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Zero-waste circular economy of plastic packaging: The bottlenecks and a way forward

Katarina Novakovic [a,*], Deepashree Thumbarathy [a], Marloes Peeters [a], Mark Geoghegan [a], Josephine Go Jefferies [b], Chris Hicks [b], Danae Manika [c], Sheng Dai [d]

[a] School of Engineering, Newcastle University, Newcastle Upon Tyne, UK
[b] Business School, Newcastle University, Newcastle Upon Tyne, UK
[c] Business School, Brunel University, London, UK
[d] School of Chemical and Process Engineering, University of Leeds, Leeds, UK

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ABSTRACT

Interest in recycling is higher than ever, with the recycling of plastic packaging waste being a significant concern for the general public and governments worldwide. However, the rate of plastic packaging waste recycling has stagnated over the past five years. This implies current strategies are insufficient and new approaches are required. We evaluate the present situation and highlight the bottlenecks that are limiting efficient recovery of plastic packaging waste using currently available systems. Difficult to recycle thermoplastics such as polystyrene and poly(vinyl chloride) are not needed in packaging, which we propose should be based on poly(ethylene terephthalate) (PET), polypropylene (PP), high-density and low-density polyethylene (HDPE and LDPE respectively). Furthermore, we draw attention to the opportunity for keeping PET/PP packaging as a single waste stream, and leaving HDPE and LDPE as a standalone stream, to enable efficient plastic separation of individual types of plastic for mechanical recycling to achieve a zero-waste circular economy for all plastic packaging.

1. Introduction

Since 1965 when the Swedish company Celloplast patented the design of the modern plastic bag, it took less than 15 years for plastic bags to dominate 80% of the European bag market and spread to USA and other countries worldwide [1]. Plastic bags are inexpensive to manufacture. The Film and Bag Federation, a trade group within the Society of the Plastics Industry based in Washington, D.C., stated that plastic bags consume 40% less energy, generate 80% less solid waste, produce 70% fewer atmospheric emissions, and release up to 94% less waterborne waste than paper grocery bags [2]. Plastic packaging protects goods and food that would otherwise perish faster and is cheaper to transport due to its lighter weight (e.g., compared to glass) thus saving energy. The Plastic Industry Association reports that plastic packaging serves its purpose at the fraction of the carbon footprint of other materials, whilst limiting food waste, which is estimated to cost the global economy £300 billion per year [3]. Each year 141 million tonnes of plastic packaging are produced worldwide, which through its production, use and disposal yields approximately 1.8 Gt of carbon emissions [4]. Plastics are estimated to account for 20% of municipal solid waste in the United States and Germany and 25% in Australia.

The Organisation for Economic Co-operation and Development (OECD), comprising of 38 countries committed to democracy and the market economy (*www.oecd.org*), globally, reported that only 9% of plastic waste is recycled (Fig. 1) while remaining plastic is incinerated, landfilled or lost due to mismanagement [5]. In landfill, the decomposition of plastic bags can take 1000 years [6], yet most plastic waste is discarded into landfill or the natural environment, including oceans. Approximately 60% of waste plastic (mainly polyethylene and polypropylene) has lower density than seawater enabling buoyant plastics to be transported by winds and surface currents and broken into smaller pieces [7,8]. There is a significant accumulation of buoyant plastics in the Eastern area of the North Pacific Subtropical Gyre. This is referred to as the 'Great Pacific Garbage Patch', which stretches between Hawaii, California, and Japan. It is estimated that there is 45–129 kt of plastic litter in this patch, which covers 1.6 million square kilometres [7].

Despite the environmental issues caused by plastic being widely reported in the news, recycling rates for plastic packaging are stagnating.

* Corresponding author.
E-mail address: katarina.novakovic@newcastle.ac.uk (K. Novakovic).

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In 2021, the U.S. Plastic Pact, reported that its 117 members produced 37% (by weight) of plastic packaging in the U.S. (~ 5.9 million tons), of which 36% was reusable, recyclable or compostable, but only 13.3% was recycled [9]. In China, the recycling rate dropped from 27.8% in 2017 to 17.6% in 2020 [10]. In the United Kingdom recycling rates have not changed in the past five years (44.9% in 2016 and 44.2% in 2021) [11]. In 2010, between 4.8 and 12.7 Mt. of plastics leached into the ocean worldwide leading to calls for comprehensive and collaborative approaches to improve plastic recycling. Despite these calls, the amount of plastics leaching is estimated to increase by an order of magnitude by 2025 compared to 2010 [8,12] indicating the inadequacy of ongoing efforts.

For example, in the European Union, policy directives aim to reduce plastic waste by facilitating a transition to a circular economy [13–15]. A European Parliament resolution (13th Sep 2018) on a European strategy for plastics in a circular economy recognises that plastic plays a useful role in our economy and in our daily lives but at the same time has significant drawbacks. A number of recommendations were made, including a strong focus on prevention, entire value chain involvement, research to develop innovative solutions, and the resolution calls on the Commission to come forward swiftly with quality standards in order to build trust and incentivise the market for secondary plastics [14]. However, the partial achievement of targets to increase levels of plastic recycling has been through exporting waste to low-cost countries [16] including China, which imported 45% of cumulative plastic waste since 1992. China's decision to ban plastic waste imports in 2018 [17] led to a 39% decrease in the EU's plastic waste exports, overloading the EU plastic waste management infrastructure which to this day is unable to respond to demand [16,18]. The problem of 'Garbage Patches' demonstrates, that managing plastic packaging waste requires a global solution to reduce unnecessary reliance on landfill. Current approaches to recycling are insufficient and a new strategy is needed. In this paper we analyse the present situation, discuss the bottlenecks and obstacles to the recycling of plastic packaging, and propose actions toward a zero-waste circular economy.

2. Current position

In the consumer goods market, plastics are used as a cheap, convenient, and durable option for food and beverage packaging. Plastic packaging materials are frequently preferred to metals (e.g., aluminium) or paper, as they preserve, protect, and extend the shelf life of food and beverages, while reducing the cost of transportation due to their light weight [19]. While different classifications of plastics exist [20], here classification based on molecular interaction to thermoplastics, elastomers, and thermosets will be used [21,22]. Plastic packaging is primarily made of thermoplastics and this category is the focus of the paper. Molecules in a thermoplastic are held together by relatively weak intermolecular forces which enable material to soften when exposed to heat, and solidify upon cooling, a characteristic of utmost importance to facilitate efficient recycling. Elastomers on the other hand are cross-linked polymers that can be stretched and once the applied stress is removed, return to their original size. Finally, the class of plastic termed thermosets, solidifies irreversibly (e.g., when heated), yielding highly crosslinked structures, i.e., with limited deformability. Fig. 2a illustrates the classification of seven types of plastic materials with a chasing arrows triangle surrounding numbers, and their ratio in the UK market in 2017. The UK was used as an example to illustrate the problem of the interchangeable use of plastic in packaging, which is a worldwide issue. The chasing arrow triangle is commonly used as a symbol for recycling, promoting the idea that products marked with these symbols can be and are recycled. This is incorrect, especially when it comes to types marked with a number 7 which denotes "other" i.e., unknown or mixed plastic.

The most common types of thermoplastics present in household waste are: poly(ethylene terephthalate) (PET, number 1), used mainly in bottles, pots and trays; high-density polyethylene (HDPE, number 2), used for example for milk bottles, films, pots and trays; low-density polyethylene (LDPE, number 4) used for films, e.g. trash bags; polypropylene (PP, number 5) typically used for pots, trays and bottle caps; and polystyrene (PS, number 6) used for pots, tubes, trays, impact resistant cushioning and shock absorption [23,24]. Although in lesser amounts, some products, such as pots, trays and films, are also made from poly(vinyl chloride) (PVC, number 3) or undeclared plastics (number 7, which are sometimes also unmarked). These thermoplastics could be efficiently remelted and reshaped into new products if the waste is appropriately separated by polymer type. This process is called mechanical recycling [25], where a single type of plastic, e.g., PET bottles are shredded, melted, and extruded to pellets which are subsequently used to produce new PET bottles. Mechanical recycling is the best way of achieving a zero-waste circular economy of plastic packaging [25]. Frequently, the terms "recycling" and "mechanical recycling" are used interchangeably, making it difficult to extract information on uptake of the mechanical recycling. Chemical recycling [26], a more energy intensive alternative, involves breaking down

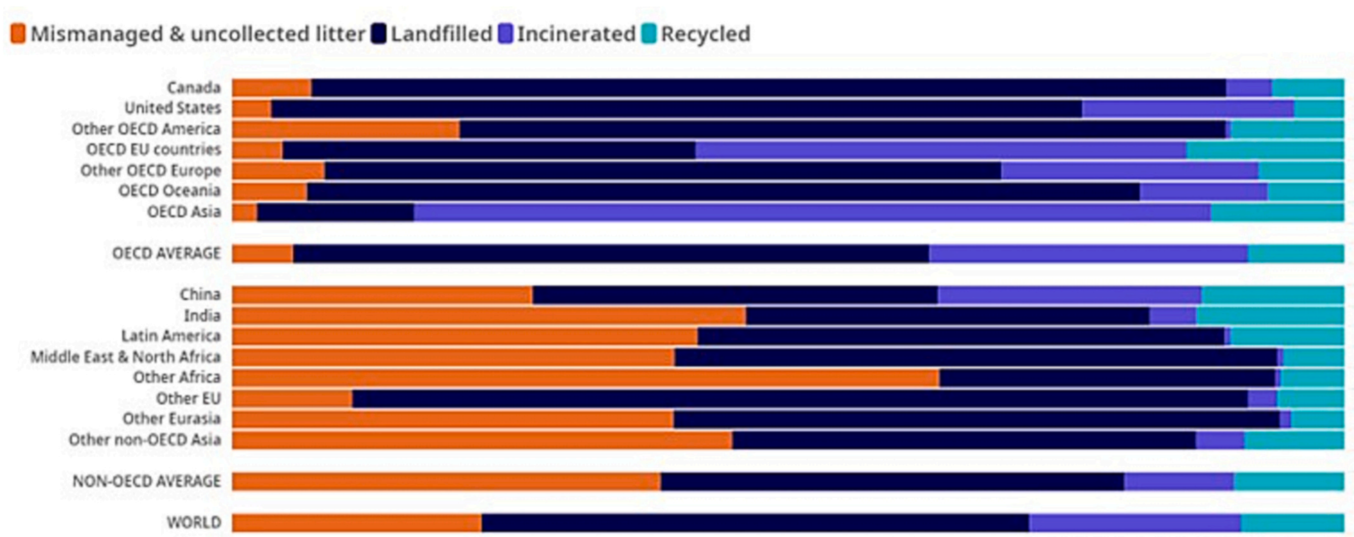

Fig. 1. Share of plastic waste recycled, incinerated, landfilled and lost due to mismanagement in 2019. Adapted from the report made by Organisation for Economic Co-operation and Development (OECD) [5].

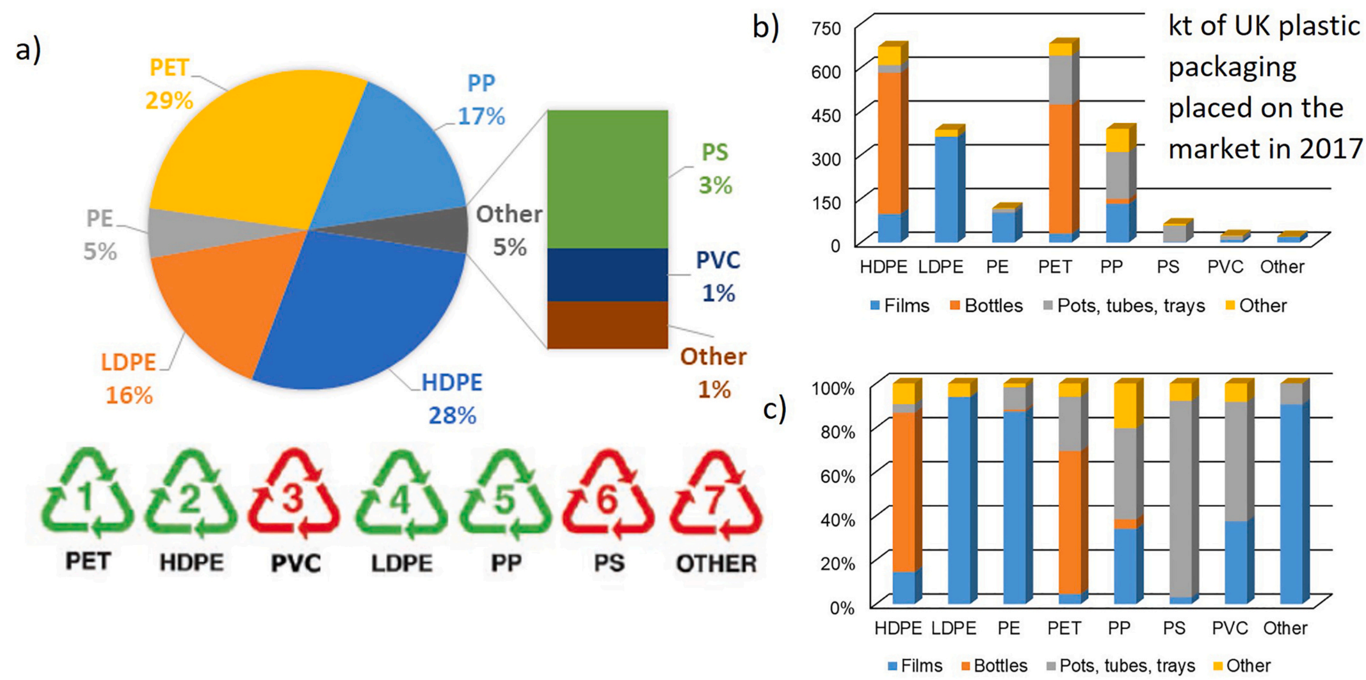

Fig. 2. Plastic packaging placed on the UK market in 2017 a) Range of different types of plastics used: poly(ethylene terephthalate) (PET), high-density polyethylene (HDPE), poly(vinyl chloride) (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and others (o), with difficult to recycle plastics denoted in red; b) Quantity of different plastic used; c) Interchangeable use of different types of plastic in same types of packaging. Adapted from [24].

materials to a range of chemicals which are subsequently separated and incurs a loss of material during the separation and purification stages. Incineration with energy recovery [27], where high calorific value plastic (41.9–46.5 MJ/kg for PS, PE and PP; compared to 45.2 MJ/kg for gas/oil and 42.3 MJ/kg for petroleum [28]) is converted to energy, and plastic material is effectively lost in a linear economy, which creates significant CO_2 emissions (673 g/kg to 4605 g/kg [29]). Although mechanical recycling is the preferred choice for plastic packaging waste, it requires separation of different types of plastics into individual streams of neat plastic to avoid contamination [30,31]. Efficient plastic separation from mixed waste remains a major challenge to plastic packaging waste recycling [32].

Focused efforts to improve recycling can make a big difference, as packaging comprises 40% of all plastic produced with the average global recycling rate being less than 20% [33]. In the UK approximately 2.36 Mt. of plastic packaging is placed on the market every year (Fig. 2b) and accounts for nearly 70% of plastic waste, of which less than half is recycled [24,34]. Improving recycling rates and making recycling efficient are critical. For food and beverage plastic packaging, the circular economy requires a stream of uncontaminated material to produce high quality recycled plastic [35]. Several ways that plastic packaging prevents efficient recycling include the interchangeable use of different types of plastic in packaging (Fig. 2c) which makes the separation of waste streams confusing for consumers and complex for waste management facilities. Another example is when the plastic packaging is labelled as recyclable but is difficult, if not impossible, to recycle because the specialist facilities required to recycle them are scarce (e.g., PS and PVC). Contamination occurs because certain plastics when disposed as mixed waste are challenging to separate (e.g., PE and PP). Furthermore, 'other' plastic (number 7, e.g. polymer blends and composites), effectively become contaminants that cause further complication [36]. Therefore, sustainable, more eco-friendly plastic packaging is counterproductive to a circular economy without a uniform and coherent strategy [37,38] to tackle the broad range of plastics currently in use (see Fig. 2) and an even broader range of plastics under development [39]. R&D falls under two categories: developing more eco-friendly bioplastics, biodegradable, or compostable materials [39,40]; and developing technology for better separation of different plastics from mixed waste [31,41]. While eco-plastics produced from biological materials have some merit, for most packaging applications they have substandard properties compared to petroleum-based plastics, or they are deemed economically unviable [39,40]. For example, polylactide (PLA), made from starches and sugars of corn, have been intensely pursued, however further improvements in mechanical and barrier (to moisture and oxygen) properties are required for a broader use [25,26]. Also, in the case of biodegradable and compostable plastic, the degradation of materials leads to a linear economy, loss of resources and financial loss, as well as introducing possible contamination of petroleum-based plastic during recycling process [42,43].

Stopping the large amount of plastic waste escaping the recycling process and generating significant environmental damage is critical [44]. Wildlife and humans are endangered by rising levels of plastic accumulating in landfills and in nature, as well as increased leaching of microplastics and chemicals [45]. Although the development of technologies for plastic sorting from mixed waste is necessary to divert as much as possible from landfill into the recycling stream, it is not sufficient to deliver a zero-waste circular economy and must be complemented by other fundamental changes including overall reduction, reuse and repair before recycling is introduced.

OECD published their first Global Plastics Outlook [46] reporting that almost half of all plastic waste is generated in OECD countries, varying from 221 kg/person/year in the United States, 114 kg/person/year in European OECD countries to 69 kg/person/year in Japan and Korea. UK households dispose of 100 billion pieces of plastic packaging annually, approximately 66 items per household per week [11]. The UK government aims to tackle the issue of non-recyclable plastic packaging by 2042 [47] through a Plastic Packaging Waste tax (2022) that incentivises reduced use and recycling of plastic packaging [48]. In response, 95% of the UK grocery market by market share in 2019 are members of a UK Plastics Pact that by 2025 aims to eliminate problematic or unnecessary single-use packaging; ensure 100% of plastic packaging will be reusable, recyclable, or compostable and that 70% of plastic packaging will be effectively recycled or composted, with an average of 30% recycled plastic across all plastic packaging [49]. While both initiatives can engage major players upstream to reduce the plastic packaging put into the market and incentivise recycling in a limited way, the scale of the problem outlined above calls for urgent action and new approaches to eliminate the loss of plastic packaging to waste.

3. What should be done?

This section considers the standardisation of plastics used for particular applications, approaches that could overcome resistance to change, moving plastic packaging to two-stream waste recycling system (one stream being PET/PP and another PEs), phasing out use of difficult-to-recycle plastic in packaging and consumer-facing technology improvements.

3.1. Standardising types of plastic that can be used for a specific type of product

A plastic product labelled with a chasing arrows logo may suggest a material is recyclable, but this is frequently not the case. Recyclability depends on the type of material, its location, and the available technology to be cost effective. This creates a high bar to recycling that in practice may discourage recycling. For example, yogurt pots are made from different plastics, and although they are labelled as recyclable, they may not be eligible for kerbside collection and recycling [50] because some are made of PS, which is difficult to recycle efficiently, and others may be made of PP, which can be easily recycled, but not when mixed with plastic milk bottles, a commonly recovered and easily recycled item. In the absence of the right technology to manage these complications, most plastic packaging is sent to landfill or incineration (either with or without energy recovery, which produces polluting gases) because it is more cost effective in the short term. One answer to reduce the complications and to help achieve better environmental outcomes is to streamline the design of plastic packaging through the use of standardised types of plastic that can be used for a specific type of product. For example, requiring all yogurt pots to be made from the same material would improve plastic packaging waste separation and mechanical recycling.

3.2. Overcoming resistance to change

Implementing this change will require a significant cultural shift in how plastic packaging is viewed by organisations and consumers [51]. Overcoming resistance to change involves disrupting established ways of working and regulating non-compliance [52,53]. Strategies to reduce plastic use and increase recycling could be based on three principles: treating plastic packaging as a high-value finite resource, thereby delegitimising waste [54]; producing plastic packaging only from materials that can be recycled effectively; and creating an infrastructure and ethos that supports and promotes a zero-waste culture across organisational boundaries to involve consumers in establishing practical solutions [55].

3.3. Moving all plastic packaging to two-stream waste recycling system, one stream being PET/PP and another PEs

From an operational perspective, plastic packaging that is discarded should be collected, separated according to the type of plastic, then melted and reformed as pellets, before being used to manufacture new products. The recycling capability for plastic bottles made from PET (body) and PP (cap) is excellent and is regularly used [56]. HDPE milk bottles are also successfully recycled [57]. These two types of bottles need to be recycled as two separate streams for PET/PP and HDPE. While both are thermoplastic materials, which can be melted and reshaped i.e., can be mechanically recycled, it is important not to mix them, as PP and PE are difficult to separate and products made from mixtures of them have poorer mechanical properties [56–58]. On the other hand, PET and PP are thermoplastics with significantly different densities which facilitates automated separation prior to energy efficient mechanical recycling. PET flakes (1.30–1.38 g/cm^3) sink in a water tank [59], while PP flakes (0.90 g/cm^3) float [60]. PET, the most used plastic in UK packaging today (70% of soft drink bottles, and 29% of all plastic packaging), and PP (17% of all plastic packaging), commonly used for bottle caps, yogurt pots, microwaveable trays and films [24], have outstanding physical properties and therefore can form the linchpin of a sustainable plastics economy. However, even when products (other than bottles) are made from PET and PP, they are not commonly recycled due to fear of contamination, which arises when similar products are made from different plastics (e.g. yogurt pots are made from PP, but also from PS, PVC and HDPE, see Fig. 2), or single packaging consisting of multiple plastics (e.g., PP pot with a PE film lid) [61].

If we were to integrate other PET and PP packaging, currently not recycled, into an efficient recycling process, based on the usage illustrated in Fig. 2, it would enable mechanical recycling of 46% of all plastic packaging waste in the UK, a significant increase from the current ~30% [62]. Going a step further, if we are to phase out the use of plastics which obstruct efficient packaging recycling (PVC, PS, blends, composites and some PE films used in multi-plastic packing) and replace them with PET and PP, based on UK usage, this would further increase recycling by a minimum of 10%, bringing the total to over 56%. Furthermore, by keeping PET/PP packaging as a single waste stream, fit for full separation to PET and PP for mechanical recycling, what would remain are PEs (HDPE and LDPE) which can be separated to neat HDPE and LDPE by appearance, rigidity, and difference in density (LDPE: 0.920 g/cm^3 and HDPE: 0.954 g/cm^3) [63] and efficiently recycled. In other words, if we succeed in achieving a two-stream plastic packaging waste recycling system, one stream being PET/PP and another PEs (HDPE and LDPE), we can facilitate close to 100% plastic packaging mechanical recycling.

3.4. Phasing out use of difficult-to-recycle plastic in packaging to approach 100% plastic packaging recycling

The use of difficult-to-recycle plastics in packaging needs to be phased out. Equally, plastic packaging should be standardised and designed with recycling in mind. In the recycling of mixed waste plastic, it is crucial to identify contamination and waste composition in relation to collection and sorting. The different polymers involved are PET, PE, PVC, PP, and PS, which makes it difficult to recycle them all together. Most of the food packaging comprises either PET or PP, whereas the majority of non-food packaging is made of PP [64,65]. The opportunity exists to exploit the low glass transition temperature (Tg) of PP ($-20°$ to -5 °C), which offers energy efficient manufacturing, and the high Tg of PET (70° to 80 °C), which provides better mechanical strength [66]. The main goal is the reuse of waste plastics through mechanical recycling and a key enabler could be an expansion in the capabilities of PP and PET in packaging beyond current applications. Employing PP-based films for labels, cling film, and thermo-shrinking packaging foils in place of PVC and PE would enable the manufacture of single plastic products (e.g., a PP yogurt pot with a PP film lid), or PET/PP products (e.g., a PET bottle with a PP cap and label sleeve). While further materials development is needed, examples already exist (e.g., CPPeel and UltraClear which is a PP-based lidding film). Replacing PVC in packaging is further beneficial because it is toxic during both synthesis and degradation [67]. Significantly, PVC has a similar density to PET and is a deleterious contaminant in the PET recycling process [68]. PP and PET pots can replace PVC, polystyrene, and composite plastic containers, including flush heat-resistant pods. At present 59 billion coffee capsules manufactured globally each year are likely to be landfilled [69]. Replacing them with recyclable plastic capsules has a major role to play in cutting plastic packaging waste. Furthermore, expanded PP (EPP) can be used for insulated packaging, in place of expanded polystyrene

[70,71]. EPP can also be used in the packing of large electric goods, and in building insulation, replacing extruded polystyrene [71,72].

The development of a circular economy requires both the infrastructure and ethos, which supports and promotes recycling. Successful recycling requires compliance and effective waste collection. In order to further promote recycling and sustainability it is necessary to have appropriate public policies, taxation, and sufficient investment to develop recycling infrastructure. The involvement of companies and stakeholders in promoting innovative business models and sustainable solutions will directly impact consumption and production patterns and lead to the removal of current barriers.

3.5. Consumer-facing technology improvements

In place of the current voluntary plastic codes, it is necessary to introduce a mandatory, highly visible, plastic numbering scheme and barcoding system to provide disposal information (in addition to product information). The feasibility of this approach has been demonstrated by the Scrapp App (*www.scrapprecycling.com/mobile-app*), which promotes the use of barcodes to sort packaging into the right bin, according to local recycling rules. The availability of information about plastic content in the barcodes can simplify consumer decision-making and help create habits that support the circular economy. The use of barcoding engages manufacturers of plastic packaging and also enables the use of machine learning for waste separation at recycling facilities. Infrastructure needs to be designed that is based on consumer behaviour to enable the efficient collection of neat streams of PET/PP and HDPE/LDPE at appropriate locations (e.g., supermarkets or kerbside collections), while making it less time consuming through an efficient numbering scheme. For packaging that still ends up in municipal facilities as mixed waste, barcoding would aid separation via machine learning. In parallel, the capacity and geographical distribution of recycling facilities needs careful consideration to minimise environmental and maximise economic impact. The incorporation of these factors is crucial as an increased circular economy does not always lead to more sustainable outcomes; sustainable process assessment is essential to maximise the value of resources used to minimise environmental impact [73].

In order to create a plastic packaging zero-waste economy, it is important to integrate the perspectives of manufacturers, consumers, and policymakers to encourage behavioural change. Social marketing approaches can be used to promote behavioural change by including upstream (government and industry) and midstream actors (local organisations, public services, and personal networks) to co-create the conditions that facilitate change among consumers [74]. Behavioural scientists have a major role to play in integrating key stakeholders through focus groups, using a convenience sample, to understand current behaviours and attitudes, knowledge about PET/PP and HDPE/LDPE waste and the circular economy, their willingness to adopt proposed solutions and their perceived benefits for the environment, and the health and well-being of each stakeholder group. An increase in public awareness and the promotion of recycling programmes can bring about the necessary behavioural change. Findings from focus groups and academic knowledge on pro-environmental behavioural change can then be used to design nudge solutions and inform industry, government, and policymakers about these approaches to promote consumer adoption of solutions designed to improve recycling behaviour.

4. Conclusion

The recycling of plastic packaging is an ongoing challenge that can be solved by a reduction in the variety of plastic used for packaging and standardisation of the type of plastic used for a specific product type. Yogurt pots, for example, should not be manufactured from many types of plastic, but rather, should all be manufactured from the same plastic. The multitude of types of plastic packaging currently on the market should be replaced with only three types of materials: PET, PP and polyethylene (both HDPE and LDPE). By focusing plastic packaging waste into two streams (PET/PP as one and polyethylene as another), and using mechanical recycling, neat pellets of PET, PP, HDPE and LDPE could be produced for further use, reuse, and recycling.

While the development of compostable and biodegradable plastic packaging is important, until they replace petroleum-based packaging, their introduction requires clarity of end-of-life disposal to avoid contamination of otherwise recyclable plastic. Similarly, the introduction of bio-based plastic that can directly replace petroleum-based plastic, for example bio-PET, requires both environmental and economic consideration. A holistic approach with support from industries, stakeholders, and government can enable the sustainable recovery of plastic packaging waste and their diversion from landfill and less favourable recycling methods. Hence, by eliminating difficult-to-recycle plastic from the market, we can aim for a cleaner and greener planet through maximising the value of our resources and minimising the waste we create, leading to stronger economic, social, and environmental benefits.

Author statement

All authors contributed to conceptualisation, writing, reviewing, and editing. KN, JGJ, CH and MG carried out investigation and writing of the original draft.

Declaration of Competing Interest

Authors have no competing interests.

Data availability

No data was used for the research described in the article.

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