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ORIGINAL PAPER

An Innovative Approach to Closing the Loop in a Circular Plastic Economy by Upcycling Single-Use Post-consumer Thin Film Plastic Packaging Waste into Durable Plastic Products

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Abstract

The waste system requires a circular economy business solution to upcycle millions of tonnes of contaminated post-consumer single-use multi-material, multilayer, plastic packaging films/foils. This waste is rarely collected for recycling, firstly because the market for such waste is new and very small, and secondly due to technical issues and cross-contamination at waste recycling facilities. Conventionally, two linear disposal routs exist, energy recovery through incineration or landfill, both having an economic cost. Being very lightweight, plastics are blown around and end up contaminating terrestrial and marine environments. This paper evaluates intrusion extrusion moulding technology with agglomeration to make products. With a 50-year first lifespan and nine more life cycles, they can be used multiple times as a substitute for wood and concrete. Public bodies can catalyse the intrusion extrusion moulding manufacturing industry by including such products during their procurement processes. The technology works and the business can be profitable.

Keywords Thin film flexible plastic waste · Circular plastic economy · Public procurement · Single-use plastics · Intrusion extrusion moulding · Packaging plastics

Introduction

Many single-use plastics (SUP), like snack bags, contain laminated flexible plastic films (LFPFs), which include different metals and many layers of up to nine different polymers (Roosen et al. 2022). For example, bags from potato crisps have an aluminium layer, multiple layers of different plastic polymers, and are covered in printing, which makes it impossible to deconstruct/recycle back into its original polymers in an economically viable (Schmidt et al. 2022) or circular manner (Ahamed et al. 2021; Baxter et al. 2016; Van Velzen et al. 2020). Furthermore, this type of post-consumer waste is dirty and contaminated with food residues (Horodytska et al. 2018), which adds to the difficulty (Lase et al. 2022) and expense of recycling. However, clean, single-polymer, non-printed, post-industrial flexible film waste (Horodytska et al. 2018; Sadat-Shojai & Bakhshandeh 2011) can be recycled in a closed loop manner. Horodytska et al. (2018) identified a lack of research into understanding the behaviour of flexible films during the whole recycling process as a barrier to closing the circular economy loop. It is claimed that well-functioning plastic recycling processes are needed to move from a linear to a closed loop (Picuno et al. 2021). However, this paper will show in the "Intrusion and Extrusion Technology" section below, that with emerging technology even LFPFs can be upcycled into durable products.

Globally, 141 million tonnes (Mt) of all types of plastic packaging is produced annually, one-third of which leaks from the waste system and pollutes the environment (WRAP 2023). In 2021, only 13% of UK Local Authorities collected thin film plastic waste (RECOUP 2022a, p. 9), most of which was not recycled in a circular manner. In 2022, for European post-consumer plastic waste, 16 Mt went to energy recovery, 7.6 Mt ended up in landfill (Plastics Europe 2024, p. 75), and 10.8 Mt were recycled back into the market; these volumes show the enormity of the recycling problem. Until now, only rigid plastics (Ecoo 2022; Govaplast 2022; Hahn Plastics Ltd 2022), sometimes with a percentage of LFPFs (Ecoo 2022; futurePOST 2019a; Govaplast 2022),

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or clean single-polymer LFPFs (reworked.com 2023) have been recycled into new products. Therefore, there is a need to understand how to close the circular economy gap with respect to millions of tonnes of the lowest grade LFPFs waste (Hahladakis & Iacovidou 2019; Heller et al. 2020; Horodytska et al. 2018; Johansen et al. 2022).

The TRANSFORM-CE project (MMU 2024) identified this recycling problem and set out to carry out research into the whole lifecycle of these plastics and to develop long-term solutions for this waste. The project consortium came from across four countries and consisted of four universities, local municipalities, and industrial partners. It secured Interreg NWE funding of €4.12 million and had a total budget of €6.93 (Interreg-NWE 2023). The aim was to develop industrial processes that could make durable products, only using 100% multi-polymer and multi-material post-consumer and soiled LFPFs from SUPs. The waste was not to be pretreated using water or chemicals and could include up to 20% of contaminants, such as sand or organic materials. The products were to be as durable as products made from recycled rigid high-grade plastics, could be recycled many times, and each time could last for many decades. This testbed research project was novel as it was something that had not been demonstrated before at a scale of 150 tonnes a year. Research was carried out for each stage of the lifecycle of plastic shown in Fig. 1.

How Are Thin Film Plastics Delt With?

In most collection systems around the world, LFPFs are not collected for recycling but are placed in the residual waste (black or grey) bins. If they do enter the municipal waste recycling system, at the first sorting stage, they are rejected into the residual waste steam (Farrukh et al. 2022; Horodytska et al. 2018). If they do get into the system, they can get in between the rotating paddles of a rotating disk sorting machine and clog up the machine (Kindle 2019; RECOUP 2020, p. 24), can be a contaminant to single-polymer waste streams (Astrup et al. 2009; Hahladakis & Iacovidou 2019; Lazarevic et al. 2010; Rigamonti et al. 2014), and can soil paper and cardboard (Kindle 2019) on contact. Therefore, flexible plastics are challenging due to technological problems and excessive costs associated with treating them using mechanical recycling (Arena & Ardolino 2022).

After collection, they have two disposal routes: the first is end-of-life destruction via burning, either to generate electricity in an energy from waste (EfW) facility or to generate heat in a district heating system. Alternatively, they can be incorporated into refuse-derived fuels used in kilns or blast furnaces (Horodytska et al. 2018; Lazarevic et al. 2010; Sevigné-Itoiz et al. 2015). The second end-of-life route is to put them directly into landfill (Ferdous et al. 2021). When landfilled, plastics can escape via flooding, surface run-off,

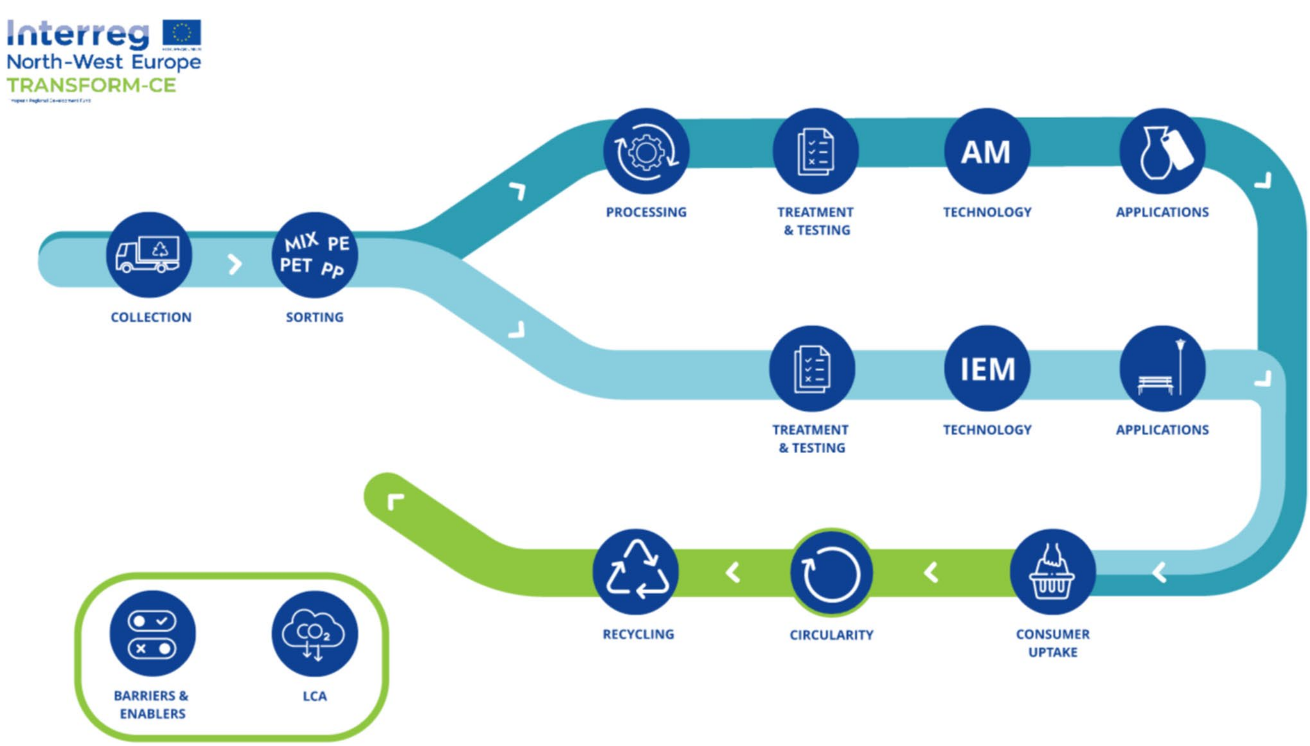

Fig. 1 Research roadmap diagram (TRANSFORM-CE 2024) comprising all the components of the TRANSFORM-CE project

and manual and animal scavenging (O'Kelly et al. 2021). Being very lightweight, they are blown around and end up contaminating, terrestrial and marine environments (Colton Jr, 1974; Fadeeva & Van Berkel 2021; O'Kelly et al. 2021; Rios et al. 2007; Van Velzen et al. 2020), get into the food chain (Mattsson et al. 2017; Seltenrich 2015; Waring et al. 2018), and kill marine life (Gall & Thompson 2015).

These end-of-life options represent the linear economy model. Horodytska et al. (2018) actually consider incineration as downcycling and contrary to the circular economy objective of keeping resources in a closed loop system (Ellen MacArthur Foundation 2023a). Therefore, scholars, (Ahamed et al. 2021; Fadeeva & Van Berkel 2021; Farrukh et al. 2022, p. 12; Horodytska et al. 2018) consider landfilling and burning as unsustainable options. There is a need to save this plastic for future generations and valorise it so that reuse and remanufacture within a circular economy (CE) model can be commercially viable. However, currently, there are no widespread options to bring contaminated post-consumer single-use LFPFs into a circular economy recycling system.

Around the world, the Ellen MacArthur Foundation, working with many organisations, has implemented Plastic Pacts (Ellen Macarthur Foundation 2023b). The European Union (EU) has a circular plastic economy agenda with ambitious targets (EU Commission 2015; European Parliament 2019), and all agree that as long as plastic is being used, it should all be collected and recycled in a circular way. Unfortunately, Hsu et al. (2021) found that "the vast majority of plastic waste still ends up in landfill or incineration"; this is not just for contaminated flexible films but also for rigid plastics that are technically recyclable. Furthermore, Hahladakis and Iacovidou (2019) found that we are far from implementing recycling targets, even when it is imperative to increase recycling rates for post-consumer flexibles (Lase et al. 2022).

Johansen et al. (2022) maintained that the implementation of a closed loop CE for plastics could help reduce landfill, incineration, and downcycling and allow plastic waste to be recycled back into the same or equivalent new products. Similarly, Mølgaard (1995) concluded "recycling of plastic is only environmentally and resource sound if it is separated into its generic plastic types, which makes it possible to produce a recycled plastic with properties comparable to virgin plastic". However, this cannot be carried out economically; thus, Horodytska et al. (2018) stated that unlike the recycling of single-polymer materials, so far there are no strategies for processing multilayer films in closed primary loops. Therefore, how are LFPFs going to be recycled in a circular economy way, when they cannot be made "back into the same or equivalent new products"? To create this shift towards a CE for plastics, there is a need to address the challenges of recycling LFPFs (Heller et al. 2020); this is what the TRANSFORM-CE project set out to do. This paper seeks to answer the question, can contaminated single-use LFPFs that contain aluminium be decontaminated and reused to make different products in an economically viable and circular manner? (See "Intrusion and Extrusion Technology" section below.) Furthermore, if yes, are there sufficient volumes of plastics to feed a new CE plastics market?

Volumes of Unrecycled Plastics

Geyer et al. (2017) estimated that since the 1950s, 8300 Mt of plastics has been produced, and if production and waste management trends do not change, about 12,000 Mt will be in the natural environment or in landfills by 2050. This means that most plastics still exist in our natural environments or in landfills (Scharff 2014). By 2020, only 12% of plastic waste was incinerated, and just 9% was recycled (Camilleri 2020).

The global production of all plastics rose from 180 Mt in the year 2000 to 400 Mt in 2022, with Europe producing 15% or 58.7 Mt of new plastic (Plastics Europe 2023). In the past, EU recycling volumes were low compared to the volumes circulating in the economy. Of collected plastic only 25% were recycled, 50% of which ended up in landfill (EU Commission 2015, p. 14). By 2016, only 11% of the plastics were reprocessed into secondary plastics. A total of 8.608 Mt went to energy recovery, 6.889 Mt to incineration, and around 6.837 Mt into landfill (Hsu et al. 2021). This equates to 22.3 Mt of plastic, that, in a circular economy, could potentially be available for upcycling into new products. Buchhorn (2022) identified 6 Mt of plastic packaging that was not recycled, just for the four countries within the TRANSFORM-CE project. In 2022, for only post-consumer plastic waste within Europe, 16 Mt went to energy recovery, 7.6 Mt ended up in landfill (Plastics Europe 2024, p. 75), and 10.8 Mt was recycled back into the market. The data shows the continuity and scale of the recycling problem.

Globally, 141 Mt of plastic packaging is produced annually, of which one-third leaks from the waste system and pollutes the environment (WRAP 2023). Worldwide growth in the packaging market is predicted to increase in monetary value between 2021 and 2027 by 45% (Statista 2023b). Presuming a monetary and volume linear correlation, this paper estimates that plastic packaging volume by 2033 will be 296 Mt, doubling this waste problem.

Approximately half the 53.9 Mt of plastic that came on the EU market in 2020 was collected. If all the amount that was landfilled and incinerated was redirected into a circular economy, 19.3 Mt would have been available for reuse (Plastics Europe 2022, 2024, p. 45). Only a small portion of this were plastic films, which in the UK was only 395 kt (RECOUP 2020, p. 9). Unfortunately, the vast majority of waste plastic in the UK including flexible plastic packaging either ends up in landfill or is burnt to make energy (SUEZ 2021, p. 9).

The challenge for recycling plastic back into a circular economy is quality, with approximately 14% of global packaging plastics being recycled (Hahladakis & Iacovidou 2018). The problems caused by plastic packaging have been known for a long time (Dey et al. 2021); however, tackling the problem has only led to limited success (RECOUP 2019). New laws have been introduced to regulate the manufacture, import, and use of plastic packaging. (The EU directive 94/62/EC on packaging and packaging waste (EU Commission 1994) extended producer responsibility scheme in the UK (UKGOV 2023).) Yet the amount of thin film plastic coming onto the market increases each year. In developed countries, plastic films account for 40–50% of plastic waste (Hahladakis & Iacovidou 2019).

In the UK, only 4% of plastic films were collected for recycling, most of which were sent for energy recovery (RECOUP 2019, p. 7) and not into the circular economy. By April 2021, only 13% of UK Local Authorities collected thin film plastic waste (RECOUP 2022a, p. 9), down from the high estimate of 17% (SUEZ 2021, p. 9). In real terms, the collection of plastic films has reduced from 80 UK local authorities in 2015 (RECOUP 2016) to 44 in 2021 (RECOUP 2022b), a compound annual reduction of circa 8%. This trend is due to their low bulk density causing technical issues during the conventional recycling processes, i.e. clogging up the machines (Kindle 2019; RECOUP 2020, p. 24), making them uneconomic for sorting and mechanical reprocessing (Horodytska et al. 2018; Lase et al. 2022; Soto et al. 2018). Furthermore, there is a lack of an offtake market in the UK for the recyclant. Similarly, in Australia, when a company called REDcycle went bankrupt, one reason given was "insufficient recycling capabilities in Australia" (The Guardian 2023). Approximately 3–4% of the packaging products used in Europe are LFPFs (Van Velzen et al. 2020). Increasing the recycling rates for post-consumer LFPFs is now imperative.

This paper will show that there is a solution for flexible plastics. It will discuss a CE solution for what currently constitutes a significant percentage of unrecycled plastics. Based on the work carried out within the TRANSFORM-CE project, LFPFs can be upcycled into durable products (Interreg-NWE 2024), thus helping waste management companies to increase their recycling rates.

The next section explains the research methodologies. In the "The Problems Associated with LFPF Waste" section, the complexity of the problem that LFPFs cause to a circular economy and the merits of recycling as opposed to landfilling or incineration are discussed. The "Intrusion and Extrusion Technology" section examines intrusion extrusion moulding (IEM) technology together with agglomeration, as a solution for the LFPF waste problem, by drawing on a use-case of the TRANSFORM-CE project. Results from some of the thermomechanical testing carried out on the final products are given in the "Intrusion and Extrusion Technology" section. The "Policy Recommendations" section identifies some policy decisions and a five-stage pathway that can catalyse the IEM industry and help increase recycling. Further work and conclusions are covered in the "Further Work" and "Conclusion" sections.

Methodology

This paper follows on from the deliverables this author (Kinn 2023b) compiled for the TRANSFORM-CE project. Academic, industry, and municipality teams from across four countries were part of the project, with each being responsible for different work packages. The overall project looked at the whole lifecycle of plastics from the disposal by consumers to the production of new products. A research roadmap diagram depicting the different stages and components of this project is given in Fig. 1 (TRANSFORM-CE 2024).

The project shed light on the intricacies of the LFPF waste problem, provided a context-rich understanding of the problem, and showed how emerging IEM technology might be used to help close the loop for this problematic waste stream.

In waste management systems, plastic waste is a cost centre as there is a "gate" cost to the company for every tonne sent for landfilling or incineration. Therefore, it was in the interest of the waste management company to sort and give the plastic to the TRANSFORM-CE project as this saved them between €100 and €150 per tonne. LFPFs can clog up the mechanical sorting machines; therefore, they are always put in the black mixed waste bin. If they do end up in the recyclant, they are manually removed before entering the sorting machinery. The LFPFs came from a special collection that was manually sorted. Thus, a negative-value waste stream becomes a positive-value product through a circular plastic economy.

The Institute of Life Sciences and Chemistry (ILC) of Hogeschool Utrecht (HU) (Baesjou 2023) carried out tests to ascertain the chemical, thermal, and mechanical properties and safety of washed and unwashed LFPF and clean single-polymer plastic carrier bags. They carried out five tests for 10 iterations on Save Plastics IEM products. The mechanical and chemical properties were tested using the following methods: (1) differential scanning calorimetry (DSC), a measure of the heat flows to and from a sample; (2) thermogravimetric analysis (TGA), to identify material losses during a heating cycle; (3) tensile strength test, to measure elasticity and mechanical failure points; (4) Shore A and D tests, for hardness of the plastic; and (5) headspace gas chromatograph (GC) followed with mass spectrometry (MS) analysis and headspace solid phase micro-extraction (SPME), to test for volatile organic compounds (see the "Results of Tests on the Save Plastics Products" section, for the results).

For the research outputs that this paper is based on, informal interviews with some of the partners and affiliates of the project (Interreg-NWE 2021) were conducted. The director and production manager at the Green Plastic Factory (Save Plastics 2024) were interviewed and provided extensive information via email correspondence about the technology and manufacturing processes. A further seven interviews were conducted with four of the project partners who provided information about plastic recycling and the circular economy. Desktop research was conducted using-peer reviewed literature, promotional videos, and write-ups on company websites. The snowballing method was employed during the literature review. Site visits to plastic recycling facilities and production plants were conducted. While this author was able to gather information at these site visits, the author is constrained about what can be put in this paper about the technology or feedstock due to commercial sensitivity. Therefore, only the technology used at the Green Plastic plot plant is discussed.

The Problems Associated with LFPF Waste

Introduction

There are many types of plastic used in packaging, and many scholars and the statistics cited in this paper do not distinguish between these different types. Furthermore, volume data is not broken down between rigid or flexible, or levels of contamination. This leads scholars to use a generalised nomenclature of "single use", "packaging", "non-packaging", "rigid", and "flexible". Therefore, this author has classified waste plastics according to their recyclability, see Table 1. The grades go down in descending order from 1 to 7. This grading system helps the reader to understand grades within the context of this paper and is not intended as an industry standard grading system. It does however show the complexity of waste plastics. The recyclability of any plastic will not only depend on the grade of the waste but also on the availability of a collection and sorting system, as well as the industrial plant to handle the recycling process. The term recycling is used in the context of a circular economy, where the waste plastic is reused to replace its original usage or made into another product. Incineration and landfill are not classified as recycling (see the "Landfill and Incineration" section below) but as end-of-life usage within a linear economic model.

Post-industrial single-polymer plastics, when kept clean, can be easily recycled. Grade 2 plastics are used for bottle-to-bottle recycling, with grade 3 being sorted and used for non-food products. This paper focuses on identifying an industrial process that upcycles all non-recycled plastics, especially grades 6 and 7, but can also include all other grades.

Are There Solutions to Close the Gap in the Circular Economy for LFPF?

Contamination, dirtiness of the LFPF waste, and a lack of mechanical recycling technologies result in recycling plants rejecting them in the waste stream (Hahladakis & Iacovidou 2018). Hence, while the benefit of laminate plastics in the supply chain is acknowledged, it is accepted that these packages are unfortunately still not recyclable (Van Velzen et al. 2020) back into new flexible film products. Iacovidou and Gerassimidou (2018) stated that, "Similarly, multilayer plastic components are difficult to recycle due to the lack of economically viable systems for segregating the various materials they are made of", something that this author sees as an unrealistic expectation. Therefore, Horodytska et al. (2018) concluded based on other scholars (Lazarevic et al. 2010; Sevigné-Itoiz et al. 2015; Shonfield 2008) that the non-recyclable fraction should be sent to energy recovery to produce electricity and district heating or used as refuse-derived fuels in kilns or blast furnaces. But should flexible

Table 1 Seven grades of plastic, from highest to lowest (this author)

Grade	Source	Polymer type	Type	Level of contamination	Recycled
1	Post-industrial	Single	Any	Clean	Yes
2	Post-consumer	Single	Rigid	Low contamination	Yes
3	Post-consumer	Mixed	Rigid	Low to medium contamination	Yes
4	Post-consumer	Single	Flexible films	Low to high contamination	Very rarely
5	Post-consumer	Mixed	Flexible films	Low to high contamination	Very rarely
6	Post-consumer	Laminated multi-polymer	Flexible films	High contamination	Extremely rare
7	Post-consumer	Laminated multi-polymer with metal and printing inks	Flexible films	High contamination	Extremely rare

films be abandoned from the recycling system? Ferdous et al. (2021, Table 3) showed that most of the scholars in their Table 3 indicated that recycling plastic waste was the best option. "Recycling has the lowest Global Warming Potential and Total Energy Use compared to the alternative options such as landfill and incineration" (Ferdous et al. 2021). Furthermore, Ferdous et al. (2021, Sect. 4.1) quoting the US Environmental Protection Agency stated that it is estimated that for every 10,000 tonnes of waste recycled, 9.2 jobs will be created, compared to only 2.8 jobs if disposed of in landfill. So why are LFPFs not recycled?

Much of the focus in academia is on recycling non-LFPFs. Schwarz et al. (2021) examined the environmental impact of 10 recycling technologies, none of which involved the upcycling of LFPFs into new products. The EU policy position is that increasing plastic recycling is essential for the transition to a circular economy. In its revised legislative proposals on waste, a more ambitious target for the recycling of plastic used in packaging was set to 55% by 2030 (European Commission 2018). Possible solutions identified in the European Strategy on Plastic Waste in the Environment (EU Commission 2013) are tax policy and landfill regulatory changes. However, there seems to be no plan or solution to close the CE loop for the LFPFs, other than landfill or burning. A lack of reliable data is given as a limiting factor to the introduction of policy and business measures that would increase plastic circularity (Hsu et al. 2021).

Hsu et al. (2021) stated that "the EU still has a long way to go to achieve a more circular plastics system". Based on their findings, they proposed six strategies for circular pathways for plastics; however, none includes the circularity of LFPFs. The focus is on increasing the volumes of recycling higher-grade plastics that are rigid or semi-rigid and banning or reducing the usage of different types of thin films.

Barriers to Circular Economy for LFPF

Major barriers to the circularity of plastics include relatively inexpensive new feedstock, incompatibility of the mechanical properties of plastic polymers with each other, lack of infrastructure for recovery sorting and processing, lack of reliable offtake markets, and low per tonne landfill gate fees (Ahamed et al. 2021, p. 5; Heller et al. 2020) (in the USA, it is $53.04 USD (Statista 2023a), in the UK, approximately £100, and in the Netherlands, approximately €150). A problem arises when they are collected in the mixed recycling waste and not separately; this adds to cross-contamination within this waste stream. Even when collected separately, for example in the Netherlands, their DKR 310 (Nedvang 2009a) contains misthrow with aluminium, rigid plastics, metals, and organic contaminants. The wrong mix of plastics can reduce the mechanical properties of a recycled product (Van Velzen et al. 2020). Therefore, there is a perceived uncertainty by industry (Ferdous et al. 2021) and consumers (Polyportis et al. 2022) as to their quality, so they are reluctant to buy them. Manufacturers cannot guarantee the quality of the recyclant they receive, and worry pellets from recycled plastic may create inferior products, so they use virgin plastics.

Operators within the waste management system are often controlled by different organisations with differing interests, adding complexity to closing the CE plastics loop (Hahladakis & Iacovidou 2019). This was apparent during the TRANSFORM-CE project, when municipal contract problems led to the cancelling of an offtake plant for waste plastics. Similarly, the Green Plastic Factory (Save Plastics 2024) lost its supplier when it lost its bid for the municipal waste contract, and Replas (2023) lost its supplier when REDcycle a specialist soft plastics recycling programme went bankrupt. One reason given by REDcycle was "insufficient recycling capabilities in Australia" (The Guardian 2023). Even though a limited new scheme for flexibles has begun (Conversation 2024), "a combined effort in improving the communication and coordination between all stakeholders and resolving the challenges related to closing the plastics loop, is urgently needed" (Hahladakis & Iacovidou 2019).

Contamination creates barriers to circularity, for example odours, but if imperceptible may not affect user interaction (Baxter et al. 2017). Therefore, there is a need for sorting, cleaning, and drying processes to remove residues (Pietrelli et al. 2017). In the absence of EU-wide standards, it can be difficult to ascertain impurity levels or suitability for high-grade recycling (EU Commission 2015). There are currently hardly any methods, except expensive tests, to ascertain the quality and composition of recyclates. This makes them expensive for manufacturers and recyclers, depending on who bears the costs (Schmidt et al. 2022). These are problems only when seeking to manufacture new thin films from LFPFs.

From an environmental point of view, recycling is always the best option. However, currently, from an economic perspective, this may not be so, as it depends on the oil price. It may be cheaper to make products from new plastics than to use recyclant when the price of oil is low (Ferdous et al. 2021). This explains why landfill was historically the cheapest option.

Landfill and Incineration

There is a debate if waste plastics should be recycled into new products, burnt, or disposed of in landfill (Cestari 2020; Roussinos 2020). Opinions differ, depending on health, economic, and environmental issues (Ferdous et al. 2021). Ferdous et al. showed from the academic literature that if plastic waste cannot be recycled, with respect to energy usage and global warming potential, it is better to landfill than burn the plastic. While Wollny et al. (2001) state the opposite, that the best process is “feedstock recycling”, which is the linear economy use of the plastic in iron smelting or the chemical depolymerisation of the plastics for the chemical industry.

Landfilling poses environmental risks, such as soil pollution, greenhouse gas emissions, and leakage of microplastics into the oceans which ultimately impacts human health; hence, it is regarded by academics as the least environmentally friendly waste management technique (Ahamed et al. 2021; Farrukh et al. 2022, p. 12; Ferdous et al. 2021; Horodytska et al. 2018). Landfill sites that are poorly maintained will lose a lot of the flexible packaging films, during downpours and storms, to rivers and seas (Van Velzen et al. 2020), causing marine pollution (Fadeeva & Van Berkel 2021). Nevertheless, by 2015, of the 6300 Mt of plastic waste generated, 79% is in landfills or the natural environment. If production and waste management strategies do not change, by 2050, approximately 12,000 Mt of plastic waste will be in landfills or in the natural environment (Geyer et al. 2017). Ferdous et al. (2021, Table 1) showed that currently, 55% of global plastics still end up in landfill.

Since 2015, some EU countries have banned the direct use of landfill for waste (Scharff 2014). All residual waste, from black/grey bins, must be sorted as much as possible for recycling and the rest is sent for incineration. Only post-incineration inert residues can be landfilled. Therefore, the only current way they deal with LFPFs is to burn them to generate energy or as a fuel. Incineration can reduce the volume of waste by 90–99%, which is a big advantage when landfilling, for example in Japan (Farrukh et al. 2022) where space is scarce (Horodytska et al. 2018). However, the main downside is the relatively high emission of carbon dioxide gases associated with incineration (Gradus et al. 2017). Furthermore, this is a waste of the plastic resource, as once burned, it is gone. Ferdous et al. (2021) stated that “Landfill disposal of waste should be considered as the last option for waste management and should be done only for nonrecyclable waste”; therefore, it is imperative that options are available to recycle LFPFs.

Are LFPFs only ending up in landfills or incineration due to waste management techniques and the lack of mechanical recycling (Hahladakis & Iacovidou 2018)? If yes, is there a niche technology that can upcycle even very low-grade plastics if they can be captured in the recycling system? What emerged from the TRANSFORM-CE project was that IEM technology with agglomeration could be a solution.

Intrusion and Extrusion Technology

Introducing the IEM with Agglomeration Process

Intrusion and extrusion moulding (IEM) is the process of heating up any type of plastic and directly or indirectly forcing it into a mould, either the hot soft plastic is directly injected into a mould attached to the extruder and after cooling removed or it is collected from the extruder as a malleable clay, weighed, and put into an open mould where a hydraulic press shapes the product. The traditional method in the IEM industry is to use a feedstock that is 100% mixed plastic waste, much of which is rigid plastic, of specific polymers, and of medium to high-grade quality. For example, a commercial company like Hahn Plastics Ltd (2022) makes products from bottle lids, which are either LDPE or HDPE.

The IEM production method can be large scale, like that of Hahn (Hahn Plastics Ltd 2022), Ecoo (2022), and Govaplast (2022), which manufacture at scale, using large amounts of waste plastic. Hahn made 60 kt of products in a single year and has a 2000 product catalogue. IEM is also carried out at a small-scale, where much of the process relies on manual labour (conceptos plasticos 2023; futurePOST 2019a; Gjenge Makers Ltd 2023; Save Plastics 2024; therecyclestudio 2023), is artisanal, and operates on the CE principle of localism (Tavri 2021).

Some of the products made include garden products, benches, fencing, footpaths, bridges, railway sleepers, and jetties; they are resistant to microorganisms growing on them, termites eating them, and moisture rotting them (Bajracharya et al. 2014). They require very little maintenance and can easily be cleaned with soapy water (Hahn Plastics Ltd 2022). Waste plastic is also used in the construction industry as an insulation material (Megri et al. 1998). Many of these products are not 100% recycled plastic; they include steel where compression strength is required within infrastructure projects, and they may be reinforced with organic fibres or fibreglass.

Most if not all the IEM manufacturers use a specific polymer mix which is mostly from 100% rigid plastics. Some of those do use flexibles but only as a small percentage mixed with the rigid. Also, the flexibles must be dry and free of contaminants, hence the use of post-industrial waste and not post-consumer waste. However, when not using IEM technology, the like-for-like recycling of post-industrial single polymers is hindered by the amount of printing on the waste. The inks on the plastics reduce the quality of recycled pellets, because the high temperature during extrusion makes them volatile, which increases the chance for defects such as bubbles occurring (Horodytska et al. 2020).

The smaller artisan companies (conceptos plasticos 2023; Gjenge Makers Ltd 2023; Replas 2023; SaveBoard 2023) do use higher percentages of flexible that are not so clean, with some only using single-polymer type while others use mixed polymers. These companies do not divulge their recipes. The only way to know if they use flexibles is through promotional videos and, in many cases, only through visuals in the videos and not the narrative provided. Therefore, this research was not able to identify if any of these companies use 100% flexibles from packaging in any of their products; however, Reworked (reworked.com 2023) do make recycled pellets from 100% polypropylene from face masks. Other uses for plastics include using bottle recyclate to reinforce soil (Babu & Chouksey 2011) and tetra packs in plasterboard replacement products (SaveBoard 2023).

The TRANSFORM-CE project, an Interreg NWE project, aimed to answer the following question: Can IEM technology be used to make products from 100% recycled LFPFs that are moist and contaminated with aluminium? If yes, then the waste management companies have an offtake market. The Green Plastic Factory (Save Plastics 2024) was a 150 tonne/year pilot plant set up to experiment with DKR 310 (Nedvang 2009a) and DKR 350 (Nedvang 2009b) Dutch recyclant to test this hypothesis.

Use-Case: The TRANSFORM-CE Project

The TRANSFORM-CE project was a proof of concept project. Its feedstock came from a special collection of LFPFs, and using agglomeration together with a bespoke IEM pilot plant, end-user products were produced. The circular plastic economy model is presented in Fig. 2. The optional washing step was not actually employed at the pilot plant and is only intended for a commercial full scale plant which may also include a magnetic separator and a windsifter.

Aims and Objectives

The TRANSFORM-CE project focused on transforming the lowest grades of post-consumer municipal waste plastics from a linear economic model into a circular economy model. The novelty of this project was to develop a pilot plant to make products from 100% multi-polymer and multi-material waste. The waste was not to be pretreated and could include up to 20% of contaminants, such as sand or organic materials. The products were to be as durable as products made from recycled rigid high-grade plastics, could be recycled many times, and each time would last for many decades. The goal was to maximise the economic value and long-term usage of what are currently short-lived single-use plastics. Both IEM technologies, direct intrusion into the moulds and manual loading of a hydraulic press, were used.

Collecting the Plastic

For this business model to be successful, there must be a long-term sustainable supply chain (Metta & Badurdeen 2012) for plastic waste and demand from the market for the products. The volumes of feedstock available for future IEM plants have been documented in a TRANSFORM-CE report (Kinn 2022). Although Save Plastics has concentrated on LFPFs that until now have not been recycled, their IEM technology can extrude polyethylene terephthalate, polypropylene, high-density polyethylene, and low-density polyethylene recyclant. The films for the pilot plant came from a special collection of 12,000 homes in Almere the Netherlands. The grades used were DKR 310 and DKR 350 and included up to 20% contaminants, such as metals, wood, and organics. As part of the experimentation, products were made from batches of LFPFs that either contained aluminium coating (SUEZ 2021, p. 7) or did not.

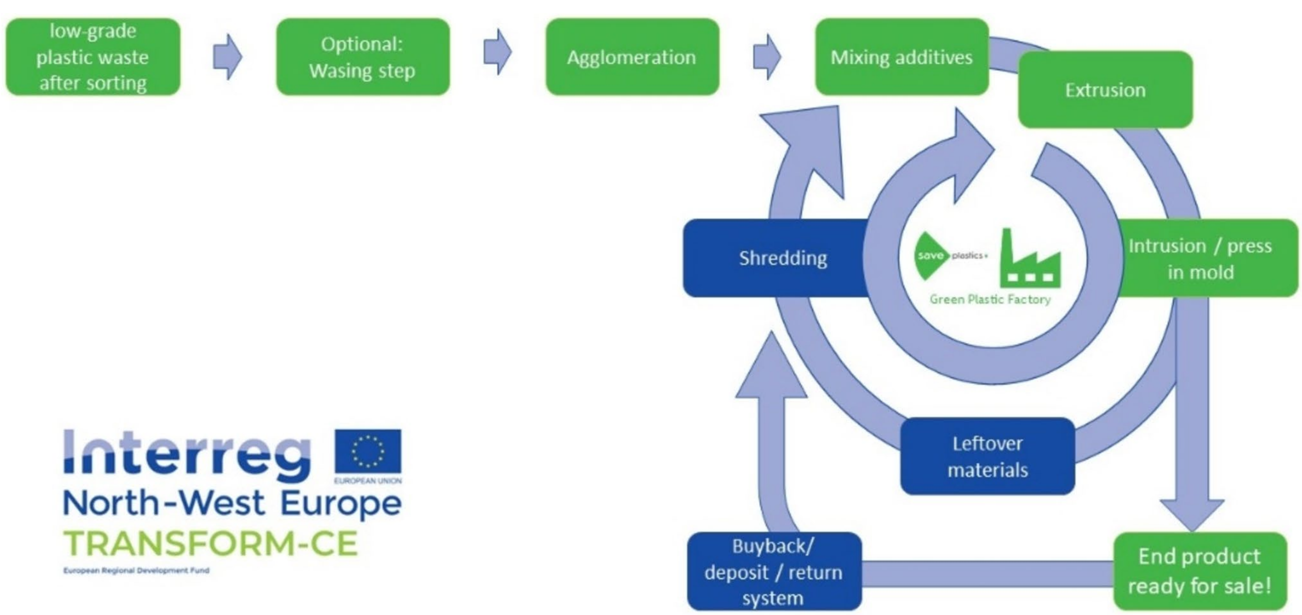

Fig. 2 The circular economy model for the Save Plastics *Green Plastic Factory* pilot project

The Manufacturing Process

Commercial companies like Hahn do not divulge the processes they use to make their products including the recipe of their plastic mix and the temperatures within their process, as they have been developed by them and are commercially sensitive. The processes developed by Save Plastics also had some elements of commercial sensitivity. As they were only using LFPFs, one process that they employed that was different from Hahn (who use ridged plastics) was the used of an agglomerator, which uses spinning and fixed blades to shred the plastic. In doing so, heat is generated, and small pieces begin to stick together forming clumps. Before all the plastic sticks together, water is poured on to it to cool it down so that only small clumps are formed. In the heat, the water evaporates. Clumps are needed, as the thin films are too light and flexible to be gravity-feed into the extruder at an operational consistent volume. The agglomeration process is key to using very small and light feedstock. To successfully manufacture durable products, it requires the speed, feed rate, time in the agglomerator, and amount of quenching water to be standardised. These processes were developed by trial and error and are the ones that are commercially sensitive. Therefore, the manufacturing process used was different from commercial processes, as it used agglomeration with 100% flexible plastics and no clean ridged plastics.

Results

Products made from ridged plastics of similar polymer using IEM technology have a guaranteed life of between 20 and 100 years (Hahn Plastics Ltd 2022; Save Plastics 2024) for each use cycle. It is not known how many times their products can be ground up and used again in a circular economy. The products made by Save Plastics using 100% LFPFs are guaranteed for 20 to 25 years. Under laboratory conditions, the TRANSFORM-CE project demonstrated that the products made from LFPFs can be melted down and reused between 8 and 10 times before the polymer chains begin to get so short that the integrity of the product is compromised. This implies that very low-grade plastic can be locked up into durable products for up to a few centuries. Chemical depolymerisation processes (Zhang et al. 2021) could then be used to bring the plastic back to its constituent polymers, so that new virgin plastic pellets can be made and the whole lifecycle begins again. Cortec (2023), a clothes hanger manufacturer in Germany, grinds up, remelts, pelletises, and remoulds their plastic hangers up to 12 times. Ferdous et al. (2021) concurred that plastic can be recycled 7–9 times; therefore, it is not understood why earlier they stated that “plastics can be recycled only once or twice without significant loss (of) the purity”.

During the research phase of the IEM plant, it was found that using damp feedstock containing up to 20% contaminants of less than 5 mm in size, the products did not suffer performance degradation. This meant that time and resources for sorting, cleaning, and drying the feedstock were minimised to just removing pieces of contaminants over 5 mm, which was a precaution to not damage the cutting blades, rather than as a requirement of the agglomeration process. While not used in the pilot plant, a wind sifter machine (P.E.Co 2023) was identified to be used in a large-scale commercial plant to separate films from heaver contaminants. Aluminium in the LFPFs dulled the agglomerator blades, increasing downtime, as they had to be swapped out and sharpened more often. However, the amount of aluminium has been identified as “too minute to be of consequence” to the product integrity and could even have added some tensile strength. However, this needs further investigation.

The feedstock for the pilot plant came from a special collection from 12,000 residents of Almere in the Netherlands. It was estimated that Almere could only provide 1000 tonnes per annum. In keeping with the CE ethos of localism (Dybdahl 2019) (Skene 2022) to achieve the lowest carbon footprint, a plant capacity of 2000 tonne/year was chosen; this equates to supply from a city of around 400,000 residents. However, in larger cities, like capital cities, as long as the CE principle of localism is maintained, larger size plants can be envisaged. See Kinn (2023a, Appendix 1) for a list of cities.

Environmental Safety Assessment

Many of the products are made to be constantly submerged in water or in earth, something that could lead to possible environmental contamination. However, Hahn and Save Plastics have carried out projects for municipalities which have passed environmental safety assessments and material testing (DEKRA 2017) that show that they are safe to be used in water and earth. Similarly, the products of another commercial manufacturer FuturePOST (futurePOST 2019a) have passed environmental safety assessments (futurePOST 2019b).

Life Cycle Analysis

Using the IEM production to upcycle LFPFs is not only beneficial for the environment but also offers economic solutions to replace traditional natural materials such as timber (Ferdous et al. 2021; futurePOST 2019a), concrete (Hahn Plastics Ltd 2022), or plaster as a 30% substitute, within a composite plasterboard replacement (SaveBoard 2023) product. High-quality wood (Oak) for construction is now becoming less available (Bajracharya et al. 2014), and softer wood, which lasts 8 to 15 years depending on the chemical treatment, is being used. Therefore, plastic which can last up to 50 years replaces up to six amounts of soft wood. Furthermore, it is estimated that remanufacturing plastic saves between 30 and 80% of the carbon emissions generated by the original processing and manufacturing processes (Voulvoulis et al. 2020).

Therefore, every tonne saved from incineration is a tonne saved for future generations and a tonne that will not become part of a possible future ecological problem within a landfill site (Canopoli et al. 2018; Cappucci et al. 2020) or in the oceans (Eriksen et al. 2014). In addition, each tonne reused saves 16.3 barrels of oil, 5774 kWh of energy used to make virgin plastic, and 22.9 m^3 of landfill space (Ferdous et al. 2021).

A TRANSFORM-CE partner, Materia Nova (2024), carried out a full life cycle analysis (LCA) on a cladding panel manufactured by Save Plastics. Their results are shown in Fig. 3 (TRANSFORM-CE 2023).

This LCA is only for the first iteration of the panel. These savings must be added up each time the product is ground up and reused. If it is reused another nine times, it would have saved ten lots of alternative materials and their carbon footprint. This is similar to the Badurdeen et al. (2018) example of a toner cartridge, in which they showed that a multi-lifecycle based approach (i.e. reuse, remanufacturing, and recycling) could provide over 20% savings in total lifecycle cost and global warming potential.

Results of Tests on the Save Plastics Products

The effects of thermomechanical recycling on the products manufactured by Save Plastics were carried out by a group at the Institute of Life Sciences and Chemistry, Hogeschool, Utrecht (Baesjou 2023). The results and comments below are all quotes from their report.

(1) Differential scanning calorimetry (DSC): the melting point of each type of plastic was in the expected range

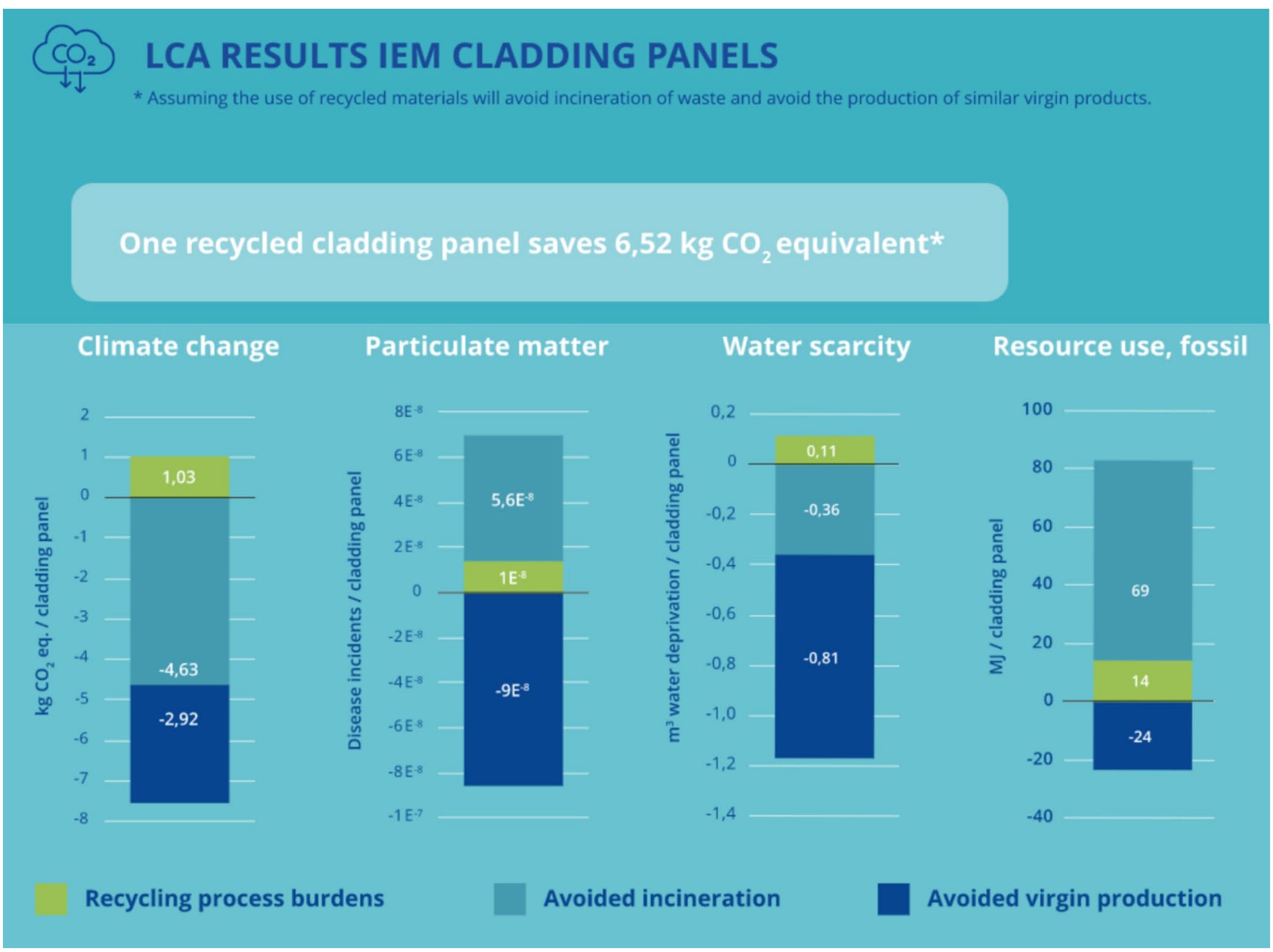

Fig. 3 The results of the LCA on a cladding panel (TRANSFORM-CE 2023)

and was not influenced by pre-treatment, i.e. washing or any additives (e.g. dyes) nor by the number of recycling iterations, compared to single-polymer clean bags.

(2) Thermogravimetric analysis (TGA): the average decomposition temperatures were between 488 and 492 °C for all the different samples. “The non-washed samples tend to have slightly lower decomposition temperatures, but this may be due to the presence of impurities that evaporate/decompose slightly below the decomposition temperature of PE, thereby giving an apparent slightly lower overall decomposition temperature”. The residual weight at 600 °C under N_2 varied “there was no clear effect of the number of recycling steps on the amount of residue. There is some minor variation, but no clear correlation. One reason may be the uncertainly of the measurements since only small amounts of material are used for TGA, and even smaller amounts of residue are left over”. Also “some of the unwashed samples appear to contain less impurities than one of the washed samples (SGM)”. As was expected, single-polymer virgin materials (LDPE, HPDE, and PP) gave residue values of between 0 and 3wt%, a value below the mixed LFPFs which had a range between 3.6 and 23.3 wt% for different samples. These variations “may be an indication of the batch-to-batch variations in the Save Plastics factory, as one batch of raw materials from the plastic dump is unlikely to be exactly the same as the next batch”.

(3) Tensile strength test: “The Youngs moduli of all measured samples fall between 150 and 450 MPa which is lower than the typical young modulus of HDPE and PP but higher than the one of LDPE, these values are indicative of a homogeneous blend of the three polymers, as is also visible in the DSC measurements. In most cases, a downward trend is observed with the number of recycling steps”. There was some degradation observed from cycles 7 and 8, but this impact will depend on the end use of the product. The single-polymer samples showed virtually no change in elasticity, meaning no degradation.

Washed samples exhibited (initially) higher maximum stresses than the non-washed samples; this may be due to the presence of wood, metal, or sand impurities, as confirmed by visual inspection. These impurities can decrease the apparent material strength as they form weak spots where tearing and fracturing can occur more easily. However, after multiple recycling steps, the differences between washed and non-washed become smaller. This may be due to the particulate impurities getting removed or ground down to a smaller size upon the repeated recycling procedure.

(4) Shore A and D tests: Each measurement was performed five times. For the Shore A test, the overall hardness averages for all samples were between 72.8 and 92.0, and the Shore A test was between 19.8 to 63 for all samples with each individual sample only changed by less than 4. It was shown that there is no clear effect of the number of recycling steps on the hardness of the samples. Also, there does not seem to be a significant difference between which samples were used. Washing does appear to have a (minor) effect, which is presumed due to the removal of sand, as the wastewater was somewhat muddy. Sand might function as a filler material, thereby increasing the hardness.

(5) Headspace gas chromatograph followed with mass spectrometry analysis and headspace solid phase micro-extraction (SPME) tests for volatile organic compounds: “The main components in all samples analysed are alkanes (such as nonadecane), alcohols and aldehydes. The alkanes are expected to be formed during polymer chain degradation which occurs during high temperature processing (extrusion). The alcohols and aldehydes are likely formed by reaction with oxygen with the reactive species formed during chain degradation. Other species stem likely from plastic additives. 5-methyl-2-furancarboxaldehyde (5-methyl-furfural) was found in the unwashed samples. The non-methylated (furfural) variety may be formed during dehydration of sugars, so we suspect this a by-product of food residue that degrades upon recycling of the plastics”.

Discussion: Advantages of Using Plastic

Products made from recycled plastic are heavy and dense and can be used as a replacement for hard woods and, in many cases, concreate, yet plastic is easy to work with and can be up to a third of the weight of concrete. Plastic products can take the same load as a comparable cocreate product and can be reinforced with steel and fibres, like glass fibre, for added strength. Plastic does not suffer the consequential degradation caused by heat expansion and cold contraction that concrete suffers from. As plastic does not absorb moisture, it will not rot, is slip-resistant, and if it does get dirty, is easily cleaned with soapy water (Hahn Plastics Ltd 2022).

During each lifecycle, these products replace wood or concrete multiple times. For example, if a wooden fence panel lasts between 10 to 15 years and an IEM plastic panel lasts 40 to 50 years, then between three and five wooden fence panels are being substituted for each lifespan of a single plastic panel. For 10 lifecycles of plastic, that would be 30 to 50 wooden panels that were not used. Therefore, a life cycle analysis (LCA) should consider the multiple wood or concrete equivalents saved over the multiple lifespans of the plastic equivalents. Furthermore, only for the first lifespan, the LCA needs to consider all the initial processes, from collecting the waste to the agglomeration stage. However, when it is reprocessed for its second iteration, it will only need to be delivered, ground up, and then extruded; all the initial stages do not need to be taken into consideration.

By moving to collecting and making products from LFPFs, which become a substitute for wood and concreate, society becomes more sustainable and works towards fulfilling the UN Sustainability Goals (SDGs) (UN 2024). Reducing plastics in the environment, by making products from it, helps with human (SDG1) and animal health (SDG14 &15), reducing water usage and contamination (SDG6), reducing present and future energy and carbon usage, which helps with climate change (SDG13), and through multiple usages increases responsible consumption (SDG12).

Offtake Market

There is a sizable offtake market for outdoor products made from recycled ridged plastic. The main current offtake market is products for municipalities and public works: Hahns' customers are both municipalities and private consumers, while FuturePost supplies the farming community. Save Plastics has shown that its products, which are made from LFPF, can compete on price and specification with those made from ridged waste plastics. However, given the low price of oil (at July 2024 prices) making the same products from virgin plastics would be cheaper. However, products made from waste do not have the carbon footprint of extraction and manufacturing into virgin plastic pellets. If the carbon footprint and ecological cost due to landfilling or incineration, that are now saved, are considered and the net carbon footprint for all future iterations that are replacing other materials (e.g. wood, concreate, or metal) is taken into consideration, the Environmental Cost Indicator (MKI) for LFPFs is lower than virgin plastics and gets lower with each iteration. Therefore, public bodies and companies who procure products based on MKI have a better buying proposition than products made from virgin plastic. The future market for outdoor products, that will replace lumber or concrete, is enormous. Quantifying this, is for further study.

Policy Recommendations

According to RECOUP (2022a, p. 9), only 13% of UK waste authorities collected LFPFs in 2021 after a downward spiral, from 80 in 2015 (RECOUP 2016) to 44 in 2021 (RECOUP 2022b). This shows that the policy to collect and recycle LFPFs in a circular way is not working. However, this project has shown that by employing the technology used in the Save Plastics pilot plant millions of tonnes of LFPFs (Plastics Europe 2022, p. 16) can potentially be upcycled in a circular manner. However, for a circular economy model to work, there must be a sustainable supply chain (Metta & Badurdeen 2012) and an offtake market.

A practical solution can be implemented through a five-stage process. (1) To secure a steady supply of feedstock, policymakers must increase the collection of all packaging plastics, starting with local government putting into the contracts of waste management companies that all LFPFs must be collected. (2) Technical innovation: Central government should put in place financial packages to secure the changes to mechanical sorting and processing equipment needed to handle LFPFs. (3) Policy for recycling plastics must move away from landfilling and incineration for energy and embrace the circular economy. (4) Help to grow an offtake market: Public procurement is the largest consumer in any country; therefore, policymakers should include in their procurement processes (Edler & Georghiou 2007; Tsipouri et al. 2015) a priority to purchase products made from 100% recycled plastic that are substitutes for wood or concrete. By doing this, they show confidence in such products which helps to grow the market (Rainville 2021); this should spill over to the consumer sector, thus growing this IEM production. (5) Funding for more research into business models and opportunities should be made so that previous failures like that of REDcycle in Australia (The Guardian 2023) should not be repeated.

Further Work

Further analysis is required to determine how much new plastic, wood, concrete, and steel have been saved by substituting plastic over its multiple lifecycles. Analysis should be carried out to assess the market size and ongoing possibilities within public procurement for these plastic products. Since a lack of reliable data is given as a limiting factor to the introduction of policy and business measures that would increase plastic circularity (Hsu et al. 2021), more research is needed in this area. The amount of aluminium in the LFPFs has been identified to possibly add some tensile strength to products; however, this needs further investigation.

Conclusions

There are many companies that produce durable products from 100% recycled plastic; however, the plastics they use are either only rigid plastics of a higher grade than thin films or their mix contains small amounts of flexible films. Annually, millions of tonnes of plastic end up in landfill, are destroyed to produce energy, or worse end up as uncontrolled waste that damages soil and the marine environments. The waste management industry therefore requires a solution to increase their recycling rate of all currently unrecycled plastics.

Save Plastics, a TRANSFORM-CE partner, used the lowest grade of municipal plastic waste, multi-polymer multi-material flexible laminated thin film packaging, to make durable plastic products with a projected lifespan of up to 50 years per production cycle. They used agglomeration with IEM manufacturing methods, to make their products. They have shown that the product can be ground up and passed through the IEM process between 8 and 10 times during its initial circular lifecycle. This gives the plastic a lifespan of many hundreds of years before it needs to be processed for further use. The plastics they used contained up to 20% contaminants and were damp, yet did not degrade their products.

Following extensive electromechanical tests, it can be concluded that in the nine recycle cycles, the material degradation was so minimal that these differences could be negligible, especially when the material is used for the type of outdoor products produced by Save Plastics. From the 10th iteration, there is a small degradation of the material, but this does not mean that the material immediately starts falling apart and can, with the inclusion of new waste or virgin plastics, continue to have more life cycles.

Current production volumes for the IEM industry, that can use recycled rigid and flexible films, are in the hundreds of thousands of tonnes. Many of these products replace wood, concrete, and metals. Given the vast amount of future plastic consumption, plastic in circulation, and in landfill, for the foreseeable future, there will be no concerns for the supply of waste feedstock.

Save Plastics has perfected a process that can upcycle millions of tonnes of waste plastic, thus mitigating ecological damage, reducing carbon emissions via incineration, and safeguarding a non-renewable resource for future generations. What is needed is for policymakers to support the waste management and IEM industries to close the circular economy gap for low-grade plastics.

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Data Availability The test data presented in this paper has been uploaded as supplementary data with this paper and is available on request from the author.

Declarations

Competing Interests The author declares no competing interests.

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