (i.e., beliefs around environmental impact of compostable plastics) and "physical opportunity" (i.e., access to appropriate waste management). "Education" and "environmental restructuring" were the intervention types selected. "Communications/marketing", "guidelines" and "restructuring the physical and social environment" were the policy options selected. Selected behavior change techniques were: instruction on how to perform the behavior, prompts/cues, adding objects to the environment and restructuring the physical environment. The resulting intervention is a disposal instruction label for compostable packaging, comprising of instructions and a logo. The next step is user testing the developed disposal instruction labels in terms of their effect on promoting the desired disposal behavior. The novelty of this study includes the development of an intervention to reduce compostable plastic waste and the explicit, step-by-step documentation of the intervention development process. The scientific significance is therefore both applied and theoretical. When evaluated, our intervention has the potential to yield insights relating to what improves compostable plastic disposal amongst citizens.

This, in turn, has key policy implications for product and package labeling. By openly documenting our method, we demonstrate a systematic and transparent approach to intervention design, providing an adaptable template and model for others.

KEYWORDS

compostable, biodegradable, plastic packaging, consumer behavior, disposal, recycling, intervention, behavior change

Introduction

In response to the plastic waste crisis, the UK Plastics Pact was launched in April 2018 where members pledged to make all plastic packaging 100% "recyclable, reusable or compostable" by 2025 in order to transition to a circular economy of plastics (WRAP, 2018). This declaration has resulted in a substantial growth of the compostable plastics packaging sector. European Bioplastics estimate the global market for compostable plastics, which was 2.11 million tons in 2018 to increase to ∼2.62 million tons in 2023 (Bioplastics, 2018). Citizen science research shows a strong demand in the UK too: 84% of UK households taking part in a home-composting experiment reported that they are more likely to choose products that are marked as "biodegradable" or "compostable" (Allison et al., 2021a). However, several aspects of compostable plastic production, use and waste management are currently unregulated, lacking or underperforming (i.e., labeling, certification, infrastructure and citizens' behavior) hindering their potential environmental benefits (Aparsi et al., 2020). This current dysfunctional system is highlighted in Figure 1.

Labeling

Compostable packaging labeling is defined by mandatory and non-mandatory labeling requirements as well as manufacture marketing strategies. General Product Safety Regulations 2005 (Government, 2005) sets out the mandatory labeling criteria for products being supplied within or into the UK and Northern Ireland by obligated producers and importers. In Great Britain, enforcement of the 2005 Regulations is carried out by local trading standards authorities and the UK Secretary of State (Standards, 2022). The Regulations set out the minimum labeling requirements for all products and packaging including display of name and address of producer and product reference or batch code (Standards, 2022).

Abbreviations: APEASE, Affordability-Practicability-Effectiveness-Acceptability-Side-effects-Equity Framework; BCT, Behavior change technique; COM-B, Capability-Opportunity-Motivation-Behavior Model.

Labeling plays a key role in providing packaging and products visibility. It also helps communicate information about material identity and disposal instructions. While special rules apply for precious metals, footwear, food and drink, and products for children e.g., prepacked food and drink must display information that includes best before or use-by date, quantitative ingredients list, and nutrition information (Companion, 2021), there are currently no special rules for compostable plastics. This means that manufacturers and suppliers of these materials are at liberty to label/market them as they prefer. The inconsistency in labeling has resulted in widespread citizen confusion surrounding compostable packaging terminology such as "home compostable," "industrially compostable," and "biodegradable," leading to growing public mistrust in compostable packaging claims (WRAP, 2007; Allison et al., 2021a; Companion, 2021).

Certification

Given that citizens struggle to distinguish the biodegradability of a waste material, it is especially important for authorities to provide definitions of biodegradability and biodegradation, and for international testing methodologies to be developed. ISO 14021:2016 standard specifies requirements for self-declared environmental claims, including statements, symbols and graphics, regarding products, not precluding legally required environmental information, claims or labeling (International Organization for Standardization, 2016). The standard does not serve as verification of environmental claims, instead requiring third party verification through an accredited certification scheme (EuropeanBioplastics, 2019). UK guidance about non-mandatory packaging communications for compostable packaging label exists, including advice to avoid statements such as "100% compostable," "compostable," "biodegradable," and "plastic free" (WRAP, 2020a).

Although information about a product's packaging material type and recycled content or disposal instructions is not currently mandatory, UK Government is consulting on the introduction of mandatory labeling of packaging under new Extended Producer Responsibility scheme reforms to

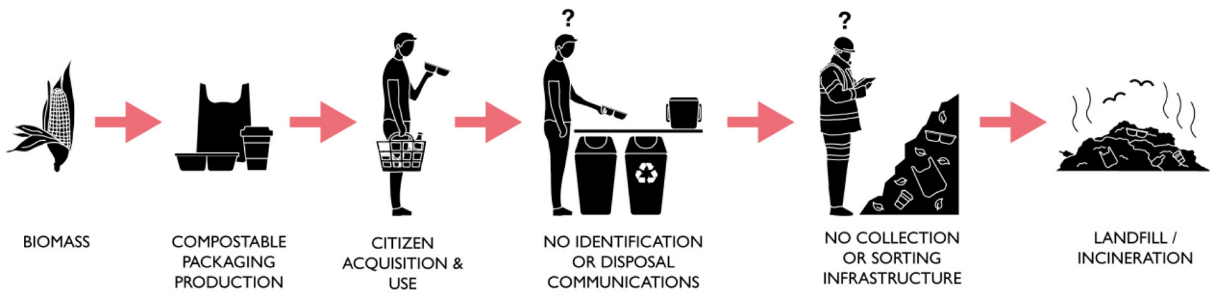

FIGURE 1
A linear economy of compostable plastics.

be introduced from late 2022 (DEFRA, 2020). Current implementation target dates are mandatory labeling for all packaging types (except plastic films and flexibles) by 2026, with plastic film and flexibles included by 2027 (DEFRA, 2020). Other comparable non-mandatory labeling schemes exist such as the On-Pack Recycling Label (OPRL). While there is no comprehensive EU legislation specifically harmonizing standards for environmental and product marketing claims, several logos and standard labels exist that can serve as a basis for evaluating claims for compostable plastics (EuropeanBioplastics, 2019).

In addition, manufacturers can obtain third party certification of industrial and/or home compostable plastic performance from a number of certification bodies that use overarching standard test criteria to demonstrate compliance. In Europe, the most important certification schemes that demonstrate compliance with EN 13432 (suitable for industrial composting conditions), are DIN-CERTCO (Germany), TÜV AUSTRIA (formerly Vinçotte) OK Compost label (Belgium), and COMPOSTABILE – CIC (Italy) (Recycling AfO, 2011). In the UK, the Association for Organics Recycling operates a certification scheme in partnership with Germany's DIN-CERTCO scheme that aligns with the requirements of EN 13432 (Foundation BP, 2019). While these certification schemes for industrially compostable plastics are a step in the right direction, there exists no legislation, at present, to enforce them. In addition, there lacks a reliable, nationally-unform system for collecting, sorting and processing compostable plastic waste in the UK. As a result, certified as compostable or not, compostable plastics represent a growing contaminant in the plastics recycling and some food waste collection systems if the system does not have the capacity to manage them.

Infrastructure

Life cycle assessment shows that the current system, with no dedicated UK-wide collection and processing facilities for compostable plastics, is not environmentally favorable (Yates and Barlow, 2013; Spierling et al., 2018). Compostable plastics could be part of a sustainable UK packaging system with improved systems for collection, sorting and processing. More work is required to ensure reliable sorting of compostable plastics; there is currently no working technical solution to the automatic separation and sorting of compostable plastics, though progress is slowly being made in this space (Taneepanichskul et al., 2022). Nonetheless, the UK Government has consulted on changes to waste collection consistency and aims to introduce mandatory food waste collection for UK households by 2023 (DEFRA, 2020). This is largely driven by policy targets to improve recycling rates, reduce contamination and improve recyclate quality across different waste streams, and to reduce the associated environmental impacts of sending organic waste to landfill (DEFRA, 2020). The proposed scheme provides a promising opportunity to reliably collect and process a growing waste stream of compostable plastics. However, there exists challenges to this. For instance, some local authorities in the UK do not want compostable plastic to go to food waste as they do not send food waste to Industrial Composting. Additionally, development of new waste infrastructure raises critical questions about UK citizens' behavioral adaptation to changes in current residual waste disposal and recycling practices and their preparedness for new and unfamiliar separate organic waste recycling infrastructure.

Citizen engagement

Engaging the public is critical for a sustainable compostable plastic packaging system. Citizens are the ones who purchase, use and initiate the end-of-life pathway of compostable plastic waste, ensuring whether or not composting takes place. Citizens' adoption of the required food waste recycling behaviors will therefore be critical for a circular economy of compostable plastics, as food waste collection is the only viable route for their management en masse. Evidence suggests, however, that more work is needed in this area. Not only are there still many UK citizens who lack access to food waste collection services, many with access still do not engage with these services (Allison et al., 2022). In addition, there is widespread confusion relating to the terms, often used interchangeably, used to label compostable plastics which also leads to confusion regarding their end-of-life management (WRAP, 2007; Allison et al., 2021a). Experiments testing people's disposal of compostable plastics support this by showing that they frequently dispose of them incorrectly e.g., in the recycling bin (Taufik et al., 2020; Ansink et al., 2022). Changes to current patterns of behavior are therefore required to fully realize the benefits of compostable plastics. Guidance for developing and evaluating the kinds of "complex" interventions needed to achieve such behavior change argue for theoretically-grounded and evidence-informed approaches (Craig et al., 2008; French et al., 2012).

Behavior change

There are various behavioral models and theories that can underpin behavior change intervention development. One example is the Behaviour Change Wheel (Michie et al., 2011, 2014) which is itself an integrative framework synthesized from 19 other existing behavior change frameworks. The Behaviour Change Wheel's purpose is to provide a comprehensive and systematic analysis of all the available intervention options using behavior change theory and the available evidence. In stages, the Behaviour Change Wheel advocates a process of systematically mapping underlying influences on a behavior to specific techniques that have been deemed to best target and influence these determinants in order to bring about the desired behavior change. More detail on the Behaviour Change Wheel and its advocated method can be found in Section Materials and equipment. While the Behaviour Change Wheel has been widely applied in health behavior change research, it has had comparably limited application in sustainability research, despite many sustainability problems being behavior change issues. There is therefore great value in illustrating the Behaviour Change Wheel's application in the present context. Of the few studies in this area, the Behaviour Change Wheel has been shown to be a valuable tool for designing interventions targeting recycling (Allison et al., 2022) and reuse (Allison et al., 2021b). It has also been used in behavior change intervention development guides for local (England, 2020) and national (England PH, 2020) government and partners therefore making it an appropriate and useful framework for the design of the present intervention. Designing our intervention using an established theoretical behavior change framework is more likely to increase its effectiveness.

Aims

The primary aim of this paper is to design an implementable behavior change intervention that promotes the desired disposal of compostable packaging. A secondary aim is to document the systematic intervention development process using the Behaviour Change Wheel method.

Materials and equipment

To improve intervention documentation, we used the GUIDED framework which provides guidance for reporting intervention development studies in health research (Duncan et al., 2020). To guide the intervention development process, we use the Behaviour Change Wheel as a theoretical intervention development framework (Michie et al., 2011, 2014). To ensure that our intervention was informed by evidence, we use peer-reviewed empirical findings, industry data and stakeholder feedback as source material.

GUIDED framework

GUIDED is a 14-item checklist which contains a description and explanation of each item alongside examples of good reporting. Its objective is to improve the quality and consistency of intervention development reporting in health research. Nonetheless, we believe the checklist items are valuable to the present circular economy context as they offer transferrable principles for good intervention documentation practice. For instance, we used the checklist to ensure that we reported:

1. The context for which the intervention was developed,
2. The purpose of the intervention,
3. The target population,
4. How published intervention development approaches contributed to the development process,
5. How evidence from different sources informed the intervention development process,
6. How published theory informed the intervention development process,
7. How guiding principles, people or factors were prioritized when making decisions during the intervention development process,
8. How stakeholders contributed to the intervention development process,
9. How the intervention changed in content and format from the start of the intervention development process,
10. Uncertainties at the end of the intervention development process (e.g., requirement for piloting),
11. According to TIDieR guidance (Hoffmann et al., 2014) when describing the developed intervention and,

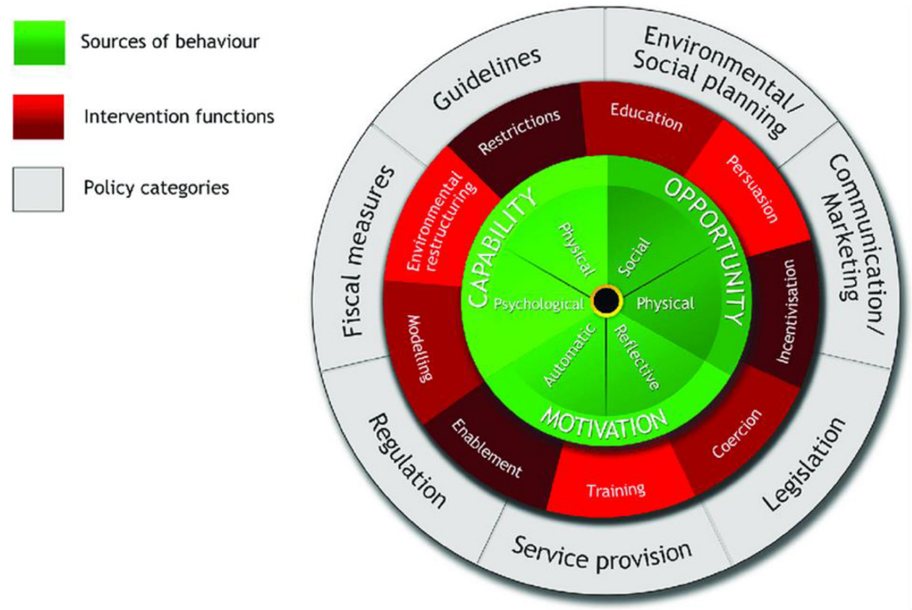

FIGURE 2
The Behaviour Change Wheel (Michie et al., 2011, 2014).

12. *Via* an open access format at the publication stage.

The items we did not report on were "use of components from an existing intervention in the current intervention development process" and "any changes to interventions required or likely to be required for subgroups" as these were not deemed applicable to the present intervention.

Behaviour Change Wheel intervention development framework

Shown in Figure 2, The Behaviour Change Wheel is a framework for designing interventions that change behavior. The wheel itself consists of three parts: (1) An inner hub which represents influences on behavior in terms of people's capability, opportunity and/or motivation; (2) A middle layer of "intervention types" which are broad ways to target underlying influences to bring about behavior change, and; (3) An outer layer which are policy options for supporting delivery of the intervention types. The components of the wheel echo the method advocated by the Behaviour Change Wheel. It involves a process of systematically mapping underlying influences on behavior to broad types of interventions and potential policy options. Not depicted in the wheel itself is an additional step after intervention types and policy options have been selected. This step involves systematically mapping intervention types to specific Behavior Change Techniques (BCTs) from the Behavior Change Technique Taxonomy (Michie et al., 2013) – a taxonomy of 93 hierarchically clustered techniques identified as being able to change behavior (e.g., action planning, goal setting etc.).

The definitions of each intervention type, policy option and BCT can be found in Appendix A. The Behaviour Change Wheel approach also advocates the use of APEASE criteria (Affordability, Practicality, Effectiveness, Acceptability, Side effects, Equity) throughout which is an evaluative framework to enhance the relevance, utility and practicability of a proposed intervention. APEASE criteria ask intervention designers to consider the following throughout their decision-making process:

- (Affordability) How costly is the proposed intervention going to be?
- (Practicability) Can the intervention feasibly be delivered as designed in the intended setting?
- (Effectiveness) How effective is the intervention at changing the target behavior?
- (Acceptability) Is the intervention deemed appropriate by key stakeholders and those receiving the intervention?
- (Side effects) Are there any potential unwanted side effects from delivering this intervention that need to be considered?

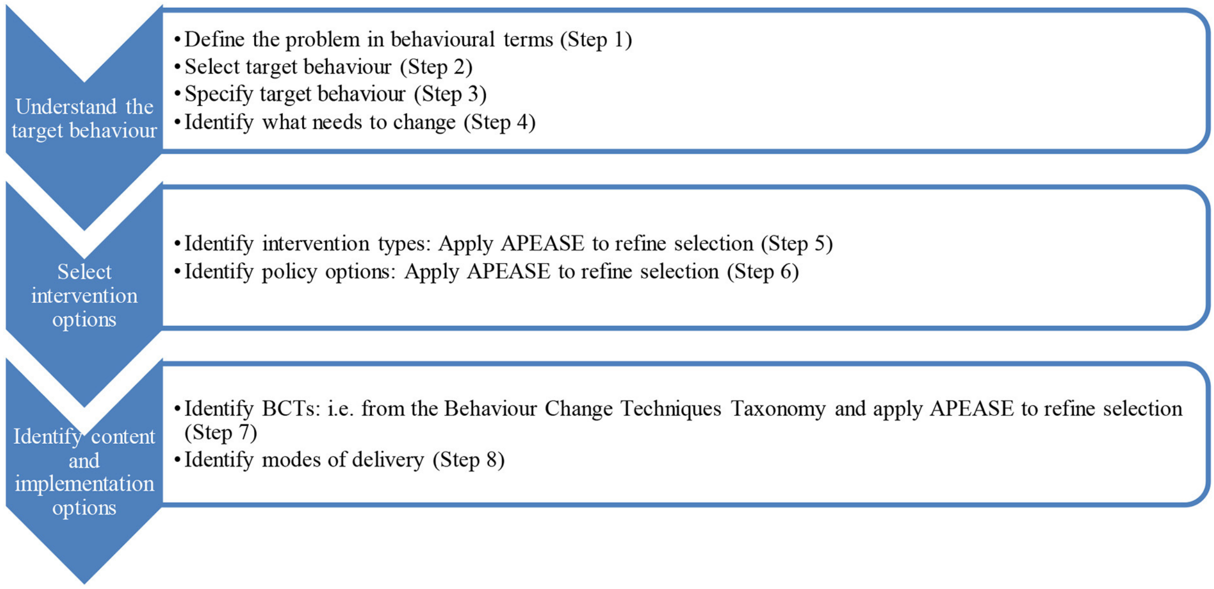

FIGURE 3
The Behaviour Change Wheel's systematic and theory driven intervention development approach.

- (Equity) Does the intervention instigate disparities between different sectors of society?

In terms of methodology, the Behaviour Change Wheel advocates three broad phases: first, to understand the target behavior; second, to identify intervention options and; finally, identify content and implementation options. These broad stages, which in turn can be broken in a series of further steps, are outlined in Figure 3. The Method and Results section are structured according to these three broad stages.

According to the Behaviour Change Wheel approach, an additional behavior change model may be used to help guide the process of understanding the target behavior. Shown in Figure 4, this is the COM-B model (Capability-Opportunity-Motivation-Behavior) (Michie et al., 2011, 2014). The COM-B model can help to identify underlying determinants of behavior i.e., identifying what needs to change (Step 4 in Figure 3). COM-B posits that for a behavior to occur there must be the capability, opportunity and motivation to perform the behavior. Capability can be psychological (e.g., knowledge) or physical (e.g., skills); opportunity can be social (e.g., social norms) or physical (e.g., environmental resources); motivation can be automatic (e.g., habits) or reflective (e.g., beliefs, intentions). These influences can be barriers, hindering a target behavior, or enablers that promote or maintain a target behavior. Identifying these barriers and enablers to a target behavior can help identify what the intervention needs to target to achieve the desired behavior change.

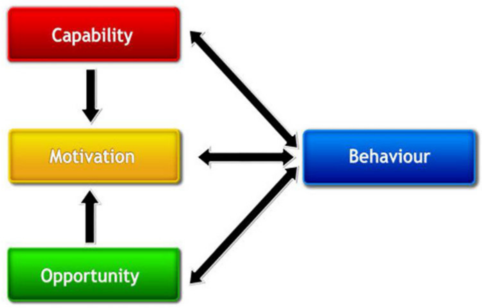

FIGURE 4
Capability-Opportunity-Motivation-Behavior (COM-B) Model (Michie et al., 2011, 2014).

Evidence

A multi-method, iterative approach was used to integrate seven sources of evidence and systematically progress through the phases outlined in Figure 3. The evidence integrated included:

- A qualitative study of barriers and enablers to buying compostable plastic packaging (Allison et al., 2021a).
- A mixed-methods study on barriers and enablers to household food waste recycling (Allison et al., 2022).

- Two experiments testing citizens' disposal of compostable plastics (Taufik et al., 2020; Ansink et al., 2022).
- A survey investigating citizen's bioplastic knowledge, perceptions and end-of-life management (Dilkes-Hoffman et al., 2019).
- A report summarizing research insights on citizen's behavior toward packaging labeling design by OPRL (OPRL, 2020).
- A review of research studies into On-pack Labeling and Citizen Recycling Behavior (WRAP, 2020b).

Stakeholder involvement was assured *via* two consultation meetings conducted on 05/05/2021 and 22/02/2022 to support the design process and ensure the practicability, relevance, utility and acceptability of the intervention. A wide range of UK stakeholders were consulted including representatives from academia, industry, not-for-profit and government. To protect anonymity, their details have been omitted. Figure 5 provides a summary of the materials and resources used as evidence.

The subsequent section details what we did in each broad stage of the Behaviour Change Wheel approach (as outlined in Figure 3) in order to select intervention types, policy options and BCTs.

Method

Understand the target behavior

Detailed in Figure 3, four steps were taken to understand our target behavior. This was approached by reviewing literature to conceptualize the problem of plastic waste in behavioral terms (Step 1). This step was followed by selecting and specifying the target behavior and broad type of plastic waste item of focus (Step 2 and 3). A synthesis of existing relevant evidence supported understanding the influences upon the target behavior (Step 4). Mapping the identified behavioral influences onto COM-B enabled a better understanding of what needed to change.

Select intervention options

The Behaviour Change Wheel guide offers guidance on the types of intervention types and policy options that are most likely to be effective at targeting physical capability, psychological capability, social opportunity, physical opportunity, automatic motivation and reflective motivation. This stage of intervention development therefore involved selecting intervention types (Step 5) and policy options (Step 6) from the Behaviour Change Wheel guidance that were most likely to be effective for changing the behavioral targets identified in our COM-B analysis in the previous step. These steps also involved a critical evaluation of possible intervention types and policy options against APEASE criteria.

Identify content and implementation options

The content (Step 7) and implementation (Step 8) options were considered and developed iteratively, in the phased approach shown in Figure 6.

Content was chosen using the Behavior Change Techniques Taxonomy to select BCTs. The Behaviour Change Wheel guide offers guidance on the BCTs most commonly used per intervention type and so this was used to support consideration. APEASE criteria were applied throughout this selection process too. BCTs found not to meet APEASE criteria were not carried forward to the next stage of intervention design. Practicality and acceptability were deemed to be of particular importance in this evaluative process by the research team given the context for implementation.

To set the scene, at the time of this study in 2022, UK Government is consulting on new mandatory labeling for packaging in the UK as part of Extended Producer Responsibility scheme reforms. The key aim of mandatory labeling is to give citizens clear information about what they can and cannot recycle using simple binary messaging i.e., "recycle" or "do not recycle" (DEFRA, 2020). The strategy for a binary label messaging system is adopted from recommendations in OPRL's Evidence Base report (OPRL) and is widely supported by industry members (Ecosurity, 2020).

Compostable packaging, with the exception of compostable packaging used in "closed loop" scenarios (i.e., where products are sold, used and disposed of within a single venue e.g., festivals), is not currently deemed recyclable and so will likely incur higher Extended Producer Responsibility fee rates, payable by obligated producers, and mandatory "do not recycle" labeling from 2023. Nonetheless, the UK Government recognizes that it may support an alternative approach to compostable packaging in the future should greater certainty over a lack of any negative effects and evidence of the benefits in end applications be demonstrated (DEFRA, 2020). Packaging types under Extended Producer Responsibility include single and multi-material primary packaging, and shipment packing. Where packaging consists of multiple components clear advice on whether each component is recyclable or not is required (DEFRA, 2020).

UK Government is currently considering two options for Extended Producer Responsibility mandatory labeling. Option 1 is the use of approved labels where Government would set in regulations the criteria that labels must meet such as format, size and appearance. In this scenario obligated producers could establish their own label or subscribe to and use labels from an existing labeling scheme (for example OPRL). A variation of this approach could be to set the requirements for "do

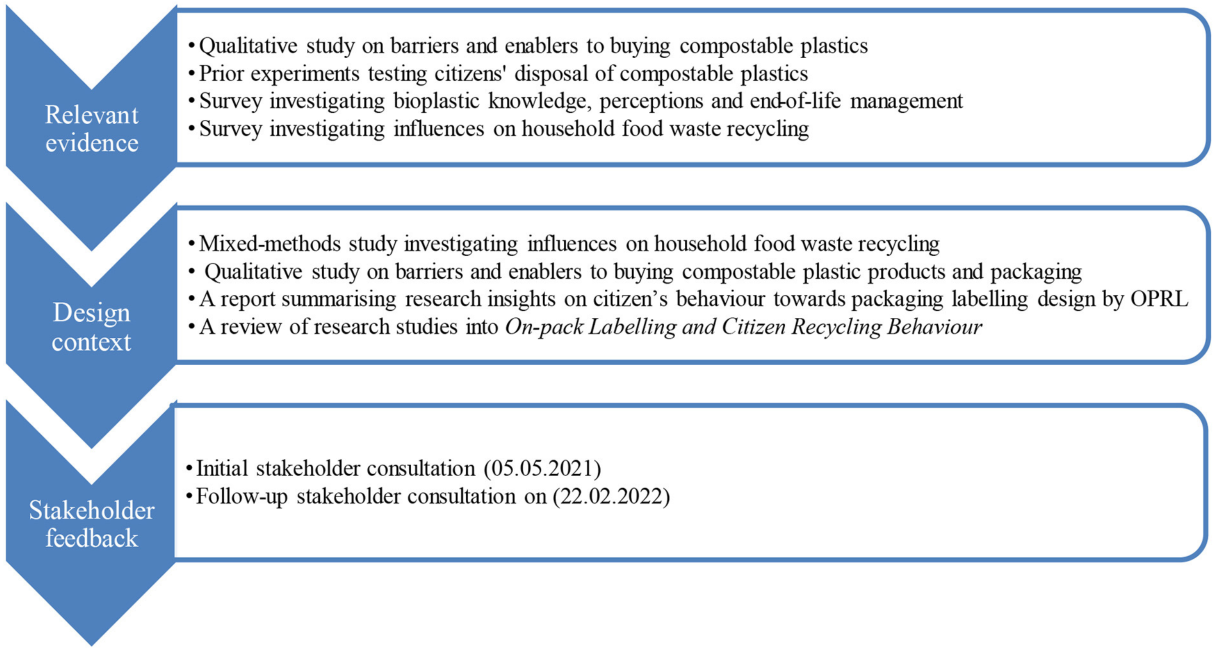

FIGURE 5
Overview of materials and resources used as evidence.

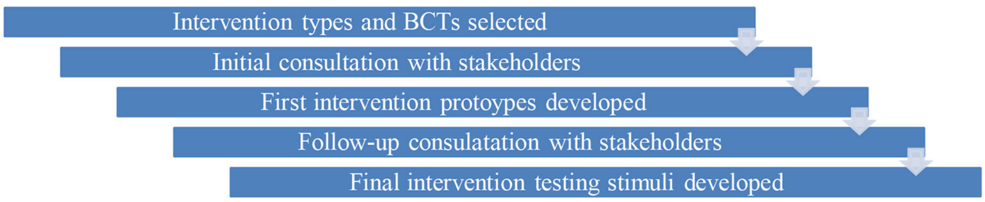

FIGURE 6
Steps taken to develop content and implementation options.

not recycle"' in Extended Producer Responsibility regulations thereby restricting how producers label packaging that is not recyclable (DEFRA, 2020). Option 2 is a government appointed single labeling scheme whereby producers would need to adhere to a single labeling scheme and use the same labels. In this scenario all obligated producers would be required to register with a single labeling scheme; the scheme operator would establish the process of registration, labeling design and auditing (DEFRA, 2020).

The implementation options for delivery of the BCTs (i.e., prototype interventions) were first developed by two members of the research team, a behavioral scientist (ALA) and architect designer (DP), with input from other members of the research team. They were then iteratively revised based on stakeholder feedback.

Results

Understand the target behavior

Define the problem in behavioral terms

In light of the UK Plastics Pact (WRAP, 2018) and the "waste hierarchy" set out in Article 4 of the European Union's revised Waste Framework (Directive 2008/98/EC) (Directive, 2008), which ranks waste management options according to what is best for the environment (Figure 7), the problem of plastic waste was conceptualized behaviorally as poor waste management i.e., a lack of reducing, reusing, recycling and composting plastic to ensure that waste is kept to a minimum and materials are kept within a circular system.

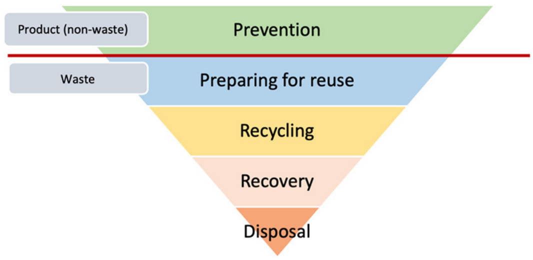

FIGURE 7
The waste hierarchy as set out in article 4 of the revised waste framework (Directive 2008/98/EC) (Directive, 2008) (Image taken from Allison et al., 2021b).

Select the target behavior

To reduce plastic waste, various behaviors relating to reducing, recycling, reusing and composting could have been selected. As highlighted in Section Introduction, disposal of compostable plastics was prioritized because compostable plastics are proliferating on the market, yet there is no system for collection, sorting or processing of compostable plastic in the UK. They are also currently unregulated and there is widespread confusion about what they are and how to dispose of them. Therefore, they are increasingly contaminating other plastics recycling and some food waste collection systems, which are not able to process compostable plastics. Improving the current system for compostable plastics is therefore likely to be an effective way of reducing plastic waste.

Figure 8 highlights what a circular economy of compostable plastics in the UK could look like. Disposal behavior (i.e., which bin the citizens put the plastics into) is key part of getting the compostable plastic "system" to work; if citizens get it wrong then the system does not work. As highlighted in Section Introduction, there is widespread citizen confusion about what compostable plastics are and how to dispose of them which leads to incorrect disposal; therefore, behavior change in this area is likely to achieve the desired outcome of reducing plastic waste.

Specify the target behavior

The selected behavior of compostable plastic disposal was further specified as: UK citizens (who), discarding compostable plastic packaging (what), in the food waste bin meant for collection by local authorities (how), at the point of disposal at an items end-of-life (when) within the home (where). While home/community-composting was another possible option, this was deemed unlikely to be feasible for the majority of urban-dwelling UK citizens who live in densely populated housing often without access to a garden (DEFRA, 2021). In addition, evidence suggests that most plastics labeled as compostable do not biodegrade in home-composts (Aparsi et al., 2020).

Identify what needs to change

As shown in Figure 5, five sources of evidence provided information on behavioral influences. One is a behavioral experiment testing disposal of compostable plastic water bottles in Germany (Taufik et al., 2020). The second is a similar study testing disposal of compostable plastic packaging in the Netherlands (Ansink et al., 2022). The third is a survey investigating perceptions, knowledge and end-of-life management of bioplastics in Australia (Dilkes-Hoffman et al., 2019). As these studies were not conducted within the present context, these findings were supplemented with a qualitative study of barriers and enablers to purchasing biodegradable and compostable plastic packaging amongst UK citizens (Allison et al., 2021a) and a survey of influences on household food waste recycling amongst UK citizens (Allison et al., 2022). Shown in Table 1, determinants of disposal behavior identified in these studies were mapped to COM-B, as this was selected as the theoretical framework to underpin intervention development.

In summary, the issue was found to be predominantly rooted in psychological capability, reflective motivation and physical opportunity. People lack knowledge of and familiarity with compostable plastics which leads to confusion in terms of what to do with these items at end-of-life. This was also related to issues of attention i.e., not being able to identify compostable packaging over non-compostable plastic packaging and not noticing the wording and logos on packaging that were put there to communicate the appropriate end-of-life instructions. Lack of knowledge and familiarity is also likely related to holding of erroneous beliefs around nature and processing of compostable plastic waste (i.e., that they can actually biodegrade and that they cannot be processed *via* mechanical recycling). In addition, without access to appropriate waste management infrastructure i.e., bins and waste collection services, people cannot dispose of these correctly.

Select intervention options

A mapping process, recommended by Behaviour Change Wheel guidance was followed. We considered and selected from a range of potential intervention types (Table 2) and policy options (Table 3), based on the types on intervention strategies considered likely to be effective at addressing the psychological capability, physical opportunity and reflective motivation related barriers identified in Section Understand the target behavior. The use of APEASE criteria, along with consideration of intervention context, assisted in narrowing down potentially appropriate intervention types and policy options. The intervention types selected were education and environmental restructuring. The policy options

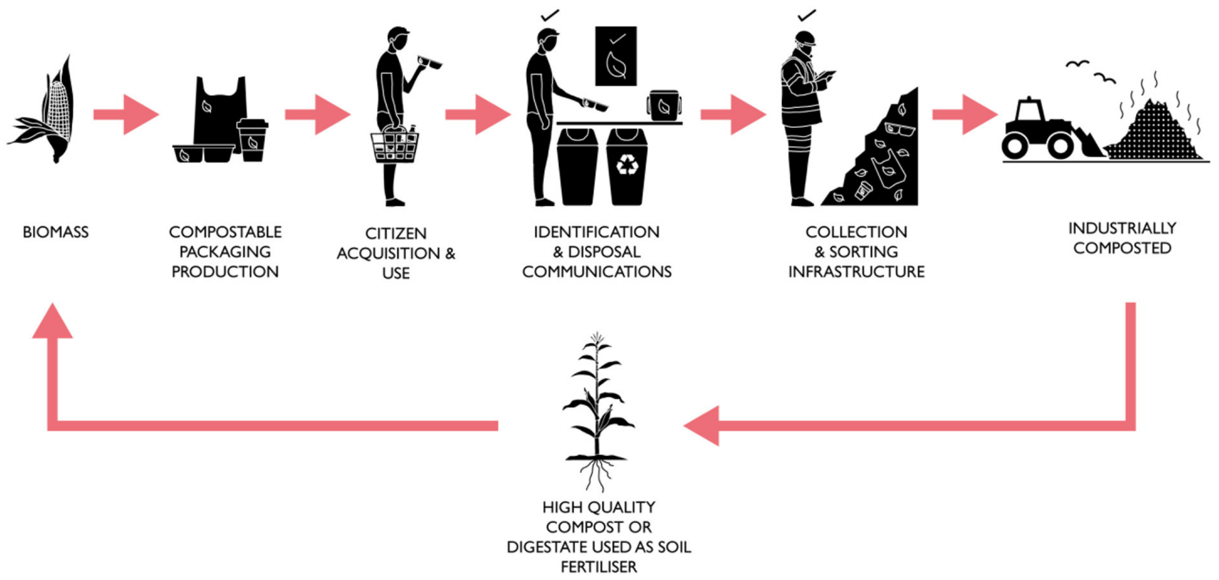

FIGURE 8
A circular economy of compostable plastics.

selected were guidelines, communications/marketing and environmental/social planning.

Four intervention types were considered inappropriate and so excluded: enablement, persuasion, modeling and training. Persuasion and modeling were not deemed likely to be very effective as the target behavior is not one where people lack motivation or inspiration to enact the desired behavior. In fact, people overwhelmingly have pro-environmental intentions and wish to "do the right thing" when it comes to compostable plastic packaging (Dilkes-Hoffman et al., 2019; Taufik et al., 2020; Allison et al., 2021a; Ansink et al., 2022). The issue rests primarily in attention and misinformation, therefore inducing positive or negative feelings or providing something for people to aspire to in order to stimulate action is unlikely to make much of a difference. Training was excluded on ground of practicality and affordability. A training programme would likely be costly to run and not practical in terms of where, when, how and by whom it could be implemented. Enablement was excluded on the grounds that, based on the behavioral diagnosis, any intervention strategy is unlikely to go beyond education and environmental restructuring.

Four policy categories were excluded: service provision, legislation, regulation and fiscal measures. Service provision was excluded as implementation of nation-wide food waste collection services are already planned by UK government; therefore, addressing the physical opportunity related barriers of access to waste management services. Fiscal measures would likely require legislation changes, something that would rely upon elected politicians' willingness to propose such changes. There would also be questions of affordability dependent on the economic climate at the time of the intervention, and thus the use of this policy category could become less acceptable. Legislation was not practical to focus on within this project as the process involved would be out of scope for a research study.

Select content and implementation options

Content

A mapping process, recommended by Behaviour Change Wheel guidance was followed. We considered and selected from a range of potential BCTs, based on the intervention types selected. Selection of potential BCTs was informed by the types of BCTs recommended in the Behaviour Change Wheel guide as most commonly used to deliver each intervention type. The use of APEASE criteria, along with consideration of intervention context, assisted in narrowing down potentially appropriate BCTs (Table 5). Table 4 presents all nine potential BCTs. Table 5 presents BCTs, separated into those that will be included or excluded from the next stage of this intervention development. Reasons for inclusion or exclusion of each BCT are assessed against APEASE criteria (Table 5). Selected BCTs at this stage included: instruction on how to perform the behavior, information about social and environmental consequences, prompts/cues, self-monitoring of behavior, adding objects to the environment and restructuring the physical environment.

TABLE 1 Table showing factors associated with compostable plastic waste disposal.

	Taufik et al., 2020	Ansink et al., 2022	Dilkes-Hoffman et al., 2019	Allison et al., 2021a	Allison et al., 2022
Phys Cap	n/a	n/a	n/a	n/a	n/a
Psych Cap	Compostable plastic familiarity Understanding terminology and labels used to communicate disposal instructions Not being able to distinguish between compostable and non-compostable plastic packaging	Compostable plastic familiarity Understanding terminology and labels used to communicate disposal instructions Attention to waste management labels and logos on packaging	Compostable plastic familiarity Understanding terminology and labels used to communicate disposal instructions	Compostable plastic familiarity Understanding terminology and labels used to communicate disposal instructions Attention to waste management labels and logos on packaging	Compostable plastic familiarity
Soc Opp	n/a	n/a	n/a	Tension with neighbors if compostable plastic is put in communal organic/food waste bins	Waste collectors think organic/food waste has been contaminated with plastic bag and so do not take the waste
Phys Opp	n/a	n/a	n/a	Access to local organic/food waste collection services	Access to local organic/food waste collection services
Aut Mot	n/a	Environmental concern	n/a	n/a	n/a
Ref Mot	Belief that plastic should always be recycled and not composted Belief that plastic can be compostable in the first instance	Personal moral norms	Perception that it is okay to litter compostable plastics	n/a	n/a

Implementation options

The outputs of Section Select intervention options and Section Content (illustrated in Tables 2–5) were taken to an initial stakeholder feedback session to narrow down the selection of BCTs. The outcomes of this meeting were the following:

- Consensus that a label designed to communicate end-of-life disposal instructions for compostable plastic packaging was the most suitable implementation option for this intervention.
- Consensus that the prototype labels tested on packaging formats as outlined in WRAP's Considerations for Compostable Packaging report, as they represent likely applications for compostable packaging in the future (WRAP, 2020a).
- Additional packaging formats requested to be tested were sauce sachets and takeaway food and drinks containers.
- There is a need to test how the wording "compost with food waste" and "recycle with food waste" are understood by citizens.
- Importance of testing different combinations of logos (WRAP "Recycle Now" logo), disposal instructions and packaging formats to see if this impacts citizen understanding of label messaging.
- The importance of testing potential alternative compostable logos to understand if this impacts citizen understanding and subsequent disposal behavior of compostable waste materials.
- Importance of testing labels alongside representative examples of packaging formats to understand if the presence of other mandatory and non-mandatory labeling impacts citizen understanding and behavior.
- Consensus regarding the utility of an online task-based experiment to test the impact of different labels on disposal behavior.
- Owing to industry support and UK Government's proposed Extended Producer Responsibility binary labeling system the OPRL label system was chosen to form the basis for prototype intervention labeling formats.

TABLE 2 Intervention types appropriate for targeting underlying behavioral influences.

COM-B	Intervention type	Definition	APEASE	Included/ exclude from next stage
Psychological Capability (i.e., attention and knowledge)	Education	Increasing knowledge or understanding	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable**, should have limited **side effects** and shouldn't create significant issues of **equity**	Included
	Training	Imparting skills	Considered potentially **effective**, potentially **acceptable**, should have limited **side effects** and shouldn't create significant issues of **equity** but not considered **affordable** or **practical**	Excluded
	Enablement	Increasing means/reducing barriers to increase capability (beyond education/ training) or opportunity (beyond environmental restructuring)	Not applicable because a strategy going beyond both education and environmental restructuring unlikely	Excluded
	Environmental restructuring	Changing the physical or social context	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable**, should have limited **side effects** and shouldn't create significant issues of **equity**	Included
Physical Opportunity (i.e., access to appropriate waste collection services)	Environmental restructuring	Changing the physical or social context	Access to the appropriate waste collection services is going to become available with the introduction of nation-wide food waste collection in 2023	Excluded
	Enablement	Increasing means/reducing barriers to increase capability (beyond education/ training) or opportunity (beyond environmental restructuring)	Not applicable because a strategy going beyond both education and environmental restructuring unlikely	Excluded
Reflective motivation (i.e., beliefs)	Education	Increasing knowledge or understanding	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable**, should have limited **side effects** and shouldn't create significant issues of **equity**	Included
	Persuasion	Using communication to induce positive or negative feelings to stimulate action	Considered **practical**, potentially **acceptable**, should have limited **side effects,** shouldn't create significant issues of **equity** but not considered **affordable** or likely to be very **effective**	Excluded
	Modeling	Providing an example for people to aspire to or imitate	Considered potentially **acceptable**, should have limited **side effects,** shouldn't create significant issues of **equity** but not considered **practical**, **affordable** or likely to be very **effective**	Excluded

Once a label had been agreed on as the implementation option, our selection of BCTs were further refined (see Table 6). This was based on evidence showing how labeling design impacts citizen disposal behavior in relation to recyclable materials and recycling systems (OPRL, 2020; WRAP, 2020b). Although these studies do not relate specifically to compostable packaging labeling, they highlight several general packaging labeling design parameters that should be considered and controlled for in the design of intervention prototype labels. Practical considerations include size, color and format of label, and position on-pack (OPRL, 2020; WRAP, 2020b). Additionally non-statutory packaging graphics and branding plays an important role for product manufacturers in advertising, marketing and brand identity. These considerations practically limit the size and location of the intervention labeling designs.

Other considerations were the limitation of space to display an intervention prototype label due to mandatory product labeling requirements under Regulations 2005 (Government, 2005). For example, pre-packed food packaging labeling must include product name and name and address of manufacturer, ingredients list (by weight from largest to smallest) and

TABLE 3 Policy options appropriate for leveraging proposed intervention options.

Intervention type	Policy option	Definition	APEASE	Included/ exclude from next stage
Education	Communications/ marketing	Using print, electronic, telephonic or broadcast media	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable**, should have limited **side effects** and shouldn't create significant issues of **equity**	Include
	Guidelines	Creating documents that recommend or mandate practice. This includes all changes to service provision	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable**, should have limited **side effects** and shouldn't create significant issues of **equity**	Include
	Regulation	Establishing rules or principles of behavior or practice	Not considered **practical** for this project as the timeline would not allow for the process of changes to current labeling regulations	Exclude
	Legislation	Making or changing laws	Not considered **practical** for this project as the timeline would not allow for the process of changes to law	Exclude
	Service Provision	Delivering a service	Implementation of nation-wide food waste collection services are already planned by UK government	Exclude
Enablement	Guidelines	Creating documents that recommend or mandate practice. This includes all changes to service provision	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable**, should have limited **side effects** and shouldn't create significant issues of **equity**	Include
	Fiscal measures	Using the tax system to reduce or increase the financial cost	Not considered **equitable** (further marginalize lower income segments of society), unlikely to be **acceptable** to citizens who will have to pay or policy makers who would probably need to instigate legislation changes, considered not **affordable** contingent on the economic climate at the time of the change	Exclude
	Regulation	Establishing rules or principles of behavior or practice	Not considered **practical** for this project as the timeline would not allow for the process of changes to current labeling regulations	Exclude
	Legislation	Making or changing laws	Not considered **practical** for this project as the timeline would not allow for the process of changes to law	Exclude
	Environmental/ social planning	Designing and/or controlling the physical or social environment	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable**, should have limited **side effects** and shouldn't create significant issues of **equity**	Include
	Service provision	Delivering a service	Implementation of nation-wide food waste collection services are already planned by UK government	Exclude
Environmental restructuring	Guidelines	Creating documents that recommend or mandate practice. This includes all changes to service provision	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable**, should have limited **side effects** and shouldn't create significant issues of **equity**	Include
	Fiscal measures	Using the tax system to reduce or increase the financial cost	Not considered **equitable** (further marginalize lower income segments of society), unlikely to be **acceptable** to citizens who will have to pay or policy makers who would probably need to instigate legislation changes, considered not **affordable** contingent on the economic climate at the time of the change	Exclude

(Continued)

TABLE 3 Continued

Intervention type	Policy option	Definition	APEASE	Included/ exclude from next stage
	Regulation	Establishing rules or principles of behavior or practice	Not considered **practical** for this project as the timeline would not allow for the process of changes to current labeling regulations	Exclude
	Legislation	Making or changing laws	Not considered **practical** for this project as the timeline would not allow for the process of changes to law	Exclude
	Environmental/ social planning	Designing and/or controlling the physical or social environment	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable**, should have limited **side effects** and shouldn't create significant issues of **equity**	Include

TABLE 4 Identification of the possible BCTs that could be used in the intervention.

COM-B	Intervention type selected	BCTs identified
Psychological Capability (i.e., attention and knowledge)	Education Environmental restructuring	• Instruction on how to perform the behavior • Information about social and environmental consequences • Information about health consequences • Feedback on behavior • Feedback on outcome of the behavior • Prompts/cues • Self-monitoring of behavior • Adding objects to the environment • Restructuring the physical environment
Reflective motivation (i.e., beliefs)	Education	• Instruction on how to perform the behavior • Information about social and environmental consequences • Information about health consequences • Feedback on behavior • Feedback on outcome of the behavior • Prompts/cues • Self-monitoring of behavior

emphasize any of the required 14 allergens, use by date, nutritional information, and storage or cooking instructions. For non-food packaging labeling other product labeling regulations apply (Companion, 2021). Therefore, "Information about social and environmental consequences" and "Self-monitoring of behavior" were excluded based on the practicality of implementing these *via* a label which would have to be very simple, with minimal wording/design. The BCTS selected were: "Instruction on how to perform the behavior," "prompts/cues," "adding objects to the environment" and "restructuring the physical environment."

Figure 9 depicts examples of disposal instruction labels and logos which could be superimposed onto a variety of different types of packaging formats and evaluated to see whether they: (a) effectively communicate the food waste bin as the disposal end-point and (b) are effective at getting people to actually *dispose* these waste materials in their food waste bins. The first row consists of variations of disposal instructions and ORPL's "Recycle Now" logo. The second row consists of potential alternative logo imagery for uniquely communicating compostability of material at end-of-life.

Discussion

This study aimed to report the multi-method process involved in designing an intervention to promote disposal of compostable plastics. A secondary aim was to do this using a theoretical behavior change framework – the Behaviour Change Wheel. Our proposed intervention involved a rigorous and structured design process built on a foundation of primary research and evidence synthesis by a team of multi-disciplinary

TABLE 5 List of included/excluded BCTs with reasons for inclusion/exclusion.

BCTs	APEASE	Included/excluded
Instruction on how to perform the behavior	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable** (for citizens, policy makers and companies), should have limited **side effects** and shouldn't create significant issues of **equity**	Included
Information about social and environmental consequences	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable** (for citizens, policy makers and companies), should have limited **side effects** and shouldn't create significant issues of **equity**	Included
Information about health consequences	Not considered applicable for the present context	Excluded
Feedback on behavior	Not considered **practical** for this context as disposal behavior is happening in the privacy of homes	Excluded
Feedback on outcome of the behavior	Not considered **practical** for this context as disposal behavior is happening in the privacy of homes	Excluded
Prompts/cues	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable** (for citizens, policy makers and companies), should have limited **side effects**	Included
Self-monitoring of behavior	Considered **affordable**, **practical,** potentially **effective**, potentially **acceptable** (for citizens, policy makers and companies), should have limited **side effects** and shouldn't create significant issues of **equity**	Included
Adding objects to the environment	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable** (for citizens, policy makers and companies), should have limited **side effects** and shouldn't create significant issues of **equity**	Included
Restructuring the physical environment	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable** (for citizens, policy makers and companies), should have limited **side effects** and shouldn't create significant issues of **equity**	Included

TABLE 6 Narrowing down selection of BCTs.

BCT	Included/excluded	Rationale
Instruction on how to perform the behavior	Included	Prioritized as lack of disposal instructions identified as key barrier to correct disposal
Information about social and environmental consequences	Excluded	Limitation of space to provide information on a label
Prompts/cues	Included	A new label on packaging delivers this
Self-monitoring of behavior	Excluded	Not practical to deliver *via* a label on packaging
Adding objects to the environment	Included	A new label on packaging delivers this
Restructuring the physical environment	Included	A new label on packaging delivers this

researchers with expertise in behavioral science, implementation science, health psychology, design, architecture and material science. This was supported by input at each stage from industry and policy experts.

The resulting intervention is a disposal instruction label for compostable plastics, comprising of instructions and a logo. In this paper, we report on influencing disposal to local food waste collections in the UK. However, the method is general and could easily be applied to a local authority, region or country that wants to use labeling to influence behavior to direct compostable plastics to a different destination other than food waste collection. Our step-by-step documentation of the intervention development process, including our systematic mapping exercises, has demonstrated a transferrable methodology and created a series of useful research outputs (i.e., tables) which can be used as guiding templates by others.

Our work has important practical applications. Unless citizens are able to dispose of compostable plastic waste materials in the correct bin, these materials will continue to contaminate other waste streams or sent to landfill and incineration. We have designed an intervention that, when evaluated, has the potential to provide important answers relating to how best to get citizens to dispose of compostable plastic waste appropriately. This, in turn, has key policy implications for product and package labeling. In addition, applying behavioral science can aid in the designing of theory and evidence-based strategies that are more likely to be effective at achieving sustainable behavior change. The UK Medical Research Council framework for designing and evaluating "complex" interventions has advocated systematic intervention development, using evidence base and theory (Craig et al., 2008). Seemingly simple behaviors, such as disposing of compostable plastic waste, are located within complex systems of several interacting groups of actors (e.g., customers, manufacturers, suppliers, policy makers), operating across different groups (e.g., individual, community, population) and at various organizational levels (e.g., local, governmental). Therefore, a key strength of this work is the intentional and systematic application of a theoretical behavior change framework to guide the intervention development process as opposed to relying on a cursory analysis or "common sense" – a common error in preventing the successful implementation of behavior change (Kelly and Barker, 2016).

Our work also has important theoretical implications. There are few published examples of the Behaviour Change Wheel applied to developing interventions sustaining environmental health e.g., (Gainforth et al., 2016; Allison et al., 2021b). Our study is therefore useful and novel in terms of its application within a circular economy context. We outline a clear process that can serve as a template for understanding and changing a wide variety of environmentally significant behaviors. The open documentation of our methods is also important for advancing behavior change science. When intervention development studies are published, they are usually included as part of a feasibility or pilot study. Publishing them as standalone studies and in line with established guidance for reporting interventions (Duncan et al., 2020) allows for a more systematic, comprehensive and transparent approach to intervention development reporting, which, in turn enhances the quality of interventions and improves learning about intervention development research and practice.

In line with the UK Medical Research Council's guidance for developing complex interventions, the next stage of this project is to pilot the prototype labels developed (Craig et al., 2008). This is likely to involve user testing. For instance, this could include exposing people to the newly developed disposal instruction labels and observing which bin they sort the waste into (e.g., a general waste, food waste or recycling bin). This will help to identify the type(s) of wording and logos that are most effective at getting people to put different types of compostable plastic packaging in the desired bin. This study could initially be piloted online to assess the approach and testing procedures as the labels are likely to require further refining prior to conducting an in-person study.

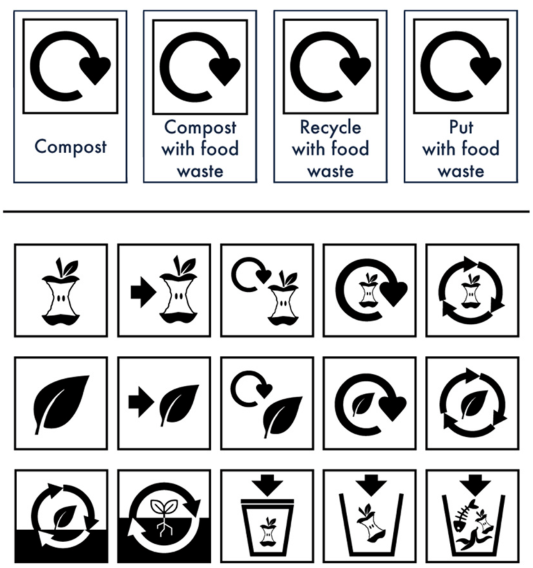

FIGURE 9
Examples of the disposal instruction labels developed.

At the conclusion of the intervention development process, we were able to describe the rationale, theoretical basis, content and delivery of the intervention. However, we were not able to investigate in detail the potential impacts of other aspects of product packaging e.g., branding, color, imagery, material texture, packaging/product format. These are very likely to influence the delivery of our disposal instruction labels and so their potential impacts in the specific context of our developed disposal instruction labels should be explored in any user testing. Existing rules and regulations (or lack, thereof) relating to package labeling and imagery are also important contextual factors to take into consideration. There is much "greenwashing" and false advertising in the area of biodegradable and compostable plastic products (Aparsi et al., 2020; Allison et al., 2021a). The introduction of a disposal instruction label is unlikely to be sufficient as an intervention strategy until products that are not compostable but claim to be are banned from the market. While focusing on regulation or legislation as policy options was deemed out of scope for the current intervention, we recommend future interventions to consider this as it will be instrumental in preventing potentially misleading imagery and claims to be put on packaging.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AA, DP, SM, and MM: conceptualization, methodology, and validation. AA: data curation, formal analysis, investigation, project administration, and writing–original draft. MM and DP: funding acquisition. AA and DP: resources and visualization. SM, MM, and FL: supervision. AA, DP, MM, SM, and FL: writing–review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2022.968152/full#supplementary-material

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Evolution of value chain and governance actor responses to the plastic leakage problem in South Africa

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An estimated 15,000–40,000 tons of plastic waste leaks into the oceans from South Africa annually. This has put the management of plastic products in the spotlight. In South Africa, life cycle management (LCM) is not a term that is commonly used however some companies have adopted LCM tools and concepts including cleaner production, sustainable procurement and design for recycling. Interviews with key value chain actors were conducted in 2017 and 2018–2019, on the influence of plastic leakage on plastic product life cycle management. In 2017, actors largely did not view themselves as responsible for plastic leakage, mostly putting blame on consumers. During the second interview period, a shift was observed wherein the actors recognized the role of product design in plastic leakage and started taking a more active role in its mitigation from the perspective of extended producer responsibility. The drivers for addressing marine pollution mirrored those for the adoption of LCM tools, including maintaining a competitive advantage and meeting investor and consumer expectations. In 2020, the South African Plastic Pact was developed and launched, which aims to create a circular economy for plastic packaging. As of October 2021, the majority of interviewed value chain actors are members. Ultimately the increasing concern surrounding plastic pollution has directly influenced value chain actors' perspectives and actions.

KEYWORDS

extended producer responsibility, life cycle management, plastic leakage, plastic pollution, plastic

Introduction

The growing concern surrounding plastic pollution has resulted in global concerted efforts for its mitigation. Although it is a global problem, an understanding of regional contexts has been recognized as a matter of key importance in its mitigation (UNEP, 2020). South Africa has been identified as one of the 20 most important national contributors to marine plastic pollution, with an estimated amount of 15,000–40,000 tons of plastic waste possibly reaching the oceans annually (Verster and Bouwman, 2020). Beach surveys conducted in South Africa have found that the majority of plastic is associated with food and beverages, including beverage bottles, snack packets, polystyrene and drinking straws (Lamprecht, 2013; Chitaka and von Blottnitz, 2019; Ryan, 2020; Weideman et al., 2020). Recent years have seen concerted efforts to address this challenge and marine pollution was declared a priority area in life cycle management (LCM) in the Medellin Declaration on Marine Litter in Life Cycle Assessment and Management (Sonnemann and Valdivia, 2017).

Life cycle management is a concept centered on the incorporation of sustainable development principles into modern business practice (Sonnemann et al., 2015). It can be considered a business management approach that aims to minimize the environmental and socio-economic burdens associated with an organization's products or services from a life cycle perspective (Hunkeler et al., 2004; UNEP/SETAC, 2007; Sonnemann et al., 2015; Bey, 2018; Nilsson-Lindén et al., 2019). More practically, it provides a toolkit for business sustainability, built on the tenets of life cycle thinking.

Multinational fast-moving consumer goods companies are increasingly employing LCM tools and concepts in their business operations to varying extents (UNEP/SETAC, 2009; Adams et al., 2015; Stewart et al., 2018). There are a number of key drivers for an organization to implement a life cycle approach including business strategy, market requirements, regulations and legislations as well as international agreements (Hunkeler et al., 2004; UNEP/SETAC, 2007; Sonnemann et al., 2015). Mapping value chains and developing criteria for product enhancement and value creation may enable organizations to gain a competitive advantage (UNEP/SETAC, 2007; Sonnemann et al., 2015). In addition, the implementation of LCM may contribute to an improved public perception. Government regulations and legislation surrounding environmental impacts may force organizations to employ a life-cycle based approach to ensure compliance.

This paper explores the extent to which enhanced knowledge of plastic leakage has influenced approaches to plastic product LCM in South Africa. This includes investigating the extent to which a life cycle management approach has been adopted by companies operating in South Africa. In addition, the challenges, barriers and drivers for the development of interventions and/or strategies are explored.

Methods

Approaches to plastic product LCM were investigated using a combination of primary and secondary data sources available in 2019. More specifically, the application of any LCM tools, design concepts and strategies (shown in Table 1) employed by Fast-Moving Consumer Goods (FMCG) companies operating in South Africa were explored using secondary data sources, including annual reports, websites and media releases. Furthermore, companies which operated in multiple countries were characterized according to their business strategies (described in Table 2) as well as whether they were listed on any stock exchanges.

TABLE 1 Life cycle management tools, design concepts, and strategies.

Tools	Design concepts	Strategies
Life cycle assessment	Sustainable product design	Sustainable procurement
Life cycle costing	Design for recycling	Cleaner production
Social life cycle assessment		Green marketing
Materiality assessment		Extended producer responsibility

TABLE 2 Company business strategies (Bartlett and Ghoshal, 1998; Hill, 2013).

International	• Product research and development (RandD), marketing and strategy centralized in home country • Limited customization of products to local markets
Global	• RandD, manufacturing and marketing concentrated in a few locations but strong headquarters in one country • Homogenized product offering to maximize on economies of scale
Multinational	• Manufacturing and marketing in different markets • Product offering customized to local markets
Transnational	• RandD, marketing and decision-making powers distributed amongst different markets • Products differentiated according to local markets

Primary data was sourced *via* semi-structured interviews with key actors along the plastics value chain, with a focus on the fast-moving consumer goods sector. The interviews explored current approaches to plastic product LCM including product design. In addition, value chain actors' depth of knowledge regarding the extent of plastic pollution and how this has influenced their practices was explored. The interviews also investigated the key factors that influence the development of strategies and interventions to address plastic pollution.

Stakeholder identification

A total of 16 stakeholders were interviewed including industry associations who can speak with authority regarding relevant industry perceptions and product designers with intimate knowledge on the design decision-making process (Table 3). Brand owners and retailers (who all had in-house brands, i.e., brands owned by the retailers) were also engaged as they play a pivotal role in bringing products to market. Formal

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TABLE 3 Consulted value chain actors and the corresponding interview period.

	Interview period	
	2017	2018/2019
Retailer A	✓	✓
Retailer B		✓
Retailer C		✓
Retailer D		✓
Brand owner A	✓	✓
Brand owner B		✓
Brand owner C		✓
Recycler A		✓
Recycler B		✓
Recycler C		✓
Industry association A	✓	✓
Industry association B	✓	
Industry association C		✓
Restauranteur A		✓
Restauranteur B		✓
Packaging designer	✓	

recyclers, who process plastic waste, were engaged as key players in waste diversion and processing. All value chain actors were directly involved in value chains for items that were identified as major contributors to marine pollution. Furthermore, their market share was also taken into consideration. Accessibility to value chain actors was a limitation as not all identified actors were willing to participate in the research.

Interview protocol and analysis

An initial set of interviews was conducted in March 2017, followed by more extensive interviews from November 2018 to March 2019. The two sets of interviews enabled a comparison of stakeholder perspectives as the conversation surrounding plastic pollution evolved.

Semi-structured interviews were conducted using a series of open-ended questions based on the aims of the research. This allowed for the interviewer to ask probing questions to elicit further information and explore different avenues which arise. Furthermore, the interview protocol also allowed for the interviewer to move back and forth between questions based on the participant's responses.

The relative influence of different factors influencing packaging design were explored *via* a short exercise conducted during the interview. The exercise required interviewees to rank the importance of different packaging design criteria with 1 being the most important.

Interviews were conducted face-to-face or *via* electronic communication, including online platforms, e-mail and telephonically, depending participant preference. They were on average 1-h long during which audio recordings were made and later transcribed.

A hybrid thematic approach was taken for interview analysis whereby a combination of a priori and grounded theory approaches were employed. A priori analysis is a deductive approach whereby themes are identified during the interview structuring phase based on the aims of the research (Miles et al., 2014). In this case, specific themes were identified based on the research questions. Grounded theory is an inductive approach to interview analysis, focused on the exploration of new theory or phenomena that arises from data (Corbin and Strauss, 2012). The use of a hybrid approach allowed for a more in-depth analysis of the key themes based on the research questions (a priori) through the identification of additional themes that emerged from the interviews. The interview analysis was conducting using NVivo 12 qualitative data analysis software.

To ensure that the research complied with ethical practices, it was reviewed by the University of Cape Town Engineering and Built Environment Ethics in Research Committee prior to data collection. To maintain anonymity no direct reference to the participants is made with identities presented in an anonymized form.

Results and discussion

Approaches to life cycle management in South Africa

Multinational companies operating in South Africa were found to adopt a number of LCM concepts across their departments, shown in Table 4. They applied different life cycle concepts to the respective life cycle stages. Sustainable procurement was practiced for materials sourcing, which often took a socio-economic perspective. Many companies employed cleaner production principles with a focus on reductions in energy and water consumption as well as carbon emissions and waste production. However, this is often based on a gate-to-gate assessment of the manufacturing facilities directly owned by the company and does not necessarily extend to suppliers. Life cycle assessments (LCA), i.e., environmental assessments of products or processes from cradle-to-grave, are not commonly conducted; when they are it is usually for new products or to support significant product improvements. Furthermore, no evidence was found of any of the surveyed companies having employed life cycle costing (LCC) or social life cycle assessment (SLCA), which

TABLE 4 LCM concepts, strategies, tools, and techniques employed by companies in South Africa in 2019.

	Business strategy	Headquarters	Stock exchange listing	Annual report	Tools and techniques				Design concepts		Strategies	
					Life cycle assessment	Life cycle costing	Social life cycle assessment	Materiality assessment	Sustainable product design	Design for recycling	Sustainable procurement	Cleaner production
ABInBev	Multinational	Belgium	✓	✓					✓	✓	✓	✓
Astral foods	Multinational	South Africa	✓									✓
AVI	International	South Africa	✓	✓				✓	✓	✓	✓	✓
Clover	Multinational	South Africa	✓	✓							✓	✓
Coca Cola	Multinational	United States	✓	✓	✓				✓	✓	✓	✓
Comestibles Aldor	Global	Colombia										
Frimax Foods	National	South Africa										
IQ Foods	National	South Africa										
Jive	National	South Africa										
Nestle	Multinational	Switzerland	✓	✓	✓			✓	✓	✓	✓	✓
Parmalat	Multinational	Italy	✓	✓				✓	✓			✓
PepsiCo	Multinational	United States	✓	✓				✓	✓	✓	✓	✓
Pick n Pay	*	South Africa	✓	✓					✓	✓	✓	✓
Pioneer Food	Multinational	South Africa	✓	✓				✓			✓	✓
Premier	Global	South Africa	✓									✓
Procter and Gamble	Multinational	United States	✓	✓					✓	✓	✓	✓
RCL	Global	South Africa	✓	✓					✓	✓	✓	✓
Rhodes Food Group	Global	South Africa	✓									✓
Richester Foods	National	South Africa										
Shoprite Holdings Ltd	*	South Africa	✓	✓					✓	✓	✓	✓
The Lion Match Company	National	South Africa										
The SPAR Group Ltd.	*	Netherlands	✓	✓				✓	✓	✓	✓	✓
Tiger Brands	Multinational	South Africa	✓	✓	✓				✓	✓	✓	✓

(Continued)

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TABLE 4 (Continued)

	Business strategy	Headquarters	Stock exchange listing	Annual report	Tools and techniques				Design concepts		Strategies	
					Life cycle assessment	Life cycle costing	Social life cycle assessment	Materiality assessment	Sustainable product design	Design for recycling	Sustainable procurement	Cleaner production
Truda Foods	National	South Africa										
Twizza	National	South Africa										
Unibisco Biscuits SA	Unknown	unknown										
Unilever	Multinational	United Kingdom	✓	✓	✓				✓	✓	✓	✓
Woolworths Holdings Ltd	*	South Africa	✓	✓	✓			✓	✓	✓	✓	✓

*Retailers were not characterized due to their complex business models which included independently owned franchises.

investigate the economic and social aspects of a product or process, respectively.

When it comes to packaging design, sustainable product design traditionally took the form of packaging reduction and light-weighting. To a lesser extent, some companies (Coca-Cola, Nestle, PepsiCo, Tiger Brands and Unilever) were exploring the use of compostable or plant-based material alternatives to plastic. Recent years have seen increasing emphasis on design for recycling and integration of recycled content, particularly for plastic packaging. As expected, these companies often practice green marketing based on the application of the aforementioned concepts.

When this analysis was conducted in 2019, extended producer responsibility (EPR), a policy approach in which producers are held responsible for their products throughout their entire life cycle, was yet to be legislated in South Africa. However, some companies practiced EPR through voluntary membership of producer responsibility organizations (PROs) particularly in the packaging industry.

Unlike large multinationals, locally based South African companies which do not have investments in other countries, and are not listed on any stock exchanges, often do not employ any LCM concepts. Their public communications are centered around product marketing, *via* a company website and various social media platforms. It is also noteworthy that these brands were identified as the major contributors to marine litter during beach surveys conducted in Cape Town by Chitaka and von Blottnitz (2019). For example, Unibisco Biscuits SA which was observed to be a major contributor of biscuit packaging, Richester Foods and Comestibles Aldor for lollipop wrappers, as well as Truda Foods and Frimax Foods when it came to snack packets.

Influence of leakage on approaches to plastic product life cycle management in South Africa

Value chain actor perspectives of plastic pollution

Value chain actor perspectives of plastic pollution were explored in order to gain insights on their understanding of the issue.

Causes of plastic pollution

As shown in Table 5, there were differing perspectives on the causes of plastic pollution, including consumer behavior, ineffective solid waste management infrastructure and practices and poor extended producer responsibility practices. Product design was also deemed as a contributing factor, in that the

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TABLE 5 Stakeholder perspectives on plastic pollution causes.

	Behavior	Product design	Extended producer responsibility	Waste management	Combination of all
2017					
Retailer A	✓				
Brand owner A	✓				
Industry association A					✓
Industry association B	✓	✓		✓	
Packaging designer					✓
2018/2019					✓
Retailer A					
Retailer B					✓
Retailer C					✓
Retailer D	✓		✓		
Brand owner A					✓
Brand owner B	✓		✓	✓	
Brand owner C	✓				
Recycler A	✓	✓			
Recycler B					✓
Recycler C	✓				
Industry association A					✓
Industry association C					✓

characteristics of the product and the intrinsic value at end-of-life influence the likelihood of escaping the value chain.

Many of the stakeholders viewed pollution causes as a complex combination of some or all factors, albeit to varying extents. Whilst they cited consumer behavior as an integral element, they believed that it was no longer adequate to view the problem from this singular perspective and instead address the multifaceted nature of the problem. All of the retailers and brand owners acknowledged they held some responsibility for the products they put on the market, both from a product design perspective and the fate of the product waste.

Although Brand Owner C acknowledged the responsibility of brand owners for their products, they viewed plastic pollution as a purely behavioral issue. This may be attributed to the fact that the value chain actor is an active participant in voluntary EPR programs and thus viewed themselves as responsible brand owners.

Whilst Recycler B attributed pollution to a combination of issues, they viewed brand owners and retailers as largely responsible, with consumers being used as a convenient scapegoat. In their opinion, brand owners and retailers need to take more responsibility for the nature of the products they put on the market and play a more active role in their management at end-of-life. Recycler B qualified this using the case of PET bottles, which have built up a relatively high recycling rate, that they attributed to the active engagement of brand owners in supporting the recycling sector.

All the recyclers emphasized the importance of product design in the fate of products at end-of-life. This is to be expected as they represent one of the options for waste treatment, thus they are familiar with the different design characteristics that may influence how that product is treated including likelihood of collection for recycling.

Perceptions of the extent of the problem

Interviewees presented a limited understanding of the extent of the plastic pollution problem. The majority were either unwilling or unable to provide an estimate of how large they believed the problem was, readily admitting their limited knowledge. Interviewees were aware that research that had been conducted in this regard, but the level of engagement with such work varied. Retailer B and Industry Associations A and C both demonstrated active engagement with this work, expressing their skepticism surrounding current knowledge. Retailer B also highlighted the limited information available regarding plastic flows within the South Africa, which was also expressed by Brand Owner A. Whilst Retailer D and Brand Owner A were willing to hazard a guess, these were mostly based on anecdotes and their own personal experiences with litter.

Stakeholder plastic pollution strategies and initiatives

Although the majority of interviewees viewed plastic pollution causes to be multifaceted, in 2017 value chain actors generally did not view themselves as playing a significant role in its mitigation; instead they put the onus on consumers when it came to addressing it. Furthermore, they did not view themselves as responsible for the fate of products at their end-of-life. Thus, the approaches of their employers were focused on consumer education and awareness raising campaigns. In addition, value chain actors supported recycling initiatives but did not view them as having a significant impact.

As plastic pollution received increasing attention between the two sets of interviews, a shift was observed in value chain actor approaches to plastic product LCM. Retailers and brand owners now increasingly viewed their role in mitigating plastic pollution from an EPR perspective, recognizing the role of product design in plastic pollution and taking greater responsibility for the fate of their products at end-of-life. Through growing appreciation of EPR, upstream value chain actors are increasingly supporting end-of-life activities that would facilitate proper disposal of their products. This is commonly done through supporting recycling initiatives either directly or through membership of voluntary PROs which have been found to play a significant role in growing the recycling landscape (Godfrey and Oelofse, 2017).

Value chain actors are also changing their product design approaches to facilitate their activities at end-of-life. Whilst South Africa has traditionally promoted design for recycling (Godfrey and Oelofse, 2017), it has gained in popularity in recent years with more companies deeming it necessary for survival. Thus, value chain actors are increasingly integrating design for recycling and/or circularity into packaging design strategies. However, Retailer A did not believe that the focus on recycling would solve the plastic pollution problem and would instead require a suite of approaches including plastic reduction and elimination. A similar sentiment was expressed by the Packaging Designer, who believed that whilst a focus on design for recycling would enable a circular economy it would not necessarily reduce littering.

Material substitution is an additional approach being implemented, one example being the substitution of plastic straws with paper or polylactide (PLA) alternatives. Furthermore, value chain actors are now reviewing the effectiveness of their consumer education initiatives, in supporting their EPR activities.

Recyclers viewed themselves as integral to waste diversion. They considered themselves a "tool" to be utilized but, the onus was on retailers and brand owners to ensure that products were designed with end-of-life in mind.

Key drivers for intervention development

As expected, value chain actors cited a desire to maintain a competitive advantage as a key driver. Retailer A highlighted that consumers would commonly refer to competitor practices when lodging complaints. Thus, retailers and brand owners keep abreast of their competitors' practices. In addition, they take note of practices of their counterparts in developed markets viewing them as predictors of future local market expectations.

Brand Owner A and Retailer D highlighted the increasing consideration of a company's sustainability efforts by investors. Thus, responding to the concern surrounding plastic pollution is seen to be imperative to a company's image. Furthermore, Retailer B noted that interventions are more readily approved by company executives for products that were in the public spotlight. For example, the rising unpopularity of straws—which have readily available material alternatives—presented a relatively easy opportunity for retailers to be viewed as environmentally responsible through material substitution.

Consumer pressure is a major driving force for intervention development, as evidenced by the shift in stakeholder approaches from 2017 to 2019. Increasing concern surrounding plastic marine pollution has led to societal pressure being placed on stakeholders to take a more proactive role. This often takes the form of campaigns led by consumers or environmental groups, one example being the campaign by WWF South Africa which advocated against the use of single-use plastics with a particular focus on items they considered to be the "worst offenders" including straws and cotton bud sticks (WWF-SA Notten, 2018).

Job creation is viewed as the major driver for the development of strategies, particularly those with a focus on recycling. In South Africa, informal waste collectors play a vital role in waste diversion. In 2018, the recycling industry provided 7,892 formal jobs whilst 58,470 people were indirectly employed including informal collectors (Plastics SA, 2019). Thus, an increase in recyclable waste would likely result in more job opportunities.

Some value chain actors view international legislation, particularly in Europe, as a precursor to similar legislations being enacted locally, and choose to comply pre-emptively. For multinational companies, compliance with legislation may be integrated into global strategies. South African based companies which export to foreign markets are also driven by compliance in their target market. In addition, they are driven by global agreements including the New Plastics Economy Global Commitment (Ellen MacArthur Foundation, 2018), which had the additional benefit of increasing the organization's image in society, portraying them as "good corporate citizens". In some export markets there are existing or emerging national Plastics Pacts, which are the "implementation" of the New Plastics Economy Global Commitment, with local and multinational companies committed to the national targets of these Plastics Pacts. These national targets are internalized in the companies, resulting in guidelines being set up and sent to suppliers of plastic packaging.

Since the interviews took place, in October 2020, a national Plastics Pact was developed and launched in South Africa, which forms part of the international Plastics Pact network under

TABLE 6 Stakeholder plastics pact membership as of October 2021.

	Plastics pact membership
Retailer A	✓
Retailer B	✓
Retailer C	✓
Retailer D	✓
Brand owner A	✓
Brand owner B	
Brand owner C	✓
Recycler A	✓
Recycler B	✓
Recycler C	✓
Industry association A	✓
Industry association B	
Industry association C	✓
Restauranteur A	
Restauranteur B	

the Ellen MacArthur Foundation. WWF South Africa together with partners the South African Plastic Recycling Organization (SAPRO), WRAP and the Ellen MacArthur Foundation conducted extensive stakeholder engagement during 2019 with the industry and government. The acknowledgment that not one organization can address the complexity of the plastic pollution problem resulted in a number of stakeholders across the plastic packaging value chain supporting the concept of this multi-stakeholder pre-competitive platform and agreeing to ambitious 2025 targets. As it stands the majority of interviewed stakeholders are members of this Plastics Pact as shown in Table 6.

Challenges and barriers to intervention development

Many of the challenges and barriers identified during the interviews are related to packaging design, including functionality and technical requirements. Of particular concern is food packaging, whereby designers are faced with the challenge of finding alternative designs that would meet food safety requirements. Retailers without production facilities for their in-house brands are constrained by the technological capabilities of their suppliers.

As expected, cost is a major barrier to the design of product interventions, including material substitution and complete redesign. Interviewees pointed out that plastic was a favored material due to its relatively low cost, thus material substitution would inevitably be associated with increased costs. They also highlighted the higher costs associated with new alternative products due to their novelty. Value chain actors have varying capacities to absorb this extra cost. For example, Retailer A indicated that their company has funds set aside to absorb additional sustainability related costs whereas Retailer D indicated that these costs would be passed onto the consumer. Industry Association B also highlighted the socio-economic implications of designing out all small format items that have been identified as problematic as some provide an affordable option to populations who cannot afford to buy in high volumes. Thus, a product redesign would need to take this into consideration.

A lack of suitable solid waste management infrastructure to manage and process waste is viewed as a challenge to the efficacy of any design interventions implemented. Whilst value chain actors are emphasizing design for recycling, interviewees often cited the potentially limited recycling infrastructure available in the country. In addition, the lack of solid waste services to separate and collect recyclables present an additional challenge. However, the interviewed recyclers all expressed confidence in their abilities to meet the additional required capacity. The lack of suitable infrastructure to process alternative materials, specifically biodegradable and/or compostable materials, was also cited as a deterrent for their adoption. Interviewees raised concerns of potential contamination of recycling streams by such materials which would impact the quality of plastic products downstream.

Retailers highlighted consumer misinformation as a challenge they face in trying to meet consumer desires. According to interviewees, some consumers demonstrate a limited understanding of the function of packaging (i.e., food safety and preservation) and the broader environmental impacts associated with alternative materials. One retailer gave the example of a consumer attacking them on their use of plastic packaging whilst simultaneously praising them for the quality of the food contained within. Retailers also highlighted the increasing popularity of alternative products in popular media which results in consumers advocating for such items without a complete understanding of the material properties.

Differing stakeholder priorities across the value chain present an additional level of complexity to strategy development. Retailer A highlighted the threat that initiatives aiming to reduce or eliminate plastic presents to their upstream suppliers, as this would effectively reduce their business throughput. Recycler B accused producers of being unwilling to adopt sustainable practices, including incorporation of recycled content or exclusion of additives that decreased recyclability, due to a desire to cut costs. They also expressed their exasperation at retailers for seemingly not exerting enough pressure on their suppliers. Furthermore, there was some contention amongst stakeholders regarding their different roles. Retailers were commonly viewed as having the most power as the interface between suppliers and consumers. Brand Owner A viewed themselves as subject to the principles adopted by retailers as they are reliant upon them for product distribution. Whereas, Retailer B described the relationship between retailers and brand owners as "co-dependent". As a result, there is reportedly some acrimony amongst stakeholders across the value chain resulting in multiple parallel initiatives.

The broader environmental impacts associated with interventions are considered to a much lesser extent with only two interviewees highlighting the potential for trade-offs; Retailer D and Recycler A highlighted that the focus on mitigating plastic pollution could result in interventions that resulted in greater damages in other ecological spheres such as climate change. In addition, some interviewees were concerned about the potential impacts of bio-based plastics on food security as they are often made from food crops.

Discussion

Adoption of LCM concepts, tools, and techniques in South Africa

LCM is not a term that is commonly used in South Africa, however there are a number of related techniques applied by FMCG companies and retailers operating locally. The extent to which LCM concepts are being adopted can be linked to a company's characteristics, including its business footprint and whether it is publicly traded. Multinational companies were found to adopt many LCM concepts including cleaner production principles, with a focus on water and energy consumption, carbon emissions and waste generation. This is to be expected as larger companies are deemed to be subject to greater public scrutiny and are thus under more pressure to behave sustainably (Chih et al., 2010; Lourenço and Branco, 2013). Furthermore, ranking institutions are placing increasing emphasis companies' approaches to environmental and social sustainability as an indicator of overall performance, increasing its importance amongst investors (UNEP/SETAC, 2006). Hence companies listed on major stock exchanges are found to make greater efforts toward their corporate sustainability (Chih et al., 2010). Multinationals are also driven to employ an LCM based approach due to market requirements as well as regulations and legislation in the countries in which they operate (Hunkeler et al., 2004; UNEP/SETAC, 2007; Sonnemann et al., 2015). In comparison, locally based South African companies that are not publicly listed, often do not employ any LCM concepts. Furthermore, their communication is often limited to product sales. This may be attributed to their relatively smaller business footprint.

In November 2021, Extended Producer Responsibility Regulations were enacted in South Africa for specific product classes including plastic packaging. Notably, the Regulations include LCM concepts which producers will have to adopt. For example, the Regulations stipulate that product life cycle assessments must be conducted within 5 years of the enactment of the regulations (DEFF, 2021). In addition, producers are required to implement cleaner production measures including design for recycling. This regulatory prescription of LCM tools should lead to their wider adoption not only by multinationals but also by smaller, locally based South African companies.

Key drivers and challenges for pollution mitigation strategy development

Key drivers for strategy and intervention development closely mirror those for adopting LCM based concepts and strategies including maintaining a competitive advantage, compliance with regulations and legislation, meeting investor expectations and meeting consumer expectations (Hunkeler et al., 2004; UNEP/SETAC, 2007; Sonnemann et al., 2015). Retailers and brand owners not only keep abreast of their competitors' practices, but also look toward their counterparts in developed markets for guidance. This may be attributed to institutional normative pressure, which is a key driver for environmental policy development, whereby companies will look toward what others are doing as an indication of their "moral" and "social" obligations (Ramus and Montiel, 2005). As a result, a company may not only copy another's policies but may also be more willing to endorse industry wide initiatives if they view their counterparts doing the same. At the time of the interviews the only legislation aimed at mitigating plastic pollution was the Plastic Bag Regulations which included the prohibition of certain bags (DEAT, 2002). As such, value chain actors view European legislation as a precursor (including the EU agreement on single-use plastics (European Parliament, 2018), choosing to comply pre-emptively. In addition, they are driven by global agreements including the New Plastics Economy Global Commitment (Ellen MacArthur Foundation, 2018), which was further exemplified by their membership of the South African Plastics Pact. This has the additional benefit of increasing a company's image in society, portraying them as "good corporate citizens". This is in line with a suggestion by Stafford and Jones (2019) that the visibility associated with plastic pollution creates an opportunity for "environmental branding" of corporations. With the local implementation of EPR Regulations for plastics and packaging in May 2021 (DEFF, 2020, 2021), value chain actors will be forced to take a more active role in the fate of their products to meet the specified targets for collection and recycling.

Many of the challenges associated with intervention development are related to the packaging design criteria. A fundamental barrier is the design of alternative products that could effectively protect and preserve the contents. Cost is a major constraint to product redesign as plastic is an attractive option due to its relatively low cost in comparison with other options. Furthermore, interviewees reported that new alternative products are associated with higher costs due to the novelty. The extent to which cost affects value chain actors differs according to their ability to absorb this extra cost.

A lack of suitable infrastructure is also a consideration for value chain actors as it would directly impact the effectiveness of their interventions. In particular, the state of solid waste management practices and infrastructure is of concern with regards to their ability to collect the waste and divert it to the appropriate waste treatment. According to Stats SA (2021), 37.3% of South African households in 2020 did not have access to waste removal services. Furthermore, source separation is not a prevalent practice in South Africa (Godfrey and Oelofse, 2017). The lack of suitable infrastructure is also a deterrent for the adoption of compostable materials due to the limited availability of industrial composting facilities in South Africa (DST, 2014).

Stafford and Jones (2019) highlight the potential for a single-minded focus on marine pollution to lead to a side-lining of other environmental threats. This was demonstrated during the interviews whereby the broader environmental impacts associated with the interventions are considered to a much lesser extents with only two interviewees highlighting the potential for trade-offs. Of particular concern were the potential impacts on climate change as previous studies comparing plastic and paper often found plastic to be the favorable option (James and Grant, 2005; Sevitz et al., 2012; Kimmel et al., 2014). However, the converse was found in a study comparing different straw materials whereby paper was found to be the favorable option (Chitaka et al., 2020), suggesting that this trade-off may be potentially negated in the South African context.

Consumer perception appears to be both a key driver and a challenge to strategy development. Value chain actors are under increasing societal pressure to develop strategies to address plastic pollution. However, retailers highlighted consumer misinformation as a challenge they face in trying to meet consumer desires. According to interviewees, some consumers demonstrate a limited understanding of the function of packaging as well as the broader environmental impacts associated with alternative materials. This has led to consumers advocating for alternative materials based on a shallow understanding of the implications. This is in line with a study conducted in 2014, whereby Scott and Vigar-Ellis (2014) found that South African consumers had an incomplete understanding of what environmentally friendly packaging is, or the benefits it provided to themselves or the environment. In addition, some consumers relied on their "common sense" to evaluate whether packaging is environmentally friendly based on the material employed (Scott and Vigar-Ellis, 2014). A similar finding was made by Lindh et al. (2016) and Steenis et al. (2017) who found that Swedish and Dutch consumers, respectively, based their perception of environmental impacts on the packaging material used leading to the belief that plastic and metal were least sustainable. Furthermore, Steenis et al. (2017) found that consumers perceived products that were deemed most environmentally sustainable from an LCA perspective as the least sustainable. This suggests that consumer perceptions have the potential to contradict their desire for sustainability (Lindh et al., 2016; Steenis et al., 2017).

Differing stakeholder priorities across the value chain present an additional level of complexity to strategy development. In particular, value chain actors reported plastic converters felt threatened by the rhetoric surrounding plastic pollution as it was commonly associated with the reduction of plastic products. Furthermore, there was some acrimony between value chain actors surrounding stakeholder roles and responsibilities in mitigating plastic pollution.

Conclusions

Whilst life cycle management is not a term that is widely used in South Africa, the evidence assembled here has shown that many large companies including multinationals have adopted LCM tools and concepts. The extent to which these concepts are adopted is linked to a company's characteristics including footprint and whether it is publicly traded. Thus, smaller companies have to date been less likely to adopt LCM concepts.

The growing concern surrounding plastic leakage has directly influenced value chain actors' practices, with some companies taking a more active role in plastic pollution mitigation. From 2017 to the next interview period in 2018–2019, a shift was observed in value chain actors' perceptions of their roles in plastic pollution mitigation. Initially, they distanced themselves from the issue then later they played a more active role in plastic pollution mitigation.

The drivers for the development of strategies to address plastic pollution mirror those for adopting LCM based concepts including maintaining a competitive advantage, compliance with regulations and legislation, and meeting investor and consumer expectations. Aligned with these LCM concepts, some industry stakeholders who acknowledge the systemic challenges of plastic leakage have welcomed the establishment of the SA Plastics Pact as a credible response to transition to a circular plastics economy. However, consumer expectations present a challenge due to some ill-founded consumer perceptions of sustainability. Cost is also a major challenge for stakeholders due to the relatively higher costs associated with material alternatives to plastic. The broader environmental impacts associated with intervention development were considered to a lesser extent, increasing the potential of trade-offs being made unwittingly.

This paper has demonstrated the factors influencing decision-making of value chain actors in a developing country when faced with an environmental challenge. It presented the challenges and limitations that need to be mitigated to ensure efficient and effective progress toward addressing issues such as pollution. In addition, the identified drivers can be leveraged to hasten progress.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by University of Cape Town Engineering and Built Environment Ethics in Research Committee. The patients/participants provided their written informed consent to participate in this study.

Author contributions

TC: substantial contributions to the conception or design of the work, the acquisition, analysis, or interpretation of data for the work, and drafting the work or revising it critically for important intellectual content. LdK: the acquisition and interpretation of data for the work. HvB: conception of the work, supervision, and provide approval for publication of the content. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author LdK was employed by WWF South Africa.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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An imperative to focus the plastic pollution problem on place-based solutions

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There is an increased focus on plastic pollution and the resultant harms in our oceans and on our shores at local, regional, and global scales. New technologies are being developed and trialed, multilateral agreements are coming into play, and the role of a circular economy is increasingly touted as the key to help solve the plastic pollution crisis. Simultaneously, we are witnessing the disruption of global supply chains from the COVID-19 pandemic, increased fuel prices and increased scope and scale of natural disasters. Individual countries are setting national targets and are developing national plans of action to combat plastic pollution. In this paper, we focus on Australia's National Plastics Plan as a case study of a national approach to addressing this transboundary issue. We discuss the Plan in relation to supply chains, the role of standards and best practices, and principles for a successful circular plastic economy. We explicitly consider the role of reverse logistics and regional approaches that could be developed and implemented within island nations. Overall, we argue for culturally appropriate, economically and environmentally place-based solutions as a necessary approach to help reduce plastic losses to the environment, acknowledging that plastics leakage to the environment is a social equity issue.

KEYWORDS

Australia, circular economy, place-based solutions, plastic, plastic supply chain, reverse logistics

Introduction

Plastic production is increasing globally at unprecedented rates. Accordingly, plastic pollution is now described as a crisis and a wicked problem (Landon-Lane, 2018; Vince and Stoett, 2018; Stoll et al., 2020), which transcends geopolitical borders and affects individuals and countries preferentially based upon wealth. Further confounding the management of wicked problems is the notion that "decisions are not allowed to be wrong" (Rittel and Webber, 1973; Landon-Lane, 2018). This 21st-century tragedy of the commons (Vince and Hardesty, 2018) affects the most remote marine environments, with plastics that weigh thousands of kilograms (e.g., derelict fishing gear; see Richardson et al., 2019) to those small enough to pass through tissues and cell boundaries (Järvenpää et al., 2022). Plastics of all sizes have been discovered in the most remote marine

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environments from the artic to the Antarctic (Kelly et al., 2020; Collard et al., 2021), including the deepest depths of the ocean in the Mariana Trench (Chiba et al., 2018). It is estimated that globally, around nearly 80% of all plastics ever produced has accumulated in landfills or the natural environment, while only 9% of all plastics have been recycled and 12% has been incinerated (Geyer et al., 2017). Plastic is estimated have a social and environmental cost of US $2.2 trillion each year (Forrest et al., 2019). An estimated 19 to 23 million metric tons of plastic waste has entered aquatic and marine ecosystems on a global scale, and this is predicted to reach up to 53 million metric tons annually by 2030 if current trends continue (Borrelle et al., 2020).

While plastic has only been in production for around 60 years, its ubiquity in society—and in the environment—is notorious. Up to 80% of the plastic found in the coastal and marine environment is sourced from the land, and we require socially, culturally appropriate, place-based solutions to prevent manufactured plastics reaching the global ocean. The plastic problem is so widespread across the world's terrestrial and marine environments that microplastics have been found in the snow on the Swiss Alps (Bergmann et al., 2019) and on the Antarctic continent (Zhang et al., 2020), as well as in the deepest depths of the ocean (Barrett et al., 2020). The impact of plastics on human health as a result of its presence in the environment is still relatively unknown, however, some evidence suggests that the leaching of endocrine disrupters from plastic can be linked to numerous human health issues (Flaws et al., 2020). The global COVID-19 pandemic has further complicated the problem resulting in an increase of single-use plastic and personal protective equipment use and waste in the environment (Prata et al., 2020; Silva et al., 2020; Schofield et al., 2021). This transboundary problem has grown exponentially. To address this, policy making needs to be responsive to maximise effectiveness.

There are a number of international measures, including treaties and soft law/governance attempts to support and encourage international collaboration to reduce plastic losses to the environment. The Honolulu Strategy is a global framework document which meant to guide countries toward reducing plastic inputs to the marine environment (UNEP, 2011). Following this, we have seen the Manilla Declaration on Furthering the Implementation of the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (2012), the G7 Action Plan to Combat Marine Litter (2015), and more recently, the Basel Convention. To date, the Basel Convention is the sole global instrument that addresses plastic waste in a legally binding framework, however, compliance is difficult to enforce (Raubenheimer and Mcilgorm, 2018). In March 2022 UNEP passed a Resolution "To end Plastic Pollution" which will begin the negotiations toward a legally binding agreement by 2024. In the meanwhile, nation states such as Australia will need to manage their plastic use through national approaches.

Australia's National Plastic Plan

Historically, waste management has happened at state and local levels. However, in 2021 the federal government announced a National Plastics Plan (DAWE, 2021), which followed the first National Plastics Summit in early 2020.

This Plan outlines that the Australian government will address plastic pollution by

> *"working with industry to fast-track the phase-out of particularly problematic plastic materials; stopping the export of unprocessed plastic waste and promoting product stewardship through the Recycling and Waste Reduction Act 2020; unprecedented investments to turbo-charge Australia's plastic recycling capacity; research to make Australia a global leader in plastic recycling and reprocessing; community education to help consumers make informed decisions and recycle correctly"* (DAWE, 2021).

The aims of the Plastics Plan include, *inter alia*, to phase out non-compostable plastic packaging, consumer education, actions to reduce plastics leaking into the marine environment and an emphasis on research. This Plan has a number of targets for the immediate future including phasing out expanded polystyrene in consumer packaging by 2022 and having 100% reusable, recyclable or compostable packaging by 2025. The *Recycling and Waste Reduction Act* (2020) provides a national framework to manage waste and recycling across Australia including waste exports (DAWE, 2021). These regulations and plans provide a national framework; however, it is the state and local governments that are responsible for waste management and recycling efforts. While the responsibility falls on local governments in national and state plans, support and resources by upper levels of government will deliver a nationally coordinated approach and ensure effective implementation. For example, in multilevel political systems, such as Australia, local governments are responsible for waste management. With increased pressure to grow recycling capabilities, more resources will be required. Additionally, successful implementation of the Plan will require developing resilient supply-chains that overcome system shocks such as oil prices affecting recycling sector economics, disruptions in global supply chains from waste bans and COVID-19, and the increasing influence of politics on the plastics sector (Ebner and Iacovidou, 2021).

The effect of COVID-19 on plastic pollution and supply chains

In December 2019, the SARS-CoV-2 virus began to spread around the world, the first pandemic of such severity in centuries. Given the severity of the respiratory syndrome that results from the novel coronavirus and its highly contagious nature, what began as a health crisis has quickly become an economic, social, political and environmental threat (Silva et al., 2020). Initially, the world experienced a global shutdown in international and domestic travel. Consequent to people becoming less mobile were decreased carbon emissions, increased sightings of wildlife in urban areas, and potentially decreased amounts of several types of plastic waste lost to the environment. However, this decrease was counteracted by the tremendous growth in single-use plastic personal protective equipment (PPE) and other medical waste associated with the pandemic (Ammendolia et al., 2021; Schofield et al., 2021). Additionally, there was a proliferation of single-use plastic bags, cups and take away containers associated with the food industry (Parashar and Hait, 2021). This demand on plastics for packaging, medical use and other applications is expected to grow (Prata et al., 2020). We have also seen plastic industry lobbyists utilize the hygiene and cleanliness concerns of customers to pressure jurisdictions to reverse or delay policies to ban or reduce single-use plastics (Prata et al., 2020; Silva et al., 2020; Da Costa, 2021).

Increasing disruptions to supply chains around the world began in early 2020 when the World Health Organization declared COVID-19 a global health emergency (Hedwall, 2020; Magableh, 2021). Supply chain disruptions have occurred for a range of products such as medicines and medical equipment including PPE, fuel, electricity, food, toilet paper and other household goods. Examples of supply chain disruptions have included demand drop (e.g., airline travel), demand surge (e.g., toilet paper, online shopping), reduction in productivity (e.g., retail or restaurant jobs), storage/access restrictions (e.g., storage warehouses, meat production and storage facilities, etc.), a shortage of raw materials (e.g., electronics parts such as memory chips, building materials) (Pujawan and Bah, 2022). These supply chain disruptions are unevenly distributed among countries, industries and communities and highlight the instability within global markets (Bassett et al., 2021; Castañeda-Navarrete et al., 2021). Countries are seeking to reduce their reliability on global markets by building and strengthening resilient regional and domestic markets. One approach that is seeing an increased focus is the shift to an increasingly circular plastics economy. This focus is heightened by the desire to buffer supply chains from system shocks (such as having resulted from the current COVID-19 pandemic, political instability, and other emergent or urgent crises (Vince and Hardesty, in press).

The potential for a plastics circular economy

The magnification of single-use plastic consumption, insufficient disposal and management during the pandemic highlighted the urgent need to close the plastic loop. Recently, there has been a shift in perspective, as countries begin to acknowledge the value of plastic and a circular plastic economy (Yuan et al., 2021). If we treat plastic as a commodity, rather than as waste, we will increase the market for material recovery. A voluntary contribution from industry has been proposed as one approach to support the elimination of plastic pollution and help drive a circular plastic economy (Forrest et al., 2019). Embedding a whole of life cycle approach that includes plastics manufacturers and multinational corporations will undoubtedly assist in changing the dial on the global community's relationship with plastic. Current circular economy solutions can often be derived from experiences and management of waste in OECD (Organization for Economic Co-operation and Development) countries and may lack applicability to low-income nations or communities (Mihai et al., 2022). This only emphasizes the need for circular economy solutions to be place-based, tailored to a region, so that they adequately address necessary social and ethical dimensions (Murray et al., 2017). For example, some argue that plastic waste in developing countries could be solved by locally managed decentralized circular economy models (Browning et al., 2021). Circular approaches need to consider context, socioeconomics and transport as well as culture, social and economic context. Approaches suitable in higher OECD countries may not be appropriate in small island developing states, for example, where land and resources are much more limited.

Australia has established an Australian Circular Economy Hub and Marketplace to support the transition for Australian companies, communities and individuals to a circular system. In Australia, the adoption of circular economy principles could abate approximately 165 million tons of carbon pollution each year (Thorpe and Carmody, 2021) and establishing a plastics circular economy has been valued at $2 trillion. Lengthening and diversifying supply-chains within a circular system will buffer supply-chains from system shocks such as disruptions caused by catastrophic weather events or pandemics. At present, recirculating many plastic polymers back into the economy are constrained by material quality, product design and current sorting, handling and processing practices (Hahladakis and Iacovidou, 2018). Advancements in reprocessing and sorting technology alongside the redesigning of plastic products will progress the quality standard improvements required to increase secondary material recovery and recycling and enable a circular model transition to succeed (Hahladakis and Iacovidou, 2018). Circular plastics solutions that are adapted to the small island context where landfill space is scarce, and waste infrastructure is often lacking are more likely to succeed. Taking a regional approach may yield more positive, collaborative outcomes, whereby materials recover is more likely to prosper, and circular businesses can develop that are place-based, socially and culturally appropriate, whilst keeping financial benefits local.

Harnessing innovations and technology opportunities

It seems that nearly on a daily basis, we learn of novel approaches to addressing the plastic waste issue. These include everything from social enterprises such as recovering thongs and turning them into artwork or toys (https://oceansoleonline.com/) to chemical recycling (Thiounn and Smith, 2020), alternative packaging materials such as seaweed (Teixeira-Costa and Andrade, 2022), refillable container systems, and the proliferation of "degradable/biodegradable" plastic bags, food containers, and other food associated items (Evans et al., 2020). Product design and recycling systems (including the collection, sorting and reprocessing of materials) is a crucial point where government and industry can work hand-in-hand to provide products to consumers that make recycling easier and advance plastic pollution reductions. Success will require collaboration across the whole lifecycle of plastic packaging production, and to date, the pace to achieving a sustainable circular plastics economy has been slow (Gerassimidou et al., 2022). Advances in plastic-alternative materials will facilitate the phase-out of problematic and hard to recycle single-use plastics, such as expanded polystyrene used for packaging fill and consumer food and beverage containers; and microbeads used in cosmetic, cleaning, and personal care products. Advances in software programs will facilitate more recycling, such as the Recycle Mate or CurbCycle App to aid consumer decision-making regarding the recyclability of a product; or AI-enabled autonomous sorting systems in material recovery facilities. Australia is funding projects advancing their technology capacity to recycling plastics and integrating plastic waste into other materials. For example, recently projects funded by the Cooperative Research Center span chemical recycling of plastics, integrating plastic waste as a concrete or asphalt aggregate, and smart/AI technologies to improve recycling facility efficiency and material quality (CRC-P, 2022).

Advances in technology to capture and clean litter trap devices on urban drainage networks will improve the capture of plastics before they reach the ocean. Advancements in product labeling and polymer composite standards will additionally facilitate increases in recycling rates. For example, simplifying the complexity of current polymers and polymer composites could improve their recirculation into new products (Kummerer et al., 2020). Make international accepted definitions for biodegradable, degradable, oxo-degradable plastic standards to improve trust and transparency in domestic and international supply-chains. Improve product labeling to provide information that makes it easier for consumers to dispose of the item correctly (Burrows et al., 2022). For example, Australia aims to have 80% of supermarket products to display the Australasian Recycling Label, a world-leading label system (United Nations Environment Programme Consumers International, 2020) which provides information on how each component of the product should be disposed (Figure 1). Furthermore, consideration of the important role logistics can play in moving material between locations is critical to reduce carbon costs, increase benefits where they are needed and advance opportunities for increased circularity.

Australia as a regional leader

A fundamental springboard that launched plastic pollution into the forefront of the minds of decision-makers was a 2015 paper which included a list of the top 20 countries that are losing mismanaged plastic waste to the ocean (see Jambeck et al., 2015). At least half of these countries are within the Asia-Pacific region. Australia, also an island nation within the region, has a unique opportunity to provide guidance and support to neighboring countries.

Australia can become a leader in reducing plastic waste domestically and in the Asia-Pacific region. One major step Australia has taken toward reducing its waste burden on other countries is banning the export of unsorted mixed plastics and unprocessed single polymer or resin plastics. Australia has a larger technological and financial capacity compared to many of its neighbors, putting Australia in a position to develop and trial different management solutions and support neighboring nations to do the same. The country has prioritized supporting community-led projects that address local environmental priorities (i.e., place-based solutions) through the Plan and has funded over 1,330 community-led projects in 2019–20 to the value of $18 AUS million.

A target of Australia's National Plastics Plan is to phase-out problematic and unnecessary single-use plastics such as expanded polystyrene packaging fill and consumer food and beverage containers. With clear targets, the country is looking at domestic business opportunities and being a regional leader. For example, the country has successfully supported industry to voluntary phase-out plastic microbeads from 99.3% of cosmetic, cleaning and personal care products sold in Australia.

Furthermore, Commonwealth procurement rules and sustainable procurement guidelines have been updated to

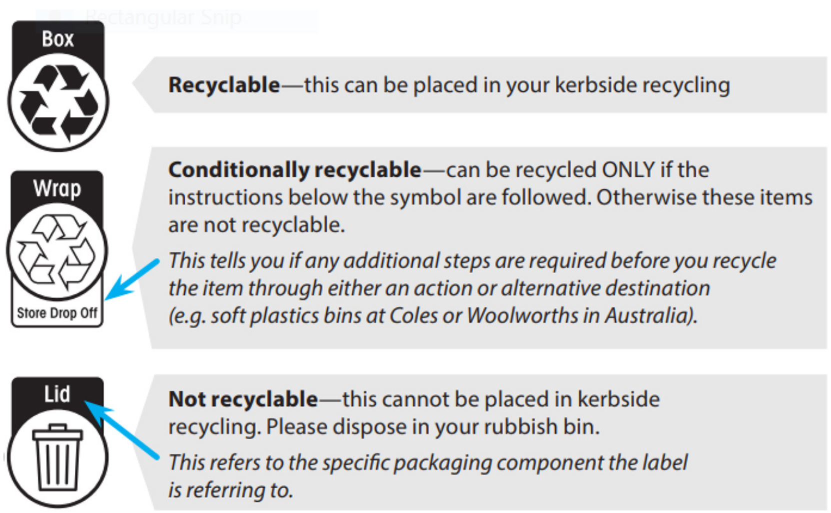

FIGURE 1
Example of the Australasian recycling label to be featured on 80% of supermarket products by 2023. The label will also be used for business-business packaging.

ensure recycled materials are purchased. Consumers can feel confident that the plastic they place in their recycling bin is recycled and placed back on the shelf as a new product for them to purchase.

The mismatch between political cycles and policy implementation—Agenda setting

A risk to any policy, particularly those that arise from surges in public interest, is its discontinued or delayed implementation due to changes in elected governments, political agenda, and public attention (Bailey, 2022). Amid the disruptions of the COVID-19 pandemic, Australia moved forward with policy actions that target reducing plastic waste. With plastic pollution identified as an important global issue, increased focus from government and industry to tackle the problem will be key. Governments often take low-risk approaches, typical of wicked problems, to deal with creeping crises such as plastic pollution (Mcconnell, 2018; Mæland and Staupe-Delgado, 2020). The "crisis overreaction" to COVID-19 was used as a political tool by many nations, such as the US, Australia and Canada to win national elections in 2020 and 2021 (Maor, 2020). The COVID-19 focus overshadowed the plastic issue. The outcome of the most recent Federal election in Australia held in May resulted in a change of government. While plastics were not a major focus of the campaign, environmental issues and climate change were key topics. The Australia National Plastics Plan does provide long-term guidance for actions that extend beyond a single policial cycle, and the change of government will determine how the Plan will continue to be utilized. The Plan's success will require collaboration between and within those implementing the Plan and its end users. Long-term political will could buffer the Plan's momentum against declining interest which often occurs during change of ministers or government (especially if the political party that forms government changes) (Hudson et al., 2019). Currently, few countries have the mechanisms need to support more robust policies (Gold 2014). Australia's commitment to UNEA and the upcoming Plastics Treaty may be the catalyst to keep plastics on the agenda.

A call to action

A fundamental shift in society's relationship with plastics can include a multitude of approaches. By treating plastic as a commodity rather than as waste and with economic incentives, materials recovery will be improved, which in turn can drive new business opportunities. There is also a substantial role for best practice guidelines and standards, whether for food safe packaging, for targets such as those set by the National Plastics Plan of Australia, or by industry, local or state governments, or from grass roots campaigns (Willis et al., 2022). Taking a regional approach to materials recovery will likely also yield benefits, particularly if reverse logistics are included in products through supply chains. It is an exciting time with the recent binding UNEA 5.2 resolution passed earlier in 2022. There is an increased will and focus on plastics from local to global scales. In this decade of the Ocean, there are multiple opportunities to shift the dial on plastics, from inception, to manufacture, through use and materials recovery. Focusing on place-based, equitable solutions will result in improved outcomes locally, regionally, and globally.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

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Global landscape analysis of reuse and refill solutions

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One important strategy to address plastic pollution is replacing disposable items with reusable ones and creating systems to support the circulation, cleaning and reuse of these items. The Global Landscape of Reusable Solutions was created to understand the evolution, current state, and potential environmental benefits of reuse and refill solutions being provided in nine distinct categories. The Landscape is a consistently updated dataset created through desktop research by researchers in seven geographic regions and engagement with experts around the world. As of June 10, 2022, the Landscape identified 1,196 solutions operating in 119 countries. The top three categories were 557 Package-Free Shops, 169 Reuse Advocacy Programs (excluding advocacy efforts by for-profit companies in the space), and 155 Reusable Cup and Container Programs. While 52 of the solutions in the global landscape are established or mature, 79.6% (952) are start-ups or small businesses (e.g., Package Free Shops with only one location). Europe has the largest number of reuse solutions with 441, and North America follows with 317. Barriers to growth for reuse solutions include solving for reusable item material and assortment, expanding and integrating reuse infrastructure, willingness of businesses to adopt reuse solutions amid concerns of impact on transaction speed and operations and acceptance by customers; and, in some locations, policies that restrict reusing and refilling containers. Adoption and scaling of reuse solutions can be supported by behavioral campaigns that normalize and promote reuse, better and more available data, sharing examples of successful systems, and increasing knowledge and understanding of reuse system design.

KEYWORDS

circular economy, plastics, plastic pollution, marine debris, reuse, refill, disposable, packaging

Introduction

Plastic pollution is already established as a pressing global issue. An estimated 11 million metric tons of plastics entered oceans in 2016, with most of the rest incinerated or landfilled (Lau, 2020). Plastics are found in all parts of the natural environment—from the deepest parts of the ocean (Peng et al., 2020) to the highest mountains (Napper et al., 2020), and even now in human blood (Leslie et al., 2022) and lungs

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(Pauly et al., 1998; Jenner et al., 2022). And plastic waste in our environment is just one part of the plastic pollution problem. Plastic production accounts for more than 3% of total U.S. energy consumption (DOE, 2022), and carbon emissions from plastic production will reach 17% of the global carbon budget by 2050 (Hamilton and Feit, 2019; Zheng and Suh, 2019).

Recycling systems are currently facing many challenges, especially related to recycling plastics. Only about 5% of the waste plastic in the United States was recycled in 2019, while 86% went to landfills (Milbrandtet al., 2022). Comprehensive modeling of all viable plastic leakage reduction strategies at their maximum realistic contribution found that recycling could only comprise 18% of the reduction of leakage of plastics by 2040, while new delivery models, reuse and reduction could represent as much as a 30% reduction (Lau, 2020).

Literature on reuse systems generally reflects the relatively new advent and spread of these systems, which are somewhat limited. A recent review of circular economy literature on plastics found that a high proportion of work focuses on the end-of-life phase, rather than examining design, production, use, or the value chain (Johansen, 2022). In calling for a more holistic view of plastics along the value chain, reuse systems are a key piece that can fill gaps and address needs for lightweight packaging while reducing overall footprints (Klemeš et al., 2021).

Waste hierarchies published by governmental (e.g., US EPA, European Commission, Thai Environmental Institute, etc). and nongovermental organizations (e.g., Zero Waste International Alliance, etc.) place Source Reduction/Prevention & Reuse at the top of the waste management hierarchy, followed by Recycling and Composting. Reuse is ranked above recycling in the "3Rs" as some life cycle assessment (LCA) findings show that reuse systems outperform single-use plastics in measures of environmental impact and bring other benefits, like reduction of waste and emissions (Hamade et al., 2020; Greenwood et al., 2021). Reuse and refill is a rapidly evolving space. However, this idea, that reusable products are always better than single-use plastics, comes with the caveat reusable products must actually be reused a certain number of times to achieve lesser greenhouse gas (GHG) emissions compared to disposable products (Miller, 2020). Other scholars have pointed out that GHG emissions are not the only measure of environmental impact that should be accounted for when drawing LCA boundaries to assess packaging options (Walker and McKay, 2021).

Though there is convergence among waste hierarchies in ranking prevention and reuse highest, recycling and composting have received high interest from corporations in addressing plastic pollution. For example, companies who have signed on to the Ellen MacArthur Foundation New Plastics Economy Global Commitment have committed to make all of their packaging recyclable, compostable or reusable by 2025, yet the evidence available to date shows that companies are leaning much more heavily on recycling and composting than reuse to achieve this goal (Ellen MacArthur Foundation., 2021). One reason companies are shying away from reuse may be that while consumers are driving the shift to reduce plastic consumption in the fast-moving consumer-good industry, their behavioral patterns are also viewed as an obstacle to change, according to a qualitative study of perceptions among industry leaders (Ma et al., 2020). Corporate commitments to reduce plastic waste entering the environment may use inconsistent definitions of the 3Rs, and concepts of reduction and reuse are mostly associated with recycling rather than redesign (Rhein and Schmid, 2020). As compostable plastics appear on more grocery shelves, the presence of both compostable and traditional plastics may lead to contaminated feedstocks in composting and recycling, and limits profitability, a necessary ingredient for expanding the availability of composting and recycling (Yesaya et al., 2021). With the goal of the circular economy to "slow, narrow, and close material resource loops", switching from fossil fuels to biologically based resources alone may not provide a fundamental shift to sustainable and regenerative supply chains (Tan and Lamers, 2021).

Of particular note is the recent COVID-19 pandemic, where businesses turned to single-use take-out packaging as a way to manage during lockdowns (Charlebois et al., 2022). While reuse systems exist in some specific consumer markets (e.g. beer and soft drinks), reusable packaging solutions are more common in the business-to-business (B2B) space rather than business-to-consumer (B2C) markets (Coelho, 2020). An additional barrier is that consumers may be more willing to engage with familiar reuse systems rather than new innovation (Greenwood et al., 2021). A consumer study in the U.K. found that when given the choice to dispose, reuse, or recycle packaging that recycling was the preferred method of waste management (Greenwood et al., 2021). However, many large multinational companies have committed publicly to increase use of reusable packaging. The current global landscape of reusable solutions has not been well-documented, therefore, the objective of this work is to categorize the growing reuse sector and determine the number and types of reusable solutions around the world. In addition, we characterize how the market of reuse solutions is evolving, which solutions are thriving, and identify barriers and enablers to growth of reuse solutions.

Methods

A reuse solution is defined in this context as an activity that directly facilitates or encourages the use and circulation of reusable packaging and food ware for the same purpose for which it was created. This research focuses on formal reuse systems—those run by an organization or business—rather than informal reuse systems, which are embedded in culture, practice, or just daily life in many parts of the world. Both types of systems are needed and valuable, and more research is needed into both.

The compilation of reuse solutions examined for this research started with a focus on the US, EU and Canada in January 2021 and was created through desk research, leveraging existing lists and using search and news articles to identify additional solutions. In August 2021, the dataset was expanded to the rest of the world with additional research conducted by student interns, university professionals, and in-region contractors in Southeast Asia, South America, and Africa. Once a publicly available solution was entered into the spreadsheet, a subset of entries (26.8% excluding Package-Free Shops or 18.2% overall) were validated by confirming, correcting, or adding any additional information by local contacts in each location. The eight operational reuse solutions (excluding Reuse Advocacy) are visualized in Figure 1, while Table 1 provides definitions, sub-categories and examples for all nine categories. The definitions of each category build on commonly used terms in this space, but have been defined by the authors.

The full dataset as it existed on June 10, 2022 is available in Excel as part of the Supplemental material. The dataset continues to be updated regularly (typically weekly) and is open and free to everyone, published publicly at (www.reuselandscape.org/database) (note that solutions that cease operating are kept in the database and marked Inactive).

Besides the category of business, the growth stages for each were identified by the researchers according to four categories outlined below. The categories of the growth stages are:

- Concept—the solution is in development or testing, but not yet operating even at pilot scale.
- Pilot/Start-up—the organization or a pilot exists, has at least some level of active operations but is still testing; pre-Series A funding for startups (Package-Free Shops businesses with one location are considered start-ups).
- Growth stage—the organization or pilot is successful and growing, receiving Series A and Series B funding rounds.
- Established—the organization is a successful business with a successful operating model. Although it may still be growing, it is well-established in at least one geography.

To further explore the industry dynamics and understand barriers to reuse adoption, 30 semi-structured interviews with reuse practitioners and experts (reuse program operators, reuse advocacy organizations and other NGOs, and impact investors) were conducted from February 2021 to February 2022 and, separately, a survey of reuse business owners garnered 27 survey responses during April and May 2022. Respondents to the survey with 27 responses came from businesses around the world,

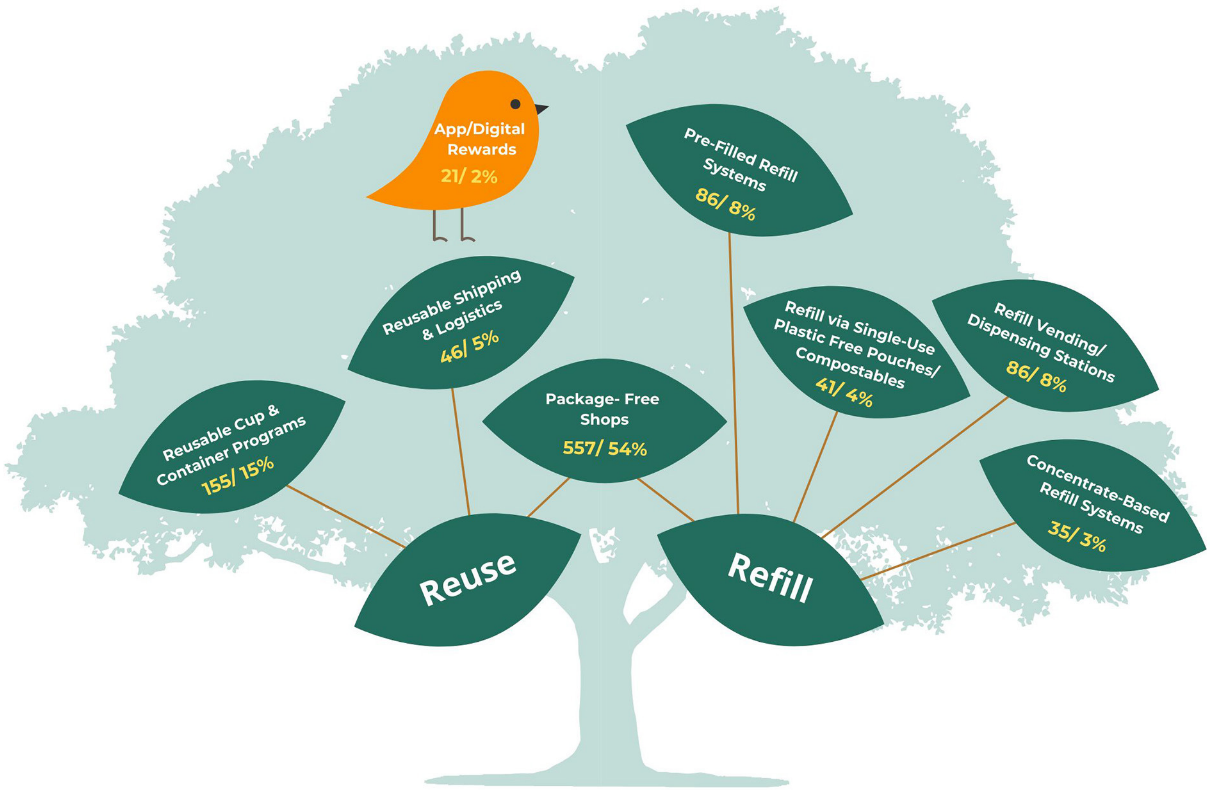
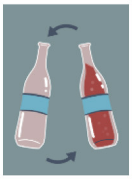


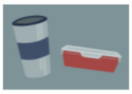
FIGURE 1
Overview of landscape of reuse and refill solutions by type and category.

TABLE 1 Category definitions and examples.

	Category	Sub-categories	Description	Examples
	Apps and digital rewards	• Reusable bag rewards • Water app/ rewards	Apps and digital rewards facilitate reuse behavior by giving users information on avoided environmental impacts, identifying reuse and refill opportunities, and/or providing discounts or rewards.	• Goodbag's reusable bags have near field communication (NFC) chips that are scanned in store to give users a choice of planting a tree, cleaning up plastic waste or receiving a discount.
	Concentrate-based refill systems	• Personal care • Home care • Perfume and cosmetics	Concentrate-based refill systems remove water from the product for transport and users reconstitute the product at home.	• Blueland's home cleaning and hand soap products are reconstituted at home with a branded tablet and tap water.
	Package-free shops	• Food and beverage • Home and personal care • Multiple	Package-free shops sell goods to consumers through bulk dispensers into owned or borrowed reusable containers. Package-free shops may have retail storefronts or exist solely online.	• Das Gramm provides zero waste grocery items both in store and *via* local delivery. Products that require packaging are available in either paper bags or returnable jars.
	Pre-filled refill systems	• Multi-brand pooling • Single brand program • Reusable bag pooling	Pre-filled refill systems use reusable packages that are filled with product by producers prior to being offered for purchase. Customers pay a deposit and receive their deposit back when they return the container.	• The German Wells cooperative provides mineral water producers with reusable glass and plastic bottles. Customers pay a bottle deposit, refunded on return. The cooperative washes and inspects the bottles before providing them to the brands to be refilled.
	Refill vending and dispensing stations	• Food and beverage • Home and personal care • Water	Refill vending and dispensing stations allow users to refill their own packaging. Some of these programs use proprietary technology to track bottle fills.	• Cozie charges users e1.50 for a proprietary container on their first purchase, then credits them e1.50 on their next refill. Customers refill using a proprietary refill station.
	Refill *via* single-use plastic free pouches or compostables	• Home care • Perfume and cosmetics • Personal care	Refill *via* single-use plastic free pouches or compostables allows users to refill their product using plastic-free pouches or compostable packaging. Most of these systems deliver refills through the mail.	• Above and beyond sells lip balm in an aluminum case. Refills ship in compostable pods that insert into the case.

(Continued)

TABLE 1 (Continued)

	Category	Sub-categories	Description	Examples
	Reusable cup and container programs	• Cup programs • Container programs	Reusable cup and container programs offer reusable cups or take out containers either for dine-in or takeaway. Programs typically charge either a deposit up front or charge a fee if it is not returned, though some use a membership model.	• Billiecup charges users a e1 deposit to ensure cups stay in the system. The deposit is refunded to the customer when they return the cup.
	Reusable shipping and logistics	• B2B • B2C	Reusable shipping and logistics includes both B2B and B2C transport. Reusable B2B shipping solutions include reusable pallets, pallet wrap, crates, and totes. B2C reusable shipping services replace single-use plastic or paper mailers and cardboard boxes with reusable packaging.	• IFCO's smartcycle program pools plastic containers amongst many parties in the produce supply chain. • Olive users shop from hundreds of e-commerce sites and receive deliveries in reusable shipping boxes, which are later picked up.
	Reuse advocacy	• Accelerator program/innovation challenge • Outreach and education • Policy advocacy and standard setting • Research • Technical assistance • Advocacy by for-profit businesses	Reuse advocacy encompasses campaigns and programs that encourage reuse.	• Habits of waste #CutOutCutlery campaign works to make food delivery services provide disposable cutlery to customers only if they request it. • Mission reuse helps businesses and municipalities with their reuse efforts through interactive webinars.

but the majority were from businesses with North American operations (21). Responses also came from Europe (7), Asia (1), Oceania (1) and South America (1). (Some businesses operate in more than one region and all locations were included in the tally of responses per geographic region). All of the companies surveyed operate in an environment where individuals can choose to use a disposable option or the reusable option. This study does not explore the aspects of consumer preferences that may lead to this decision, but rather is focused on what businesses report about their own experiences.

Results and discussion

As of June 10, 2022, the landscape of reuse solutions contained 1,196 distinct solutions globally. Solutions that encourage reuse included 161 Reuse Advocacy activities by non-profit organizations and 94 Reuse Advocacy activities by for-profit companies. There were 1,027 solutions identified that directly facilitate reuse and refill (this includes the 86 companies that also advocate for reuse policy). Just over half of these solutions are Package-Free Shops (54%), which provide opportunities for both reuse and refill. Even with extensive research, it is likely that Package-Free Shops are still under-represented in this analysis as it is challenging to identify some of these very local shops around the world.

The reuse category of solutions comprised 20% of the total and included Reusable Cup & Container programs (15%) and Reusable Shipping and Logistics (5%). The refill category of solutions comprised 24% and included Refill Vending and Dispensing Stations (8%), Pre-Filled Refill Systems (8%), Refill *via* Pouches or Compostables (4%), and Concentrate-Based

Refill Systems (3%). Apps and Digital Rewards are 2% of the total, and can be an enabler of other solutions as well (Figure 2). Refill solutions tend to be for branded products, typically replace primary product packaging, and largely reflect a commitment from individual brands to provide refill options. In contrast, within the reuse solutions category the solution providers are more often startups providing services rather than selling products. Reusable Shipping and Logistics solutions are replacing secondary or tertiary packaging with packaging-as-a-service and Reusable Cup and Container programs are replacing disposable foodware with foodware-as-a service. In this way, Package-Free Shops are more like refill solutions, as they are replacing single-use packaging for the products that they sell.

Reuse and refill solutions were identified in 119 countries across seven regions. Europe has the highest number of solutions identified (404), followed by North America (297) and then Asia (188). The mix of solutions is relatively consistent across those three regions. Organizations that operate globally (defined here as in at least 2 different regions) offer an even mix of solutions compared to individual regions. Regional differences in number and mix of solutions may be driven by consumption patterns, policy and regulatory context, alignment of reuse with existing cultural norms or legacy systems, appetite of local investors to fund new solutions, and other factors (Xanthos and Walker, 2017) (Figure 3). Despite dedicated efforts in Africa and the Middle East, researchers were unable to find as many solutions offered in these areas. This does not necessarily mean that they do not exist. It must also be acknowledged that this research focused specifically on "formal" reuse and refill, meaning companies that are providing reuse and refill solutions, which excludes "informal" reuse and refill practices that are embedded in daily habits and cultural norms still in many parts of the world. As a result, it is possible that countries that still have strong informal reuse practices appear to be doing less on reuse and refill, when in fact the opposite is true. Further study of informal reuse and refill practices as well as how to encourage their adoption would be of great value to this field and would be complementary with this research.

The trajectory of new business launches followed a steep upward trajectory from 2014 and was interrupted in 2020 due to the COVID-19 pandemic. There were 81 new solutions launched in 2021 compared to 172 in the last full year before the pandemic, though this gap is almost entirely explained by fewer new Package-Free Shops, with the number of other types of solutions being launched holding consistent with pre-pandemic levels (Figure 4). With people doing less in-person shopping during the pandemic, a decrease in the launching of shops such as this is reasonable. In some cases, reuse and refill practices were specifically limited or hindered by COVID-19 policies (Patrício Silva et al., 2021).

The vast majority of solutions (79.8%) are pilots or startups, indicating the young age of this field. It is important to keep this early stage sector maturity in mind when considering the barriers and enablers to growth. In Growth Stage, Package-Free Shops are the largest share, which here means shops with at least two locations, followed by Reusable Cup and Container programs and Refill Vending and Dispensing Stations, indicating that at least some of these businesses have been able to get traction with consumers. Of the established solutions, Reusable Shipping and Logistics make up 34.8% (16) and Pre-Filled Refill Systems make up 30.4% (14), which are primarily bottle pooling programs within bottle deposit return schemes (see Figure 5). It makes sense that the bulk of established solutions are in Shipping and Logistics and Pre-Filled Refill Systems because these are the two main 'reuse legacy' businesses. Business-to-business transport packaging services have existed for many years, while bottle pooling was a pre-plastic solution that has endured in certain parts of the world and is being expanded now in others.

Refill *via* Single-Use Plastic Free Pouches or Compostables grew the fastest over the last 3 years, followed by Concentrate-Based Refill Systems and Pre-Filled Refill Systems, though all categories expanded in the total number of solutions offered since 2019 in spite of the pandemic. This makes sense because these are refill models that customers can take part in from home *via* ecommerce. The growing number of reuse and refill solutions are expanding the opportunities for businesses and consumers to take action to address plastic waste and participate in the circular economy. The number of solutions being offered has grown significantly since 2014 and certain types of solutions are continuing to grow despite the disruption from COVID. The space is overwhelmingly populated with start-ups and small businesses, with more than half of these being individual shops offering products in reusable or refillable package formats. The growth of reuse and refill could be described as the emergence of a movement as much as a market.

Barriers and enablers to the adoption and scaling of reuse and refill solutions

The results of the 30 semi-structured interviews identified six key barriers to the growth of reuse: (1) solving for reusable item material and assortment, (2) integration with existing infrastructure including accessing or installing washing capacity, (3) convincing businesses to try the reuse solution out, (4) the presence of restrictive policy and lack of reuse-focused lobbying, (5) insufficient funding / investment in the space, and (6) consumer behavior and awareness. A lack of alignment on what the "best" material for reusable items is was noted—with tension between the perceived benefits of plastic (lightweight—and therefore lower GHG emissions in transport—and durable) and the perceived risks (leaching of chemicals and microplastics into food and beverages and looks dirty with wear) as well as related tradeoffs for other materials (glass/ceramic is inert but

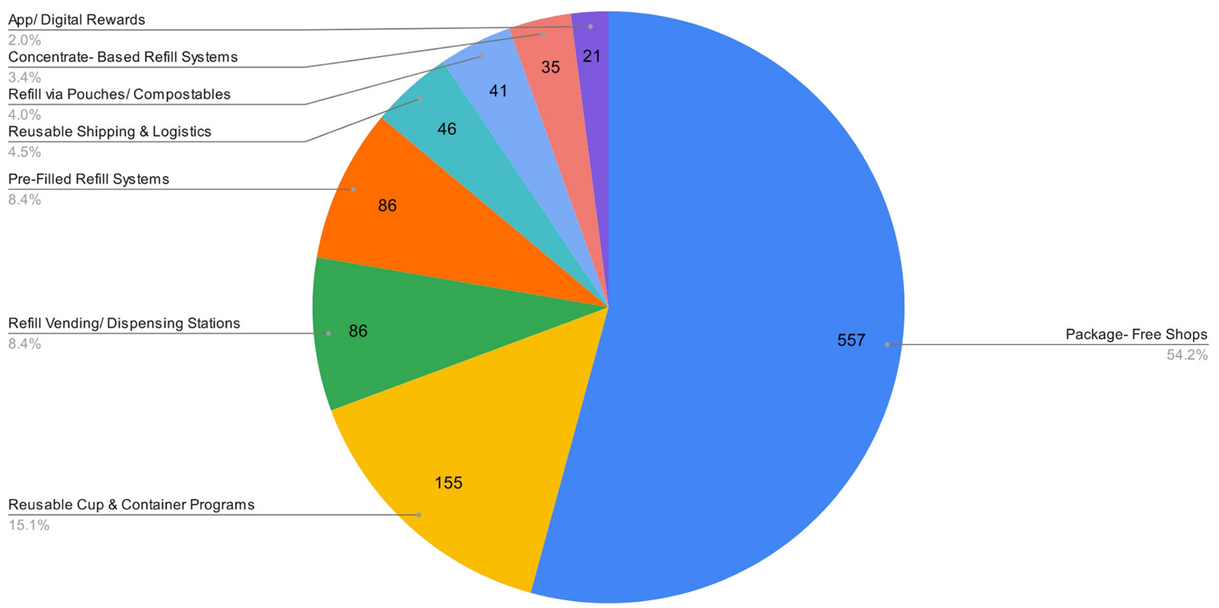


FIGURE 2
Reuse and refill solutions by category.

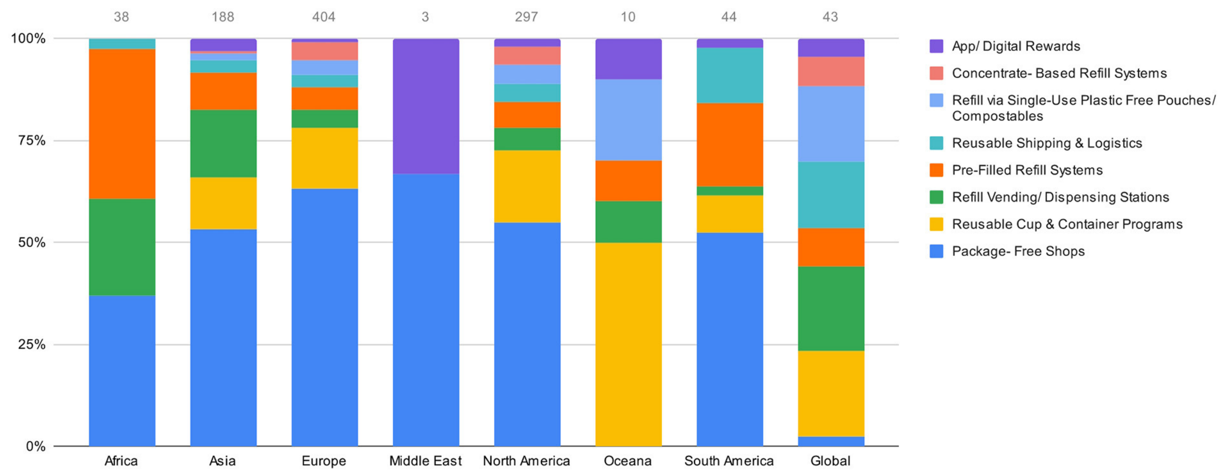


FIGURE 3
Reuse and refill solutions by type and active region.

heavy and not as durable, stainless steel is a high impact material but durable and safe). It should be noted that all six items listed above could be considered system-level challenges, meaning they must be solved by the sector collectively rather than by businesses individually. Indeed, this reveals a significant need for field-building for reuse and refill in general, supporting the cultural shift that must occur with both businesses, consumers and providers of capital. Additionally, the relationships between the barriers and their solutions suggests a logical sequencing that enables some barriers to provide unlocks for others. For example, getting consumers on board with and even demanding reuse and refill solutions could enable policy shifts as well as greater business adoption. Integration with existing or new infrastructure may be facilitated by greater adoption by businesses and securing funding, and would inform the reusable item material and assortmnet, underlining the importance of interoperability of systems. Reuse standards organization PR3 has released draft standards for each aspect of reusable systems to support the development of interoperable systems from the beginning.

In the survey of 27 reuse business owners, similar barriers were identified. The top concern was the perception by

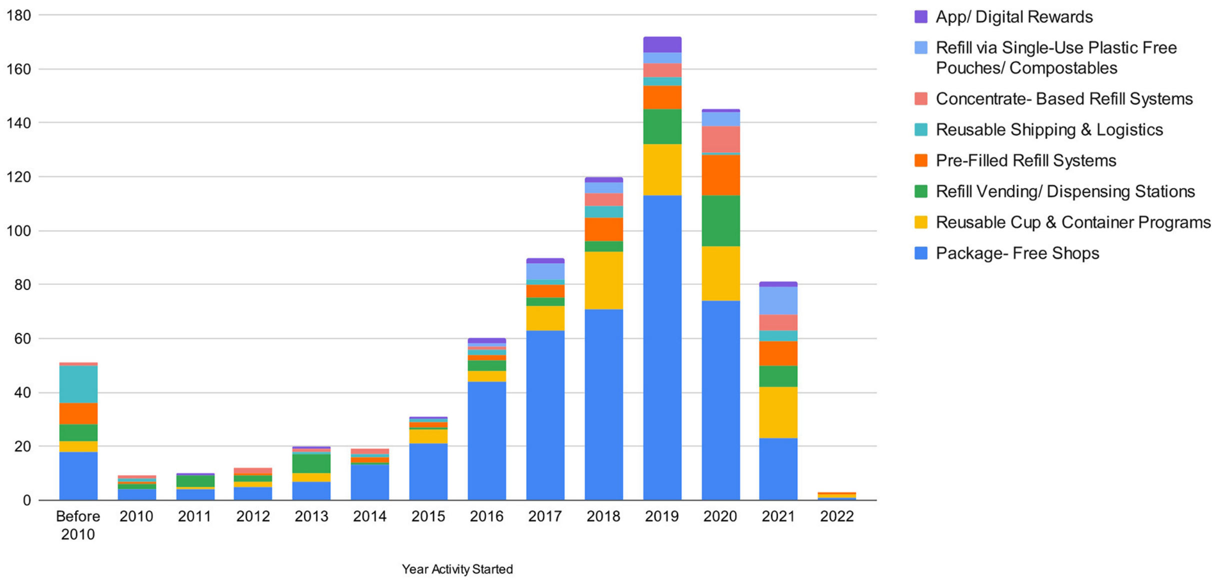


FIGURE 4
Reuse and refill solutions by launch year.

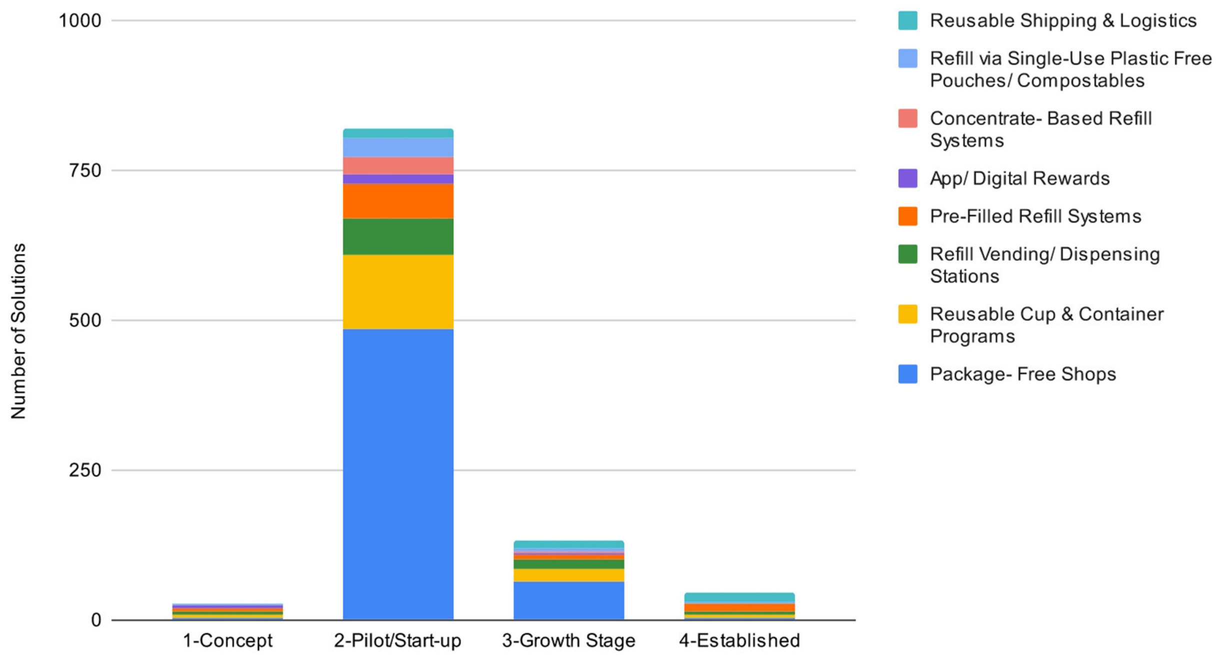


FIGURE 5
Reuse and refill solutions by growth stage.

restaurant owners that using reusable foodware would have a negative effect on operations because it would slow down transactions and consumers would not accept it, followed closely by lack of consumer awareness about the solution—meaning consumers didn't even know it was an option. Funding was mentioned but was not a dominant concern and tended to be ranked third after restrictive policies (Figure 6 top half). Additional write-in answers included the need for bi-directional logistics, better cooperation with others in the supply chain or community, balancing complexity with a

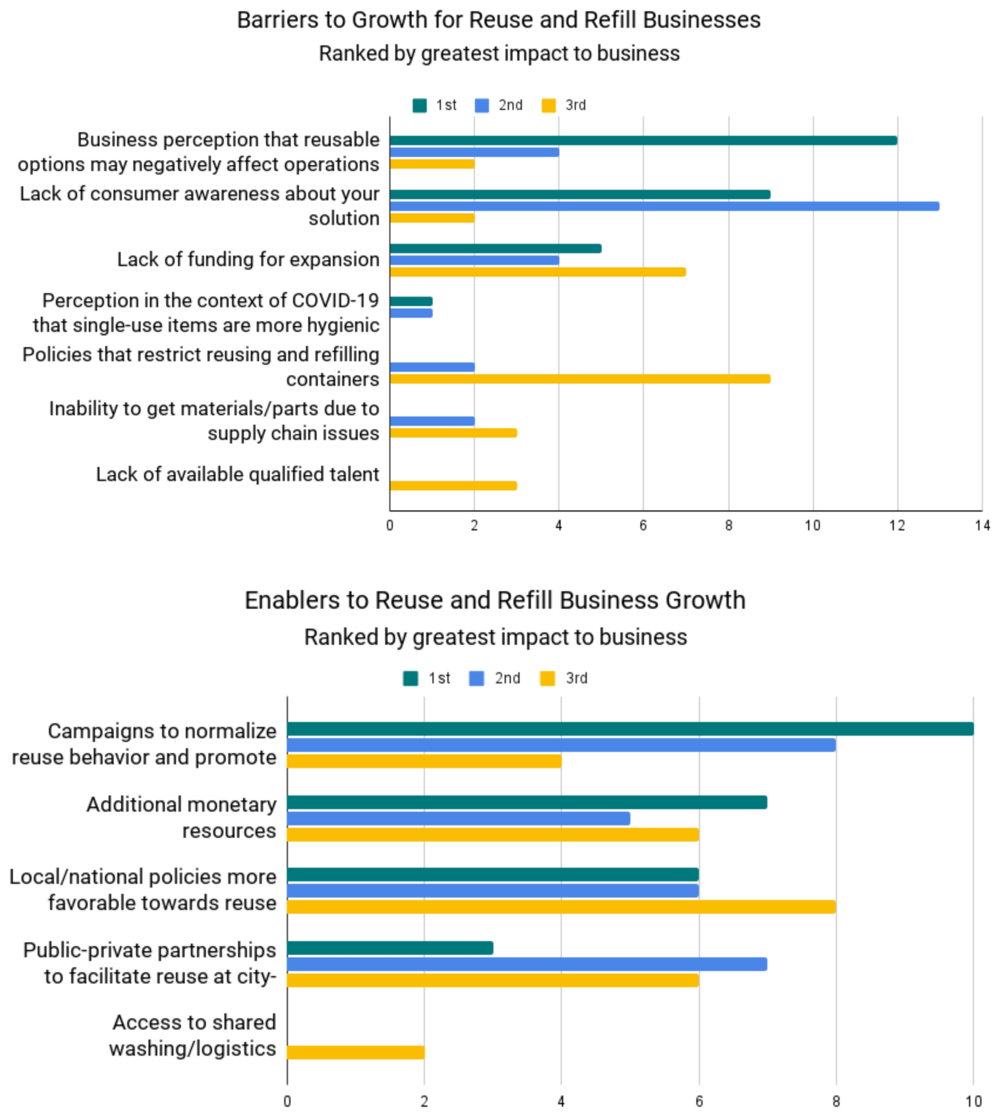


FIGURE 6
Barriers and enablers to growth for reuse and refill businesses, per survey of reuse business owners.

desire for a large number of SKUs (stock-keeping units), and the cost of reusables compared to disposables. These barriers are also largely system-level challenges more than individual business challenges and reflect the nascency of the sector as lack of awareness, understanding, and proof points are significant obstacles for businesses. Respondents saw different solutions to getting to parity on cost, with some seeing highly efficient, large-scale reuse systems as the path to economic sustainability whereas others are looking to policymakers to level the playing field.

In the interviews, the top enablers for reuse and refill business growth were identified as the existence of successful models, better data, increased system design expertise (to ensure systems meet high consumer expectations and have lower environmental impact), and enabling policies. The survey results surfaced "campaigns to normalize and promote reuse behavior" as the top enabler. The second one was additional monetary resources, which had not shown up as highly in the barriers list (Figure 6 bottom half). Additional write-in answers included efforts to thwart greenwashing from "fake reuse" solutions providers (e.g., more durable "souvenir" cups with no mechanism for facilitating reuse), integration with food delivery services, campaigns informing consumers of health risks from microplastics and chemicals of concern including PFAS, and subsidies or incentives for those adopting reuse.

Synthesizing the barriers and enablers across both the interviews and the survey: even with the growth trajectory of reuse and refill solutions over the last several years, businesses, consumers, and funders overall are still looking for clear demonstrations of the viability of reuse and refill solutions at sufficient scale to overcome operational and logistical questions, economic uncertainty, and current consumer habits tied to disposability.

Summary

The nearly 1,200 solutions identified and analyzed here show that there is strong interest from these businesses as well as their customers to use refill and reuse solutions to reduce waste from disposable packaging and products, in particular single use plastics. 78% of these solutions are displacing primary packaging, 20% are displacing disposable foodware or secondary or tertiary packaging, and the remaining 2% are apps that support reuse and refill behavior. Europe and North America currently have the highest number of identified solution providers, and Asia has just under half the number found in Europe. The fewer number of solutions identified in other regions may be due to the authors' research limitations, less interest from businesses or customers in those regions in reuse and refill solutions, or the presence of informal reuse practices that make formal solutions less necessary, or some combination of the three. The field of reuse and refill solutions is still nascent, with the majority of businesses at a start-up stage of growth, and the sector is continuing to grow rapidly, picking up speed again following the COVID pandemic.

The growth of reuse and refill businesses and advocacy is enabling a needed shift in how modern society consumes products, but it is not currently happening fast enough to move the needle on the global scale of plastic pollution or climate change. Many different actors in society have the ability to support the growth of these new delivery models: governments can remove restrictions and pass enabling legislation; investors and philanthropic funders can support businesses using or providing reuse and refill models; city workers, urban planners and mission-based recyclers can partner with service providers to integrate reuse and refill infrastructure into their communities; businesses can adopt new delivery models and invest in optimizing with the same level of focus and resourcing as has been given to the single-use packaging model; and marketers and the entertainment industry can normalize reuse and refill models for consumers so it just becomes part of daily life.

Considering reuse and refill as essential to reducing plastic pollution and GHG emissions, it is critical to consider how these solutions can be grown in a way that accomplishes these goals. As the interview and survey responses identified, this growth can build on the success of pilots, but this will require a growing number of people with expertise in reuse systems and more data on how to optimize these systems. At the same time, reuse and refill must become familiar ways to consume products, while meeting consumer expectations and needs. The policy environment is also a critical piece—both ensuring the absence of restrictive policies and supporting the passage of enabling policies. While there are examples of reuse and refill on six continents and 119 countries, the growth and development of these solutions is not happening evenly across geographies. This creates opportunities for learning across geographies but with the recognition that solutions must be tailored to local context and culture.

It is easy to forget that it was not that long ago that single-use packaging was not available. While legacy reuse systems may provide helpful models and inspiration, reuse and refill models in the twenty first century can leverage the best available technology, hygiene systems, human-centered design insights, supply chain optimization, and life-cycle data to meet the needs of consumers today and for a very long time.

Data availability statement

The specific dataset presented in this study can be found in the Supplementary material. The live, continuously updated reuse landscape database can be found at the link below: https://www.reuselandscape.org/database.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

EM and KG designed the database and the website to host it, reached out to each organization listed to ask them to validate their information, conducted the interviews, wrote and analyzed the survey, and analyzed the dataset. KG did a significant portion of the desk research in the US and Europe, worked with researchers in other regions to support them in their research, and also created the charts. KY did the literature review and provided input on the analysis and discussion. JJ provided overall guidance and support on the interviews, survey, data analysis, and insights. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Authors EM and KG are employed by Moss & Mollusk Consulting.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2022.1006702/full#supplementary-material

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The capabilities and deficiencies of life cycle assessment to address the plastic problem

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Plastic is a ubiquitous material that has caused major environmental impacts. Ecosystem damage from improperly disposed plastic waste is the most visible of these impacts; however, plastic also has less visible environmental impacts throughout its supply chain. At the same time, plastic is not unique in possessing severe, often invisible, environmental impacts that occur throughout its life cycle. Life cycle assessment (LCA) is a helpful tool can be used to contextualize the environmental impacts of plastic compared with alternative solutions or material substitutes. LCA can broaden our understanding of the environmental impacts of a product beyond what is the most obvious and visible, taking a comprehensive view that encompasses raw material extraction, manufacturing, transportation, use, and end-of-life. LCA can be used to target specific areas for improvement, understand and evaluate tradeoffs among different materials, and can be helpful to avoid environmental problem-shifting. This review provides an overview of the LCA process and describes the benefits and limitations of LCA methods as they pertain to plastic and plastic waste. This paper summarizes major trends that are observed in prior LCA studies, along with a discussion of how LCA can best be used to help resolve the plastics problem without causing other unintended issues. The life cycle perspective analyzes the environmental impact associated with a specific product, often comparing the environmental impacts of one alternative to another. An alternative perspective analyzes the aggregated environmental impacts of the entire plastic sector, analyzing the full scope and scale of plastics in the environment. Both perspectives provide meaningful data and insights, yet each provides an incomplete understanding of the plastics problem. The comparative LCA perspective and the aggregated environmental impact perspective can complement one another and lead to overall improved environmental outcomes when used in tandem. The discussion highlights that reduced consumption of the underlying need for plastic is the only way to ensure reduced environmental impacts, whereas interventions that promote material substitution and or incentivize shifts toward other kinds of consumption may result in unintended environmental consequences.

KEYWORDS
marine litter, comparative LCA, circular economy, plastic bag bans, waste management, reduced consumption

Introduction

Life cycle assessment (LCA) is a tool to systematically evaluate the environmental impacts of products or systems (Vignon et al., 1992). It is often used to support design or policy decisions related to improving the sustainability of a product, to select among alternative materials, or identify consequences or tradeoffs that are not immediately obvious. Life cycle methods and datasets have evolved significantly over the past decades to improve overall data availability, robustness, and usefulness (Laurin, 2017); however, LCA practitioners widely acknowledge its imperfections and the need to continually improve the tool (Huijbregts et al., 2001; Reap et al., 2008; McKone et al., 2011; Hauschild et al., 2013; Bergerson et al., 2020).

Plastic, and plastic waste specifically, is an environmental issue that is studied by multiple intellectual communities, each with different research traditions and perspectives. Recently, there have been conversations in the scientific literature and popular press debating the extent and severity of the plastic issue. The debates include whether public perception of ecosystem risk corresponds to scientific evidence (Burton, 2017; Backhaus and Wagner, 2020; Völker et al., 2020; Catarino et al., 2021; Zhou et al., 2021), as well as the relative importance of plastic waste to other pressing environmental challenges (Stafford and Jones, 2019a; Ford et al., 2022). There have also been debates surrounding the potential effectiveness and impact of proposed solutions such as implementation of plastic bans (Lewis et al., 2010; Martinho et al., 2017; Wagner, 2017; Herberz et al., 2020; Macintosh et al., 2020; Völker et al., 2020; Meert et al., 2021; Gómez and Escobar, 2022; Huang and Woodward, 2022). Some researchers studying the impacts of plastic waste have critiqued life cycle thinking approaches for inappropriately analyzing the impact of plastic waste (Walker and McKay, 2021). While certain perspectives may never be fully resolved, this review seeks to provide insights on the usefulness and limitations of LCA to evaluate the plastic challenge and contrast the LCA perspective with an aggregated environmental perspective that focuses on the magnitude of total impact.

Specifically, this review seeks to (1) summarize major insights from the LCA community regarding the environmental impact of plastics and plastic waste; (2) discuss the limitations of LCA as it relates to plastic waste and identify where improvements can be made; and (3) discuss how different perspectives can lead to different conclusions and how to integrate these perspectives.

Background

Environmental impacts of plastic

Plastic products are ubiquitous in society. The use of plastic has rapidly increased over the past decades due to relatively inexpensive production costs and a range of physical properties that have allowed technological advances across various industrial and product sectors (World Economic Forum, 2016). As with any material, plastics contribute to environmental impacts throughout their life cycle (APME, 2003): impacts associated with drilling for natural gas of which they are derived, manufacturing into the product or product pre-cursor, transportation, potential fugitive emissions during use, and end-of-life (Dormer et al., 2013). In addition to the emissions associated with energy use during all of these phases, plastics also contribute to resource depletion, consuming fossil fuel reserves through the conversion to plastics, even when recycling is available (Geyer et al., 2016; Zink and Geyer, 2019). Finally, plastics contribute to environmental impacts at their end-of-life, both in terms of waste management or recycling (Hou et al., 2018), or *via* leakage into ecosystems (Scagnetti and Lorenz, 2022).

As of 2015, plastics were responsible for 1,781 Mt CO_2-eq throughout their entire life cycle, consisting of production (1,085 Mt), conversion (535 Mt) and end-of-life (161 Mt), which represents over 3% of overall global GHG emissions (Zheng and Suh, 2019). Although the majority of plastic is landfilled with a much smaller portion recycled, between 4.8 and 12.7 million Mt of plastic waste was estimated to enter the ocean from coastal countries in 2010 (Jambeck et al., 2015). In the United States, it is estimated that ∼2% of plastic "leaks" into the environment, either through improper disposal or abrasion of materials during their normal use (i.e. tire wear, shedding from textiles) (Heller et al., 2020). Roughly 30% of plastics are considered durable, with an intended long-term use in construction, electrical, or consumer product use (Heller et al., 2020). Many plastics, particularly those used in the packaging sector, are designed for a single use with very short lifespans prior to end-of-life (Heller et al., 2020).

What is LCA and how is it used?

LCA is a tool that provides a framework for a comprehensive, systematic analysis of the environmental impacts of a product or process. LCA can be used to understand the full scope of impacts of a single product in its entirety or can be used to compare multiple products. It is used to evaluate all aspects of a product from raw feedstock extraction through its end-of life (i.e. cradle-to-grave) or can focus on specific portions of a supply chain, such as the environmental impacts before a product reaches the market (i.e. cradle-to-gate). Taking a holistic and systematic approach throughout the entire life cycle is critically important when trying to find solutions to specific environmental problems because there are numerous instances where the intended solution to one environmental problem caused a different kind of environmental issue (Davis and Thomas, 2006).

The major elements of an LCA are (1) goal and scope; (2) life cycle inventory; (3) life cycle impact assessment; (4) interpretation (Vignon et al., 1992). The goal and scope phase defines the research questions the assessment intends to answer, the environmental impacts that will be included, the data that will be collected, and the boundaries of the analysis. The life cycle inventory phase consists of data collection, verification, and sensitivity analysis. The life cycle impact assessment phase translates the material, energy, and emissions data compiled during the inventory phase into appropriate metrics to quantify the environmental impacts of interest. The interpretation phase discusses the overall results of the study, including helping to contextualize the results and highlighting the assumptions and limitations of the study. The phases of an LCA are often conducted iteratively to best tailor the assessment to its specific purpose.

LCA methods have become significantly more robust since their inception, with larger numbers of datasets becoming available from which to draw inventory data and increasing levels of sophistication and complexity. Nevertheless, some of the harshest critics of LCA methods are LCA practitioners themselves, with multiple formal and informal working groups seeking to improve challenges that persist in LCA's implementation (SETAC, 2001; Rosenbaum et al., 2008; Sonnemann and Valdivia, 2017; Bergerson et al., 2020). While the LCA method has specific requirements that are dictated by the International Organization for Standardization (ISO) (2006), much of the guidance within ISO allows a degree of flexibility to allow practitioners to make methodological choices that align with the goals of a particular study. This flexibility allows an LCA to be suited to a given purpose but can have a confounding effect where different LCAs of the same product produce seemingly different results. Much of the criticism levied at LCA tends to focus on one of three major issues: the boundaries of the analysis (Matthews and Small, 2000; Frijia et al., 2012; Choudhary et al., 2014; Kakadellis and Harris, 2020), data uncertainty and data quality (Huijbregts et al., 2001; SETAC, 2001; von Bahr and Steen, 2003; Lo et al., 2005; Tan et al., 2007; Hung., 2009; Mullins et al., 2011; de Kleine et al., 2014; Pernollet et al., 2017; Xue et al., 2017), and appropriately capturing the environmental impacts (Knoepfel, 1996; Notarnicola et al., 1998; Goedkoop and Spriensma, 2001; Bare et al., 2003; Rosenbaum et al., 2008; Hauschild et al., 2013; Ernstoff et al., 2019; Saling et al., 2020).

Defining the boundaries and functional unit of an LCA is one of the most critical decisions of the process and can greatly influence the overall results of a particular analysis (Deng and Williams, 2011; Frijia et al., 2012; Ng et al., 2013). While most LCA examine the full supply chain of a product "from cradle-to-grave" that include all stages of resource extraction, transportation, manufacturing, use, and disposal, there are valid reasons to truncate the analysis. For example, some LCA may focus on the "cradle-to-gate" boundary that do not include the consumer use or disposal phases in order to focus on impacts within the scope of a manufacturer's control. Similarly, different boundaries can be drawn associated with "attributional" and "consequential" impacts (Brander et al., 2009; Earles and Halog, 2011). An attributional boundary definition only includes the materials and energy that are directly associated with a given product. Meanwhile, a consequential boundary also includes estimation of indirect impacts that can result from changes that are induced by adoption of the product. In each of these cases, different boundary choices are likely to lead to different results (Bamber et al., 2020; Schaubroeck et al., 2021).

Lack of quality data is an issue frequently cited in the LCA literature (Miì A I Canals et al., 2011; Hetherington et al., 2013; Sanju?n et al., 2013; Fernando Morales-Mendoza and Azzaro-Pantel, 2017). Data may not be available because the product is new and there is not a sufficient basis for data collection or there may be an inventory flow that is particularly difficult to measure, such as fugitive emissions. Fugitive emissions are unmeasured releases of an emission to the environment that occur outside of the designed flow of materials (Wanichpongpan and Gheewala, 2007; Brandt, 2011; Wang et al., 2018; Grubert and Brandt, 2019). Also termed "leakage", fugitive emissions of plastic are the primary mechanism for plastic debris to enter aquatic environments and one of the current challenges of LCA for plastic products (Chitaka and von Blottnitz, 2021; Scagnetti and Lorenz, 2022). Marine litter often originates from communities where modern waste collection infrastructure is lacking or by inefficient capture of plastics by waste collection, leading to significant amount of plastic leakage in some contexts (Jambeck et al., 2015; Geyer et al., 2017).

Finally, much discussion has surrounded the methods that LCA practitioners use to characterize the environmental impacts of a product, which is particularly relevant for the case of plastic emissions[73]. The life cycle inventory phase of LCA collects raw data regarding energy and material inputs and emissions and wastes, but raw emissions data does not provide a full picture of actual environmental impact. The life cycle impact assessment phase is needed to translate the raw inventory data into a measure of environmental impact (Goedkoop and Spriensma, 2001; Norris et al., 2001; Jolliet et al., 2003; Bare and Gloria, 2006; Hauschild et al., 2013). A subset of the LCA research community has dedicated efforts to developing appropriate methods and tools to perform environmental impact assessment, characterizing and quantifying the environmental impacts associated with specific emissions and the causal linkages between emissions and impact (Jolliet et al., 2003; Landis and Theis, 2008; Rosenbaum et al., 2008; Hauschild et al., 2013; Speck et al., 2015; Huijbregts et al., 2017; Wenning et al., 2017). Life cycle impact assessment highlights that "environmental impact" is not a singular entity, but multiple categories of impact that affect the environment differently. LCA practitioners must select the environmental impact categories they will measure in the context of the study (van Hoof et al., 2014). Different studies may elect to focus on a subset of impact categories that are deemed the most relevant or for which data are known to be available. Common environmental impact categories include climate change, energy use, eutrophication, smog formation, ozone depletion, human toxicity, ecotoxicity, acidification, ozone depletion, and natural resource depletion (Bare, 2011). Additional impacts categories, such as methods to estimate the impacts of marine litter, are actively in the process of development and discussed in greater detail below.

There are methods to translate different kinds of emissions into a metric associated with a specific environmental impact category, which are known as midpoint indicators (Jolliet et al., 2004). For example, carbon dioxide, methane, and nitrous oxide are all greenhouse gas emissions, but nitrous oxide is much more powerful than carbon dioxide. Therefore, all greenhouse gas emissions have a conversion factor to translate each kind of emissions into a similar midpoint indicator, in this case, a global warming potential measured as mass of CO_2-equivalents (IPCC, 2014). Endpoint indicators aggregate midpoint environmental impact categories into overall damage categories such as human health, biodiversity, and resource scarcity (Huijbregts et al., 2017).

When interpreting the results of an LCA, it is important to remember that all materials require energy and create emissions throughout their life cycle. All materials have some level of electricity-related and transport emissions, as well as environmental impacts that are specific to the material. Plastics are derived from fossil fuels and do not degrade easily, which lead to various ecological issues. Meanwhile, metals and glass require mining during their raw material extraction process and high temperatures during their manufacture. Pulp & paper production has significant aquatic loading of COD and BOD, whereas bio-based products (cotton, natural fibers, bioplastics) tend to consume large quantities of fresh water and land, while also contributing to aquatic nutrient and pesticide pollution. These tradeoffs are inherent and real and cannot be fully rectified by LCA or any other assessment tool. There is no manufactured material that is devoid of environmental impact; therefore, it is relatively rare to find comparative LCA where one alternative is better in all measured impact categories unless an alternative is able to reduce or eliminate consumption of materials. While plastic is certainly responsible for a host of environmental impacts including damage to marine life, LCA methods highlight that substituting alternative materials for plastic without an actual reduction in consumption are likely to create different environmental impacts elsewhere (Miller, 2020).

For proper interpretation of any LCA study, it is important to know what environmental impact categories are being measured and included in the study. Some impacts are relatively easily captured and have a direct, linear relationship with inventory emissions. This is the case with GHG emissions, where: (1) GHG emissions are relatively straightforward to estimate within the context of life cycle inventory data collection; (2) there are well established relationships between GHGs with different radiative properties to be able to translate into CO_2 equivalents (i.e., methane is 25 stronger than CO_2); (3) the relationship between emissions and impact can be reasonably approximated as linear (i.e., 100 kg CO_2-eq has ten times greater impact than 10 kg CO_2-eq). In addition, GHG emissions are not location specific; a kg of CO_2 emitted in on geography has the same overall impact as a kg of CO_2 emitted elsewhere. Even so, GHG emission inventories can be highly uncertain in specific contexts. For example, estimating the fugitive methane emissions from natural gas extraction are highly variable and are difficult to quantify without direct measurement (Howarth et al., 2011; Alvarez et al., 2012). Also, because CO_2-eq are a midpoint impact category that are used as a proxy for overall damage, an LCA that reports climate emissions in terms of CO_2-eq is generally not accounting for the full damage associated with CO_2 emissions, including impacts of elevated GHG on oceans due to increased temperatures and acidification.

Environmental impacts not related to climate change tend to be more difficult to capture within LCA, due to both data availability and the nature of specific impacts. Although marine litter is a great example, it is not the only case where impacts are difficult to estimate from inventory results. For example, forest fragmentation that can be associated with some bio-based products has similar challenges (Seager et al., 2009). Similarly, quantifying noise pollution's impact to ecosystem and human health is difficult to quantify (Meyer et al., 2017). Fugitive emissions occur in many common pathways and are not often reported in LCA, for example coal dust that causes air pollution during rail transport or infrequent events such as coal ash or fracking fluid spills (Vengosh et al., 2009; Chen et al., 2017). Despite the challenges, there have been major efforts to improve characterization of a variety of environmental impacts beyond climate change (Knoepfel, 1996; Notarnicola et al., 1998; Goedkoop and Spriensma, 2001; Bare et al., 2003; Rosenbaum et al., 2008; Hauschild et al., 2013; Ernstoff et al., 2019; Saling et al., 2020), including efforts to create an impact indicator for marine litter.

Development of metrics to appropriately assess marine litter

In contrast to GHG emissions, marine litter associated with a single-use plastic application is (1) highly variable and difficult to measure (Malli et al., 2022); (2) the relationship between marine litter and physical ecosystem damage is complicated and the science surrounding environmental impact is still being debated (Salieri et al., 2021); (3) does not necessarily exhibit linear behavior between amount of discarded plastic and damage to ecosystems (Woods et al., 2016). A kg of plastic discarded in a coastal community with poor waste management infrastructure will have a different probability of ecosystem damage compared to a kg of plastic discarded in an inland community with well-developed management capabilities. In addition, estimating the probability that a given piece of discarded plastic will eventually cause ecosystem damage is difficult to measure directly. Finally, there is likely a non-linear relationship between marine litter and ecosystem damage. Marine litter can damage ecosystems in multiple ways, including physical damage associated with strangulation or ingestion of larger plastic debris, accumulation of microplastics in the digestive system, and toxicity associated with microplastic.

Multiple efforts to better estimate "plastic leakage" are ongoing to improve life cycle inventories and impact assessments of plastic materials. The Medellin Declaration on Marine Litter in 2017 established a commitment by the LCA community to provide evidence-based guidance for inclusion of plastic pollution in LCA, including both improved methods for calculating the fraction of plastics that are released into the environment and methods to estimate the resultant environmental damage (Sonnemann and Valdivia, 2017). The Marine Impacts in LCA working group was formed to help coordinate and disseminate efforts to reduce this gap in LCA methods (Boulay et al., 2021). Multiple efforts to integrate marine litter impacts alongside more long-standing impact categories are ongoing and vary in levels of complexity and robustness (Civancik-Uslu et al., 2019; Saling et al., 2020; Boulay et al., 2021; Lavoie et al., 2021; Stefanini et al., 2021; Woods et al., 2021; Corella-Puertas et al., 2022; Maga et al., 2022; Tang et al., 2022). The purpose of this review is not to discuss or debate different impact assessment metrics for plastic waste, but instead to highlight differences in scientific viewpoints that are likely to continue to occur in the use of LCA for evaluating the plastic challenge, irrespective of the development of suitable LCA impact metrics for marine litter.

Review of results from prior plastic LCA studies

Numerous LCA studies have evaluated the environmental impacts of plastic, which have been synthesized *via* a number of existing reviews (Al-Salem et al., 2009; Miandad et al., 2016; Deviatkin et al., 2019; Schwarz et al., 2019; Walker and Rothman, 2020; Alhazmi et al., 2021; Anshassi et al., 2021; Bishop et al., 2021; Davidson et al., 2021; Rodrigues Da Silva et al., 2021; Gómez and Escobar, 2022; Kan and Miller, 2022). It is not possible to make universal statements about the relative environmental impacts of different kinds of materials, since a material's physical properties may be more suitable for different functions, which in turn affects performance and subsequent environmental impact (Weidema et al., 2004). Nevertheless, some general trends and observations emerge in the context of the reviews.

Tradeoffs among different environmental impact categories

As discussed above, "environmental impact" is not a single entity but multiple different kinds of environmental impact categories. Many comparative LCA uncover tradeoffs among different impact categories, often finding that there is not one product that is universally superior in all impact categories (Prado et al., 2022). Ultimately, the extent to which a decision-maker prioritizes different impact categories often guides the decision toward particular alternative. The extent to which a decision-maker values the tradeoffs uncovered in LCA is an inherently subjective process. Although though there are some methods available to help a decision maker better evaluate the tradeoffs, the fundamental issue of tradeoffs are not eliminated (Hertwich and Hammitt, 2001).

The overall plastic sector is responsible for significant global GHG emissions (Zheng and Suh, 2019); however, the climate impacts of an individual plastic product compared to an alternative using different materials is often lower on an LCA basis (Kouloumpis et al., 2020; Kelly and Dai, 2021). A recent cross-sector study found that plastics had lower GHG emissions than non-plastic alternatives in 13 of 14 cases, representing GHG savings from 10 to 90 percent (Helmcke et al., 2022). Meanwhile, multiple LCA studies on food containers show that plastic often exhibits a lower environmental impact relative to non-returnable glass and metal on a variety of environmental impact categories (Humbert et al., 2009; Saleh, 2016; Boesen et al., 2019). The results when comparing plastics to returnable glass, paperboard, and bio-based materials are mixed (Xie et al., 2011; Scipioni et al., 2013; Abejón et al., 2020). Although climate impact is often smaller for plastic, there are additional environmental impact categories to consider, including the impact on ecosystems.

The small number of studies that quantify marine litter or physical ecosystem damage have indicated that plastic tends to be the worst option with respect to that environmental impact category (Civancik-Uslu et al., 2019; Gao and Wan, 2022). This sets up a tradeoff where substituting plastic with another material such as glass may lead to reductions in marine litter at the expense of greater greenhouse gas emissions (Kouloumpis et al., 2020). That doesn't mean that the substitution shouldn't occur; but it is important for decision makers to be cognizant of that tradeoff. One study indicated that when included in a larger impact framework weighing multiple impact categories, marine litter does not change the overall rankings of products (Gao and Wan, 2022); however, the extent of the tradeoff will be

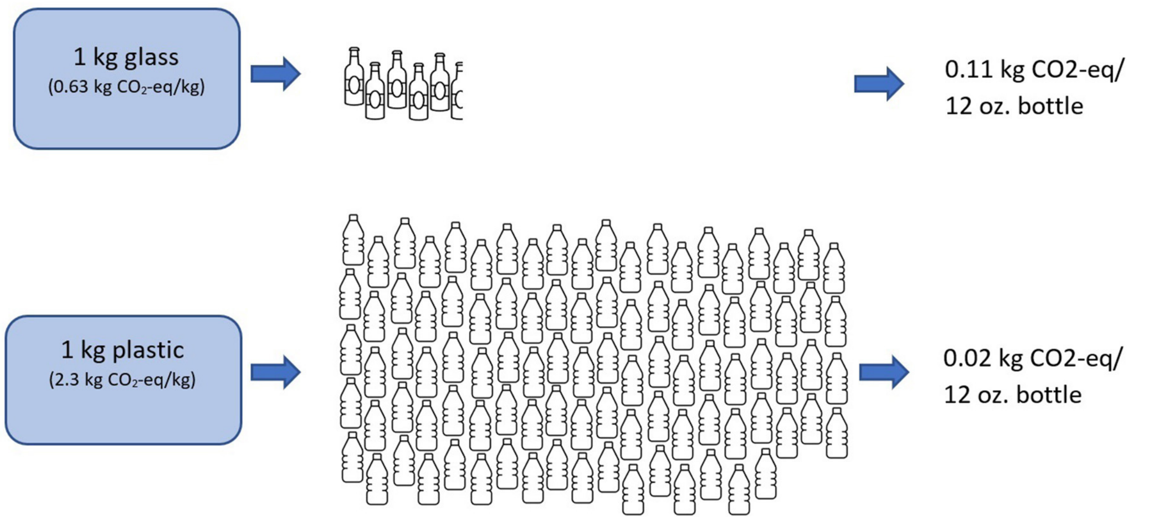

FIGURE 1
1 kg of glass and plastic to be used to produce 12 oz beverage containers, assumed to contain 10.3 g of PET for plastic and 180 g of glass and yielding 5.6 and 97 containers respectively. Assumes 2.3 kg CO_2-eq/kg PET and 0.63 kg CO_2-eq/kg glass.

different depending on the specific product system analyzed and prioritization of the impacts.

Different prioritizations of environmental impact categories can lead to different decisions. On one hand, those who value plastic pollution as the primary issue will likely prioritize any solution that reduces plastic pollution (Lavers et al., 2022). On the other side of the argument, those who prioritize climate change or another environmental impact may argue that alternative solutions should be promoted, even if they do not lead to a decrease in plastic production (Stafford and Jones, 2019a; Abejón et al., 2020). Some have argued that it is essential to develop solutions that do both–mitigate climate change and reduce the quantity of plastic waste (Stafford and Jones, 2019b; Miller, 2021; Ford et al., 2022). And certainly, there are some solutions–such as minimizing overall consumption–that can achieve win-win scenarios by getting at the root cause of many environmental issues simultaneously. Reduced consumption is often one of the only ways to reduce environmental impact across all environmental impact categories without resulting tradeoffs. Nevertheless, some level of material consumption will always need to occur. As LCA has consistently shown, it is relatively rare to find an option that reduces all environmental impacts at the same time. In these instances, the tradeoffs will be present and preferred "least damage" scenarios need to be chosen. Ignoring the tradeoffs that arise with a solitary focus on plastic waste reduction will likely lead to unintended consequences (Miller, 2020), and has the potential to distract from finding more holistic solutions. The following section describes some of the potential unintended consequences and how LCA is used to identify them.

Unintended consequences of plastic elimination or substitution

Every LCA is suited to a particular purpose and system, so it is not possible to make universal assertions regarding the life cycle results of one material vs. another. One of the foundational requirements of LCA is to define a "functional unit" that can provide a comparison based on commensurate performance. Common measures of mass or volume are not always appropriate functional units. As an example, 1 kg of steel has very different physical properties when compared to 1 kg of a plastic polymer, which has very different physical properties to 1 kg of glass. Depending on the ultimate application and performance of these materials, the functional unit of a product may require more or less mass than other materials. Figure 1 demonstrates this concept, showing the relative number of 12 oz bottles that can be made from similar masses of glass and plastic and the subsequent difference of reporting GHG emissions on a functional unit basis. Even though the GHG emissions associated with producing 1kg of glass is lower than those associated with producing 1 kg of plastic (0.63 kg CO_2-eq/kg glass vs. 2.3 kg CO_2-eq/kg plastic), the impacts per product are lower for plastic because 1 kg of plastic produces 17 times the containers than a similar mass of glass.

LCA ensures that alternatives be compared on an appropriate functional unit basis, so as not to derive inappropriate conclusions. While a kg of polymer may generate more GHGs than a kg of glass, it is not an appropriate conclusion that glass has less climate impact than plastic. LCA methods highlight the importance of evaluating alternatives on a systematic basis.

LCA can also highlight potential unintended consequences of proposed alternatives. One specific proposed solution to plastic waste pollution is the implementation of plastic bag bans. A few recent LCA studies have evaluated the potential outcomes of bag bans, including a recent review that summarized the comparative impacts of reusable bags with single-use plastic bags (Gómez and Escobar, 2022). Although data is still relatively scarce, the review discusses the potential impact of plastic bag bans on consumer behavior, identifying three possible scenarios. First, fewer bags may be used overall as consumers forgo the need for any bag in certain circumstances. Second, single-use carrier bags of alternative materials (i.e., paper) may be used as a substitute. Finally, plastic bag bans may incentivize greater use of reusable carrier bags by customers. In all likelihood, any bag ban will result in some mixture of these outcomes (Martinho et al., 2017).

Decreased overall consumption of bags without any direct or indirect substitution will result in lower environmental impact. The other potential scenarios identified are more nuanced. The review found that substitution to single-use paper or other alternatives will result in greater global warming and ecotoxicity (Gómez and Escobar, 2022). In addition to direct changes associated with potential bag substitutes, there may be indirect changes to consumption patterns, such as greater consumer purchases of more durable garbage bags to compensate for the lack of single-use thin film plastic bags reused as waste bags (Martinho et al., 2017).

For reusable bags, consumers need to reuse the reusable bags a sufficient number of times in order to realize an environmental benefit over the single-use item to account for the greater material intensity that causes its durability. The number of reuses that are required for a reusable bag to "break even" with its single-use plastic counterpart is highly variable and depends on the type of material used, the environmental impact category in question, and a variety of other assumptions (Lewis et al., 2010). While not specifically focused on carrier bags, a number of LCA studies have highlighted the importance of consumer reuse to demonstrate environmental benefits of reusables over single-use plastic (Woods and Bakshi, 2014; Potting and van der Harst, 2015; Blanca-Alcubilla et al., 2020; Fetner et al., 2021). Certain reusable items may never break even with single-use plastic on certain impact categories, due to the impacts of washing the reusable alternative being greater than the single-use item (Fetner et al., 2021).

There are also numerous case studies in the LCA literature dedicated to the use of plastic in food packaging and potential tradeoffs that can arise between packaging and food loss (Silvenius et al., 2014; Wohner et al., 2019). One of the most difficult aspects of LCA of food packaging is to appropriately capture the performance of packaging materials with respect to food waste (Heard et al., 2019; Heller et al., 2019; Kan and Miller, 2022). With unique physical properties to be able to product preservation, plastics can often improve the shelf life of specific foods better than other packaging alternatives, and food production can be environmentally intensive, particularly in the context of meat or dairy. Therefore, in addition to merely analyzing the environmental impacts of the packaging, an appropriately conducted LCA should also examine any change in performance.

Discussion

When considering the plastic waste problem, there are generally two perspectives that are used to categorize the extent and severity of environmental impacts of plastic. The life cycle perspective analyzes the environmental impact associated with a specific product, often comparing one product alternative to another and assessing which has lower impact (Abejón et al., 2020; Helmcke et al., 2022). An alternative perspective analyzes the environmental impacts of the plastic sector in aggregate, analyzing the full scope and scale of plastics in the environment (Jambeck et al., 2015; World Economic Forum, 2016; Geyer et al., 2017). Both perspectives provide meaningful data and insights, yet each provides an incomplete understanding of the plastics problem. These differing perspectives may exacerbate some of the divisions in discussions surrounding solutions to plastic waste. When evaluating only comparative impacts, it may be easy to overlook the bigger picture and the aggregated impacts of the plastics industry (Walker and McKay, 2021). When evaluating only the aggregate impacts of plastic, it may be easy to overlook other environmental issues that may be created by well-intended solutions (Miller, 2021). Understanding and integrating these perspectives may be necessary to come up with satisfactory solutions to plastic waste challenges.

Researchers working specifically on the issue of plastic pollution tend to focus on the aggregate current and future impacts of plastics on aquatic systems (Jambeck et al., 2015; Verma et al., 2016; Kubowicz and Booth, 2017; Schnurr et al., 2018; Kosior and Crescenzi, 2020; Saling et al., 2020; Walker and McKay, 2021). Researchers who focus on the aggregate impact of plastic highlight the magnitude of environmental impacts for which the plastic sector is responsible. As earlier discussed, plastic is ubiquitous and the industry is responsible for major environmental impact given the size of the industry (Jambeck et al., 2015; Zheng and Suh, 2019). Anticipated exponential growth in the plastics industry will only exacerbate the impacts of plastic across a range of environmental impact categories.

As the transportation and electricity industries undergo large-scale transitions to lower carbon futures, the proportion of climate emissions associated with the plastic sector is expected to increase significantly (World Economic Forum, 2016). This aggregate perspective highlights the overall damage for which the plastic sector is responsible and underscores the need to reduce the impacts of the industry. At the same time, the aggregate perspective does not usually account for the potential consequences that may occur as a result of material substitution away from plastic (Miller, 2020). Focusing only on reducing the aggregate impact of plastics without also assessing the potential consequences of increases in alternative materials may cause a different suite of environmental issues. It may be easy to develop simple heuristics that imply any reduction of plastic will result in environmental improvement. While reduction in plastic use will reduce the specific environmental impact of marine litter, the overall system is complicated and requires a more holistic approach (Gao and Wan, 2022). When elimination of plastic results in actual reduction of consumption, there is likely an environmental benefit (Ford et al., 2022). When reducing plastic increases the consumption of another material, there are likely tradeoffs that will occur (Lindh et al., 2016). When material substitutes or indirect consequences occur as a result of plastic elimination (i.e., increased food waste), the aggregate impact on the environment is not guaranteed to be favorable (Silvenius et al., 2014; Heller et al., 2019).

In contrast to the aggregate approach, LCA practitioners tend to focus on the environmental impacts of plastic in comparison to other alternatives rather than the aggregate impacts of plastic. Most LCA compare the impacts of plastic relative to other alternatives to perform a similar function. This comparative perspective is useful to help inform design decisions about a specific product, answering questions such as "Is it better to make this cup out of metal or plastic?" (Millet et al., 2007). Comparative LCA provide insights into the material(s) that produce the fewest environmental impacts for a given product function and identify tradeoffs among environmental impact categories, such as marine litter and GHG emissions (Hertwich and Hammitt, 2001; Gao and Wan, 2022). LCA can also offer insights into how to resolve potential tradeoffs or where to focus efforts to result in the greatest improvement potential across emission categories. At the same time, the life cycle perspective does explicitly discuss the aggregate impact of individual product choices. The comparative life cycle perspective can identify an alternative with fewer environmental impacts; however, that alternative may still cause a great deal of environmental damage. Just because one alternative is "better" in a given impact category does not actually mean that it is "good" (McDonough and Braungart, 2002; Schnitzer and Ulgiati, 2007). Therefore, LCA information that indicates that a preferred alternative can be potentially misleading or misinterpreted, where the actual environmental impact of plastics is not fully considered.

In order to find effective solutions to the plastic problem, it will be essential to understand both the aggregated impacts of the entire plastic economy and the comparative impacts of plastic relative to other materials. Neither of the aggregate or relative perspective is better or worse; both can be useful. Ideally, they complement one another. One major question to ask should be, "If it's better, will it matter?" This involves understanding the overall size of a product's market and the aggregate scale of environmental impact (Bergerson et al., 2020). A 2% reduction in emissions associated with something that is responsible for 10% of the aggregate impact is going to have greater effectiveness than something with a 10% reduction of 1% of the aggregate impact.

Conclusions

To summarize, LCA has the potential to make valuable contributions to the overall plastic debate by helping to identify potential unintended consequences of proposed solutions that could cause environmental problem shifting. While an imperfect tool, LCA can be used to place the effects of environmental policy and design decisions into context and provide rigorous and systematic analysis. LCA will never be able to rectify systemic tradeoffs among different materials, such as the marine litter pollution of single-use plastic compared to the additional BOD/COD loading from paper. Nevertheless, LCA can quantify the impacts of individual materials and help provide a framework to discuss those tradeoffs.

Certain LCA studies may point out tradeoffs associated with material substitution, particularly since relative to other materials, plastics tend to consume relatively low amounts of energy, which tends to translate to lower overall emissions. On an aggregate basis, the GHG emissions associated with plastics are large; but the relative GHG emissions of individual products tend to be quite small. Although LCA may be able to identify alternatives with fewer environmental impact, the aggregate impacts of plastic use cannot and should not be ignored. Just because a product alternative has fewer environmental impacts does not actually mean that the alternative is actually sustainable.

The comparative LCA perspective and the aggregated environmental impact perspective can complement one another and lead to overall improved environmental outcomes when used in tandem. While material substitution may not necessarily lead to improved outcomes, there are ways to reduce both marine litter and GHG emissions simultaneously. The plastic waste issue highlights the need to focus on reduced overall consumption rather than material substitution at a similar level of consumption. Interventions that lead to a true reduction of consumption will reduce overall environmental impact. Merely shifting away from plastic as a priority area of focus without understanding the full consequences of a material substitution has the potential to create environmental problem shifting and not achieve sustainable outcomes.

Author contributions

SM was responsible for compiling and writing the manuscript.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Galápagos and the plastic problem

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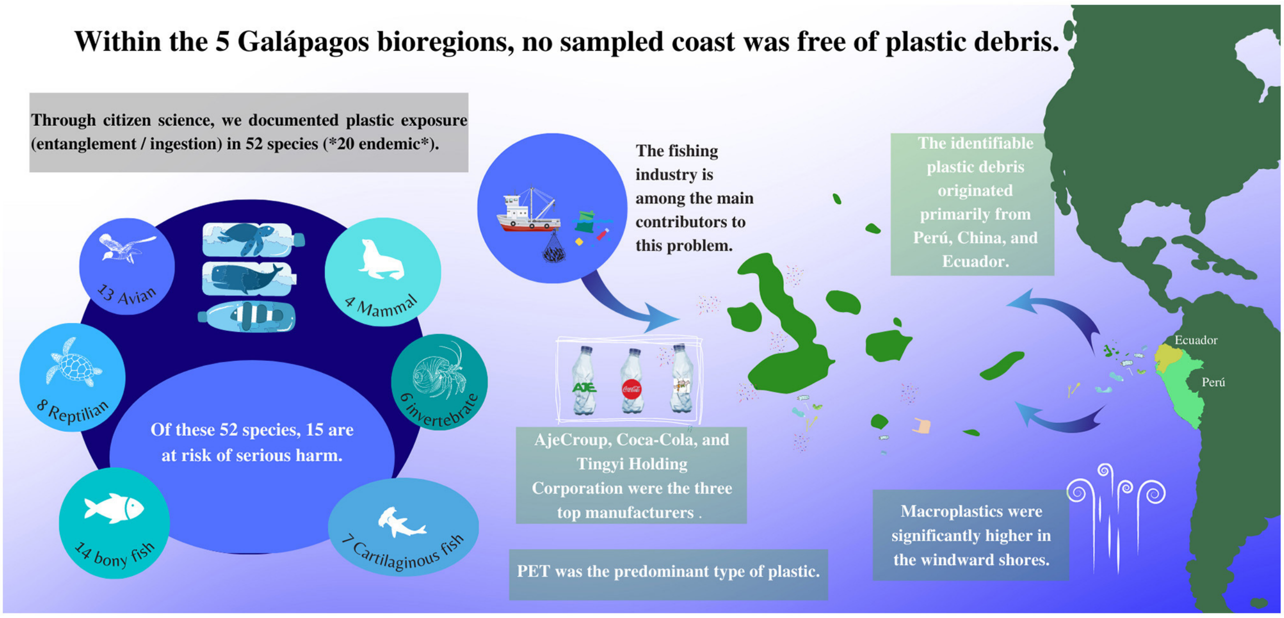
Plastic pollution (PP) is an ongoing, pervasive global problem that represents a risk to the Galápagos archipelago, despite it being one of the world's most pristine and well-protected regions. By working closely with citizen scientists, we aimed to quantify and map the magnitude and biological effects of PP. With macroplastic abundance ranging from 0.003 to 2.87 items/m^2, our research indicates that all five sampled Galápagos bioregions are contaminated with PP along their coastlines. The distribution of this debris is not uniform, with macroplastics significantly higher on the windward shores. Based on the identification information found on the examined items, Polyethylene terephthalate (PET) was the most predominant type of plastic originating from both consumer and fisheries-based products deriving primarily from Perú, China, and Ecuador. The top three manufacturers were AjeCroup, Coca-Cola, and Tingy Holding Corporation. Through citizen science, we documented PP exposure in 52 species (20 endemic) in Galápagos terrestrial and marine environments, with exposure occurring in two ways: entanglement and ingestion. These included reptiles (8 species), birds (13 species), mammals (4 species), cartilaginous fish (7 species), bony fish (14 species), and invertebrates (6 species). The top five species with the greatest risk of serious harm due to entanglement (in decreasing order) were identified as green sea turtles, marine iguanas, whale sharks, spine-tail mobulas, and medium-ground finches. In contrast, Santa Cruz tortoises, green sea turtles, marine iguanas, black-striped salemas, and Galápagos sea lions were at the highest risk of harm due to the ingestion of plastics. Our research indicates that PP is a growing problem in the Galápagos archipelago and that additional work is necessary to mitigate its impact now and in the future.

KEYWORDS

Galápagos, macroplastics, ingestion, entanglement, threat, assessment, citizen science

1. Introduction

Plastic pollution (PP) is discarded, lost, or abandoned plastic debris that builds up, persists, and is not degraded in the environment to the point that it could pose difficulties for animals, their habitats, and human populations (Joyner and Frew, 1991). The first synthetic plastic, Bakelite, was invented in 1907 as an environmental alternative to natural plastics such as amber, ivory, and tortoiseshell (Mossman, 2017). Discarded, lost, or abandoned plastic has



GRAPHICAL ABSTRACT
The main findings of this study are presented visually, showing how many and which species of animals are most at risk, the main countries of manufacturing and manufacturers that were predominant, and the direction of pollution.

since become permanent and pervasive pollution. It is a widespread and escalating problem, with 51 trillion microplastic particles floating in the oceans of the world (Eriksen et al., 2014; Van Sebille et al., 2015). Plastic pollution (PP) is also found in polar regions to the tropics and from surface waters to the depths of the ocean (Pruter, 1987; Laist, 1997; Thompson, 2004; Andrady, 2011; Gall and Thompson, 2015; Taylor et al., 2016; Brahney et al., 2020; Kane et al., 2020; Rillig and Lehmann, 2020; Lucas-Solis et al., 2021; Pakhomova et al., 2022). Plastic pollution has been identified in the human blood, liver, lung, stool, placenta, and breast milk (Ragusa et al., 2021, 2022; Jenner et al., 2022; Leslie et al., 2022). Given the ubiquity of PP, it is imperative for scientists, managers, decision-makers, and the public to comprehend its sources and potential harm to the environment and human health (Jambeck et al., 2015; Smith et al., 2018; Shi et al., 2022).

Plastics have several advantages over conventional materials when used with care. However, when not disposed of properly or leaked into the environment, they pose an existential social, environmental, and economic threat (Beaumont et al., 2019; Williams and Rangel-Buitrago, 2022). Global data indicate that plastics were uncommon along coastlines before 1950. Today, there may not be a single coastline on the planet that is entirely free of plastics (Bergmann et al., 2015). Approximately three-quarters of the world's coastlines have been affected by marine litter in the form of plastic waste (Thompson, 2004; Browne et al., 2010; Andrady, 2011; Jambeck et al., 2015; Law, 2017). This problem has spread to all ocean basins (Pakhomova et al., 2022). There has been rapid growth in the production and use of plastics in both wealthy and developing countries. This rapid production and indiscriminate plastic use, combined with linear economic strategies, have contributed to the widespread presence of plastic pollution (Jambeck et al., 2015; Lau et al., 2020; Lavers et al., 2022; Williams and Rangel-Buitrago, 2022). In addition, plastic pollution production and disposal are linked to climate change owing to the extraction of fossil fuels and their impacts on ecosystems (Ford et al., 2022; Lavers et al., 2022).

The improper disposal of plastics is a serious issue, as recycling infrastructure is not efficient, and a circular economy has yet to be successfully implemented because plastics leak into the environment and the amount of plastic in circulation increases in size (King and Locock, 2022; Williams and Rangel-Buitrago, 2022). Most importantly, there are currently insufficient regulations to encourage proper disposal (Willis et al., 2022). Accordingly, modeling plastic production and management scenarios indicate that 710 million metric tons of plastic waste will enter aquatic and terrestrial ecosystems by 2040; even with immediate and agreed-upon global administration, it could have catastrophic effects on humanity and the environment (Lau et al., 2020).

Plastic pollution (PP) continues to exponentially impact the oceans worldwide (Jambeck et al., 2015; Serra-Gonçalves et al., 2019). Globally, over 1400 marine species interact with plastic debris (Claro et al., 2019), posing a significant threat to wildlife. These threats include ingestion, entanglement, and habitat degradation, which have sublethal and lethal effects on marine animals. Chronic exposure to PP can affect feeding, energy, growth, health, and reproductive output (Gall and Thompson, 2015; Li et al., 2016; Galloway et al., 2017; Law, 2017; Lavers et al., 2019; Senko et al., 2020; Yamashita et al., 2021). Accumulation of PP in marine food webs can affect the entire ecosystem (Galloway et al., 2017; Smith et al., 2018). Moreover, the plastic pollution crisis is more pronounced in protected oceanic and isolated islands (Lavers and Bond, 2017). In addition, there is a notable trend

FIGURE 1
Macroplastic categorization process. CSIRO categorization system (Schuyler et al., 2020) with adaptations. Categories are: HPF (Hard plastic fragments); FISH (Engine oil bottles, fishing buoys, fishing nets, monofilament fishing line, eel traps, plastic rope, string, twine); BB (Plastic beverage bottles); BC (Beverage bottle caps); BAG (Plastic bags); HI (Household items, razors, toothbrushes, deodorants, toys, straws, popsicle sticks, utensils, cutlery, food containers, tetra pack, plastic cups, plastic packing straps, shoes, sandals, balloon, cigarette, cloth item); FP (Film plastic food wrap, chip bags, "other" soft plastic); OB (Other bottles, i.e., shampoo, kitchen oil); LPI (Large plastic items, i.e., buckets, boxes, tubes); FOAM (Any foam); RUB (Rubber gloves or other rubber items, i.e., tires.); OC (Other caps/lids); OTHER (Other items, i.e., glass, metal, paper). The measuring tape was 10 m in length. This figure shows a macroplastic density of 2.10 items/m^2 from the windward remote San Cristóbal Island in El Pescador (LAT-0.917083°; LONG–89.404444°).

between windward and leeward plastic debris deposition rates on islands, with windward coastlines being more polluted with plastic debris than leeward coastlines (McDermid and McMullen, 2004; Morishige et al., 2007; Debrot et al., 2013; Hidalgo-Ruz and Thiel, 2013; Brignac et al., 2019; Rangel-Buitrago et al., 2019; Nichols et al., 2021). This places species on remote islands and those that forage and nest on windward coastlines at a potentially greater risk of their health being affected by plastic pollution.

The Galápagos archipelago, also known as the Enchanted Islands, is located 972 km west of mainland Ecuador and is home to unique biodiversity. It consists of 13 large and six small islands, 107 islets and rocks, a total area of ~8,000 km^2, a coastline of 1,753 km, and a marine reserve covering 198,000 km^2 (Edgar et al., 2008; Denkinger et al., 2014; DW News, 2022; Hearn et al., 2022). The evolutionary paradigm was developed based on adaptations to the Galápagos volcanic environment (Darwin, 1876). Since 1959, the Ecuadorian government has maintained strict regulations for more than 97% of the archipelago. It has been largely successful in protecting this unique ecosystem from anthropogenic pressures such as overfishing, overpopulation, invasive species, and hunting species (Denkinger et al., 2014). Consequently, most non-urban areas of Galápagos maintain conditions before human presence. In other words, 97% has remained well-managed and restored (Izurieta et al., 2014; Negru et al., 2020). Despite its isolation, the islands are safeguarded; therefore, we may observe almost the same environment as Darwin observed nearly 200 years ago. Nonetheless, it is paradoxically vulnerable to stresses from human-caused global factors such as climate change and plastic pollution (Alava et al., 2022).

Consequently, PP continues to be present on the most remote Galápagos coastlines. During the preceding 5 years, fishermen, volunteers, residents, scientists, and park rangers removed 71 metric tons of plastic waste from the remote beaches of Santa Cruz, Baltra, Floreana, Santiago, Isabela, Pinta, Marchena, and San Cristóbal. This waste was unloaded and sorted on the islands of Santa Cruz and San Cristóbal before being transported to municipal waste facilities for final disposal (Galápagos National Park Directorate, 2020; Galapagos National Park Directorate, 2021a,b,c; Alarcon and Alvarado, 2022). This demonstrates that the Galápagos Marine Reserve (GMR) is no exception to the global plastic pollution crisis. Consequently, it is necessary to document the possible adverse effects of exposure to PP, establish a baseline for endemic species, feeding areas, and populations, and monitor the patterns of the presence and absence of PP. Thus, addressing crucial knowledge gaps and providing the data required for decision makers to advocate timely intervention and mitigation measures.

At a global scale, the endemic wildlife of the Galápagos archipelago is of critical importance (Ballesteros-Mejia et al., 2021). Anecdotal reports indicate that several of these species are directly affected by plastic debris. However, standard information is not currently available. Therefore, it is necessary to assess their scope to develop specific conservation plans to reduce the potential impacts of plastic pollution on wildlife in Galápagos. Our research aims to provide the first comprehensive analysis of an innovative *in situ* effort to investigate the distribution, composition, source, and environmental impact of plastic pollution at an archipelago scale. We also generated a threat assessment based on the dangers and potential risks posed by plastic debris exposure to Galápagos wildlife, allowing us to identify and rank the most at-risk species.

TABLE 1 Macroplastic categories adapted for the Galápagos study using the CSIRO protocol (Schuyler et al., 2020).

Categories	Meaning
HPF	Hard plastic fragments.
FISH	Engine oil bottles, fishing buoys, fishing nets, monofilament fishing line, eel traps, plastic rope, string, twine.
BB	Plastic beverage bottles.
BC	Beverage bottle caps.
BAG	Plastic bags.
HI	Household items (razors, toothbrushes, deodorants, toys, straws, popsicle sticks, utensils, cutlery, food containers, tetra pack, plastic cups, plastic packing straps, shoes, sandals, balloon, cigarette, cloth item).
FP	Film plastic (food wrap, chip bags, "other" soft plastic).
OB	Other bottles, i.e., shampoo, kitchen oil.
LPI	Large plastic items, i.e., buckets, boxes, tubes.
FOAM	Any foam.
RUB	Rubber gloves or other rubber items, i.e., tires.
OC	Other caps/lids.
OTHER	Other items, i.e., glass, metal, paper.

2. Materials and methods

2.1. Macroplastic density (items/m^2)

There are five major bioregions in Galápagos, each with distinct oceanographic conditions, species diversity, distribution, composition, and endemism (Edgar et al., 2004; Castrejón and Charles, 2020). To determine the macroplastic density (items/m^2) for the typically inaccessible and vast irregular 1,753 km Galápagos coastline (Edgar et al., 2008). Field sampling was conducted on 20 remote (no public access) shorelines covering the five Galápagos bioregions. On each selected island, a 50 m transect was laid parallel to the water on the leeward side, and another 50 m transect was laid parallel to the water on the windward side of the same island ($n = 2$ for each island) for a total of 20 transects. All visible plastic elements and fragments larger than 5 mm between the water and vegetation lines of this transect were removed and stored for subsequent laboratory examination. Following the method used by Jones et al. (2021), the shoreline area was calculated using satellite images (obtained from Google Earth, May 2022) to allow us to convert the data into macroplastic density (items/m^2) for each of the transects.

Macroplastics were counted and classified (Figure 1) using an adapted Galápagos CSIRO classification protocol

TABLE 2 Scoring criteria for the threat scale on reported species with PP interactions in Galápagos.

Score	1	2	3
(S^T) Species distribution or taxon origin	(U) Unknown or not evaluated	(M) Migratory	(E) Endemic
		(N) Native	
(S^C) Conservation status	(DD) Data deficient	(NT) Near threatened	(EN) Endangered
	(NE) Not evaluated	(VU) Vulnerable	(CR) Critically endangered
	(LC) Least concern		
(S^F) Feeding type	(C) Carnivorous	(O) Omnivorous	(Pl) Planktivorous
			(H) Herbivorous
(S^H) Species habitat and ecology	(TN) Terrestrial natural	(TW) Terrestrial wetlands	(MI) Marine intertidal
			(MO) Marine oceanic
			(MN) Marine neritic
			(TU) Terrestrial urban
(S^E) Entanglement	No evidence	Moderate ≥1 up to 3 evidence	Major ≥3 evidence
(S^I) Ingestion	No evidence	Moderate ≥1 up to 3 evidence	Major ≥3 evidence

S^T, species distribution or taxon origin; S^C, conservation or IUCN red list status; S^F, feeding type; S^H, species habitat and ecology; S^E, entanglement; S^I, ingestion.

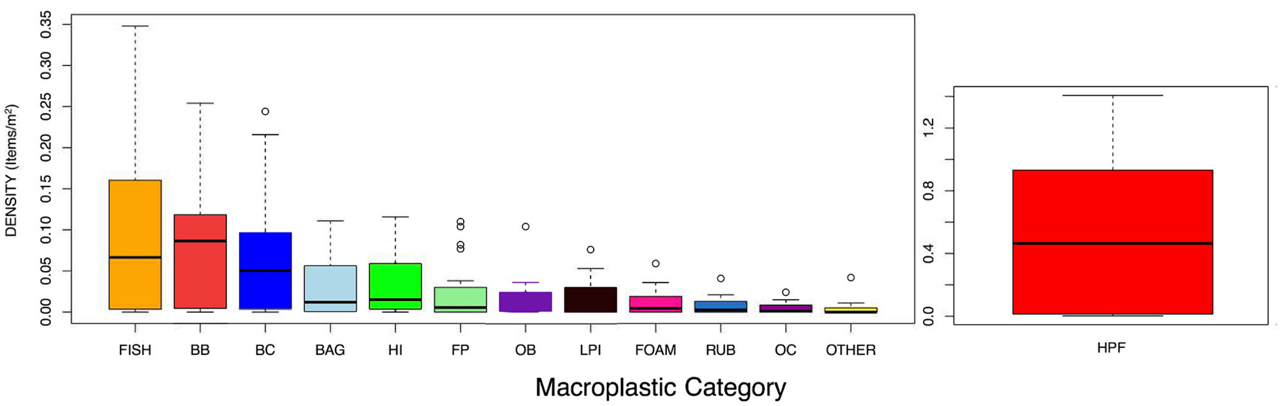


FIGURE 2
Macroplastic category density (items/m^2) for all surveyed sites in the five bioregions. CSIRO categorization system (Schuyler et al., 2020) with adaptations. Categories are: HPF (Hard plastic fragments); FISH (Engine oil bottles, fishing buoys, fishing nets, monofilament fishing line, eel traps, plastic rope, string, twine); BB (Plastic beverage bottles); BC (Beverage bottle caps); BAG (Plastic bags); HI (Household items, razors, toothbrushes, deodorants, toys, straws, popsicle sticks, utensils, cutlery, food containers, tetra pack, plastic cups, plastic packing straps, shoes, sandals, balloon, cigarette, cloth item); FP (Film plastic food wrap, chip bags, "other" soft plastic); OB (Other bottles, i.e., shampoo, kitchen oil); LPI (Large plastic items, i.e., buckets, boxes, tubes); FOAM (Any foam); RUB (Rubber gloves or other rubber items, i.e., tires.); OC (Other caps/lids); OTHER (Other items, i.e., glass, metal, paper).

(Schuyler et al., 2020). These categories are listed in Table 1. To conduct a more comprehensive and detailed search for information regarding the polymer type, the manufacturer of the item, and the country of origin, a random subsample of 30 items from each transect/location with a potential identifier (such as legible inscriptions, stamps, or labels) was selected. Information from the Society of the Plastics Industry (SPI) code was recorded to identify the polymer types. In 1988, SPI established a classification system to enable consumers and recyclers to differentiate between various plastic types. By regulation, manufacturers imprint an SPI code or number on the bottom of every plastic product (Mertes, 2019). Finally, we identify the manufacturer and country of origin by examining the information contained in legible inscriptions, stamps, and labels. Google Lens was used to collect information on items with inscriptions in languages unknown to us.

2.2. Galápagos wildlife interactions with plastic pollution (ingestion or entanglement)

ArcGIS Survey123 was used to conduct citizen science surveys (accessible *via* the link https://arcg.is/0bTLKv and Supplementary Figure 2). The survey collected photographic or video evidence of interactions between the wildlife of Galápagos and plastic pollution (ingestion or entanglement). Similarly,

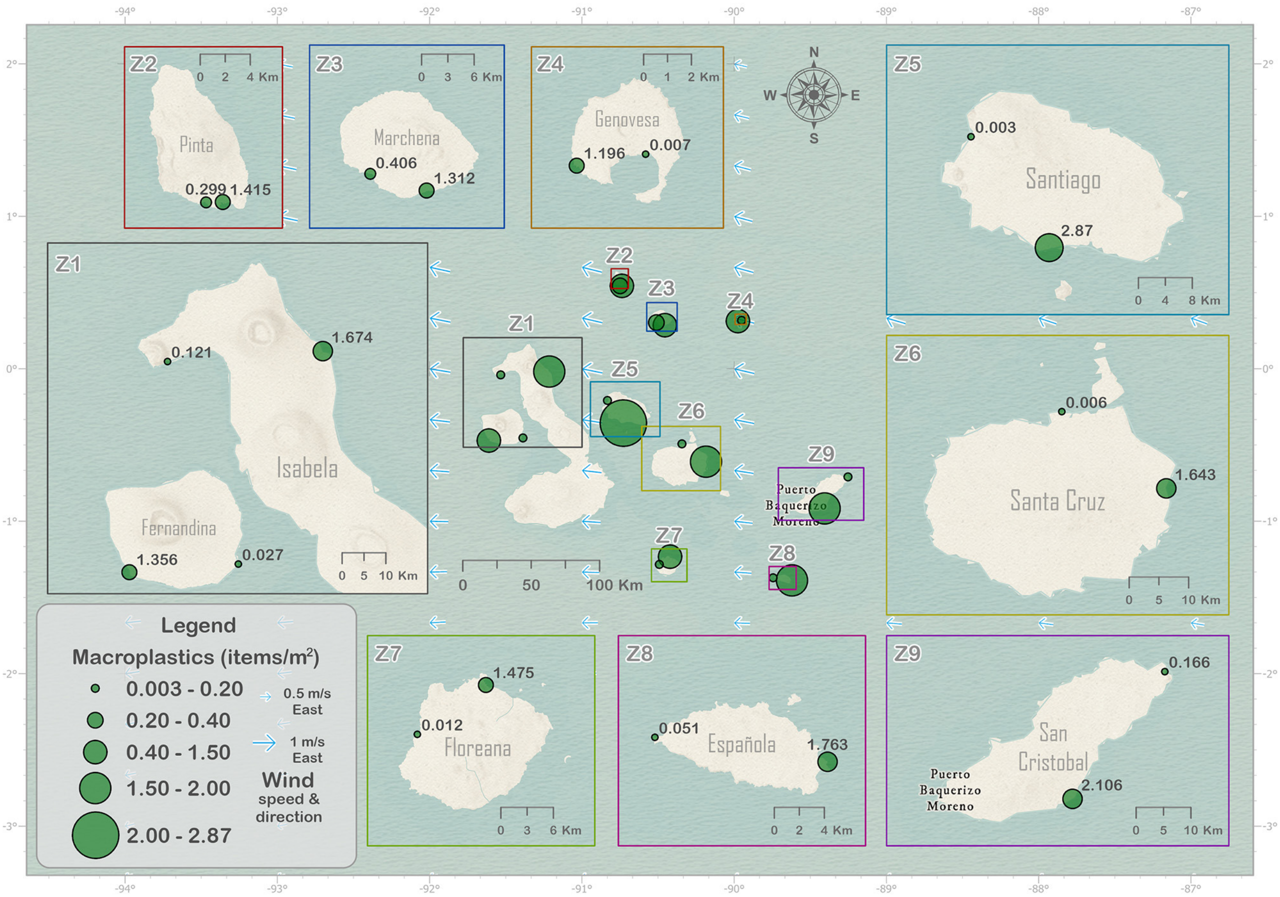


FIGURE 3
Macroplastic total density (items/m²) for all sample sites in the Galápagos Archipelago. In the map, we divided our sample sites into 9 Zones/Islands (Z) to improve data visualization. Z1: Fernandina and Isabela Island; Z2: Pinta island; Z3: Marchena island; Z4: Genovesa island; Z5: Santiago Island; Z6: Santa Cruz Island; Z7: Floreana island; Z8: Española Island; Z9: San Cristóbal Island. Wind data were derived from the Global Ocean Data Assimilation (SODA) dataset, which is a part of the Global Ocean Data Assimilation System (GODAS), from the National Oceanic and Atmospheric Administration (NOAA) of the US. The u and v components of the wind currents over the oceans were plotted on a grid of 0.5°arc-degree over the Galápagos area, and the yearly average was presented as the wind speed and direction. The range of wind speeds was between 0.1 and 1 m/s. The predominant wind direction throughout the year is NWW at most locations in Galápagos, south of the equator (NCAR, 2022).

records were collected through social media. Only those species that possessed clear photo or video evidence were considered for the threat assessment.

2.3. Galápagos wildlife plastic pollution threat assessment (PPT)

Once species with PP interactions in Galápagos were confirmed, the priority scoring method developed by Wilcox et al. (2016), Jones et al. (2021), and Roman et al. (2022) were adapted and used. We constructed a threat assessment for the reported species using scores for distribution or taxon origin (S^T), IUCN conservation status (S^C), feeding type (S^F), habitat and ecology (S^H), entanglement harm (S^E), and ingestion harm (S^I). Table 2 presents the scoring criteria and threat categories used to rank the Galápagos species most affected by PP based on the distribution, diet, conservation status, habitat, and PP evidence available for each species. The International Union for Conservation of Nature (IUCN) Red List of Threatened Species (https://www.iucnredlist.org/) and The Charles Darwin Research Station Natural History Collections database (https://www.darwinfoundation.org/en/datazone) were consulted for information on distribution or taxon origin, conservation status, feeding type, habitat, and ecology. Finally, to calculate the priority species at a high threat of entanglement and ingestion in Galápagos, we used the following equations:

$$\text{Entanglement threat (E)}$$
$$(E) = S^T \times S^C \times S^F \times S^H \times S^E$$
$$\text{Ingestion threat (I)}$$
$$(I) = S^T \times S^C \times S^F \times S^H \times S^E$$

3. Results

3.1. Macroplastic density (items/m²)

All Galápagos-sampled shorelines contained macroplastics. The density of the surface plastic debris varied from 0.003 to

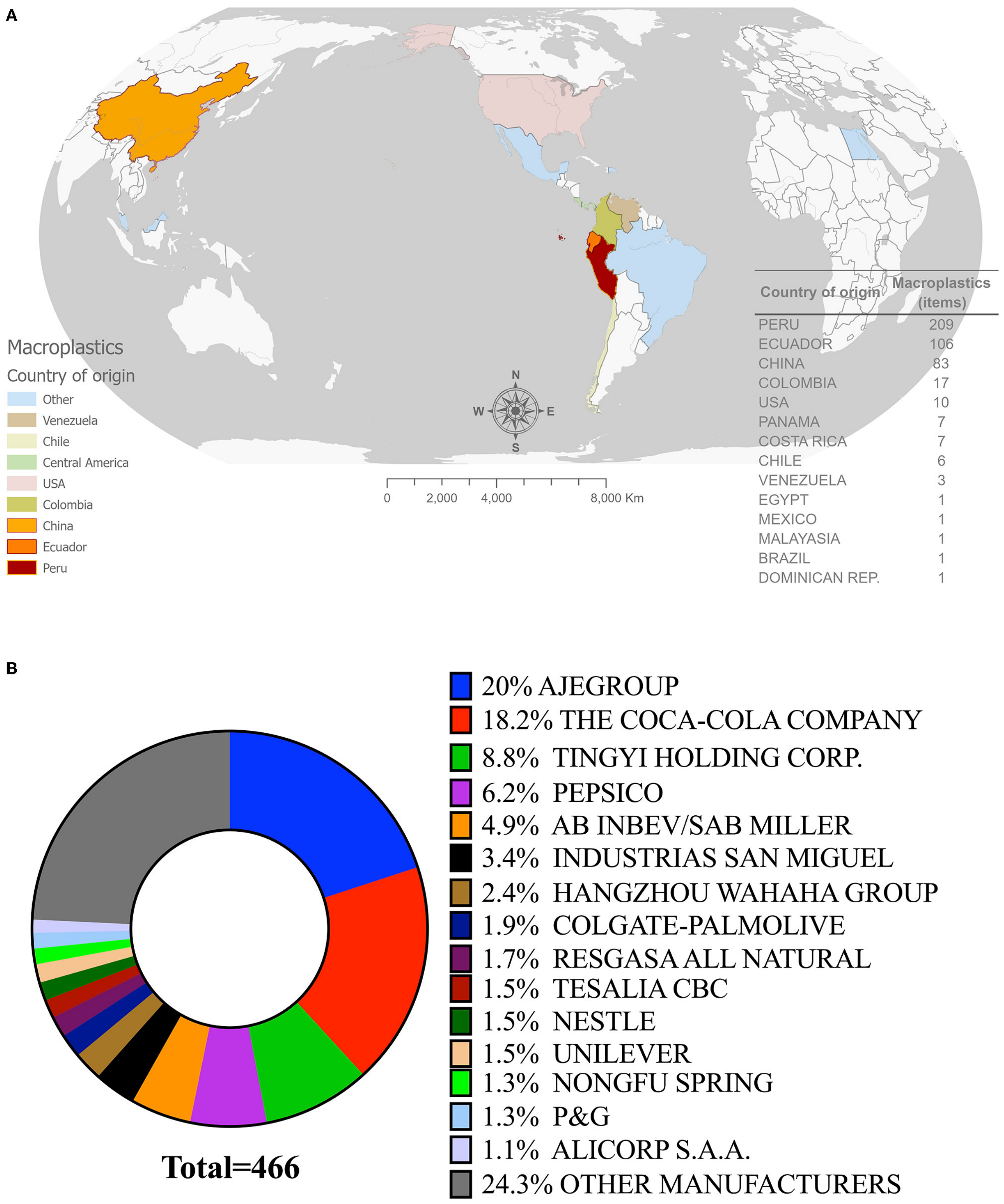


FIGURE 4
(A) Countries of origin of the examined macroplastics. Country of origin was identified from a random subsample of 466 items with a potential identifier (legible inscriptions, stamps, or labels) from all transects/locations in this study. A potential identifier was used to perform the search using Google Lens. Google Lens was a way to collect data on items with inscriptions in languages unknown to us, such as Mandarin. Countries with stronger colors: more items from that country were found. **(B)** The 15 top manufacturers of examined macroplastics.

2.87 to items/m^2. At 0.51 (SEM = 0.11) items/m^2, hard plastic fragments (HPF) were the most prevalent plastic classification category at all sampled sites, followed by fishing-related items (FISH), which numbered 0.09 (SEM = 0.02) items/m^2. Plastic beverage bottles (BB) with 0.08 (SEM = 0.02) items/m^2 were the third most prevalent category of macroplastics at all the sample sites (Figure 2).

The windward coast of Santiago Island had the highest density (2.87 items/m^2), while the leeward site on the same island had the lowest density (0.003 items/m^2) (Figure 3, Zone 5). The highest concentrations of macroplastics were observed on the windward coastlines of the archipelago. All windward study sites had a macroplastic density of 1.68 (SEM = 0.15) items/m^2, while all leeward study sites had a macroplastic density of 0.11 (SEM = 0.04) items/m^2. Macroplastic density (items/m^2) was significantly different between all windward and leeward sites (paired t-test, $t = 9.06$, $df = 9$, $P < 0.0001$).

After analyzing 466 macroplastic objects collected from the shores of Galápagos, the country of origin, manufacturer, and polymer type were determined for each study site. The most frequently identified source countries were Perú with 13.9 objects (SD = 6.9), China with 5.9 objects (SD = 3.5), and mainland Ecuador with 5.8 objects (SD = 3.7) (Figure 4A). In total, 98 manufacturers were established (Table 3). AjeGroup (20%), Coca-Cola Company (18.2%), and Tingy Holding Corporation (8.8%) had the highest proportion of plastics in the archipelago-sampled coasts (Figure 4B). Finally, the predominant type of plastic was polyethylene terephthalate (PET) at 12.3 objects (SD = 7.8) and high-density polyethylene (HDPE) at 3.1 objects (SD = 2.2).

3.2. Galápagos wildlife interactions with plastic pollution (ingestion or entanglement)

We received 197 reports on Galápagos wildlife PP interactions (entanglement or ingestion) *via* email, social media, and ArcGIS Survey123. Seventy-eight scientists, 34 citizens, 24 naturalistic guides, 20 anonymous individuals, 16 park rangers, 12 students, 10 tourists, and four fishermen submitted the reports. We documented PP exposure in 52 species (20 endemic, 24 native, 5 migratory) in terrestrial and marine environments of the Galápagos Islands, with exposure occurring *via* entanglement and ingestion (see Supplementary Figure 1 for more evidence). These included reptiles (8 species), birds (13 species), mammals (4 species), cartilaginous fish (7 species), bony fish (14 species), and invertebrates (6 species) (Table 4).

3.3. Galápagos wildlife plastic pollution threat assessment (PPT)

Plastic pollution (PP) posed the greatest threat to 15 of the 52 species examined in this study. Santa Cruz tortoises (*Chelonoidis porteri*) had the highest ingestion threat score among reptiles. The green sea turtle (*Chelonia mydas*) was most susceptible to entanglement. Among the evaluated avian species, the medium-ground finch (*Geospiza fortis*) and Galápagos flightless cormorant (*Phalacrocorax harrisi*) experienced the greatest risk of entanglement. Lava gull (*Larus fuliginosus*) had the highest ingestion score. Among mammals, the Galápagos sea lion (*Zalophus wollebaeki*) has the highest risk of entanglement and ingestion. The elasmobranchs most susceptible to entanglement and ingestion are the whale sharks (*Rhincodon typus*) and spinetail mobula (*Mobula japonica*). The teleost fish species that were most susceptible to entanglement and ingestion were black-striped salemas (*Xenocys jessiae*) and white-spotted sand bass (*Paralabrax albimaculatus*). Finally, the invertebrates most susceptible to PP were green sea urchins (*Lytechinus semituberculatus*), Ecuadorian hermit crabs (*Coenobita compressus*), and sally lightfoot crabs (*Grapsus grapsus*) (Figures 5, 6 and Table 4).

4. Discussion

Our threat assessment score provides a rapid, accurate, and efficient method for measuring the interaction between plastic pollution and species in any region. This method can be used to target species for more in-depth assessments of health and environmental impacts. This method considers the abundance of various species and their sensitivity to plastic debris, thereby allowing conservationists to rapidly identify the species most likely to be affected by plastic pollution. The universality of the impact assessment method is already being utilized in our regional project: Pacific Plastics Science to Solutions (PPSS) (https://www.pacificplasticssciencetosolutions.com/), on eastern Pacific species. We compared the species to those found in Galápagos and determined whether there were any differences or similarities with the species from other regions. Using a similar scoring method, *C. mydas* ranked first in entanglements off the coast of Perú (Eliana Alfaro 2022 personal communication).

Microplastic and nanoplastic surveys have yet to be conducted throughout the rest of the Galápagos archipelago. For example, microplastics have been found in beach sediments, benthic sediments, and in the digestive systems of marine invertebrates at all study sites on San Cristóbal Island. The most recent publication, which used citizen science, found more than 2,500 microplastic particles per m^2 on Santa Cruz Island (Jones et al., 2022). These studies have begun to demonstrate the abundance of plastics on islands and the risks that PP poses to wildlife. However, research has been limited to tourist shorelines and shorelines in urban areas. Jones et al. (2021) explored remote areas, but only one Galápagos Island (San Cristóbal). Standardized research must continue to comprehend the macro-, micro-, and nanoplastic densities of the five bioregions. Only then will we be able to understand the sources, sinks, and patterns of PP deposition to effectively address this global problem.

Our findings indicate that the Galápagos archipelago conforms to the well-established pattern observed on other isolated oceanic islands, where the highest concentrations of plastic debris were found on the most remote, off-limit, and windward coasts (Morishige et al., 2007; Debrot et al., 2013; Hidalgo-Ruz and Thiel, 2013; Lavers and Bond, 2017; Perez-Venegas et al., 2017; Monteiro et al., 2018; Brignac et al., 2019; Rangel-Buitrago et al., 2019). Multiple factors can affect the deposition rates, in addition to windward and leeward effects. Morishige et al. (2007) found that

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TABLE 3 Ranking of 98 manufacturers from 466 macroplastic items collected from the Galápagos Archipelago, in which information could be identified.

Manufacturer	*n*	Proportion	Manufacturer	*n*	Proportion
AJEGROUP	93	19.96	RECKITT	1	0.21
THE COCA-COLA COMPANY	85	18.24	TEXACO	1	0.21
TINGYI HOLDING CORP.	41	8.80	CMD-ZEPOL	1	0.21
PEPSICO	29	6.22	ECUAORGANIC	1	0.21
AB INBEV/SAB MILLER	23	4.94	JET	1	0.21
INDUSTRIAS SAN MIGUEL	16	3.43	ACTIVE PRODUCT S.A.	1	0.21
HANGZHOU WAHAHA GROUP	11	2.36	AFRICA'S BEST	1	0.21
COLGATE-PALMOLIVE	9	1.93	COLORESCIENCE	1	0.21
RESGASA ALL NATURAL	8	1.72	CONFITECA C.A.	1	0.21
TESALIA CBC	7	1.50	JGB S.A	1	0.21
NESTLE	7	1.50	VIVANT	1	0.21
UNILEVER	7	1.50	AQUAVIVA BOTTLING CO.	1	0.21
NONGFU SPRING	6	1.29	GANTEN	1	0.21
P&G	6	1.29	PICCO ENTERPRISE	1	0.21
ALICORP S.A.A.	5	1.07	AQUAFIT S.A.	1	0.21
KSF-ASIA MARKET	5	1.07	BIC CORPORATE	1	0.21
GRUPO GLORIA	4	0.86	CERVEJAS DA MADEIRA	1	0.21
LA FABRIL S.A.	3	0.64	GRUPO BICOLOR	1	0.21
BJARNER C.A.	3	0.64	KIMBERLY-CLARK	1	0.21
EDUARDOÑO S.A.	3	0.64	ALKOFARMA	1	0.21
CCU-Chile	3	0.64	PICA	1	0.21
VISTONY	3	0.64	SUPERMAXI	1	0.21
DURAPLAST S.A.	3	0.64	YAMBAL	1	0.21
JABONERÍA WILSON S.A.	3	0.64	AGUA PELICAN BAY	1	0.21
JOHNSON & JOHNSON	2	0.43	MEDIFARMA S.A.	1	0.21
PURISSIMA S.A.	2	0.43	NIKE	1	0.21
CHEVRON	2	0.43	NUTRIVITAL S.A.	1	0.21
JONJEE HI-TECH IND.& COM.	2	0.43	ÁGUA MINERAL TIMBU	1	0.21
DIMABRU CIA LTDA	2	0.43	LACOFA	1	0.21
DON JORGE S.A.C	2	0.43	LÁCTEOS SAN ANTONIO	1	0.21
BRINSA S.A.	2	0.43	NATURA & CO	1	0.21
PDVSA	2	0.43	ABG-GALÁPAGOS	1	0.21
EP PETROECUADOR	2	0.43	CIG S.A.	1	0.21
CORPORACIÓN AZENDE S.A.	1	0.21	GILCA LTDA	1	0.21
MONSANTO COMPANY	1	0.21	POLINPLAST SAC	1	0.21
GENERAL MILLS INC.	1	0.21	LA POLACA GUSTLAC S.A.	1	0.21
GRUPO BIMBO S.A.B.	1	0.21	REAL S.A.	1	0.21
CALBAQ S.A.	1	0.21	PPC FLEXIBLE PACKAGING	1	0.21
ESTRELLAAZUL S.A.	1	0.21	DANEC S.A.	1	0.21
LA MEJOR SAS	1	0.21	ECUAQUIMICA	1	0.21
C.A ECUASAL	1	0.21	LABORATORIOS ZOO	1	0.21

(Continued)

TABLE 3 (Continued)

Manufacturer	*n*	Proportion	Manufacturer	*n*	Proportion
AQUALINDA PANAMA S.A.	1	0.21	MAGAP	1	0.21
NATURE'S PHARMA	1	0.21	SIKA S.A.	1	0.21
INDUFAR CIA. LTDA	1	0.21	ADM (COMPANY)	1	0.21
C'ESTBON BEVERAGE CO.	1	0.21	EMPAQPLAST S.A.	1	0.21
SHENYANG XIN YI YUEN CO	1	0.21	HESSTONE S.A.C.	1	0.21
AMALIE OIL CO.	1	0.21	GRUPO DIANA	1	0.21
APOTHECARY PRODUCTS	1	0.21	ILE C.A.	1	0.21
GULF	1	0.21	JOHNSON OUTDOORS INC	1	0.21

plastic debris deposition was significantly higher in the Hawaiian Islands during El Niño Southern Oscillation (ENSO) than during La Niña events. Therefore, standard long-term monitoring of plastic debris in Galápagos is recommended. Mestanza et al. (2019) found that the province with the best litter quality was the Galápagos Islands, where 88% of the beaches received an "A" rating (from "A"-excellent to "D"-poor) based on the EA/NALG (2000) scale. This is because the author sampled tourist beaches close to population centers. As shown in our study, the windward side of each surveyed island contained the highest concentrations of macroplastics. Our study focused on remote coastlines with no public or tourist access ($n = 20$) that were systematically sampled. To the best of our knowledge, and based on a review of the relevant literature, this is the first attempt at measuring plastic pollution on shorelines and in species at the archipelago level.

The primary macroplastic sources observed in this study were Perú, China, and mainland Ecuador. For Perú and Ecuador, the findings are consistent with the oceanographic patterns that sustain the archipelago's unique biodiversity (Houvenaghel, 1978; Palacios, 2004). Therefore, it is anticipated that plastic pollution will continue to flow from mainland Ecuador and Perú to Galápagos. This was further supported by high-resolution computer models that showed that floating plastic particles that enter the ocean in Perú, Ecuador, Colombia, and Chile could reach the Galápagos Islands (Van Sebille et al., 2019). However, these models indicate that it is highly improbable that PP released in Asia would reach the Galápagos Islands (Van Sebille et al., 2019). Regardless, China was the second largest source of macroplastics identified in our study. This perhaps echoes the "open secret" of the enormous industrial fishing fleet that surrounds the Galápagos Marine Reserve (GMR) and illegally fishes outside and within its boundaries (Schiller et al., 2015; Alava et al., 2017; Alava and Paladines, 2017; Hearn and Bucaram, 2017; Van Sebille et al., 2019; Bonaccorso et al., 2021; Vega Granja, 2022). The labels on the analyzed China-origin products were legible, lacking biofouling, and containing recent expiration dates, thus suggesting that they experienced little environmental degradation and were likely to have been in the water and on the beaches for a relatively brief period. It is likely that the poor waste management systems of industrial fishing fleets are responsible for the abundance of plastics with China origins on the islands (Donnelly et al., 2020; Moreno, 2021; Schofield et al., 2021; Alava et al., 2022; Leonhardt, 2022). It is important to note that the items found cannot be readily purchased in Galápagos or mainland Ecuador, further supporting the theory that they originated from the Chinese fishing fleet.

Contemporaneously with our research, a group of Santa Cruz Island residents called "Frente Insular" initiated an intensive coastal clean-up program and ecological activism. Upon examining the collected objects, they noticed a consistent "China origin trend" that correlated roughly with when the Chinese fleet began fishing in the Galápagos region (Rust, 2020; Moreno, 2021; Alarcon and Alvarado, 2022). The industrial ships that encircle the GMR are, in essence, floating cities that remain at sea for 2 or 3 years while their crews rotate, and no one knows or keeps track of where their trash ends (Moreno, 2021; Leonhardt, 2022).

The Galápagos marine reserve species may be negatively affected by ingestion, entanglement, and transfer of invasive species caused by plastic pollution. The Galápagos Islands are located at the convergence point of several major marine currents, which allows species from the eastern Pacific Ocean to arrive (Ballesteros-Mejia et al., 2021). Keith et al. (2018) found in Galápagos that plastics associated with fishing, such as rope, fishing nets, and buoys, were the most likely to be colonized by marine hitchhikers and accounted for 88% of the total weight of plastics colonized by marine organisms. Except for sponges and mollusks, fishing-related plastics supported the greatest diversity of organisms, with relatively high numbers in all the other groups. The only non-native species detected was the stalked barnacle *Dosima fascicularis*. A pleustonic specialist, which has been considered introduced but does not display characteristics that can classify it as invasive as it is a fugitive species that is readily outcompeted by local barnacle species (Cheng and Lewin, 1976; Blankley and Branch, 1985; Zambrano and Ramos, 2021). Nevertheless, plastic debris provides an effective "raft" for plants and animals to enter the Galápagos Marine Reserve, thereby emphasizing the need for vigilance (Keith et al., 2018).

Globally, fishing resources are overexploited. Each year, the world catches and harvests ∼200 million tons of fish and shellfish (FAO, 2020). The scale of these activities to obtain resources is sufficient to endanger marine life and generate an enormous amount of marine debris that is inappropriately managed (Richardson et al., 2021, 2022). When this stress is added to the impacts caused by climate change, ocean acidification, unsustainable aquaculture, oil drilling, and habitat destruction,

TABLE 4 The 52 species recorded interactions with plastic pollution (PP) in the Galápagos Islands (entanglement or ingestion) and the threat scale in Galápagos for the reported species.

Species	Taxon origin	IUCN	Feeding type	Habitat and ecology	Entanglement threat	Ingestion threat	Pooled threat
Reptilian							
∗Santa Cruz tortoise (*C. porteri*)∗	E	CR	H	TN, TU	81	243	162
∗Green sea turtle (*C. mydas*)∗	N	EN	H, O	MN, MO, MI	162	162	162
∗Marine iguana (*Amblyrhynchus cristatus*)∗	E	VU	H	MN, MI	108	108	108
Hawksbill turtle (*Eretmochelys imbricata*)	M	CR	O	MN, MO, MI	72	72	72
San Cristóbal lava lizard (*Microlophus bivittatus*)	E	NT	O	MI, TN, TU	72	36	54
Olive Ridley (*Lepidochelys olivacea*)	M	VU	O	MN, MO, MI	72	24	48
San Cristóbal tortoise (*Chelonoidis chathamensis*)	E	EN	H	TN, TU	27	54	41
Santa Cruz lava lizard (*Microlophus indefatigabilis*)	E	LC	O	MI, TN, TU	36	18	27
Avian							
∗Medium ground Finch (*G. fortis*)∗	E	LC	H	TN, TU, MI	81	27	54
∗Lava gull (*L. fuliginosus*)∗	E	VU	O	MN, MI	36	72	54
∗Flightless cormorant (*P. harrisi*)∗	E	VU	C	MN, MI	54	36	45
Small ground Finch (*Geospiza fuliginosa*)	E	LC	O	TN, TU, MI	54	36	45
Waved Albatross (*Phoebastria irrorata*)	E	CR	C	MN, MO, MI	27	54	41
Galápagos penguin (*Spheniscus mendiculus*)	E	EN	C	MN, MI	27	54	41
Oyster catcher (*Haematopus palliatus* galapagoensis)	E	VU	C	MI	18	36	27
Galapagos mockingbird (*Mimus parvulus*)	E	LC	O	TN, TU, MI	18	36	27
Brown pelican (*Pelecanus occidentalis* urinator)	E	LC	C	MN, MO, MI	9	27	18
Yellow warbler (*Setophaga petechia* aureola)	E	LC	C	TN, TU, MI	18	9	14
Nazca Booby (*Sula granti*)	N	LC	C	MN, MI	18	6	12
Red-Footed Booby (*Sula Sula*)	N	LC	C	MN, MI	6	12	9
Great frigatebird (*Fregata minor*)	N	LC	C	MN, MO, MI	12	6	9
Mammal							
∗Galápagos sea lion (*Z. wollebaeki*)∗	E	EN	C	MN, MO, MI, TU	81	81	81
Galápagos fur seal (*Arctocephalus galapagoensis*)	E	EN	C	MN, MO, MI	54	54	54
Humpback whale (*Megaptera novaeangliae*)	M	LC	Pl	MN, MO	36	18	27
Short-finned Pilot Whale (*Globicephala macrorhynchus*)	M	LC	C	MN, MO	12	6	9

(Continued)

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TABLE 4 (Continued)

Species	Taxon origin	IUCN	Feeding type	Habitat and ecology	Entanglement threat	Ingestion threat	Pooled threat
Cartilaginous fish							
∗Whale shark (*R. typus*)∗	M	EN	Pl	MN, MO	108	54	81
∗Spinetail mobula (*Mobula japanica*)∗	N	EN	Pl	MN, MO	108	54	81
∗Scalloped hammerhead (*Sphyrna lewini*)∗	N	CR	C	MN, MO	36	18	27
Galápagos shark (*Carcharhinus galapagensis*)	N	NT	C	MN, MO	24	12	18
Black tip shark (*Carcharhinus limbatus*)	N	VU	C	MN, MO	24	12	18
Spotted eagle ray (*Aetobatus narinari*)	N	NT	C	MN	12	24	18
Galápagos bullhead shark (*Heterodontus quoyi*)	N	LC	C	MN	12	6	9
Bony fish							
∗Black-striped salema (*X. jessiae*)∗	E	VU	Pl	MN	54	108	81
∗Whitespotted sandbass (*Paralabrax albomaculatus*)∗	E	EN	C	MN	27	54	41
Flathead Mullet (*Mugil cephalus*)	N	LC	H	MN, MI	18	36	27
Bacalao grouper (*Mycteroperca olfax*)	E	VU	C	MI, MN	18	36	27
Razor surgeon fishes (*Prionurus laticlavius*)	N	LC	H	MN	18	36	27
Swordfish (*Xiphias gladius*)	N	LC	C	MN, MO	6	12	9
Wahoo (*Acanthocybium solandri*)	N	LC	C	MN, MO	6	12	9
Yellow fin tuna (*Thunnus albacares*)	N	LC	C	MN, MO	6	12	9
Striped Bonito (*Sarda orientalis*)	N	LC	C	MN, MO	6	12	9
Ocean whitefish (*Caulolatilus princeps*)	N	LC	C	MN	6	12	9
Mexican hogfish (*Bodianus diplotaenia*)	N	LC	C	MN	6	12	9
Pacific Sierra (*Scomberomorus sierra*)	N	LC	C	MN, MO	6	12	9
Almaco Jack (*Seriola rivoliana*)	N	LC	C	MN	6	12	9
Mottled Scorpionfish (*Pontinus clemensi*)	N	LC	C	MN	6	12	9
Invertebrate							
∗Green sea urchin (*L. semituberculatus*)∗	N	NE	H	MN, MI	36	18	27
∗Ecuadorian hermit crab (*C. compressus*)∗	N	NE	O	MI	36	12	24
∗Sally lightfoot crab (*G. grapsus*)∗	N	NE	O	MI	24	12	18
Giant barnacle (*Megabalanus peninsulari*)	U	NE	Pl	MI	9	18	14

(Continued)

TABLE 4 (Continued)

Species	Taxon origin	IUCN	Feeding type	Habitat and ecology	Entanglement threat	Ingestion threat	Pooled threat
Xanthid crab (*Eurypanopeus planus*)	U	NE	O	MI	12	6	9
Anemona (*Anthopleura nigrescens*)	U	NE	C	MI	6	3	5

Only species with confirmed video or photographic reports were considered for the threat scale. Table organization, as proposed by Thiel et al. (2018), with adaptations. The threat scale is calculated, including species distribution or taxon origin that can be U, unknown or not evaluated; E, endemic; N, native; and M, migratory. Conservation status or IUCN Red List classification can be DD, data-deficient; NE, not-evaluated; LC, least concern; NT, near threatened; VU, vulnerable; EN, endangered; and CR, critically endangered. Then, the feeding type can be C, Carnivorous; H, Herbivorous; O, omnivorous, and Pl, Planktivorous. Finally, species habitat and ecology can be MI, marine intertidal; MO, marine oceanic; MN, marine neritic; TU, terrestrial urban; TW, terrestrial wetlands; or TN, terrestrial natural. The weighting for each of these categories is presented in Table 2.

many ecosystems and the services they provide are pushed to the edge of collapse. Artisanal and industrial fishing is among the largest global sources of plastic pollution (Rochman, 2018; Stafford and Jones, 2019; Richardson et al., 2021, 2022); Galápagos is no exception. Our macroplastic classification category FISH, which includes all fishing-related items (industrial and artisanal), was the second most prevalent category across all sampled study sites.

Prevention is the most effective method of combating plastic pollution (Hardesty and Wilcox, 2011). Once plastics enter the ocean, it is challenging to remove or manage them, particularly when they degrade into microplastics and nanoplastics. Therefore, to reduce the prevalence of plastic pollution, the entry of plastics into oceans must be prevented. Plastic waste management is challenging for island communities, such as the Galápagos Islands, as they are sent to landfills. The Isabela, San Cristóbal, and Santa Cruz Islands waste management facilities receive all the trash generated by the islands' 25,244 residents (INEC, 2016) and 271,238 tourists as of 2019 (Caisaguano et al., 2019). On each island, non-recyclable and recyclable materials are buried in landfills. The same applies to all macroplastics collected during the annual Galápagos coastal clean-up campaigns funded by the Coca-Cola Company in partnership with Conservation International (DeSmit, 2019). Extreme weather conditions can cause plastic movement and sometimes interfere with human systems, resulting in their release. Therefore, the key recognized sources of plastic debris in the Eastern Pacific area and globally should adhere to the recommendations of Kirchherr et al. (2017), Jenkins et al. (2019), Wang et al. (2020), and King and Locock (2022). Perhaps then, the Galápagos plastic problem will be resolved. (1) Advocate a circular economy by introducing 6Rs of waste management (refuse, reduce, reuse, repurpose, real-recycle, and remediate), in which manufacturers have direct responsibility for items generated after their useful life; (2) Trash traceability: to track the success of the 6Rs and ensure that legislators, consumers, and producers are aware of the life cycle of manufactured plastic items; and (3) innovate to create plastic-enhanced construction materials from plastic waste that has been collected but cannot be recycled using standard procedures; and (4) Continue urban and remote cleanups to raise awareness and monitor the success of waste management programs.

Multiple local and international institutions, such as governments, academic institutions, municipalities, and non-governmental organizations, are aware of global and local plastic pollution problems. Plastic bottles are one of the highest-recorded macroplastic items found in this study. In 2015, the government of Galápagos enacted a ban on single-use plastics, based on the preliminary findings of our study, which became effective in 2018 (Klingman, 2015; Consejo de Gobierno de Régimen Especial de Galápagos, 2018). This mandates that companies such as Coca-Cola be required by this law to sell their products on the Galápagos Islands as part of a 100% return program. The next step is to apply the same strategy globally. Global legislation and management of single-use plastics should be the next step in mitigating this growing problem on oceanic and protected islands. However, it is essential to note that despite the current legislation, many banned single-use plastic items remain in the Galápagos Archipelago. Consequently, the enforcement of current local laws is vital. To protect our remaining pristine ecosystems from plastic pollution, local, regional, and global legislation as well as the enforcement of legislation regarding single-use plastics are required.

5. Conclusions

This is the first comprehensive assessment of plastic pollution distribution, composition, source, and impact on animals within the Galápagos archipelago. Macroplastics were observed on every shoreline surveyed throughout the archipelago, including every major island. The prevailing wind direction affected the distribution and macroplastic density (items/m^2), with the windward coast of Santiago Island having the highest density of plastics, while the leeward coast had the lowest density. Hard plastic fragments (HPF) are the most common type of debris, while fishing-related waste is the second most common and distinguishable category of macroplastics. The main countries of origin of the examined macroplastics were Perú, China, and Ecuador, and they were primarily produced by AjeCroup, Coca-Cola, and Tingyi Holding Corporations. While oceanographic models indicate that waste from Perú and mainland Ecuador could certainly reach Galápagos, it is highly improbable that plastic debris released from China could. Therefore, it is hypothesized that debris with Chinese markings may have been sourced from large fishing fleets surrounding the Galápagos marine reserve. However, further research is required.

Our study uncovered evidence of 52 species (including 20 endemic species) interacting with plastic pollution through ingestion and entanglement. Moreover, 15 of

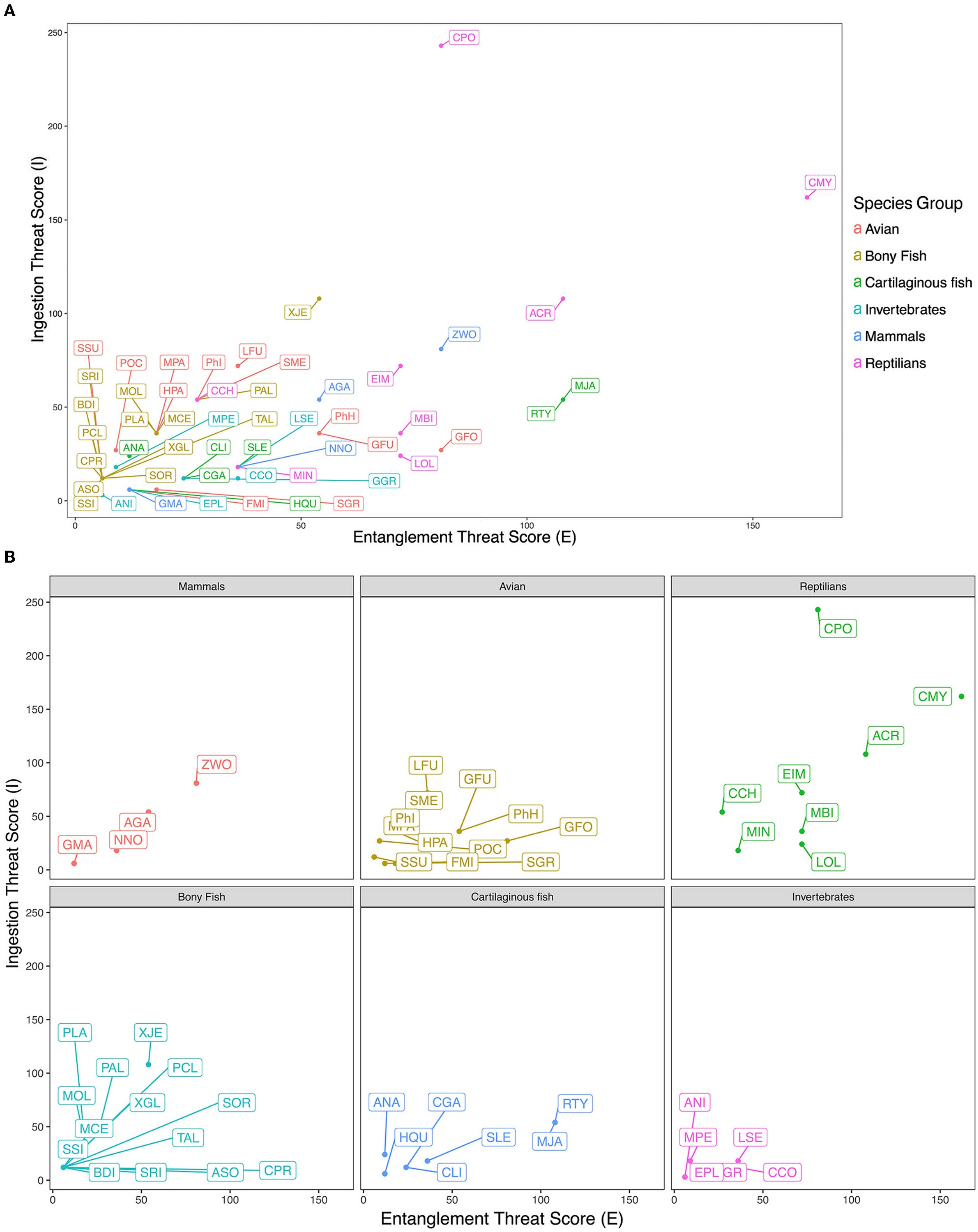

FIGURE 5

(A) Calculated plastic pollution threat scores for the 52 species evaluated in this study. Entanglement Threat Score (E); Ingestion Threat Score (I). AVIAN: *Medium ground Finch *(G. fortis)* GFO*; *Lava gull (*L. fuliginosus*) LFU*; *Flightless cormorant (*P. harrisi*) PhH*; Small ground Finch (*Geospiza fuliginosa*) GFU; Waved Albatross (*Phoebastria irrorata*) PhI; Galápagos penguin (*Spheniscus mendiculus*) SME; Oyster catcher (*Haematopus palliatus galapagoensis*) HPA; Galápagos mockingbird *(Mimus parvulus)* MPA; Brown pelican (*Pelecanus occidentalis urinator*) POC; Nazca Booby (*Sula granti*) SGR; Red-Footed Booby (*Sula Sula*) SSU; Great frigatebird (*Fregata minor*) FMI. BONY FISH: *Black-striped salema (*X. jessiae*) XJE *; *Whitespotted sandbass (*Paralabrax albomaculatus*) PAL*; Flathead Mullet (*Mugil cephalus*) MCE; Bacalao grouper (*Mycteroperca olfax*) MOL; Razor surgeon fishes

(Continued)

FIGURE 5 (Continued)
(*Prionurus laticlavius*) PLA; Swordfish (*Xiphias gladius*) XGL; Wahoo (*Acanthocybium solandri*) ASO; Yellow fin tuna (*Thunnus albacares*) TAL; Striped Bonito (*Sarda orientalis*) SOR; Ocean whitefish (*Caulolatilus princeps*) CPR; Mexican hogfish (*Bodianus diplotaenia*) BDI; Pacific Sierra (*Scomberomorus sierra*) SSI; Almaco Jack (*Seriola rivoliana*) SRI; Mottled Scorpionfish (*Pontinus clemensi*) PCL. CARTILAGINOUS FISH: *Whale shark *(R. typus)* RTY*; *Spinetail mobula (*Mobula japanica*) MJA *; *Scalloped hammerhead *(Sphyrna lewini)* SLE*; Galápagos shark *(Carcharhinus galapagensis*) CGA; Black tip shark (*Carcharhinus limbatus*) CLI; Spotted eagle ray (*Aetobatus narinari*) ANA; Galápagos bullhead shark (*Heterodontus quoyi*) HQU. INVERTEBRATES: *Green Sea urchin (*L. semituberculatus*) LSE*; *Ecuadorian hermit crab *(C. compressus)* CCO *; *Sally lightfoot crab *(G. grapsus)* GGR* Giant barnacle *(Megabalanus peninsulari)* MPE; Xanthid crab (*Eurypanopeus planus*) EPL; Anemona *(Anthopleura nigrescens)* ANI. MAMMALS: *Galápagos sea lion *(Z. wollebaeki*) ZWO*; Galápagos fur seal (*Arctocephalus galapagoensis*) AGA; Humpback whale *(Megaptera novaeangliae)* NNO; Short-finned Pilot Whale (*Globicephala macrorhynchus*) GMA. REPTILIANS: *Santa Cruz tortoise *(C. porteri)* CPO*; *Green Sea turtle *(C. mydas)* CMY*; *Marine iguana *(Amblyrhynchus cristatus)* ACR*; Hawksbill turtle *(Eretmochelys imbricata)* EIM; San Cristóbal lava lizard (*Microlophus bivittatus*) MBI; Olive Ridley *(Lepidochelys olivacea)* LOL; San Cristóbal tortoise *(Chelonoidis chathamensis)* CCH; Santa Cruz lava lizard *(Microlophus indefatigabilis*) MIN. **, High scores. **(B)** The calculated plastic pollution threat score for each group of species (mammals, avian, reptilian, bony fish, cartilaginous fish, and invertebrates).

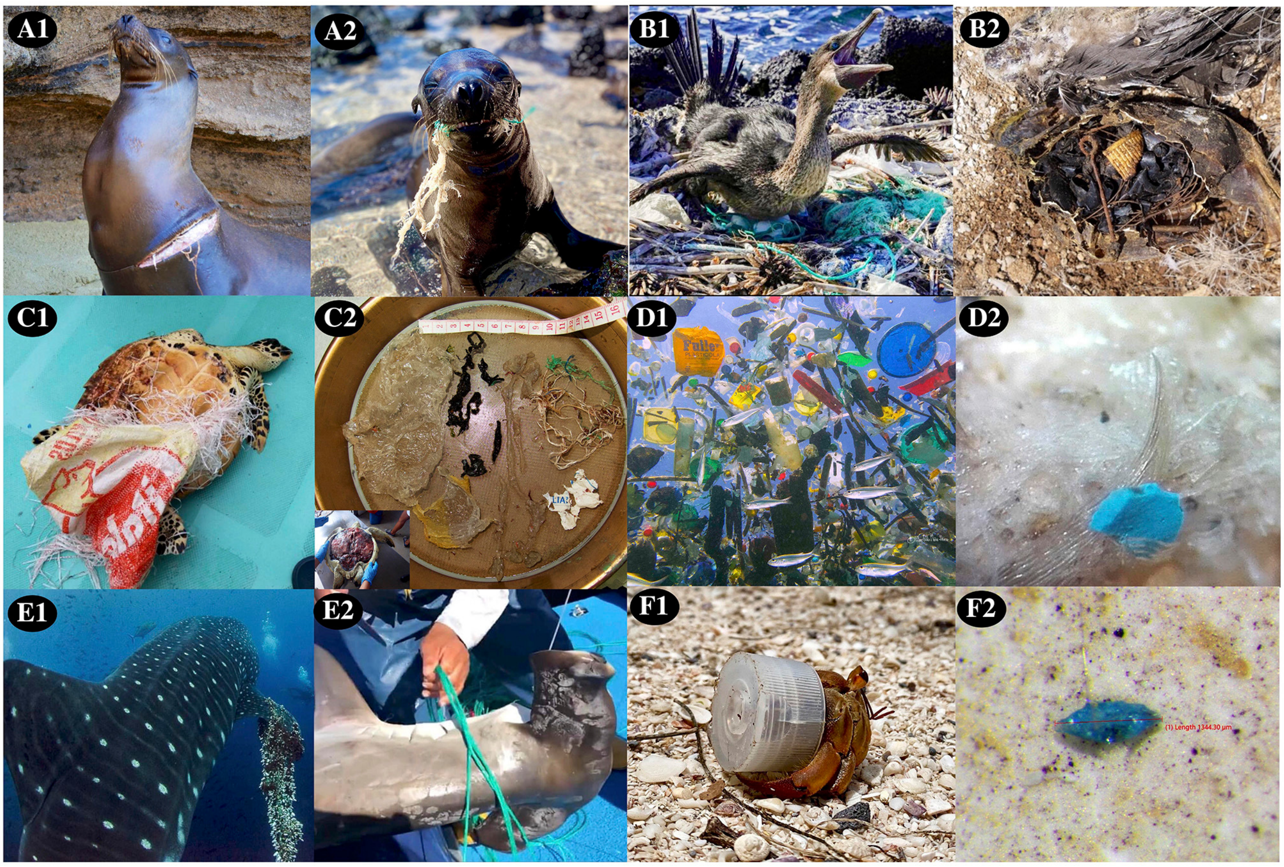

FIGURE 6
Examples of records of the evident interaction between plastic pollution (PP) and native and endemic species of Galápagos (entanglement or ingestion) used for the PP Galápagos wildlife threat assessment (PPT). Information for each figure is provided with the author's name. All the participants agreed that this information was included in the study. MAMMALS **(A1):** Galápagos Sea Lion (*Z. wollebaeki*) entanglement San Cristóbal island © Carolina Pesantez; **(A2):** *Z. wollebaeki* possible ingestion San Cristóbal island © Juan Pablo Muñoz-Pérez. AVIAN **(B1):** Flightless Cormorant (*P. harrisi*) entanglement Isabela Island © Rodrigo Buendia; **(B2):** Waved albatross (*Phoebastria irrorata*) ingestion and dead Española Island © Sebastian Cruz. REPTILIANS **(C1):** Hawksbill turtle (*Eretmochelys imbricata)* entanglement San Cristóbal island © Shinobi Chauca; **(C2):** Green Sea Turtle (*C. mydas*) ingestion and dead San Cristóbal island © Juan Pablo Muñoz-Pérez. BONY FISH **(D1):** Black-striped Salema (*X. jessiae*) possible ingestion of Rábida island © Juan Pablo Muñoz-Pérez; **(D2):** Wahoo (*Acanthocybium solandri)* microplastic ingestion Fernandina Island © Alice Skehel. CARTILAGINOUS FISH **(E1):** Whale Shark (*R. typus)* entanglement Darwin Island © Jenny Waack; **(E2):** Scalloped Hammerhead (*Sphyrna lewini*) entanglement and dead San Cristóbal Island © Galápagos Sky. INVERTEBRATES **(F1):** Ecuadorian hermit crab (*C. compressus*) entanglement San Cristóbal island © Juan Pablo Muñoz-Pérez; **(F2):** Giant barnacle (*Megabalanus peninsulari*) microplastic ingestion San Cristóbal island © François Oberhansli.

these species were ranked as being at the greatest risk of severe harm on the Galápagos Islands because of the possibility of ingesting or becoming entangled with PP. The top four species at overall risk of PP interactions in Galápagos include (1) Santa Cruz tortoises (*C. porteri*); (2) Green sea turtles (*C. mydas*); (3) Marine iguanas (*Amblyrhynchus cristatus*); and (4) Galápagos sea lion (*Z. wollebaeki*).

Our research indicates that plastic pollution is a problem in the Galápagos Islands; however, it is not restricted to this region. Therefore, global solutions must be implemented to alleviate global plastic pollution crises. Those who have learned to collaborate and improvise more effectively in the natural world have succeeded (Darwin, 1876). The Galápagos Islands have a relatively small human population, strict immigration laws, and a unique system of nature protection. As a result, the archipelago provides the opportunity and duty to serve as a "social and natural laboratory" to generate data for solving the complex global socio-ecological issue of plastic pollution.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JM-P, GL, DA-R, CV, BW, and KT contributed to the study conception and design. JM-P, EC, RR, AJ, and HV organized the databases. LZ-A organized the database and produced the maps. JM-P performed the statistical analyses and wrote the first draft of the manuscript. GL, AS, CV, DA-R, BW, and KT wrote sections of the manuscript. JM-P, GL, DA-R, AS, EC, RR, AJ, HV, and KT worked in the field and laboratory to collect and analyze samples. JM-P and KT secured funding and managed the approval of the necessary research permits, ethics, and field logistics. All authors contributed to the development, synthesis of the information, contributed to manuscript preparation, manuscript revision and read, and approved the submitted version.

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Conflict of interest

BW was employed by Ecolibrium, Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2023.1091516/full#supplementary-material

SUPPLEMENTARY FIGURE 1

Additional examples of the evident interaction between plastic pollution (PP) and native and endemic species of Galápagos (entanglement or ingestion) used for PP Galápagos wildlife threat assessment (PPT). Information for each figure is provided with the author's name. All the participants agreed that this information was included in the study. MAMMALS **(A1)**: Short finned Pilot Whale (*Globicephala macrorhynchus*) entanglement Española Island © Manuel Yépez; **(A2)**: Galápagos Sea Lion (*Z. wollebaeki*) entanglement Caamaño island © Cian Luck; **(A3)**: Galápagos fur seal (*Arctocephalus galapagoensis*) possible ingestion Fernandina Island © Tui de Roy; **(A4)**: Humpback whale (*Megaptera novaeangliae*) entanglement and dead Isabela Island © Erika Carrera. AVIAN **(B1)**: Brown Pelican (*Pelecanus occidentalis urinator*) ingestion and dead Santa Cruz Island © Andrea Loyola; **(B2)**: Galápagos Penguin (*Spheniscus mendiculus*) apparent ingestion Isabela Island © BirdTrips Ecuador; **(B3)**: Oyster catcher *(Haematopus palliatus galapagoensis)* Santa Cruz Island © Kiyoko Gotanda; **(B4)**: Red-Footed Booby (*Sula sula*) possible ingestion San Cristóbal Island © Santiago Izuaste. REPTILIAN **(C1):** Santa Cruz Giant Tortoise (*C. porteri*) ingestion Santa Cruz Island © Andrea Loyola; **(C2)**: Marine Iguana (*Amblyrhynchus cristatus*) probable ingestion Santa Cruz Island © Getty Images; **(C3)**: Santa Cruz lava lizard *(Microlophus indefatigabilis)* entanglement Santa Cruz Island © Diego Intriago; **(C4)**: Olive ridley turtle (*Lepidochelys olivacea*) entanglement *San* Cristóbal Island © Shinobi Chauca. BONY FISH **(D1)**: Almaco Jack (*Seriola rivoliana*) ingestion Española Island © Santiago Inzuaste; **(D2):** Yellow Fin Tuna (*Thunnus albacares*) ingestion Isabela Island ©Alice Skehel; **(D3)**: Ocean whitefish (*Caulolatilus princeps*) ingestion Santiago Island ©Alice Skehel; **(D4):** Mottled Scorpionfish *(Pontinus clemensi)* ingestion San Cristóbal island © Cisne Zambrano y Maria del Mar Quiroga. CARTILAGINOUS FISH **(E1)**: Galápagos shark (*Carcharhinus galapagensis*) entanglement and dead Española Island © Manuel Yépez; **(E2)**: Spinetail mobula (*Mobula Japanica*) entanglement and dead Isabela Island © Ericka Carrera; **(E3)**: Galápagos Bullhead Shark (*Heterodontus quoyi*) entanglement and dead Fernandina Island © Ericka Carrera; **(E4)**: Spotted Eagle Ray (*Aetobatus ocellatus*) possible ingestion Isabela Island © anonymous. INVERTEBRATES **(F1)**: Anemona (*Anthopleura sp.*) entanglement San Cristóbal Island © Olivia Burleigh; **(F2)**: Xanthid Crab (*Eurypanopeus planus*) entanglement Santa Cruz Island © DPNG; **(F3)**: Sally lightfoot crab (*G. grapsus*) entanglement Santa Cruz Island © Johan Gonzalez; **(F4)**: Green Sea Urchin (*L. semituberculatus)* entanglement San Cristóbal Island © Adam Porter.

SUPPLEMENTARY FIGURE 2

Survey of wildlife interactions with plastic pollution in Galápagos.

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Policy implications for gaps in traditional plastic waste material flow analysis: Palmerston North, New Zealand

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The Basel Plastic Waste Amendments reflect growing global concern about the illegal plastic waste trade as waste colonialism. Comprehensive analyses of plastic waste material sources, pathways, and fates are needed for effective plastic waste trade policy. Plastics waste flows from Palmerston North, New Zealand to Malaysia highlight potential gaps in plastic waste trade policies. The authors recommend strengthening New Zealand's national waste policy framework and the Basel Convention's Plastics Amendments by basing policy responses on critical transboundary plastic waste material flow analyses, establishing harmonized definitions including "recyclable" and "environmentally sound recycling"; regulating contamination thresholds and container inspections; and waste trade traceability, transparency, compliance, enforcement, and remediation; reclassifying fluorinated polymers and thermosets as "hazardous"; and prioritizing principles of prevention, proximity and precaution over future investments in the management of plastic waste.

KEYWORDS

plastic waste, Basel Convention Plastic Waste Amendments, Basel Convention, waste colonialism, New Zealand, material flow analysis, global plastics treaty

Introduction

Since 1988, more than a quarter of a billion tons of plastic waste has been exported around the globe (Environmental Investigation Agency, 2021, p. 19). Plastic waste exports are a widespread waste management practice in OECD countries and yet importing countries are increasingly receiving contaminated and otherwise unrecyclable plastic waste designated as "recyclable". However, only an estimated 10% of all plastic waste ever produced has been diverted for the intention of recycling. The vast majority (∼76%) has accumulated in landfills or the natural environment while about 14% has been incinerated (Geyer, 2020, p. 27–28).

China was the biggest importer of post-consumer plastics globally until it became overwhelmed by supply (Wang et al., 2020). Brooks et al. (2018, p. 3) estimated that in 2016, plastic waste imports to China contributed an additional 10.8% to the waste generated locally. China's National Sword policy, enforced in 2018, banned imports of a range of plastic wastes and highlighted waste dumping as a global phenomenon. China's policy was precipitated not only by the increasing volumes of waste sent to China, but also the increasing rates of contamination of those shipments. Contaminants can include dirt, liquids, non-recyclable plastics and other materials.

When importing countries receive shipments of waste that do not reflect export documentation or contain contaminated bales, they may declare these illegal and send them back to the exporter. However, financial guarantees may be difficult to obtain in which case shipments may be landfilled, dumped, or burned in the absence of safe and responsible waste management alternatives (Franklin-Wallis, 2019). Mislabeled or contaminated shipments of plastic waste returned to exporters can be redirected to other non-OECD countries (Wood, 2019). In addition to the financial, environmental, human health, and human rights impacts, the trafficking of plastic waste can hinder development by fueling corruption, and other forms of organized crime and poverty in some countries (INTERPOL, 2020). The illegal waste trade can also divert valuable resources away from zero waste responses. The illegal plastic waste trade is big business: "With an estimated worth of up to €15 billion in the EU alone, the illegal trade in plastic waste is facilitated by a serious lack of transparency and accountability that operates in the sector" (Environmental Investigation Agency, 2021, p. 5).

China's National Sword policy saw a huge diversion of plastic waste imports to South and Southeast Asian countries, prompting them to implement their own national policies and legislation to discourage the illegal trade of plastic waste throughout 2018 and 2019. These countries are now also presenting similarly high plastic waste mismanagement rates as China: Malaysia (57% mismanaged), Indonesia (83%) and Thailand (75%), while Turkey send 90% of their waste to landfill (Environmental Investigation Agency, 2021, p. 7). "Almost all countries that receive or have received large quantities of imported plastic waste are those that also have some of the highest mismanagement rates in the world" (Environmental Investigation Agency, 2021, p. 9).

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (the Basel Convention) is an international treaty designed to reduce the movements of hazardous wastes between nations (specifically from developed to less developed countries), and to promote national waste management self-sufficiency. In 2019, in response to increasing cases of the illegal trade in plastic waste, the 14th Conference of the Parties to the Basel Convention unanimously adopted the Plastic Waste Amendments. The adoption of the Amendments was bound by 186 states and the European Union (Secretariat of the Basel Convention, 2019). The Plastic Waste Amendments to the Convention introduces the changes to the Convention including the following new categories for plastic waste:

> *Annex II: Y48*, lists plastic waste, including mixtures of such wastes, that are subject to the prior informed consent (PIC) procedure (excluding those that would fall under A3210 or B3011).
> *Annex VIII: A3210*, clarifies the scope of plastic waste presumed to be hazardous and therefore subject to the PIC procedure.
> *Annex IX: B3011* replaces B3010 and *clarifies the type of plastic wastes presumed not to be hazardous* plastic waste destined for recycling in an environmentally sound manner and almost free from contamination and other types of waste[1] that remain excluded from the PIC procedure (certain single polymers or mixtures of PE, PP and/or PET).

The Plastic Waste Amendments specify that plastic exports must meet specific criteria or be subject to PIC. Basel's prior informed consent (PIC) procedure is based on four key stages: notification, consent and issuance of movement document, transboundary movement, and confirmation of disposal as per Article 6, paragraph 1 of the Basel Convention and Decision VIII/18 of COP8 (Basel Convention, 2006). However, the PIC process is ineffective when accurate identification of plastic wastes remains a challenge and when there an ongoing lack of agreement about what constitutes hazardous plastic wastes. Evidence of ineffective contamination assessments is seen in ongoing transboundary flows of Y48 which can be buried in shipments labeled as paper waste and textiles and in refuse-derived fuel (RDF).

According to the Amendments, PIC is required except for the following criteria: single separated and non-halogenated [e.g., no polyvinylchloride (PVC)] polymers except cured resins and six fluorinated polymers that are destined for recycling/reclamation of organic substances which are not used as solvent (R3, Annex IV); "almost free from contamination"; or mixed polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). All other mixed plastic waste is subject to PIC. Breach of any of the articles of the Basel Convention, including the Plastic Waste Amendments is considered illegal waste trade.

In addition to ongoing challenges associated with PIC procedures is the lack of definition of "almost free from contamination" within the text of the Convention. This lack of definition leaves member states with the responsibility of setting their own contamination limits while respecting the spirit of the Convention. In the absence of clear guidance on contamination thresholds, a risk is presented to receiving countries who feel compelled raise their contamination thresholds where they have entered into trade relationships with more powerful countries (a cause and symptom of ongoing waste colonialism). Vague references to contamination rates in the Convention also poses a risk to exporting member states when their contamination threshold may be considered higher than "almost free from contamination".

Exemption for PIC procedures also requires that Annex II plastics are not only almost free from contamination but also free from "other types of waste". Annex II, VIII, and IX imply that 'other types of waste' are plastics other than "mixtures of plastic waste, consisting of polyethylene (PE), polypropylene (PP) and/or polyethylene terephthalate (PET), provided they are destined for separate recycling of each material and in an environmentally sound manner".

While some changes in the global waste trade have been made, three and a half years after COP 14, transboundary movements of plastic waste continue to sustain waste colonialism. For example, the Bamako Convention (1991) was signed by 25 African

1 I.e., consisting almost exclusively of waste of one type of plastic polymer as per Annexes II, VIII, and IX.

countries in response to the failures of the Basel Convention at that time (UNEP, 2019). The Basel and Bamako Conventions emphasize power imbalances in the transboundary movement of waste. The discourse around waste colonialism often centers on corporate imperialism, the neoliberal phenomenon of international corporate expansion, corporate manipulation of production and consumption patterns (Pratt, 2011), and corporate influence over policy and society (Prahalad and Lieberthal, 2008). In short, waste colonialism draws attention to the power structures embedded within the movement of waste, including plastic waste.

This paper draws on the findings of a material flow analysis of plastic waste conducted by the second author in the city of Palmerston North New Zealand in 2019. The case study highlights some weaknesses in municipal and national traditional plastics material flow analyses, ongoing challenges associated with the Plastic Waste Amendments to the Basel Convention three and a half years after coming into force as well as national and international waste trade policy.

The paper starts with some of the weaknesses in the traditional application of plastics material flow analyses and how the transparency and traceability of plastic waste could more be more effectively captured. A harmonized definition of "environmentally sound management" which is currently lacking in the Basel Convention would support the transparency and traceability of municipal and national plastic waste flows. A case is then made for New Zealand and other Basel member states to set their own regulated contamination thresholds to support accurate municipal and national plastics waste flow analyses and contamination assessments. Finally, the authors argue for the identification of hazardous chemicals in municipal and national plastics waste flow analyses.

Plastics material flow analysis

NZ has not been an innocent in growing cases of waste dumping in non-OECD countries as waste colonialism. In 2020, NZ exported 58% of our plastic waste exports by value to Malaysia, Indonesia, the Philippines, Thailand, and Vietnam: a 22% increase since China's National Sword policy was enforced. High levels of contamination in NZ's plastic waste exports were made public when, in 2019, Indonesia sent five containers of plastic waste back to NZ due to an unacceptably high rate of contamination. However, they were lost in transit and were never repatriated (Woolf, 2019).

Material flow analysis is an analytical method to quantify flows and stocks of materials or substances within a system. Effective material flow analyses could significantly contribute to strengthening policy to stop hazardous and illegal trade in plastic waste. However, research quantifying flows of plastic waste rarely expand system boundaries beyond domestic borders and seldom investigate the fates of waste post-export (Van Eygen et al., 2017; Eriksen et al., 2020). For example, a study conducted on the flows of PET, PE, and PP in Europe to evaluate the potential for a circular economy for plastics simply present plastic waste exports as "losses" (Eriksen et al., 2020). Furthermore, the fate of traded waste is commonly characterized according to its intended or theoretical fate as "recyclables". Therefore, seldom is a determination made about the volumes of exported plastic waste "responsibly recycled" in the receiving country.

Some studies have analyzed the domestic flows of plastic waste in NZ (MfE, 2009; Eunomia, 2018; WasteMINZ, 2020). However, there is limited information on the characteristics of this waste. In particular, the waste is rarely characterized beyond "recyclables": resin 1 PET and 2 High Density Polyethylene (HDPE), respectively, and "mixed plastics" resins 3–7. In addition, little is known regarding the fate of NZ's plastic waste exports. A study commission by NZ's Ministry for the Environment reported "limited transparency" in the plastic waste industry (Eunomia, 2018, p. 24). The lack of data transparency is a significant barrier to comprehensive and transboundary material flow analyses of traded plastic waste and is exemplified by vague references to "recyclable" plastic waste.

Transparency, traceability, and "environmentally sound management"

The recyclability of plastic waste is based on a number of characteristics including polymer type, product design, and presence of additives and/or impurities including colorants, flame retardants and other materials or polymer types (e.g., multilayer) (Faraca and Astrup, 2019; Hahladakis and Iacovidou, 2019), as well as external contaminants. "Recyclability" is also contingent on collection and sorting, and the ability of waste managers to secure markets as was the case in Palmerston North. While many polymers are theoretically recyclable and designated as "recyclable" in source countries, this does not mean receiving countries have the available resources, capacity, or technology to recycle those polymers either at all, at a particular time, or in a manner that is safe for the environment and human health.

There is a lack of transparency regarding the fate of exported plastic waste at municipal level in NZ. The Palmerston North City council requires the broker based in Australia to ensure buyers in Malaysia are legitimate recyclers. However, when the Waste Operations Supervisor (pers. comm, 2020), was asked if they could be confident that all the waste exported to Malaysia was recycled and not dumped/landfilled and/or burned, they were unable to respond with any certainty.

In 2019, consumers in Palmerston North, NZ generated 2,679 tons of plastic waste (Figure 1). One thousand nine hundred and eighty tons formed kerbside waste which consists of unrecyclable plastic waste and some recyclable plastic which may have ended up in that stream due to human error when categorizing waste. Recyclable plastic is collected in two ways; by kerbside pick-up (614 tons) or *via* drop-off sites (85 tons) where the public can bring their recyclables.

Of the 2,679 tons of plastic waste generated in Palmerston North, 83.1% was landfilled, whilst 349 tons were sent for local recycling and the remaining "recyclable" plastic waste materials were exported to Malaysia. However, Malaysia has exceeded its capacity to import other country's plastic waste. While Malaysia has an installed recycling capacity of 515,009 tons, in 2021 it imported, on average, 835,000 tons of plastic waste each year in addition to an estimated 2.4 million tons of plastic waste produced domestically (Environmental Investigation Agency, 2021). This goes some way

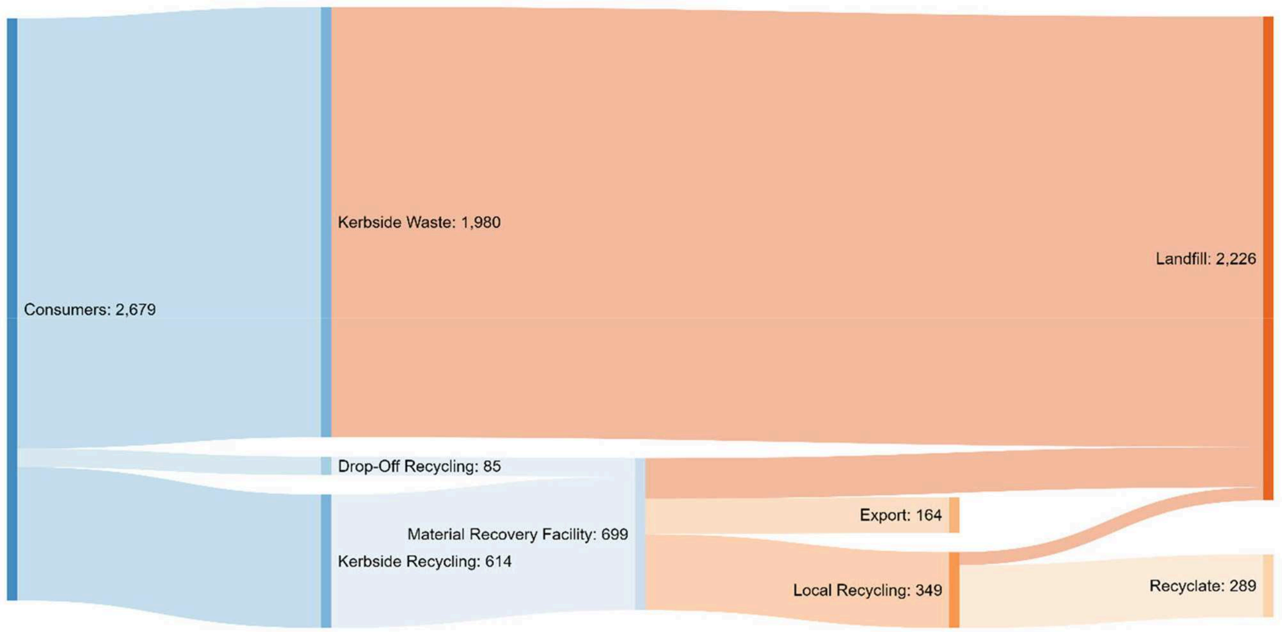

FIGURE 1
Plastic waste flows from Palmerston North in 2019.

to explaining why, of the plastic waste exported from Palmerston North to Malaysia in 2019, only an estimated 37% was "potentially recycled" in the best-case, dropping down to 11% in the worst, where the unrecycled waste is either dumped, landfilled, or burned.

The Palmerston North City Council operates a material recovery facility (MRF), based at the Awapuni Resource Recovery Park, where mixed (i.e., plastic, paper, glass, and metal) recyclable materials are sorted and diverted to treatment as appropriate. The material recovery facility sorts plastic waste into five categories:

- PET Clear (bottles)
- HDPE Natural (milk bottles)
- HDPE Colored (janitorial)
- PP (ice cream and yogurt containers)
- Mixed Plastics (PET, PVC, LDPE, PP, PS, and Other)

The recyclables are manually sorted, with PET, HDPE and PP separated individually from the stream while it is transported along a conveyer belt. The final stream constitutes "mixed plastics". PET contributed 38.1% to plastic collected in 2019 (shown in Figure 2), whilst HDPE contributed 26.4% and PP 11.6%. Whilst Palmerston North accepts all plastic resin types, they reported no solid LDPE items (e.g., container lids and squeezable bottles). PET, HDPE and PP are diverted to local recyclers as far as possible whilst the "mixed plastics" are exported to Malaysia for recycling.

The Basel Convention Amendment lists are difficult to distinguish not only because of the lack of clarity regarding the phrase "almost free from contamination", but also the lack of agreement about "environmentally sound management" of plastic waste. The Basel Plastic Waste Amendments includes provisions for the "environmentally sound management" (ESM) which the Basel Convention as "taking all practicable steps to ensure that hazardous wastes or other wastes are managed in a manner which will protect human health and the environment against the adverse effects which may result from such wastes" (UNEP, 2014, p. 11). However, what those steps should be are matters of ongoing debate. In addition, the proximity principle of the Basel Convention's preamble states that "hazardous wastes and other wastes should, as far as is compatible with environmentally sound

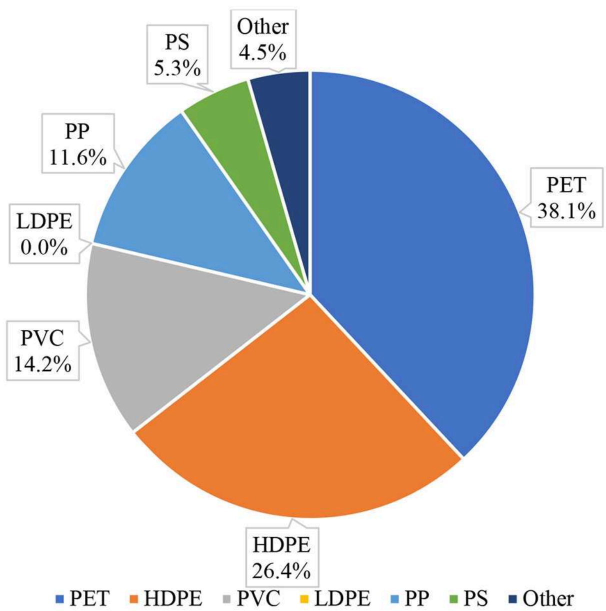

FIGURE 2
Composition of collected recyclables from Palmerston North.

and efficient management, be disposed of in the State where they were generated" (UNEP, 2014, p. 17). However, this principle is disregarded in the case of plastic waste trade, particularly where OECD country waste is sent to non-OECD countries where there is capacity for "environmentally sound and efficient management" of any kind is lacking.

Some plastics and additives are not yet listed as hazardous in the Amendments, yet are hazardous when thermally treated, and cannot be recycled in an environmentally sound manner. Yet, the Amendment states that B3011 and Y48 bales (subject to PIC) must be "destined for recycling in an environmentally sound manner and almost free from contamination and other types of wastes". In addition, it is not clear how the new Basel rules relate to RDF which contain hazardous polymers and additives. The new Basel Convention Amendments require trade controls for all mixed plastic wastes not destined for environmentally-sound recycling. However, RDF classified as an "alternative fuel" containing PVC and other hazardous halogenated plastics is routinely exported for burning (e.g., to fuel cement kilns) rather than recycling. "Recycling" is also vaguely defined in the Convention as "recycling/reclamation of organic substances which are not used as solvents (R3 in Annex IV, sect. B)". From this definition, recycling does not assume "mechanical recycling" and may also imply processes marketed by the petrochemical industry as "chemical/advanced recycling". Indeed, thermal (pyrolysis and gasification) and solvent-based recovery processes for plastic waste have been marketed as novel "chemical recycling" or "advanced recycling" (GAIA, 2022, p. 2). These technologies present environmentally *un*sound waste management due to extremely high energy requirements, dioxins, and other hazardous emissions, including as contamination and other outputs, and microplastic emissions (Shen et al., 2021; Yang et al., 2021).

A small intersessional working group of the Basel Convention co-led by China, Japan, and the United Kingdom prepared a draft of updated technical guidelines on the environmentally sound management of plastic wastes (UNEP/CHW.15/6/Add.7) (UNEP, 2022a). However, GAIA (2022, p. 1) suggest these guidelines provide more confusion than clarity.

Contamination thresholds and assessments

As has been noted, "contamination" of recyclable plastic waste remains vague in the Convention, and acceptable contamination rates are not stipulated. NZ's export rules do not state a contamination threshold. Exporters are only required to match or better that of the receiving country (if, indeed, the receiving country has declared a contamination threshold). A lack of standardized monitoring and reporting means there are limited data on types of plastic waste exported and contamination rates. China's contamination threshold before their plastic waste import ban was 0.5%. Their contamination rate is now set to 0% and Indonesia has a 2% contamination threshold (Basel Action Network, 2022). If Palmerston North is an indication of contamination levels in NZ's national plastic waste exports (16–25%), much of NZ's plastic waste is not likely to meet the Conventions requirement that exports are "almost free from contamination".

The Convention does not require exporters or importers to comply with standardized contamination assessment methods, nor reporting protocols. Nor does it identify those responsible for assessing contamination rates (either exporter prior to shipping or importer on arrival at destination). In the case of Palmerston North, infrequent and irregular audits are conducted of mixed waste bales for export *via* a randomized sampling system. Comprehensive assessments are costly, and the onus often lies largely on non-OECD receiving countries to assess shipments on receipt (Basel Action Network, 2022). For example, Malaysia returned 3,000 tons of plastic bales to the UK, Saudi Arabia, and Canada in 2019 due to improper labeling (Shrikanth and Palma, 2019).

The need to distinguish uncontrolled plastic waste (B3011) from controlled wastes (Y48) under the Basel Convention is an ongoing challenge. Plastic products originally holding toxic contents (such as janitorial products) may be co-mingled with plastic waste destined for the manufacture of food or beverage containers. A broad range of grades and/or polymer qualities are potentially captured in mixed bales including the presence of additives and colorants which influence "environmentally sound" "recyclability". The World Trade Organization's Harmonized Commodity Description and Coding System (HS) is an internationally recognized classification system for the international trade of good used by customs authorities. The HS comprises about 5,000 commodity groups. Each of these groups are identified by a six-digit code. Countries can refer to these codes in establishing national import/export rules.

Countries can continue to mislabel contaminated bales of otherwise recyclable plastic waste with hazardous plastic waste, and thereby, exploit the HS code classifications of exported plastic waste (Dominish et al., 2020, p. 18). For example, plastic waste exported from NZ from 2017 to 2019 was classified as either polymers of ethylene or styrene, or as general plastic waste (i.e., HS heading 3,915 which encompasses all plastic waste types) (Figure 3). Enforcement is further complicated by the broad definitions of "waste" applied across member states. For example, the EU Waste Framework Directive

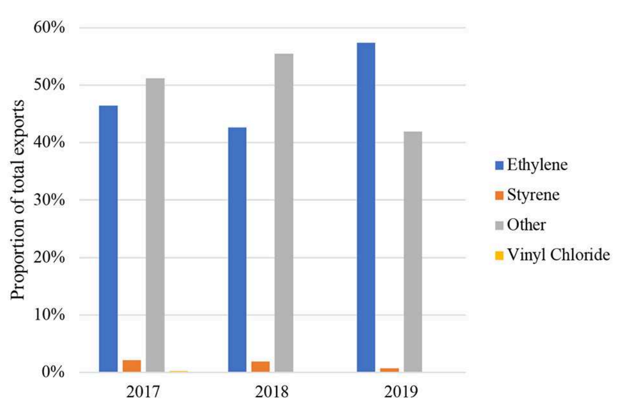

FIGURE 3
Plastic waste exports by HS code classification (adapted from Stats NZ). The "Other" category refers to mixed plastics wherein the resin type is not specified.

Article 3 (European Union, 2008) does not distinguish between "second hand" or "waste". The Waste Shipment Regulation (WSR) transposes the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (Basel Convention) into EU law. In addition, different countries use different coding systems. For example, EU countries can use the WSR codes or the HS codes (D'Amato et al., 2019).

In 2017, polyvinyl chloride (PVC) was also reported as an exported plastic waste stream in New Zealand (NZ). However, it was not identified by HS coding in subsequent years. This suggests PVC was no longer separated from other plastic types during collection and sorting and that Palmerston North exported "mixed plastic" waste constituting a mixture of PET, PVC, PP, PS and Other (resin code 7) plastic types reported under the HS code for "Other" plastic waste. Under the Basel Convention's Plastic Waste Amendments, these mixed bales from Palmerston North were contaminated by PVC and PS and, therefore, subject to PIC. PVC is a halogenated polymer and the additives used renders it "hazardous" under the Convention. PVC therefore contaminates single or mixed bales of plastic waste rendering them "unrecyclable" as this would affect their chemistry and thus their mechanical properties (Braun, 2002, p. 2172). Should the mixed bales be used as RDF, the presence of PVC would introduce contaminants resulting in the release of harmful carbon monoxide and hydrogen chloride gases (Choi, 2004, p. 49). Nevertheless, PVC continues to be traded by some countries without PIC:

A shipment of PVC plastic…that left Newark on February 16 (2021) for Gujarat, India, could potentially run into obstacles under Basel rules because India is a Basel signatory, and PVC trade is restricted under the rules (Tabuchi and Corkery, 2021).

Polyvinyl chloride (PVC) and polystyrene (PS) have been listed alongside polyurethane (PU) and polycarbonate (PC) as "priority" pollutants, the most "problematic" of all plastics and thus requiring classification as "hazardous" materials (Rochman et al., 2013). PS, for example, is particularly difficult to recycle and it contains toxic constituents including its building blocks, styrene monomer, a suspected carcinogen (World Health Organisation, 2019). PS, PVC, PC, and PU "can be carcinogenic and can affect organisms in a similar way to the hormone estrogen" (Rochman et al., 2013, p. 170; Farrelly and Shaw, 2017). The Basel Plastics Amendments has recognized the problematic nature of these plastics by requiring PIC for their trade.

Parties to the Basel Convention may have different interpretations of the types of plastic scrap and waste that is covered by Basel listing Y48 and requiring PIC. While exemption from PIC implies that bales should not be contaminated by "other wastes" as other than "mixtures of plastic waste, consisting of polyethylene (PE), polypropylene (PP) and/or polyethylene terephthalate (PET)", Y48 plastic wastes continue to cross borders uncontrolled, and contaminated with "other wastes" other than plastics including and paper and cardboard; and plastic waste has been found buried in paper waste, in refuse-derived fuel (RDF), and as textile waste shipments (e.g., B3011 Annex IX listings) (IPEN, 2022a).

The Palmerston North Waste Operations Supervisor reported their mixed waste bales as "desirable" due to the prospect of receiving PET in the form of food trays, which, at the time were not being separated for domestic recycling. This is what has been referred to by waste exporters as "sweetening" the bales. This supports the findings of a recent NZ study which reported that exporters admitted that they regularly add "sweeteners" to low value mixed plastic bales in the form of higher value resins (i.e., PET and HDPE) (Eunomia, 2018, p. 22). Furthermore, it is speculated that receiving countries rely on cherry picking the valuable plastic waste from the mixed stream and dumping or burning the rest. A recent study estimated that only 16% of PET bottles consumed in Malaysia are collected for recycling (GA Circular, 2019). This contradicts the global trend in which PET bottles are widely collected for recycling along with polyethylene (PE) and polypropylene (PP) (Moh and Abd Manaf, 2014). For example, in South Africa, where PET bottle collection rates surpassed 50% in 2015 and continue to rise (PETCO, 2022). Therefore, "sweetening" mixed bales with PET may conversely be considered "contamination" in shipments destined for Malaysia.

Fluorinated polymers, condensation products, and thermosets

The fluorinated polymers, condensation products, and thermosets listed in Annex IX have several Annex III hazardous characteristics and contain additives with hazardous characteristics (Ozaki et al., 2000; Jiang et al., 2010; GAIA, 2020a,b; Lohmann et al., 2020) and yet they are exempted from the Y48 listing of plastic wastes in Annex II because it is assumed they can be "recycled in an environmentally sound manner and almost free from contamination and other types of wastes" in the destination country (IPEN, 2022b). Many of these polymers are unrecyclable and all trigger human health and environmental concerns during thermal degradation (GAIA, 2020b; IPEN, 2020).

Fluorinated polymers belong to a family of chemicals called per and polyfluorinated alkyl substances (PFAS) which are known for their toxicity and include several persistent organic pollutants recognized under the Stockholm Convention (OECD, 2018; Korzeniowski and Buck, 2019). In August 2022, the US EPA issued a proposal to designate two PFS [perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS)] hazardous substances under Comprehensive Environmental Response, Compensation, and Liability Act or "Superfund" (EPA, 2022). Polytetrafluoroethylene (PTFE) as a fluoropolymer and thermoset (cured resin) was not exempted from Y48 and thus requires PIC. However, thermosets and condensation products (a subset of thermosets), cannot be reprocessed (recycled) through thermal treatments, and due to their application, products made from PTFE are not free from contamination and other types of waste. Therefore, fluorinated polymers do not meet the Y48 listing criteria; nor do they qualify for exemptions (IPEN, 2022b).

The lead author communicated the hazardousness of fluorinated polymers and thermosets to NZ's Ministry of Foreign Affairs and Trade in the public consultation period prior to the transposition of the Basel Plastic Waste Amendments into national legislation. The NZ Government decided not to restrict these polymers in its domestication of the Amendments in to NZ's Imports and Exports (Restrictions) Prohibition Order (No. 2) 2004 (MfE, 2020; Parliamentary Counsel Office, 2022).

Actionable recommendations

The authors propose national material flow analyses of plastic waste are needed that extend beyond NZ's national borders, as demonstrated by the case of Palmerston North. These national material flow analyses should assess exported shipments of plastics labeled "recyclable" to ensure that the contents are not just theoretically recyclable but recyclable in practice in the receiving country at the time of trade. Data transparency would be greatly supported by harmonized definitions of "recyclable plastic," "contamination," and "environmentally responsible recycling".

Municipal and national material flow analyses should critically assess whether plastic waste shipments are destined for "environmentally sound recycling". The authors consider the only responsible way to recycle plastic waste' to be plastic to plastic (P2P) mechanical recycling limited to PE, PP, and PET. Basel member states should be required to quantify volumes of exported plastic waste that are guaranteed to be responsibly recycled in the receiving country. This should factor in the capacity of the importing country to recycle a resin type at a particular time. The work of the intersessional working group of the Basel Convention to prepare a draft of updated technical guidelines on the environmentally sound management of plastic wastes (UNEP/CHW.15/6/Add.7) (UNEP, 2022a) should be delayed enabling more time to strengthen the guidelines. The guidelines could be strengthened by clearly identifying plastic waste streams that fall under the plastic amendments including multiple Basel Annex IX entries for uncontrolled wastes that could overlap with controlled plastic wastes (especially the Y48 listing); clarifying the difference between environmentally *sound*, and environmentally *unsound* recycling and other forms of plastic waste management; accounting for climate emissions; clearly defining "contamination" distinguish uncontrolled (B3011) from controlled plastic wastes (Y48) (GAIA, 2020a). The growing scientific evidence illustrating the environmental and human health harms of thermal recovery technologies should be included in the Basel Convention's incineration guidelines (D10 and R1).

Countries that export plastic waste as "responsible waste management" must expand the scope of their system boundaries in plastic waste material flow analysis if they are to accurately reflect the fate of their plastic waste in receiving countries. In the case of Palmerston North, it was found that only 11–37% of exported plastics were potentially recycled. Essentially, Palmerston North city is externalizing the cost of its own inability to manage plastic waste onto other non-OECD countries. Expanding the scope of plastic waste flow analyses will more accurately reflect the efficacy of toxic-free circular economies for plastics and support the faithful domestication of member states' obligations to the Basel Convention. Expanding the scope of plastic waste flow analyses will also illuminate the need for Palmerston North and countries like NZ to establish circular systems and responsibly manage their own domestic waste in the spirit of the Basel Convention's proximity principle.

Improved waste trade traceability and transparency from municipalities such as Palmerston North as well as national monitoring, evaluation, and reporting as part of NZ's National Plastics Action Plan would improve material flow analyses of exported plastic waste while ensuring plastic waste exports are destined for environmentally responsible waste management that is also protective of human health and rights.

Further, the monitoring of plastic waste flows should include total exports actually recycled to ensure a system of accountability between the exporter and the recycler.

"Recycled" plastic waste should be reported as the volume of plastics an importer can convert to recyclate for P2P mechanical recycling instead of the volume received by the recycler. This would account for the weight contribution of contaminants in waste plastics which, in the case of Palmerston North, ranged from 16 to 25%.

A binding international standard for contamination limits in global plastic waste flows would resolve the problem of the currently vague definition of "almost free from contamination and other wastes" and that OECD countries bear the responsibility for rigorous container inspections to identify and report contamination rates prior to export. These inspections would be part of an enhanced programme of regulatory compliance optimization and liability for Basel members. Countries who export plastic waste that does not meet the criteria of the Basel Plastic Waste Amendments must be liable for the full cost of repatriation and remediation if necessary. Setting clear contamination definitions and thresholds would offer greater clarity and certainty for municipalities such as Palmerston North, exporters, and importers and would support the avoidance of liability.

Fluorinated polymers and thermosets including condensation products must be accounted for in all plastic waste material flow analyses. Due to their known hazardousness, the authors advocate for the exclusion of these polymers from Annex IX of the Basel Convention. Despite their exclusion from Y48, Palmerston North, NZ and other exporters and exporting countries should list fluorinated polymers and thermosets as restricted plastics in their own import/export rules and municipal policies and ban their export to non-OECD countries to reflect the Basel Convention Ban Amendment (UNEP, 2022b). A binding international standard for contamination limits should clearly state "free from contaminants including hazardous and toxic materials, substances, and other wastes" and exporters should bear the burden of proving the absence of these contaminants.

Based on decision BC-14/9, the Conference of Parties requested the Basel Secretariat to propose the amendment of the HS to identify 10 waste types (Basel Convention, 2011; Basel Action Network, 2022). This could help municipalities and national customs distinguish between waste streams and shipments of B3011 and Y48 plastic waste. Additional codes should accommodate waste-based or alternative fuels such as RDF. Enforcement measures should be in place to ensure exporters correctly use the current HS codes, namely 382,510 for municipal waste or 3,915 for plastic wastes.

Conclusion

The authors have identified significant weaknesses in the plastics waste flow analysis of one municipality, Palmerston North, NZ. New Zealand's national waste policy framework nor import-export rules require the kind of comprehensive assessments of plastic pollution leakage at municipal and national levels needed to understand the true pathways and fates of plastics and to strengthen plastic waste trade policies to protect human rights and health, and the environment in receiving countries. The authors also identified ongoing weaknesses in the Basel Plastic Waste Amendments which could be resolved with clarity and harmonization of key definitions, improved data collection, greater transparency in the monitoring and reporting of plastic waste flows, particularly from OECD countries to non-OECD countries.

The authors' recommendations would significantly address weaknesses in national and international plastic waste trade policy and reduce illegal plastic waste trade activities. However, ultimately, the most effective responses to transboundary waste dumping are preventative measures based on the precautionary and proximity principals and supported by the global plastic pollution treaty approved at the fifth session of the United Nations Environment Assembly. The priority must be on preventing the production of unnecessary and toxic plastics that cannot be safely mechanically P2P recycled. This will require investing more heavily in responses that focus on the top of the waste hierarchy to establish prevention, reduction, reuse, refill, and repair systems that support a toxic-free global circular economy (Zaman and Newman, 2021; Blumhardt and Prince, 2022).

Author contributions

TC and TF conceptualized and designed the case study. TC conducted the research for the case study, analyzed the data, and approved the final submission. TF drew on the conclusion of the study to conceptualize and write the first draft of the policy brief. Both authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Automatic identification and classification of compostable and biodegradable plastics using hyperspectral imaging

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In the UK waste management systems biodegradable and compostable packaging are not automatically detected and separated. As a result, their fate is generally landfill or incineration, neither of which is an environmentally good outcome. Thus, effective sorting technologies for compostable plastics are needed to help improve composting rates of these materials and reduce the contamination of recycling waste streams. Hyperspectral imaging (HSI) was applied in this study to develop classification models for automatically identifying and classifying compostable plastics with the analysis focused on the spectral region 950–1,730 nm. The experimental design includes a hyperspectral imaging camera, allowing different chemometric techniques to be applied including principal component analysis (PCA) and partial least square discriminant analysis (PLS-DA) to develop a classification model for the compostable materials plastics. Materials used in this experimental analysis included compostable materials (sugarcane-derived and palm leaf derived), compostable plastics (PLA, PBAT) and conventional plastics (PP, PET, and LDPE). Our strategy was to develop a classification model to identify and categorize various fragments over the size range of 50 x 50 mm to 5 x 5 mm. Results indicated that both PCA and PLS-DA achieved classification scores of 100% when the size of material was larger than 10 mm x 10 mm. However, the misclassification rate increased to 20% for sugarcane-derived and 40% for palm leaf-based materials at sizes of 10 x 10 mm or below. In addition, for sizes of 5 x 5 mm, the misclassification rate for LDPE and PBAT increased to 20%, and for sugarcane and palm-leaf based materials to 60 and 80% respectively while the misclassification rate for PLA, PP, and PET was still 0%. The system is capable of accurately sorting compostable plastics (compostable spoons, forks, coffee lids) and differentiating them from identical looking conventional plastic items with high accuracy.

KEYWORDS

hyperspectral imaging, deep learning, principal component analysis, automatic sorting, industrial composting

1. Introduction

There has been a recent growth in the production and use of compostable plastics in an attempt to reduce the impact of conventional plastics on the environment (WRAP, 2022). These types of plastics are designed to biodegrade at their end of life in controlled systems such as industrial composting (Song et al., 2009). Bioplastics production worldwide is projected to increase from 2.23 million tons in 2022 to around 6.3 million tons in 2027 (Bioplastic, 2022). In 2019, the global compostable plastic market was valued at $991.2 million and is predicted to reach $3,102.6 million by 2027 (AMR, 2022).

Typically, compostable plastics are manufactured fully or in part from biomass and include polylactic acid polymers (PLA), polybutylene adipate terephthalate (PBAT) and starch-based polymers. PLA is typically used to produce cup lids, salad boxes, tea bags, coatings for coffee cups, food containers and cartons. PBAT and starch-based plastics are often used for plastic films such as magazine wraps and caddy liners. Apart from compostable plastics, other biomass-derived substances are also used to produce packaging such as sugarcane and palm leaf.

The advantages of compostable packaging are realized when these types of packaging are industrially composted and do not enter the environment or pollute other waste streams or the soil (Purkiss et al., 2022). Currently, most compostable plastics are treated as a contaminant in the recycling of conventional plastics such as HDPE and PET, reducing their value. Moreover, when composting various types of organic residues, the finished product always contains a certain amount of other materials such as flakes of plastic film (REA, 2021). Therefore, contaminants have to be eliminated in order to improve compost quality. Currently, trommel and density sorting are applied to screen the compost and reduce the presence of other materials. However, the levels of contaminants from the current screening process is unacceptably high (SEPA, 2019). To improve the accuracy of the current system advanced sorting technologies need to be developed (Xu and Gowen, 2020).

In this study we use hyperspectral imaging (HSI) in a one step process to identify different materials. We apply shortwave infrared (SWIR) in the range 950–1,730 nm to identify not just only different types of conventional plastics (PP, PET, and LDPE) and compostable plastic (PLA, PBAT) packaging but also compostable materials (palm leaf and sugarcane-based materials) with various sizes from 50 x 50 mm to 5 x 5 mm. The technique we have developed is notably different to Moroni and Mei (2020). The novelty arises from our use of machine learning methods. We used mean centering (MC) and standard normal variate (SNV) algorithms and applied these to reduce the impact of possible external sources of variability and highlight sample spectral differences that allowed a more accurate interpretation and classification of the model. We have also used spectral information to successfully develop unsupervised principal component analysis (PCA) and partial least square discriminant analysis (PLS-DA) to differentiate packaging material types and to classify unknown packaging material samples. A detailed description of our HSI method is presented, including the hardware and software components. Results are shown at a laboratory scale where we use this method to successfully identify different sorts of conventional, compostable, and biodegradable packaging materials over a range of sizes to a high degree of accuracy. We also discuss the real world applicability of this technique in waste processing systems.

1.1. Background

Taneepanichskul et al. (2022) recently identified a variety of suitable sorting technologies for compostable plastics such as gravity-based sorting, triboelectric sorting, image based identification, spectral based identification, hyperspectral imaging, and tracer based sorting suitable for this task. The analysis showed that each technique has its advantages and disadvantages in terms of effectiveness, cost and environmental footprint. Hyperspectral imaging technology was identified as one of the most suitable non-destructive techniques to identify compostable packaging. It has the potential to be integrated with existing waste sorting systems, as well being economically feasible and a sustainable way to sort compostable plastics (Biopak, 2022; Taneepanichskul et al., 2022). For example, the power consumption for the identification process is very low. When compostable plastics are comingled with other materials such as recyclable plastics or food waste, HSI is one of the most effective techniques for differentiating between them since it combines imaging technology and spectroscopy into one approach. Moreover, it is able to detect the spectral signature of each pixel of the acquired image in different wavelength regions (visible, near infrared, short-wave infrared, etc.) according to the characteristics of the selected sensing device. One potential drawback however is the large amount of spectral information collected by HSI from the sample surfaces that must be processed in order to make sorting decisions in real time.

For large pieces of plastic (50–500 mm), Balsi et al. (2018) have used shortwave infrared (SWIR) spectral imaging in the range of 900–1,700 nm for the spectral characterization of polymers including PS, PVC, PLA, PET, PC and three types of PE (LDPE, HDPE and LLDPE). The absorption peaks of different types of plastic were identified by a continuum removal method (Balsi et al., 2018). Bonifazi et al. (2013) have applied hyperspectral imaging to enhance the efficiency of polyolefin recycling systems (Bonifazi et al., 2013). Recently Moroni and Mei (2020) used hyperspectral imaging to separate PS, PET, and PLA samples at their different stages of the life cycle (virgin to plastic waste). In order to separate these three types of plastics they used a sequential method. The first spectral index of 1,170–1,650 nm used hyperspectral imaging to separate polymers with flame retardants to allow grouping of plastics with the same polymer type and additive content necessary for recycling. A decision tree that included a partial least square and hierarchical models was then used to identify the types of plastic. The accuracy was higher than 90% in all cases.

2. Materials and methods

2.1. Sample preparation

The packaging materials used in this experiment consisted of virgin conventional plastic including PP, LDPE and PET, compostable plastic namely PLA, PBAT and biodegradable packaging—palm leaf derived packaging and sugarcane-derived packaging. The materials were all sourced from commercial producers and are provided in Table 1. The sources of material are also provided in Table 1.

The samples were cut into squares of various sizes and divided into two sets, one for training and a testing dataset. The training dataset was the dataset used to build the classification model. It was an input into the machine learning algorithms to allow the model to associate spectral imaging data with known material classifications. The testing dataset was the dataset that contains unseen data to test the model accuracy in determining material classifications. It was used to evaluate the performance of the model. The sizes of materials in the training dataset and testing dataset ranged from square samples cut from thin films 50 x 50 mm—20 x 20 mm and 10 x 10 mm—5 x 5 mm, respectively, as shown in Figure 1. These are similar to those carried out in previous studies (Moroni et al., 2015).

The population in these experiments was 210. We used a krejcie-morgan table to calculate the sample size in the training dataset, which was determined as 140 (Krejcie and Morgan, 1970). For the 140 samples in the training dataset and 70 samples in the testing datasets, the details are shown in Table 2. We adopted a random sampling strategy to select the sample order for the training datasets.

TABLE 1 The details of materials tested.

Material	Sources
PP	Retail samples, Vesey Arts and Crafts
LDPE	Retail samples, Marks & Spencer
PET	Production samples, Biopak
PLA	Retail samples, Vegware
PBAT	Production samples, Confidential
Palm leaf derived packaging	Retail samples, Biopak
Sugarcane derived packaging	Retail samples, Biopak

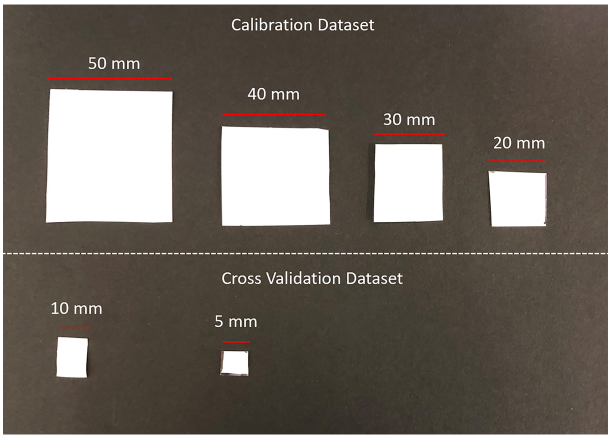

FIGURE 1
The size of samples PP, LDPE, PET, PLA, PBAT, sugarcane derived packaging and palm leaf derived packaging in a Calibration Dataset (50 x 50 mm, 40 x 40 mm, 30 x 30 mm, and 20 x 20 mm) and Cross Validation Dataset (10 x 10 mm and 5 x 5 mm).

2.2. Hyperspectral imaging equipment and data acquisition

HSI acquisitions and analyses were carried out a laboratory in the Department of Mechanical Engineering, University College London. There are four main components of hyperspectral imaging system which are a hyperspectral camera, light source, conveyor belt and lens (Xiong et al., 2014) (Figure 2A).

In this study, hyperspectral images were collected by a HySpex Baldur S-640i N covering the spectral range 950–1,730 nm, with a spectral resolution of 3.36 nm, for a total of 232 wavelength bands. The hyperspectral camera was used with a 1 m working distance 16° FOV (Hyspex, 2021). The images were acquired by scanning the image line by line: the spatial pixels size was 0.44 mm. Every sample scanned by the system produced image information in the form of an x-y grid of pixels, and for each pixel a spectrum was recorded, yielding a hyperspectral data cube for each sample. The hyperspectral camera was adjustable in height and angle. In this case, the height between lens and objects was set at 100 cm. The angle between the lens and objects was 90°. The halogen lamp produced an intense and continuous spectrum from 400 nm to 2,500 nm. The acquisition platform also consisted of a conveyor belt (700 x 215 x 60 mm) with adjustable speed (Figure 2B). Acquisition was controlled by a PC equipped with specialized acquisition and pre-processing software: HyspexGround (Hyspex, 2019) which was used to perform the acquisition, to collect spectra, and to perform preliminary spectral analysis.

System calibrations were carried out by recording a black and a white reference image. The black image (B) was acquired to eliminate the dark current effect of the camera sensor. The white reference image (W) was acquired adopting a standard white ceramic tile under the same conditions as the raw image. Equation 1 describes the calculation used to perform for image correction:

$$I = \frac{[I_0 - B]}{[W - B]} \quad (1)$$

where I is the corrected hyperspectral image in a unit of relative reflectance (%), I_0 is the original hyperspectral image, B is the black reference image (∼0%), and W is the white reference image (∼99.9%).

2.3. Spectral data preprocessing

After image correction the background noise was removed by an initial reduction of the range of the wavelengths investigated. The first and last spectral bands were excluded in order to reduce the size of data (spectral variable). Some spectral bands that gave the noisiest data were also eliminated. Subsequently, the background of each image was removed. After that the hyperspectral data were preprocessed using mean centering (MC)

TABLE 2 List of samples in the training dataset and testing dataset.

Types of material	Material	Description	Size	Number of replicates	Type of data
Conventional plastics	PP	Polypropylene	50 x 50 mm	5	Training
			40 x 40 mm	5	Training
			30 x 30 mm	5	Training
			20 x 20 mm	5	Training
			10 x 10 mm	5	Testing
			5 x 5 mm	5	Testing
	PET	Polyethylene terephthalate	50 x 50 mm	5	Training
			40 x 40 mm	5	Training
			30 x 30 mm	5	Training
			20 x 20 mm	5	Training
			10 x 10 mm	5	Testing
			5 x 5 mm	5	Testing
	LDPE	Low density polyethylene	50 x 50 mm	5	Training
			40 x 40 mm	5	Training
			30 x 30 mm	5	Training
			20 x 20 mm	5	Training
			10 x 10 mm	5	Testing
			5 x 5 mm	5	Testing
Compostable plastic	PLA	Polylactic Acid	50 x 50 mm	5	Training
			40 x 40 mm	5	Training
			30 x 30 mm	5	Training
			20 x 20 mm	5	Training
			10 x 10 mm	5	Testing
			5 x 5 mm	5	Testing
	PBAT	Polybutylene adipate terephthalate	50 x 50 mm	5	Training
			40 x 40 mm	5	Training
			30 x 30 mm	5	Training
			20 x 20 mm	5	Training
			10 x 10 mm	5	Testing
			5 x 5 mm	5	Testing
Compostable materials	Palm Leaf derived material	Palm leaf	50 x 50 mm	5	Training
			40 x 40 mm	5	Training
			30 x 30 mm	5	Training
			20 x 20 mm	5	Training
			10 x 10 mm	5	Testing
			5 x 5 mm	5	Testing
	Sugarcane derived material	Sugarcane	50 x 50 mm	5	Training
			40 x 40 mm	5	Training
			30 x 30 mm	5	Training
			20 x 20 mm	5	Training
			10 x 10 mm	5	Testing
			5 x 5 mm	5	Testing

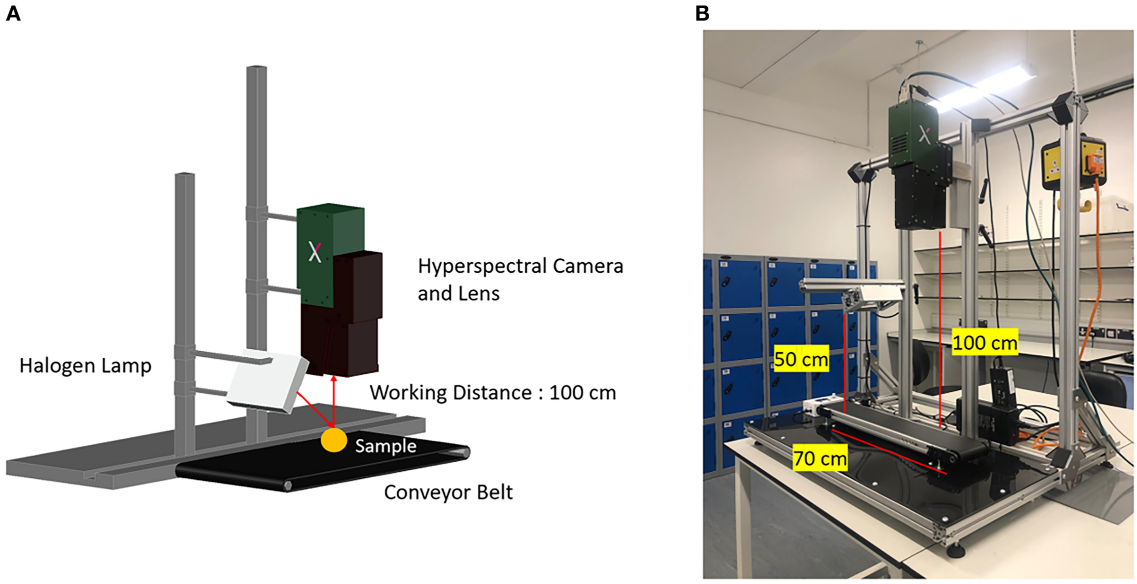

FIGURE 2
Images of hyperspectral camera system. **(A)** Components of HSI system. **(B)** Dimension of HSI system.

and standard normal variate (SNV) algorithms to reduce the impact of possible external sources of variability and highlight sample spectral differences that allowed a more accurate interpretation and classification of the model. For mean centering, the first stage is often to subtract the average from each variable. The objective of mean centering is to ensure that all results will be interpretable in term of variation around the mean. This is especially crucial if the variables differ significantly in their relative magnitudes, otherwise the values with the greatest variance will be favored in regression analysis. For SNV analysis this technique removes the multiplicative interferences caused by scatter and particle size effects from spectral data. SNV removes scatter effects by centering and scaling each individual spectrum. The method assumes that the absorbance of each wavelength point in the spectrum meets a certain distribution such as a Gaussian distribution. Each spectrum was calibrated based on this assumption. The average value of a spectrum was subtracted from the original spectrum, and then the result was divided by the standard deviation.

2.4. Spectral data analysis

The SWIR region gives chemical information about the investigated materials (sugarcane and palm leaf derived packaging, PLA, PBAT, PET, PP and LDPE) since most absorption bands in this range arise from overtones of N-H, C-H and O-H vibration. Spectra were analyzed using Breeze software version 2022.1.5 (Hyspex, 2019). After a spectral data preprocessing step, principal components analysis (PCA) was applied to explore the data, to define classes and to evaluate the best algorithms for further classification model development, setup, and implementation. The chosen method for classification and validation was the partial least-squares discriminant analysis (PLS-DA).

2.4.1. Principal component analysis (PCA)

PCA converts an observational dataset from potentially correlated variables into linearly uncorrelated variables, namely a principal component (PC). The first PC accounts for the highest variability in the dataset. Therefore, most of the information are captured in PC1. The remaining amount of variance become subsequent principal components in descending order (Farrugia et al., 2021). In hyperspectral imaging, this technique is applied directly to the pixel of hyperspectral image. In the data pre-processing step the data cube is rearranged. The pixels of region of interest are considered as a set of correlated variables to which PCA is applied. The score matrix Z is given by Equation 2:

$$\mathrm{Z} = \mathrm{XW} \tag{2}$$

where the rows of the input matrix $X \in \mathbb{R}^{K\times L}$ represent the spectral values for K = M × N (pixels) over L spectral bands (λ). $W \in \mathbb{R}^{L\times P}$pixels is the loading matrix, the columns of which represent the eigenvectors of the covariance matrix of X. The columns of W provide the transformation functions that map the pixel spectral vectors into PCs. The columns of $Z \in \mathbb{R}^{K\times P}$represent the PC scores which are the representations of X in the PC space (Figure 3). Each PC image is the product between the pixel spectral vectors of X and a column of W. Each PC image is obtained by reshaping each PC making up Z, to a two-dimensional representation (Abdi and Williams, 2010). In this study 120 samples of different types and sizes of plastics were used in the training dataset. Subsequently, a PCA was

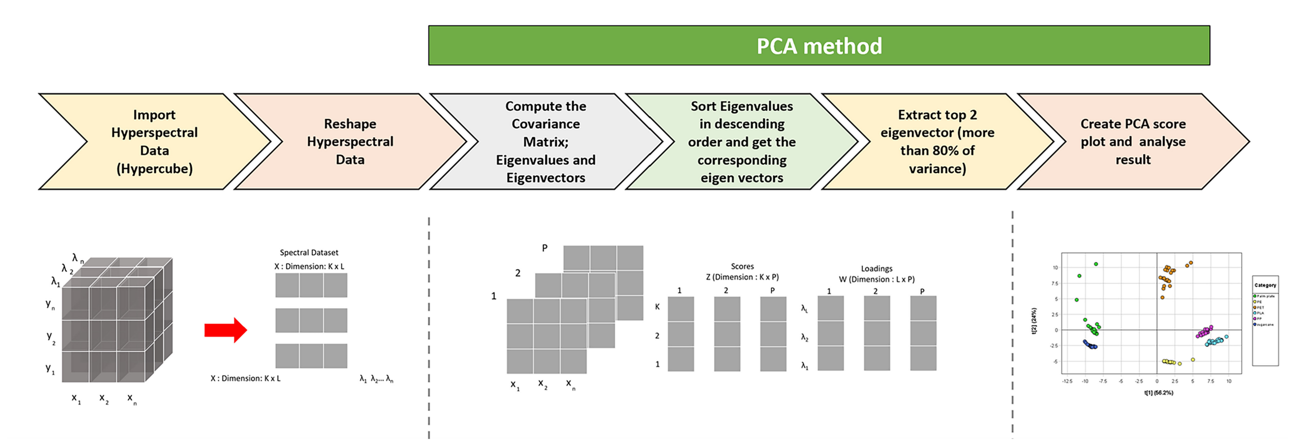

FIGURE 3
Reshaping of hyperspectral datacube and PCA method.

applied for visualizing and confirmation of good clustering (Jolliffe, 2005).

To summarize, the PCA method can be divided into six major steps as shown in Figure 3. The hyperspectral data is imported and then reshaped.

There are many techniques for PCA to transform the data such as hotelling transformation but all of them have the same mathematical model: the eigenvalues are computed, sorted in descending order and used to create a PCA plot where materials that are similar are located close together (Serranti et al., 2011, 2015, 2019).

2.4.2. Partial least square and discrimination analysis (PLS-DA)

PLS-DA is considered as a supervised method of PCA in the sense that this method achieves dimensionality reduction but it takes the class label in consideration. It combines partial least square (PLS) and discriminant analysis (DA). The PLS regression technique is applied to find latent variables (LVs) with maximum covariance with Y variables. The main difference between PLS regression and PLS-DA is that the dependent variable in PLS-DA has a categories scales whereas the dependent variable has a continuous scale in PLS regression. Thus PLS-DA can be applied as a classifier. In PLS-DA, the linear equation is modeled by latent variables. This allows graphical visualization and the understanding of the relations by LV scores and loadings (Wold et al., 2001).

There are six data processing steps that were used to form a PLS-DA analysis. Firstly, latent variables are computed based on an original dataset. Next the computed latent variables are plugged into a linear regression model to calculate a prediction value and then the cut off value is selected to classify types of material. Normally, we selected 0.5 as a cutoff point. If the prediction score is <0.5, it is classified as 0. If the prediction score is more than one, it is classified as 1 (Serranti et al., 2011, 2015, 2019). Each class of material is displayed as a different color. After calibration, the performance of the model was assessed using a test dataset. In this study, there were 80 samples in the testing dataset containing 8 different types of plastics with small size (10 x 10 mm and 5 x 5 mm).

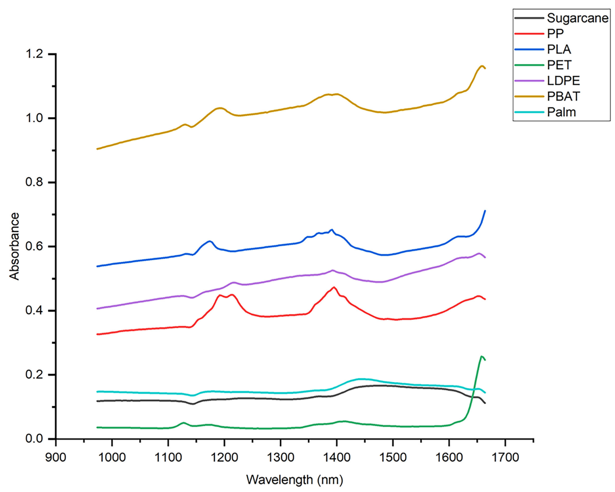

FIGURE 4
Raw absorbance spectra of sugarcane derived packaging, PP, PLA, PET, LDPE, PBAT and palm leaf derived packaging acquired by hyperspectral camera (HySpex Baldur S-640i N).

3. Results

The experiments were carried out with a range of different packaging materials using hyperspectral imaging (Table 2). The purpose of the experiments was to generate PCA and PLS-DA classification models and assess the performance of model. Figure 4 shows the raw absorbance spectra of sugarcane derived packaging, PP, PLA, PET, LDPE, PBAT and palm leaf derived packaging acquired by hyperspectral camera (HySpex Baldur S-640i N).

The pre-processed data using mean centering (MC) and standard normalized variation (SNV) normalization is shown in Figure 5.

3.1. Principal component analysis

For each of the training samples, after collecting a hyperspectral data cube and the pre-processing step, the PCA was applied to reshape the data cube and reduce data dimensionally. For each sample, a PCA score plot was generated allowing the identification of seven different groups of materials according to the material spectral signature (Figure 6).

In this experimental set up, the majority of variance was captured by the first two principal components (PCs), where PC1 and PC2 explains 56% and 24.4% of the variance, respectively. The PCA model results shows the separability of the different classes of materials. From the PCA score plot, the compostable material (palm and sugarcane derived), compostable plastic (PLA, PBAT) and conventional plastic (LDPE, PP, PET) shows the high level of separability. There is no overlap between each type of material in training dataset although palm is the least clustered.

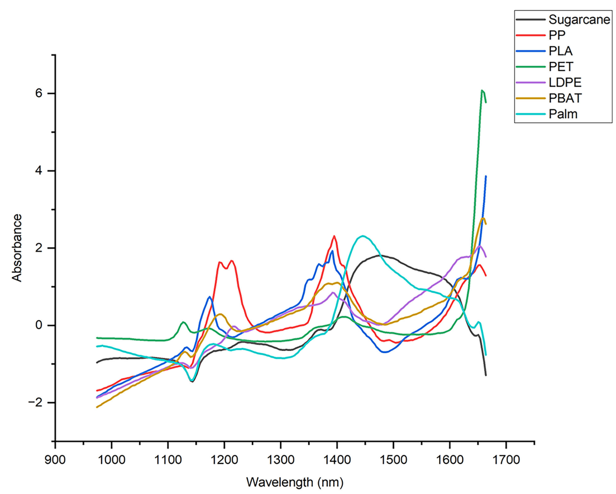

FIGURE 5
Pre-processed spectra using mean centering (MC) and standard normalized variation (SNV) normalization of sugarcane derived packaging, PP, PLA, PET, LDPE, PBAT and palm leaf derived packaging.

3.2. Partial least square discriminant analysis (PLS-DA)

The PLS-DA model of 7 classes of various sizes of materials built on the training dataset showed a captured variance of 80% with two latent variables.

Subsequently the value of accuracy, misclassification rate, R^2 (R square) and RMSE (Root-mean-square deviation), sensitivity and specificity of each type of materials were calculated to measure the performance and robustness of the classification model. The sensitivity and specificity value ranged from 0 to 1. These values provide the information about model performance. The higher the values are, the better the model. From Table 3, it illustrated that the performance model on training dataset was very high because sensitivity and specificity values of all materials were 1. Moreover, the accuracy model was 100% and misclassification rate was 0% for all types of materials. R^2 and RMSE values also proved the robustness of classification model. R^2 was >96% and RMSE was lower than 0.07 for all types of materials in the training dataset.

After we ensured that the performance and robustness of the classification of model were adequate, we applied it to the testing

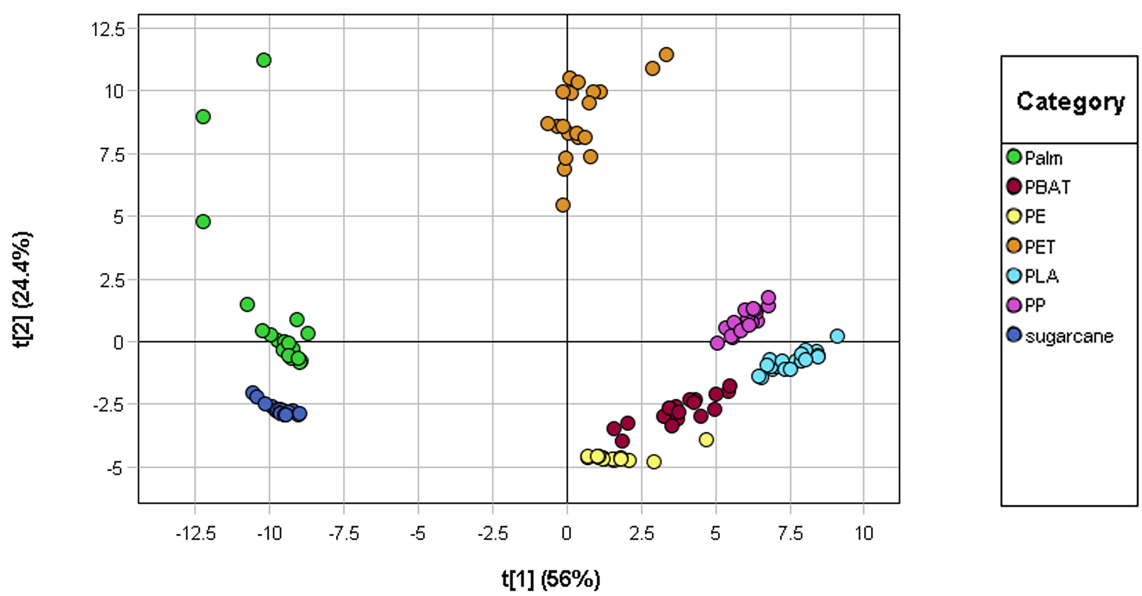

FIGURE 6
P1-PC2 score plots of palm leaf derived packaging, sugarcane-based packaging, PBAT, PLA, PE, PET, and PP after the application of SNV and mean center pre-processing.

TABLE 3 Accuracy, misclassification rate, specificity, and sensitivity values.

	Accuracy	Misclassification rate	Specificity	Sensitivity	R^2	RMSE
Training dataset						
Palm leaf derived packaging	100%	0%	1	1	98%	0.05
Sugarcane based packaging	100%	0%	1	1	98%	0.04
LDPE	100%	0%	1	1	97%	0.06
PLA	100%	0%	1	1	100%	0.02
PBAT	100%	100%	1	1	96%	0.07
PP	100%	0%	1	1	99%	0.03
PET	100%	0%	1	1	100%	0.02

TABLE 4 Accuracy, misclassification rate, specificity and sensitivity values for seven classes PLS-DA model in testing dataset obtained for the seven classes PLS-DA model on training dataset.

	Quantity	Accuracy	Misclassification rate
Palm leaf derived packaging	5	80%	20%
Sugarcane derived packaging	5	100%	0%
LDPE	4	100%	0%
PBAT	5	100%	0%
PLA	5	100%	0%
PP	6	100%	0%
PET	5	100%	0%

dataset (10 x 10 mm and 5 x 5 mm) to classify types of materials. The accuracy, misclassification rate, sensitivity and specificity values determined are shown in Table 4.

For both compostable plastic (PLA, PBAT) and conventional plastics (PP, PET and LDPE), these values were very high (>90%). However, the sensitivity value of compostable materials (palm and sugarcane derived) was 40%.

Figure 7 illustrates PLS-DA seven classes' model applied to the cross validation set to predict the type of materials that shows the corresponding classified hyperspectral images. It appears that in the 7-classes model, sugarcane, palm, PLA, PBAT, LDPE, and PET are recognized with 100% accuracy. Even if some pixels are misclassified, the majority of them belong to the correct class in each object. These sporadic errors in prediction are probably due to the surface roughness of the sample, highlighting the scattering effect of the light, or to the presence of dirtiness on the sample surface. In this study, PLS-DA was used to perform a good discrimination among classes of materials and to define predictions in new hyperspectral images, adopting pre-processing algorithms defined in the PCA step. Each category is independently modeled on the others and a sample can be assigned to only a class or even to more classes or can be rejected by all classes. The PLS-DA model obtained, instead, assigns only one of the available categories, based on its spectral signature, to each unknown sample in the hyperspectral image, making interpretation of the results easier. The results of PLS-DA, applied to hypercubes, are prediction maps, where each class is defined by a different color.

The size of samples also has a tremendous effect on the accuracy of the model. In training datasets, the size of sample is bigger than the testing dataset. Therefore, the overall accuracy of the model is higher than the testing set. For example, the accuracy of palm leaf derived packaging on the training dataset was 100% while the accuracy of the testing dataset dramatically decreases to 40%. However, the accuracy level of conventional plastic (PP, LDPE and PET) and compostable plastic (PLA, PBAT) on the testing dataset is still very high. It can identify and differentiate types of plastic when the size is 5 x 5 mm.

3.3. Real world applications

The PLS-DA classification model was also applied to classify and detect compostable materials in the market—black plastic cutlery and white PP plastic cutlery, sugarcane-based packaging and a white PLA lid. All of these materials we loaded onto the conveyor belt in a random jumbled arrangement. Figure 8 shows the PLS-DA model applied to detect compostable materials in the market (plastic plate, plastic lid and cutlery). The result shows that the model correctly identified white PP plastic cutlery and PLA lid and sugarcane-based packaging as shown in Figure 8B. Black plastic cutlery could not be detected because the pigments they contain absorbed too much light (Figure 8B), and no detectable signal could be evaluated for material identification.

The model has also been applied to classify overlapping small sized materials (10 mm), and it provided perfect classification result as demonstrated in Figure 9 and Table 5. Most pixels of the materials were predicted correctly but some pixels (red) were misclassified due to surface roughness and the scattering of light. Thus, the acquisition conditions such as angle of the halogen lamp, integration time, frame rate and speed of conveyor belt has an impact on the quality of hyperspectral images and accuracy of the system.

The other issues that affect the real-world application of this technique are the time required to classify each sample and the cost of the system. The system provides real time analysis which makes high throughput possible, the classification rate being determined

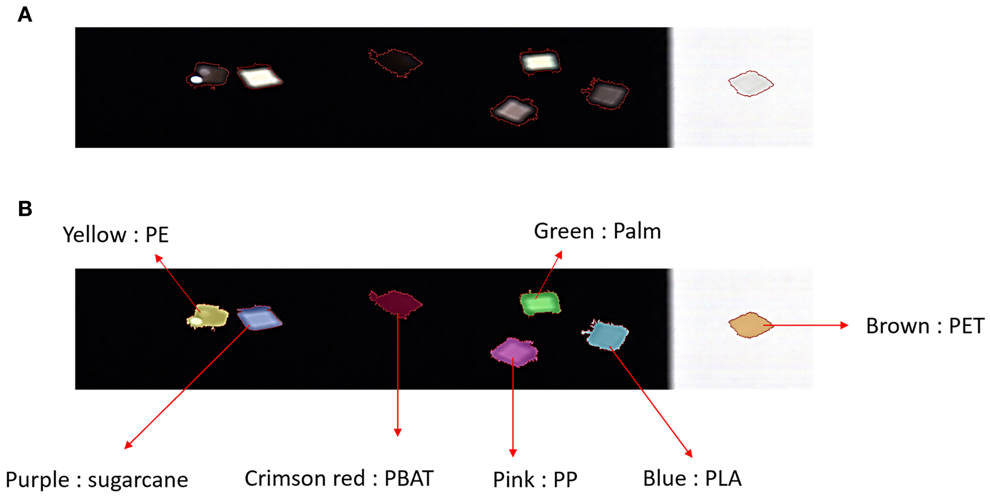

FIGURE 7
PLS-DA seven classes' model applied to cross validation set to predict type of materials. **(A)** RGB optical image obtained by the hyperspectral camera, **(B)** the hyperspectral image overlayed with the classification color (yellow: PE, blue: PLA, pink: PP, crimson red: PBAT green: palm leaf, purple: sugarcane, brown: PET).

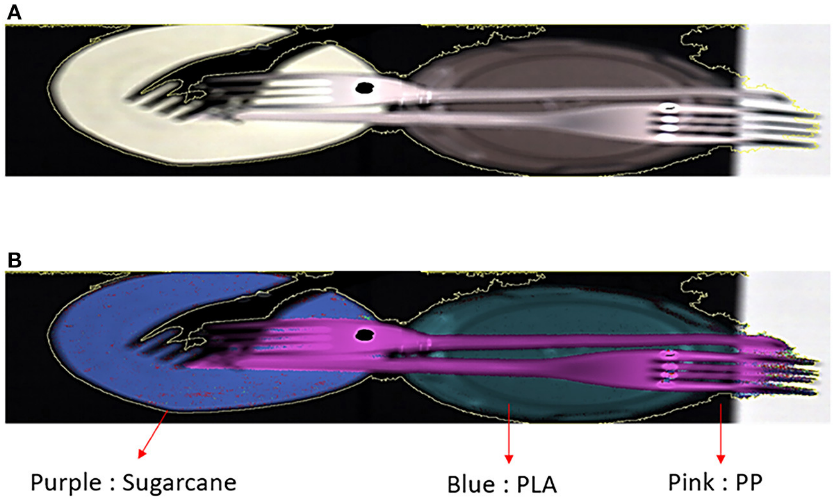

FIGURE 8
PLS-DA model applied to detect compostable materials in the market (plastic plate, plastic lid and cutleries). **(A)** RGB optical image obtained by the hyperspectral camera (HySpex Baldur S-640i N), **(B)** the hyperspectral image overlayed with the classification color (purple: sugarcane, blue: PLA and pink: PP).

by the computing power. However, the cost of hyperspectral imaging technology is higher than current sorting technologies. The estimated price of hyperspectral cameras currently range from \$45,000 to \$49,800 (Optosky, 2022).

4. Discussion and conclusions

The combination of HSI in the SWIR range (950–1,730 nm) and multivariate data analysis (MDA) were applied to distinguish types of materials. The dataset comprises various size of compostable materials (sugarcane and palm leaf derived), compostable plastic (PLA, PBAT) and conventional plastics (PP, LDPE and PET).

The approach in this work was to differentiate between 7 types of materials (sugarcane, palm, PP, LDPE, PET, PBAT, and PLA) with various size (50 x 50 mm, 40 x 40 mm, 30 x 30 mm, 20 x 20 mm, 10 x 10 mm, and 5 x 5 mm) and predict types of materials as well as determine the performance of the model. For training datasets, the sizes of materials were larger than the testing dataset as mentioned in the methods section. The PCA score plot was developed on the training dataset. The result clearly illustrated that the model built can perfectly differentiate between types of materials. There is also no overlap among the classes. It can be concluded that the variation among types of samples can be attributed to the

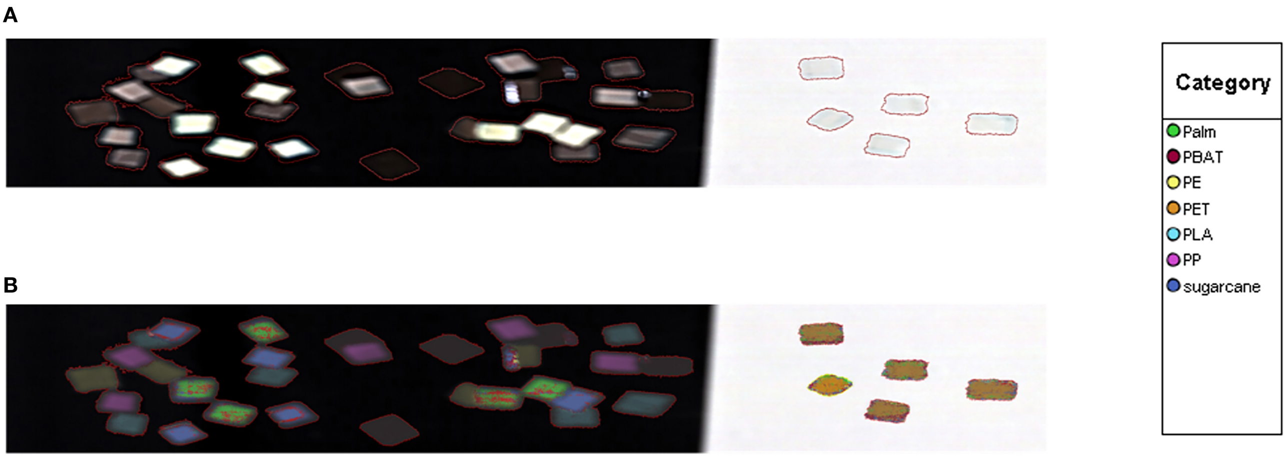

FIGURE 9
PLS-DA model applied to detect small size (10 mm) of materials. **(A)** RGB optical image obtained by the hyperspectral camera, **(B)** the hyperspectral image overlayed with the classification color.

TABLE 5 Accuracy and misclassification rate of overlapping small materials.

	Accuracy	Misclassification rate	Specificity	Sensitivity
Testing dataset				
Palm leaf derived packaging	40%	60%	1	0.6
Sugarcane derived packaging	60%	40%	1	0.4
LDPE	90%	10%	1	0.9
PLA	100%	0%	1	1
PBAT	90%	10%	1	0.9
PP	100%	0%	1	1
PET	100%	0%	1	1

chemical structure of the materials. After that, a PLS-DA model with pre-processed MSC and SNV was developed to classify types of materials. The accuracy, misclassification rate, sensitivity and specificity values were calculated to measure the performance of the classification model. It gave a satisfactory result where the accuracy and misclassification of the model was 100 and 0% for all types of materials. Furthermore, both sensitivity and specificity were 1.

Since the performance of the model on training datasets was very good, the model was applied to classify types of materials on the testing dataset. The performance of the model was also measured. It gave an excellent classification result. The partial least squares discriminant analysis (PLS-DA) model pre-processed with MSC and SNV was successful and achieved with 100% accuracy for PP, PET, PLA. The accuracy for LDPE and PBAT classification was 90%, while the accuracy level for palm and sugarcane-based packaging classification was 40 and 60% respectively. A few errors in misclassification occurred due to the roughness of surface and scattering of light.

The model has also been applied to overlapping samples and real-world compostable packaging. The model also gave good results. For overlapping small samples, the misclassification rate of palm leaf derived packaging was 20% while other types of material were 0%. However, the hyperspectral imaging system has a limitation in common with other IR detection systems, in cannot reliably detect dark materials because of light absorbance effects.

The classification technique that we have developed is different to the approach reported by Moroni and Mei (2020). Both systems are able to identify compostable plastic (PLA) with very high accuracy. While the accuracy of their model was more than 95%, our classification model was 100%. The results of Maroni and Mei study also demonstrated that the spectral indices had a tremendous impact on performance of the separation system, where accuracy of the system dropped from 100 to 96% when the spectral indices (λ_1 / λ_2) changed to 1,120/1,370. While our study focused on size resolution, the accuracy decreased with sample size for certain materials (e.g., palm-leaf derived packaging).

Our system is capable of accurately sorting compostable plastics at the typical product scale (compostable spoons, forks, coffee lids) and differentiating them from identical looking conventional plastic items with high accuracy. For the system to be adopted by industrial composters, the classification speed needs to be increased to match the conveyor speeds in use, and real-time robotic removal of the plastics needs to be demonstrated.

The compostable plastic market worldwide is predicted to reach $3,102.6 million by 2027. The full environmental advantages of compostable plastic will only be realized if these plastics does not pollute other waste streams and do not enter the open unmanaged environment. HSI is a promising technology due to real time sorting: it has high accuracy (99%), low power consumption and no additional chemicals or water are needed. Some recycling plants are interested in HSI because it is able to enhance sorting purity of plastics recycling collections and industrial composting. Nevertheless, the operational costs of this sorting technology are significant and can only be justified by higher revenues from the increased performance of recycling and industrial composting facilities (Taneepanichskul et al., 2022).

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

NT conducted experiments. NT, HH, and MM analyzed the data. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Marine plastic: The solution is bigger than removal

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Despite the increase in the documentation on, and interest in marine debris, there remains a gap between the analytic information available and the recommendations developed by policy and decision makers that could reduce this pollutant. Our paper summarizes some successful initiatives across policy, industry, infrastructure and education; and where they sit in the value chain of plastic products. We suggest that a multidisciplinary approach is required to most effectively address the marine plastic litter problem. This approach should emphasize (1) minimizing plastic production and consumption (where possible), and waste leakage; by (2) improving waste management (taking into consideration the informal sector) rather than focussing on clean-up activities. We then suggest some steps that once addressed would assist policy professionals, and a wide variety of entities and individuals with decision-making to reduce marine plastic litter. We suggest the creation of a user-friendly framework (tool) would facilitate transparency and democratization of the decision-making process across stakeholders and the wider community. This tool would be most useful if it comprised information on (i) defining appropriate metrics for quantifying plastic waste for the study/work case; (ii) providing a list of possible interventions with their key associated enabling and disabling factors, (iii) identifying the main influential factors specific to the situation/region; (iv) recognizing the risks associated with the selected interventions and the consequences of these interventions on the most influential factors; (v) objectively ranking solutions using the information gathered (metrics, targets, risks, factors) based on the regional, national, and/or international context. This tool then provides an opportunity for user groups to explore different suites of options for tackling marine plastic pollution and co-create a suite that is optimum for them.

KEYWORDS

marine plastic, solutions, pollution, litter, debris

1. Introduction

Marine debris is an escalating challenge that is recognized globally (Lau et al., 2020). Plastic is often the largest proportion of this observed debris (Galgani et al., 2015) and has been found across the planet in some of the most remote locations. This is primarily because plastic is a durable, light and inexpensive material, and its manufacture is increasing annually (OECD, 2022). Thus, plastic debris is a global issue that continues to grow.

Marine plastic debris causes a wide variety of ecological and socio-economic problems (Beaumont et al., 2019). The proven and suspected impacts on marine organisms and ecosystems are far-reaching such as: entanglement of individuals, smothering and community change (as an invasive species vector) to ecosystems (Galloway et al., 2017; Koelmans et al., 2017). Plastic debris also results in income losses and increased costs for ocean users and coastal communities (Watkins, 2017; Schuyler et al., 2018). In recognition of these wide-ranging effects, efforts to decrease plastic use, waste and pollution have surged in the past decade (Karasik et al., 2020) and targets increasingly made (e.g., UN Sustainable Development Goal 14.1).

To decide where to focus interventions that minimize ocean and coastal plastic debris, the source, pathway, type, amount, and location of accumulations must be considered. Plastic debris is mostly leaked into the ocean from populated land (Jambeck et al., 2015) and some types of debris (e.g., fishing gear) are deposited directly into the marine environment (Browne, 2015; Galgani et al., 2015). A recent study based on analysis of litter collection databases (Morales-Caselles et al., 2021) presents a conceptual model of the most likely pathways of the most frequent litter items. However, the exact pathways taken by plastic debris into the ocean, its degradation and fate are diverse and currently poorly understood, making it hard to predict patterns and amounts of marine debris. Although, we do know that rivers are the major conduit for plastic debris (González-Fernández et al., 2021). Indeed, plastic abundance estimates, calculated from different source data diverge greatly. For instance, estimates in surface waters vary between 0.27 million tons (Eriksen et al., 2014) and 0.09–0.24 million tons (Van Sebille et al., 2015) and this is likely to be just a portion of the total extent of existing plastic pollution. A mismatch between these estimates and that of plastic leakage from land (estimated at 4.3–12 million tons per year; Jambeck et al., 2015) still exists. Differences between estimates could occur because there is no clarity on the magnitude of plastic in reservoirs such as seabed sediment (Martin et al., 2022), ice (Obbard et al., 2014) organisms (Kvale et al., 2020) and the water column (Choy et al., 2019). Recently some (Weiss et al., 2021; Mai et al., 2022; Weiss and Ludwig, 2022) have argued that there is no or much less of a mismatch between estimates of plastic pollution being leaked vs. found in the ocean. Nevertheless, more work will be required to truly understand the residence times of plastic pollution within reservoirs.

Additionally, there is little understanding and data on the flux/transportation between said reservoirs within the environment (Hoellein and Rochman, 2021). Although some accumulations do occur in offshore environments (e.g., ocean gyres), the relative size of these accumulations in proportion to overall plastic pollution, even if unknown, is likely smaller in comparison to nearshore areas. The uncertainty of plastic abundance in offshore environments is due to limited observations, the low resolution and the simplified assumptions of current modeling studies, and lack of in-depth knowledge of some key ocean processes (Van Sebille et al., 2020). Furthermore, the transboundary nature of marine plastic and its constant movement is reflected by features such as windrows (Ruiz et al., 2020; Andres et al., 2021). Together, these factors mean it is hard to estimate the size of the marine plastic debris problem, communicate about it and prioritize interventions to reduce it (Hartmann et al., 2019). This also indicates that it is hard to determine exactly where large accumulations of plastic debris might be located, and how they change. However, plastic debris is most likely to be located close to the main source of leakage e.g., at locations on or near land. As policy makers are currently operating in data-poor environments, applying the precautionary principle should prevail (Meidl, 2019) until a larger body of evidence regarding risk is built. Despite the extensive interest in the subject, the increased implementation of product specific policies (e.g., Adam et al., 2020) and business decisions to reduce plastic waste, it continues to be a "wicked" problem (Zijp et al., 2016; Stafford and Jones, 2019; Stoett and Vince, 2019) that needs multiple holistic solutions. Here, we briefly summarize key learnings from current marine plastic interventions and detail next steps that could assist decision makers with assessing and prioritizing future initiatives.

2. Measuring debris

Despite many national and regional initiatives and guidelines to assess plastic debris (e.g., OSPAR Indicator Assessments, descriptor 10 of the EU's Marine Strategy Framework Directive, NOAA's Marine microplastics database and many more), there remains patchy data on global, regional and local pattens of its accumulation. Considering the vastness of the marine environment, currently funded research and citizen scientists projects are unlikely to capture the full and evolving extent of marine debris in the sea surface and beaches. To address this, there have been recent innovations using aerial drones (e.g., Andriolo et al., 2022), other imaging technologies (JRC, 2016), and remote sensing options using satellite technologies (e.g., Maximenko et al., 2019; Topouzelis et al., 2019). Furthermore, automatic detection of debris is now permitting quicker estimation of abundance in some areas (e.g., Veerasingam et al., 2022). However, further innovation and community engagement are required to usefully utilize these technologies to support marine plastic minimization globally. To ensure these tools support the development of indicators and their long-term monitoring and assessment then a clear, standardized approach regarding metrics, targets and threshold levels should be implemented using a global standard. The opportunity to do this has arisen within the negotiations of a binding treaty on the life cycle of plastics, based on the recently approved UNEA 5.2 resolution.

3. Waste minimization

As plastic production keeps increasing, so does plastic waste (OECD, 2022). Curbing plastic production (e.g., non-essential items) would minimize the amount of plastic that could become mismanaged waste and end up in landfill or the environment. There is a long lead time to achieve this curbing, therefore other interventions should be considered. There has been growing public awareness and institutional responses regarding marine plastic waste globally. Interestingly, some public attitude surveys place government and industry at the heart of the responsibility for reduction in plastic waste (Dilkes-Hoffman et al., 2019) although these are only two sectors where change can occur. Globally, responses cover individual responsibility, corporate and industrial measures, government policy, education efforts, and take place at any point in the plastic life cycle and waste-stream. Thus, many different initiatives have been conceived and developed (Table 1). An extensive list of instruments and technology initiatives have been collated (Karasik et al., 2020) and numerous case studies assessed (Global Plastics Policy Centre, 2022) but because the exact

TABLE 1 Examples of responses and knowledge gaps to reducing marine plastic waste across its life cycle.

Type of response	Prevention (upstream)			Removal (downstream)
	Policy	Industry and infrastructure Reducing/ recycling/ Waste management	Education (engagement, motivation, mindset)	Collection
Actors	At individual/ corporate/ institutional/ government/ international.	At corporate/ academic/ institutional/ government international.	At individual/ corporate/ academic/ institutional/ government/ international.	At individual/ academic/ institutional/ government/ international.
Actions (Order of priority)	- Promote policies that support a circular economy - Policy **engaging with industry** (producer responsibility). - **Regulating** production, use & full **life-cycle** of the product (recycling and waste management).	- Foster and promote **circular economy** principles in industry (product full life cycle & producer responsibility). - Refuse, reduce, reuse, recycle, recover, redesign.	- Seek **agents of change** (such as children). - Encourage being "**plastic sensible**".	**Requirements** Long-term real solution; **minimize unintended** consequences on the environment & ecosystem (precautionary principle). Have a **framework** - include all factors and prioritize.
	Follow the **precautionary principle** when drafting policy (scientific evidence takes time to build, it is needed as a basis for policy).	- Being "**plastic sensible**" (reducing plastic consumption, single and non-single use). - Take precautionary principle into account.	- Raise **awareness** (consequences & costs, circular economy). - Change **behavior** (reducing consumption). - Closing the loop: refuse-reduce-reuse-recycle-recover-redesign.	**Size dependent** - Focus could be macro or microplastics. - Passive or active methods? - Technological or human focused?
	Regulate and enforce policies to ensure consequences (economic, ecosystem/environmental, emotional, ethical, local consequences). - **Enforce** and advise monitoring. - Use **economic incentives*** (deposit schemes).	**Waste** - Improve waste management pathways and waste collection; (emphasis on developing countries). - Improve waste-water treatment (emphasis on developing countries).	**Clean-ups*** multi-purpose (actual removal; ocean literacy; environ-mental awareness). - **Education programmes** (school; high-schools; institutions; monitoring & citizen science; youth engagement; NGOs).	**Locations** Rivers & water courses. Coast & ports/marinas. Beach clean-ups. Open ocean.
	Taxing* production/packaging/-single-use plastic/plastic bags. Policies for **specific items***: - fishing gear; (fishing for litter programmes, size of vessel => costs); - plastic blasting in shipyards.	**Innovation** - Investigate new ways of recycling plastic polymers. - Find alternatives to plastic packaging.	**Citizen science + outreach***. - Educational videos/on-line courses/MOOCs.	What is the future of waste collection?

*Indicates interventions with shorter time frames (e.g., 0.5–3 years). The bold texts indicate keywords.

nature of interventions and their outcomes are context specific, prioritization of actions is still complex.

Prevention initiatives aim at reducing the amount of plastic produced and circulating in the waste stream, and also the amount of waste leaked into the environment. These initiatives include actions, such as developing alternative materials or re-design using circular economy concepts, taxes and levies for plastic goods (Powell, 2018), continued education, recycling programmes and technological developments. Policy opportunities focus on a holistic approach that considers a circular economy, providing additional benefits such as more cost-effective processes which incentivise change. However, more regulatory and punitive approaches maybe needed to support behavior change (European Commission Directorate-General for Environment, 2018a,b). Industry measures should mirror policy opportunities with consideration of their global footprint and innovation. Educational initiatives, both formal and informal, are best targeted at specific groups and operated alongside other programmes to maximize the impact of both (Table 1).

Removal interventions can vary from small, focused and community led (e.g., beach clean ups) through to large-scale infrastructure projects. In addition to the reduction of plastic, the most successful of these projects also include an educational and public awareness component (Rayon-Vina et al., 2019) to also minimize the leakage and connect people to their local environment. Effective removal projects require specific consideration of target debris and location, so bespoke solutions are often best, but as there are very few evaluations of success that include the entire procedure all the way through to processing of collected waste, there are little data to help inform decision-making. To support long-term positive change, projects should have a "planned legacy" and be carefully assessed for their risk (e.g., environmental and socio-economic) as well as their opportunities.

3.1. Litter prevention

3.1.1. Policy and regulations

The MARPOL (73/78) convention was the first legislative instrument for plastic waste and sought to prevent dumping waste at sea. Since then, many international and multilateral policy initiatives have been implemented to deal with the protection of the marine environment from plastic polluting activities (Gold et al., 2014; Chen, 2015).

Prioritizing interventions to minimize marine plastic litter and the implementation timescales are key to the initial reduction of plastic items (e.g., Cristi et al., 2020) in the marine environment. For instance, single-use plastic item bans have been effective in specific contexts, and therefore are considered as a relatively quick way of reducing waste load if conditions are favorable, e.g., alternatives readily available at same cost level, etc., (Xanthos and Walker, 2017). While single item bans cannot solve all marine waste challenges, they do provide opportunities for relatively rapid and cost-effective removal of a significant source of plastic from the waste stream. They are therefore considered useful initial actions for a range of regions (e.g., Royle et al., 2022) and they are often a useful step toward more complex interventions requiring greater community and stakeholder involvement that may need longer timescales.

Global (e.g., Lau et al., 2020), regional (e.g., European Commission Executive Agency for Small Medium-sized Enterprises, 2020; Omeyer et al., 2022; South East Asia) and national (e.g., USA; Milibrandt et al., 2022) assessments and subsequent models (e.g., Zero Waste Europe, EU Green Deal) and tools (e.g., Breaking the Plastic Wave Pathways Tool, Plastic Drawdown) have provided clear pathways for waste evaluation and policy appraisal. However, prioritizing long-term investment of interventions can be challenging without aligning waste minimization with other policy objectives and global targets. With this in mind, the alignment of waste management with health and wellbeing policies that was conducted in a recent assessment (Farrelly et al., 2021) provided important insight about the interactions of complex issues, revealing the value of analysis across objectives and interventions toward the UN Sustainable Development Goals.

Many multinational programmes exist today to support national and regional policy development and implementation (e.g., Commonwealth Clean Ocean Alliance, the UN Decade of Ocean Science for Sustainable Development, GEO Blue Planet Marine Litter Working Group). Despite widespread interest there is still no binding policy that addresses land-based sources of plastic pollution. There is now an agreement for an international treaty on plastic pollution stemming from its trans-boundary nature (Borrelle et al., 2017; Silva Filho and Velis, 2022) and steps toward this have started with the first Intergovernmental Negotiating Committee meeting conducted at the end of 2022. However, it is still unclear as to whether this treaty will address the plastic pollution issue entirely, and by what means (e.g., by curbing its production, Bergmann et al., 2022). Due to the context-specific nature required in interventions, national and regional policies are generally developed individually through incentivising or prohibitive programmes (e.g., bottle deposit schemes), taxes and levies (e.g., plastic bag levy, Rethink Plastic- Zero Waste Europe) or bans (e.g., single-use plastic ban) (Abbott and Sumaila, 2019). For example, plastic bags, are a topic where the national governments have collectively made the most policies, and where prohibitive regulations were most commonly used (Karasik et al., 2020). In this case it is still not clear if these are an overall success for the environment, due to the potential impacts of some of the materials used to replace plastic (Gómez and Escobar, 2022). In conclusion, powerful vectors of change can come from national regulations that contribute to international behavior change, such as waste import and export bans (Brooks et al., 2018), although mechanisms to connect these are often still undeveloped.

3.1.2. Industry including waste management and innovation

As producers of plastic, consumers and recyclers of plastic products and waste, industry holds a key to the solution of plastic waste reduction. This is the logic behind the EU Extended Producer Responsibility policy (EPR, Lorang et al., 2022). In the context of the "Waste Framework Directive" (2008/98/EC), and the "Packaging and Packaging Waste Directive" (94/62/EC) the EPR is used as a policy tool so that the producer has a responsibility of the post-consumer phase of the product, i.e., when it becomes waste. Industry also has a major part to play in how plastic and product life cycles are considered in the future. Many waste reduction strategies make good economic sense and have been implemented across the sector (e.g., Operation Clean Sweep). Coupled with these, industry has the opportunity to deliver radically different products using the concepts of circular economy to improve product design and reduce plastic waste through extended producer responsibility schemes. The shift is already seen in some sectors and supported *via* networks such as the "*Circula El Plástico*"[1] (Chile).

Additionally, for industry, gaps identified (Woodall and García-Hermosa, 2016) include opportunities to explore technological and novel material development (Cordier and Uehara, 2019) as well as to improve recycling and further development of polymer identification and sorting methods, improve knowledge on degradation and biofouling, and support more innovative ideas currently in the research phase (e.g., edible food packaging). Recycling, polymer identification/sorting, and degradation of marine plastic litter are interconnected subjects but the links, as yet, are not fully understood.

Global recycling levels are still low, some estimates from 2017 are as low as 9% (Nikiema and Asiedu, 2022) and cited as only 16% for the waste management industry, water treatment and associated sectors (Kaza et al., 2018). These low numbers reflect the many region-specific challenges including widespread lack of formal waste management collection systems in low-income countries, where the informal sector has bloomed. While the informal sector is vital in many low-income nations, it is rarely taken fully into account in budget calculations, partly because it is often hard to quantify. This exclusion overlooks the role of informal processes in the waste management industry. This lack of recognition and value can have negative impacts for the workers (with precarious

1 https://circulaelplastico.cl/en/ The Chilean Plastic Pact.

living conditions) who may lose their livelihood and fall deeper into poverty. When considering interventions in the waste management industry, integrating and coordinating these two sectors provides better outcomes, whilst improving the conditions for informal workers (e.g., Jenin Solid Waste and Environmental Management Project) is an important target globally (i.e., SDG 11).

3.1.3. Education leading to personal behavior change

Education is an important tool to reduce plastic waste (Thompson et al., 2009) and has proven to have a positive impact on the issue (Maddox et al., 2011). Additionally, education programmes can be targeted at specific ages or sectors of society; groups/communities; or focus on particular messages. Children are recognized as "agents for change" especially regarding environmental issues and thus many of these programmes include this age-group (Walker, 2017). The educational programme delivery is often successfully conducted (for all ages) alongside other marine plastic reduction initiatives (Löhr et al., 2017). To illustrate this, education is an important component of beach clean-ups (e.g., UK Marine Conservation Society) which do not solve marine waste in the long-term, although they do provide opportunities for data collection and awareness campaigns. Moreover, the topic of plastic pollution has an important role as a gateway to other global issues such as climate change, especially as it is so closely linked (Ford et al., 2022), and also has a trans-boundary component to it. There are currently a huge range of resources that can be used in education programmes on marine debris. These are pitched at different levels and different sectors of society [e.g., Green Indonesia, Massive Open Online Course (MOOC) on Marine Litter]. In addition, courses on marine biology, coastal management, marine pollution, ocean literacy and stewardship often present marine plastic impacts and how individual people can change their behavior to reduce them (SEPEA Science Advice for Policy by European Academies, 2019).

3.2. Removal: A small part of the solution

General consensus in the community considers that removal of plastic pollution from the environment is not optimal as a standalone action, as it is not a long-term solution (e.g., Nizzetto and Sinha, 2020), and it will only "solve" a fraction of the problem. Removal actions unsupported by other interventions (e.g., educational as in cleanoceanproject.org) should be considered as "quick and temporary fixes" and must be complemented with plastic waste minimization actions that stop plastic pollution entering the environment. These mean emphasizing life-cycle solutions at product conception, reducing or banning single-use unnecessary products and improving waste management. Indeed, some clean-up activities for macro litter, perform a joint function of educating and visualizing the plastic pollution problem for communities (e.g., beach clean-ups, fishing for litter activities and water wheels), as well as providing waste removal opportunities.

The success of the physical removal of plastic pollution from the natural environment depends on multiple aspects such as: size, abundance and type of plastic, location, methodology, and type of environment (e.g., coastal waters, open-ocean, rivers). A good example of focused and specific marine litter removal with reasonable success are the "Fishing for litter" initiatives (https://fishingforlitter.org). Other relevant points to be considered are the proposed removal location, consequences of the impact of the removal, and subsequent actions required to get the plastic to waste management sites (Sherman and Van Sebille, 2016). Schemes targeting plastic waste removal are most beneficial when located near existing infrastructure (e.g., transport links, industrial reprocessing plants, etc.,) to minimize additional development requirements and fuel consumption needs. Furthermore, collection or removal schemes should be designed to minimize the chance of biological "by-catch" (unintended entanglement or capture of organisms) and should also be targeted near the source of the waste leakage and where accumulations are found (e.g., estuary mouths, coastal areas) (Haarr et al., 2019; Falk-Andersson et al., 2020). A recent study based on analysis of litter collection databases (Morales-Caselles et al., 2021) identified coastal areas for collecting plastic waste before it moves to deeper open ocean. Many different initiatives exist and have been reviewed. Microplastic and macro waste collection methods (Microplastic: Padervand et al., 2020; macro waste Schmaltz et al., 2020) exhibit differing challenges and levels of success. For instance, some successful and simple removal projects have targeted particular pathways and capture waste before it enters marine systems (e.g., storm drains, Baltimore wheel).

While microplastic removal is technically possible (Karasik et al., 2020; Padervand et al., 2020), just a few methods are currently available (at the scale that would be required to make significant changes in ocean locations) that would not result in large-scale changes to biological communities. However, on land, some waste-water treatment processes can remove >95% of microplastics from waste-water (e.g., Talvitie et al., 2017) preventing further spread of this pollutant, and so filtering and gravity methods, biological and binding methods, membranes and physical capture (Karasik et al., 2020) should be considered useful tools to reduce this type of pollutant. These types of removal methods are developing more widely and mostly focus on waste-water.

Underpinning any intervention is a cost-benefit analysis and include aspects such as costs to the environment and communities, as well as the financial outlay. The financial cost of an intervention to remove marine plastic is rarely in the public domain, although some examples do exist (e.g., Burt et al., 2020, for a small-scale approach) costs range widely depending on situation (Nikiema and Asiedu, 2022). All negative (including unintended) consequences of plastic removal interventions must be considered at the planning stage (as with any development and activity) and the precautionary principle ought to be applied. For example, the debate on the impacts of mechanical beach cleaning is still ongoing, an activity that has been going on for decades (Zielinski et al., 2019).

To recap, in the authors' opinion, removal interventions require an appropriate accompanying narrative and activities, as they can deflect messages of resource sustainability, personal responsibility and industry accountability.

4. Thoughts on strategies for reducing marine plastic debris

Plastic waste is not only a marine problem, it is also a global societal challenge (Jambeck et al., 2020). Debates about which solution is best for marine plastic continue as there is a growing realization that not all plastic pollution is the same (having different components, sources and pathways into the environment). It will not be feasible or realistic to remove all plastic already in the environment, neither is it appropriate or possible to stop the immediate production of all plastic (Patterson, 2019). It is more realistic to radically reduce the waste leaking into the ocean (and reducing production of certain items) while developing alternative materials, and hence reduce the overall burden entering the environment. In specific situations removal interventions that are most beneficial to the environment and local communities may help.

Reviews comparing similar interventions across different nations, (e.g., plastic bag bans, Xanthos and Walker, 2017; Knoblauch et al., 2018; Nielsen et al., 2019) have been successful in elucidating the drivers that are enabling and inhibiting these policies. Together these studies and others (e.g., Rochman, 2016; Critchell et al., 2019; Godfrey, 2019) show that no "one" solution to the marine plastic pollution is perfect for all scenarios. Instead, solutions require a location and case-specific focused approach. The key to reducing marine plastics will have to be multifaceted, as the processes that originate it are numerous, complex and overlapping. These solutions will need to be enacted at multiple points in the life cycle and waste stream of the plastic objects, and will need, in some cases, multinational agreements. A better understanding of the flux, sinks, sources and reservoirs of plastic waste will also help target and prioritize appropriate interventions.

The amount of published literature on marine plastic pollution has increased annually (Aretoulaki et al., 2020) as have the actions being implemented to reduce this problem. However, there remains limited scientific evidence as to which of these interventions should be prioritized, and the local conditions and national circumstances required for them to be most successful (see Global Plastics Policy Centre, 2022; Nikiema and Asiedu, 2022). Debate about what defines a successful intervention and its context continues as the body of scientific evidence slowly grows, and zero plastic waste pollution remains far from practical in most cases.

Based on the points discussed throughout the paper, we suggest some steps that could be useful to support stakeholders and the wider community in decision-making regarding plastic pollution interventions with measurable outcomes and action accountability. In addition, the information gaps and analyses suggested in the steps below would be useful in supporting negotiations of a global plastics treaty, and potentially useful in the implementation of actions required to achieve some of the agreed targets. We think it is necessary to:

1- Scope the issue by agreeing on the metrics to quantify the presence and type of plastic pollution to compare the situation before and after intervention or interventions. This would help define, *a priori*, what is to be considered a success and provide an indication of achievement over time.
2- Use a list of possible interventions (e.g., Karasik et al., 2020) and their context specific nature to identify the interventions suitable for the current situation/region/context. This short-listing process supports focused discussions for stakeholders.
3- Identify the main influential factors that are context specific to the situation/region (e.g., socio-economic, socio-cultural perspectives, behavioral, legal, infrastructure, timeline, value for money, perception of waste impacts, long-term additional benefits). Providing further opportunity for engagement between stakeholders and decision-makers.
4- Establish potential risks associated with the selected interventions, building on Schmaltz et al. (2020) and Nikiema and Asiedu (2022) and combining them with the most influential factors in the specific context/region of the situation. Taking into consideration the influence and consequences of those in the specific context (indicating sources of risk) for the success of each intervention.
5- Bringing together the interventions, metrics, targets, most influential factors and risks as an assessment tool to provide the opportunity for decision-makers to objectively rank (prioritize) and choose a suite of actions that are most likely to be successful, given their specific circumstances, location, and the challenges that may be faced at a regional, national and international context.

Based on the points above we suggest the relevance of creating a user-friendly tool. This means a tool that provides an interface for users to input and access information and options available, and to test their ideas in a simple manner.

Various modalities should be considered, to help ensure wide engagement of the tool across sectors. This could include platforms such as a website, a phone app and/or printed material. This would facilitate transparency and democratization of the decision-making process across stakeholders and the wider community and would comprise information from above points. Additionally, the global plastic treaty, that is under negotiation could be an invaluable opportunity to request the eventual signatory countries to report on current plastic debris and how they change overtime.

5. Concluding statements

Given the diversity and complexity of the marine environment and of the sources of marine litter, there is no one solution to this wicked problem. Instead, a portfolio approach of multiple actions that are specific to the local/regional context is required. The choice of interventions to minimize plastic items and waste (in general and their arrival in the marine environment) should be taking into consideration a host of pertinent factors, such as socio-economic, socio-cultural, behavioral, infrastructure, legal, timeline, value for money, local infrastructure, perception of waste impacts, unintended consequences, and long-term additional benefits. We therefore suggest a tool designed to facilitate transparency and democratization of methodologies by gathering pertinent information from diverse sources and sharing it across sectors. This tool would present the current problem and share a list of possible interventions that could be adopted by decision-makers. It would also provide understanding of possible challenges that may arise from interventions. Thereby, could be a useful mechanism to help choose, prioritize and optimize interventions.

Plastic waste is not an isolated challenge; it is highly linked to other global challenges such as climate change and resource over-exploitation. Decisions to minimize marine plastic debris should also consider a holistic view of the region/area/context and other challenges present when prescribing interventions. This addresses the fact that marine plastic debris is a trans-boundary issue and to best tackle it, therefore, requires cooperation across geographically close and distant countries. As solutions are diverse, they operate at an optimum over different set of geographical, sectorial and temporal scales. In conclusion, marine plastic pollution can only be reduced when interventions are part of a suite of well-designed actions that are diverse and take full account of the specific context.

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Conflict of interest

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