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Highlights

- 35% of 149 ± 11 kt of plastic waste was reused/recycled in Northern Ireland (2018).
- Improved data monitoring needed for transition to a circular plastics economy.
- Standardised designs, and dialogue between manufacturers and waste sector necessary.
- Designed-in contamination should be minimised to improve recyclability.
- Life cycle assessment of planned changes required to avoid negative consequences.

Abstract

Plastics are used in a wide range of applications generating significant waste streams. This is driving policy interventions to increase circularity, reduce waste and improve resource efficiency. However, information on plastic waste flows is not widely available across regions and nations. With an overarching aim to make recommendations for supporting the transition to a circular plastics economy in Northern Ireland, this study used quantitative uncertainties to conduct regional material flow analysis and geospatial mapping to identify local hotspots. It was observed that 149 ± 11 kt of plastic waste were produced in Northern Ireland (79.2 kg/capita) in 2018. Reuse and recovery for recycling reached up to 35%, while 62% of plastic waste was landfilled with the remainder (3%) incinerated. This study found that there are increasing amounts of plastic waste locked in sectors with long product lifetimes, such as the construction sector with 21.3 kt for 2018. It is therefore important to consider the processing capacities and environmental impacts of plastic waste management, not only for current plastic waste flows but also for tackling possible future growth of these flows. The results indicate that there is a need for a holistic all-island approach for effective

plastic waste management in both Northern Ireland and the neighbouring Republic of Ireland. Furthermore, stricter enforcement of existing waste management rules and regulations could prevent the need for additional policies to support a circular economy. This research provides robust scientific data to aid the transition to a circular economy for plastics in the region.

Keywords: Plastic waste management; Packaging; Circular economy; Material flow analysis (MFA); Extended Producer Responsibility (EPR); Northern Ireland

1. Introduction

Plastics are used in a wide range of applications due to their advantageous properties such as lightweight, cost-effectiveness, affordability, strength and durability (Thompson et al., 2009). The success of plastics is reflected in global production levels escalating from 2 million tonnes (Mt) per year in 1950 to 350 Mt per year in 2015 (**Fig.1)** (Ritchie and Roser, 2018).

However, increased use of plastics has led to environmental concerns. Conventional plastics are manufactured utilising fossil fuels, with 4% of annual petroleum production used for feedstock and another 3-4% for energy supply during production processes (Van Eygen et al., 2017). While the pace of plastics production and their applications have accelerated, the development of viable waste management systems has remained stagnant (Turner and Holmes, 2015). Plastic waste is commonly found in the environment (Alam et al., 2018). During fragmentation by weathering, microplastics can be generated (Jambeck et al., 2015; Nakashima et al., 2012; Eriksen et al., 2014), causing human health concerns (Prata et al., 2020), soil contamination and negative impacts on seed germination (Bosker et al., 2019). Plastic pollution has been recognised as a **planetary threat** impacting almost every freshwater and marine ecosystem (Borrelle et al., 2020). Proper management of plastics using circular economy principles can ensure resource efficiency and mitigate environmental impacts.

The circular economy principles, where materials are recirculated, reduced, reused, recycled, and recovered, have been increasingly adopted by governments, e.g., in China (National People's Congress, 2021), the European Union (EU, European Commission, 2018) and Japan (MOE Japan, 2019). In the United Kingdom (UK), the Plastics Pact aims "to move away from a linear plastics economy, where we take, make and dispose of plastic, and move towards a circular system where we keep plastic in the economy and out of the natural environment" (WRAP, 2018). To identify opportunities for reduction, reuse, and recycling, it is imperative to understand stocks and flows. This can be achieved using material flow analysis (MFA) which is an approach to **model the flow of materials** through the anthroposphere (Kawecki et al., 2018).

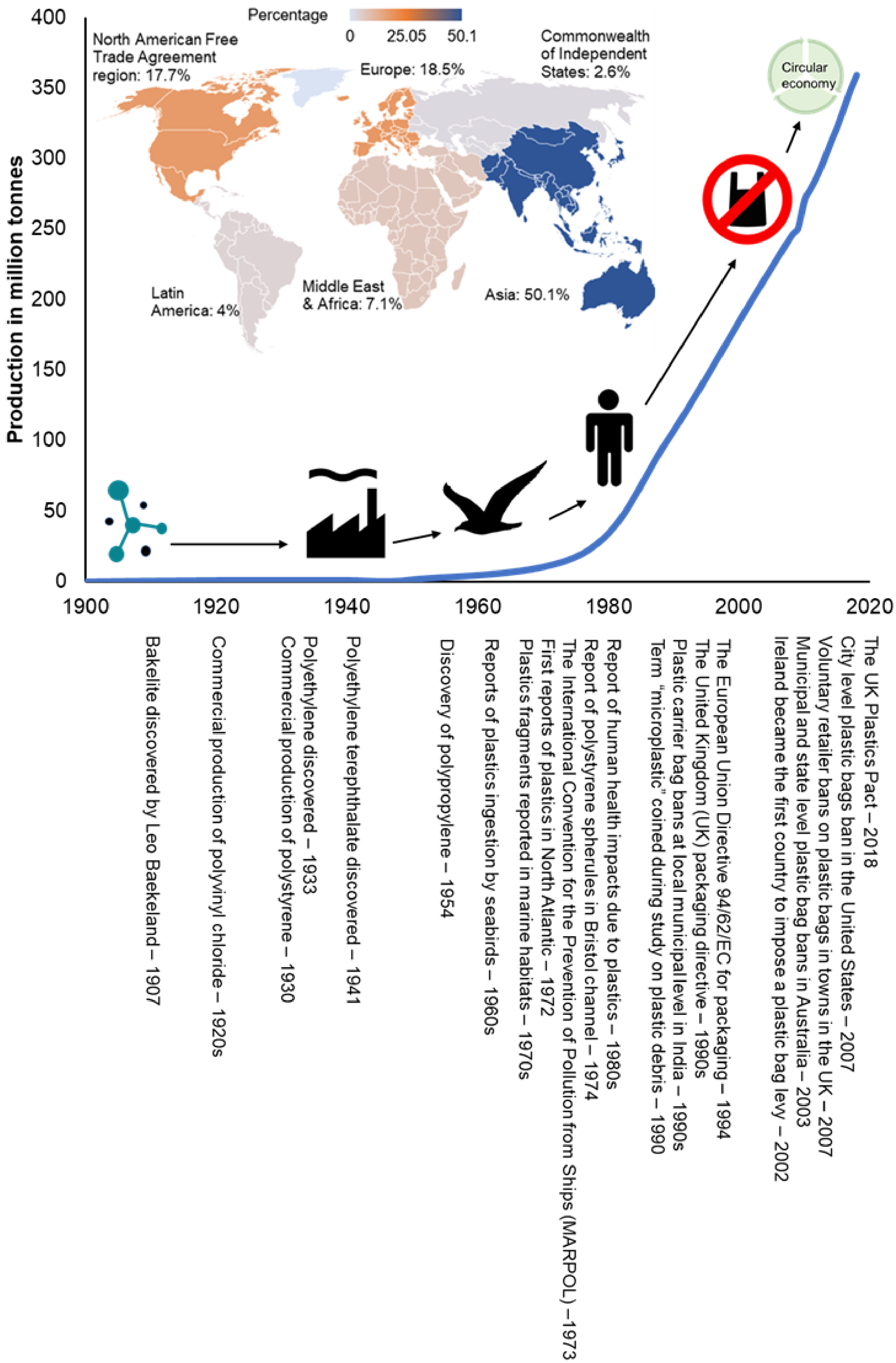

Fig.1. Timeline showing discovery and widespread production of plastics along with concerns and legislative measures. Solid blue line shows plastic production in million tonnes per year (Statista, 2021) and the map depicts the % production of the global total created using Bing maps (PlasticsEurope, 2018).

In recent research, MFA has been used to evaluate plastic packaging stocks and flows in Austria (Van Eygen et al., 2018), Germany (Picuno et al., 2021), Japan (Nakatani et al., 2020), Ireland (EPA Ireland, 2020), Italy (Lombardi et al., 2021), the Netherlands (Brouwer et al., 2018) and South Korea (Jang et al., 2020). In a similar vein, Ciacci et al. (2017) estimated polyvinyl chloride stocks and flows in Europe from 1960 to 2012, Eriksen et al. (2020) computed stocks and flows for polyethylene (PE), polyethylene terephthalate (PET) and polypropylene in Europe, and Jiang et al. (2020) evaluated trends in China's plastic economy from 1978 to 2017 for five types of polymer.

Research has been undertaken on plastic stocks and flows using static MFA such as in Austria for the year 2015 (BMNT, 2017), Denmark for 2016 (DEPA, 2019), the EU for 2016 (Hsu et al., 2021), Japan for 2013 (MOE Japan, 2018), Trinidad and Tobago for 2016 (Millette et al., 2019), and the UK for 2016 (Domenech et al., 2020). Detailed uncertainty analysis was conducted in the 2010 Austrian study by Van Eygen et al. (2017), and in a more recent probabilistic flow analysis to evaluate polymer specific mass flows for commodity plastics across Europe and Switzerland by Kawecki et al. (2018). Material flow analysis of plastics in the United States in 2015 was performed by Di et al. (2021) by accounting for overarching uncertainty of 10% for the use stage in data sources. Qualitative uncertainty based MFA was used by Olatayo et al. (2021) to discuss challenges and solutions to improve circularity for plastics for South Africa in 2017.

This study builds on previous research by including: (1) detailed data quality analysis *and* quantitative uncertainties to conduct an MFA, and (2) geospatial mapping to identify local hotspots requiring development of advanced plastic waste management infrastructure. The goal is to use the findings to make recommendations for supporting the transition to a circular plastics economy. The paper focuses on the Northern Ireland context; the region follows EU environmental regulations, including the Waste Framework Directive (European Commission, 2008), and therefore has a similar waste landscape to the EU. Previous research on plastic waste flows in Northern Ireland (rx3, 2011) did not include the plastic consumption stage and did not undertake uncertainty analysis. This study goes beyond previous work by evaluating plastics consumption to understand the plastic stocks locked in various sectors which could potentially enter waste streams after the completion of the useful life cycle. All calculations were made for 2018 (January-December) as the reference year.

2. Methods

2.1 Material flow analysis

For evaluating plastic waste flows a **static MFA** was used, which includes the flows and stocks of materials through a holistic system that is defined in space and time. It encompasses the quantification of sources, pathways, intermediate by-products, and final sinks of the material in physical units (Klinglmair et al., 2015; Zoboli et al., 2016). The overall analysis applies the law of conservation of mass. The procedure entails outlining the goals and opting for relevant substances, system boundaries, and processes. The software STAN v2.6.801 (available at STAN, 2012) was used to perform the MFA calculations using the standardised method (Van Eygen et al., 2017).

For the model, the system boundary consisted of product distribution and consumption, along with plastic waste production and treatment. The trade of plastics into and out of Northern Ireland was not considered, since data on the primary production of polymers and import-export statistics are only available for the UK as a whole. This is in line with the approach used in rx3 (2011).

Material flow analysis studies are simplified models of the real-world system, and thus are inherently uncertain (Lloyd et al., 2007). In this method: (1) The quality of each input data point was characterised qualitatively using five quality indicators shown in **Eq. (1)** following method in **Supplementary Material: Table S1**; and (2) The quantitative uncertainty values were derived based on coefficients of variation (CV, standard deviation divided by mean) for each data quality indicator score, which are described by continuous characterising functions, i.e. uncertainty increases exponentially with worse scores (see Laner et al. (2015) for more details) (**Supplementary Material: Table S2**). The overall uncertainty of each data point was determined using **Eq. (1)**. The estimated input uncertainties were then propagated through the model using Gaussian error propagation and the material flow results were given as mean values and relative standard deviations of a normal distribution. This is in line with the approach used by Van Eygen et al. (2018) and Kawecki et al. (2018).

$$CV = \sqrt[2]{CV_{reliability}^2 + CV_{completeness}^2 + CV_{temporal\ correlation}^2 + CV_{geographic\ correlation}^2 + CV_{other\ correlation}^2} \quad (1)$$

where, CV = Coefficient of variation, $CV_{reliability}$ = CV according to the reliability, $CV_{completeness}$ = CV based on the completeness, $CV_{temporal\ correlation}$ = CV based on time span recorded, $CV_{geographic\ correlation}$ = CV based on the geographic distribution, $CV_{other\ correlation}$ = CV based on the products and technology captured in the data source

2.2 Description of plastic waste flows

The plastic flows across society consist of four main phases:

(1) **Trade and production of plastics: Primary polymers** are produced by the chemical industry. The primary polymers and finished products are imported and exported.

(2) **Aggregate product use:** Following domestic production, import and export, products are distributed over consumption sectors. These products are then used by consumers and **accumulate as stocks** in respective consumption sectors.

(3) **Waste collection:** When products are discarded by consumers, waste flows go to the waste management stage, including collection and sorting systems. In Northern Ireland, municipal waste is **collected through a multi-bin system** at household kerbsides and civic amenity sites by local authorities and/or private companies. Generally, each household pre-sorts their waste in differently coloured bags and/or bins, e.g., separate bins for organics and garden waste; cardboard; recyclable packaging including glass, aluminium, and plastics; and non-recyclable waste such as films. However, there is no region-level standardisation for availability and type of bins/bags and collection systems (more details in **Section 4**).

End-of-life vehicles are accepted free of charge at Authorised Treatment Facilities following Waste Management Licensing Regulations (Northern Ireland) (2003). Healthcare waste is collected in accordance with HTM07-01 (2013). Farm wastes are produced on a 'farm' in the course of 'farming' and are gathered by farm waste collectors which could be operating under the commercial association of collectors, i.e. the UK Farm Plastics Recycling Scheme (UKFPRS Ltd, 2020; Zero Waste Scotland, 2020). Waste electrical and electronics equipment is collected, and then dismantled/recovered by Designated Collection Facilities regulated by The Waste Electrical and Electronic Equipment Regulations (2013). Mattresses, rugs, and furniture are collected via local authority kerbside bulky waste collections and/or at Household Waste and Recycling Centres (WRAP, 2012a).

(4) **Treatment:** Plastic waste that can be cleaned and retain functionality, such as clothing textiles, is reused. If reuse is not possible, the plastic waste stream is handled through recycling and recovery. Materials recovery facilities **separate the co-mingled recyclables** into individual material streams and provide quality raw materials to industry or reprocessors (WRAP, 2016). Reprocessors process recyclable plastics to recyclate, typically using mechanical recycling techniques. In Northern Ireland, recyclable plastics such as PET bottles are transported to private recyclers to produce plastic products. Non-recyclable plastics (e.g. mixed plastics), and/or those without viable recycling infrastructure and end markets, are either landfilled or sorted, baled and supplied to refuse-derived fuel producers for energy recovery facilities outside the region (DEFRA, 2014).

In this study, municipal plastic packaging recycling maps were produced using annual data provided in WasteDataFlow (n.d.) (verified by the Environment Agency) and open-source cross-platform desktop geographic information system application QGIS 3.4.5 (QGIS, 2019).

2.3 Data sources

Data (**Table 1**) were gathered from the waste management monitoring information of the 11 local government districts (local councils) and national waste treatment statistics reported by the Department of Agriculture, Environment and Rural Affairs. This was supplemented with data from literature and expert meetings with government and non-governmental organisations. As the data for many waste categories is not updated regularly and is not available on an annual basis, all calculations were made for 2018 (January-December) as the reference year.

The quantity of plastic used for packaging was estimated using the plastic packaging waste data as a proxy. WRAP (2019) justifies use of waste proxy, because: (1) There is a lack of data for non-packaging plastics due to the longer lifetime of the products, an absence of any regulatory requirement for companies to report production by material type, and a lack of data showing the domestic production placed on the UK market versus imported non-packaging plastics; and (2) Estimating plastic packaging consumption by using the packaging placed on the market by producers can lead to underestimation of the mass of packaging. This is because businesses below the *de minimis* threshold (i.e. with a turnover less than £2 million/year and that handle <50 t/year of packaging) are not required to report the data under the current producer responsibility scheme (Eunomia, 2018).

Where data was not available (estimated values in **Table 1**), an uncertainty value was selected (41.3% if related literature available and 124.6% where no literature was present) following the uncertainty categorisation method (expert estimate) by Laner et al. (2015) (**Supplementary Material: Table S3)**. After considering reuse, recycling and incineration, the remaining plastic waste was considered to be disposed of in landfills (**Supplementary Material: Table S4)**.

Table 1: Data sources for material flow analysis of plastics in Northern Ireland.

Sector	Assumptions and data sources[a,b]			
	Consumption	**Waste quantity**	**Compositional factor (% plastics in waste stream)**[c]	**End-of-life management: reuse, recycling and incineration**
Packaging	Waste data as proxy was used for estimating plastic packaging consumption for households from annual data provided in WasteDataFlow (n.d.) and commercial and industrial sector from WRAP CYMRU (2020)	Household waste from kerbside collections and civic amenity sites (WasteDataFlow, n.d.). Commercial and industrial waste from (WRAP CYMRU, 2020) scaled from Wales to NI population	Eunomia (2018)	Household packaging recycling from WasteDataFlow (n.d.). Commercial and industrial packaging recycling % assumed same as % household packaging recycling[d]
Commercial and industrial	Waste data as proxy was used for estimating hard plastics in commercial and industrial sector (WRAP CYMRU, 2020)	Hard plastic waste quantities in commercial and industrial sector in Wales (WRAP CYMRU, 2020), adapted using population estimates of Wales and NI	100%	The recycling rates of municipal waste were used from Wasteflowdata (n.d) in line with rx3 (2011)
Construction	UK data from Domenech et al. (2020) scaled to NI population	2009 waste production data for construction and demolition sites (RES148-001, 2011) adapted using NI Composite Economic Index (NICEI, 2020) for the construction sector from 2009-2018	Apricod (2004), Llatas (2011), Eunomia (2018)	RES148-001 (2011) for plastic waste reused at construction and demolition sites without further treatment
Automotive	UK data from Domenech et al. (2020) scaled to NI population	DAERA (n.d.)	Mashek et al. (2016)	Recycling and incineration estimated as 2.5% each[e]
Electronics	UK placed-on-market data provided by Environment Agency (2020) scaled to NI population	UK Environment Agency waste electrical and electronic equipment collected data by Environment Agency (2019) scaled to NI population	Maisel et al. (2020)	Recycling and incineration % assumed the same as that in the UK (WRAP-WEEE, n.d.) as the majority of the waste electrical and electronic equipment is sent to Britain for treatment (rx3, 2011; expert communications)
Healthcare	Waste data as proxy from Percival (2019)	UK data from Percival (2019) scaled for NI population for healthcare plastic waste	100%	Recycling data from Percival (2019) Incineration estimated as 80%
Farm	Waste data as proxy was used for	Farm plastic waste was	100%	Plastic fraction collected from

	estimating farm plastics (European Commission DG Env, 2011)[f]	estimated from UK farm plastics values (WRAP, 2006) using agricultural area in NI relative to UK (DAERA, 2019)		farms for recycling from WRAP (2006)
Furniture	UK data from Resource Futures (2012) scaled for NI population	Wales data from (WRAP CYMRU, 2020) scaled for NI population for commercial sector Household furniture waste derived by using ratio of commercial:household furniture from Resource Futures (2012)	Estimated as 2%	End-of-life management proportions Resource Futures (2012)
Clothing textiles	UK data from WRAP (2012b) scaled for NI population	WRAP (2012b) UK data scaled for NI population	WRAP (2012b)	End-of-life management proportions from purchase of pre-owned clothing (WRAP, 2012b)
Other	Waste data as proxy by using ratio from Resource Futures (2012)	Rugs, mattresses, and underlay from WRAP (2012a) UK data scaled for NI population Plastic waste present as cutlery, sports equipment, shoes etc. assumed as 1% of household waste from WasteDataFlow (n.d.)	Rugs, mattresses and underlay from Anthesis (2018)	Reuse data from Resource Futures (2012)

[a]Mid-year population estimates for the United Kingdom (UK), Northern Ireland (NI) and Wales were taken from annual data by UK GOV (n.d.).
[b]For some calculations, estimates from Wales were used because they represent the most up-to-date UK data.
[c]Compositional factors taken from references are provided in the **Supplementary Material: Table S4**.
[d]This is because the UK has adopted a definition of municipal waste that includes both household waste and waste from other sources that is similar in nature and composition and so includes a significant proportion of waste generated by businesses (WRAP, 2020a).
[e]Currently, plastic materials from end-of-life vehicles tend to be landfilled because there are no viable alternative markets. One exception is the removal by some dismantlers of bumpers as these are generally made of a single material (impact modified polypropylene) for which there is market demand (estimated as 2.5% in the present study).
[f]Common plastic farm wastes are pesticide containers, bags and sheets, old machinery, and packaging.

3. Results

3.1 Plastic stocks and flows

Total plastics consumption in Northern Ireland in 2018 was 217 ± 11 kt (**Fig.2)**. Packaging was responsible for the highest consumption among all sectors at 47%. The commercial/industrial and construction sectors accounted for 15% and 12%, respectively, while the automotive and electronics sectors each contributed 4%. Sectors with the lowest consumption were farm, healthcare, and furniture, accounting for 4% of the total.

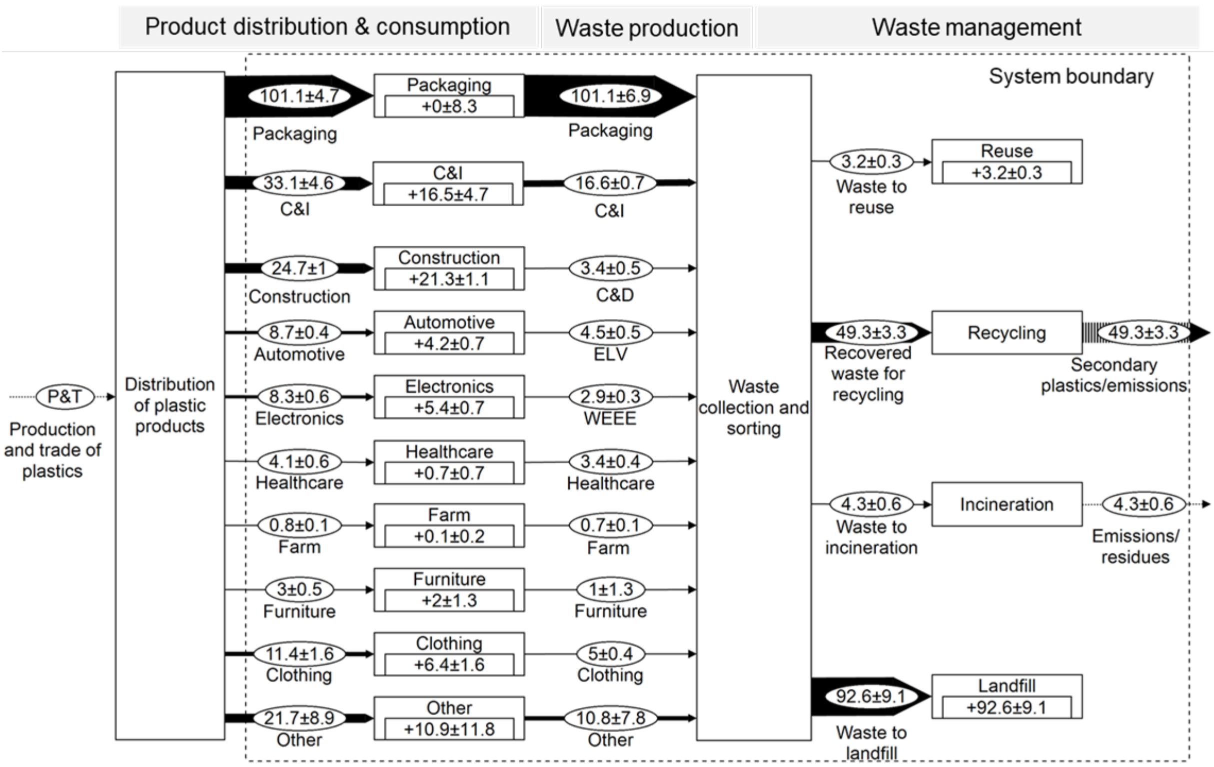

Fig.2. Plastic flows across Northern Ireland in kt (kilo tonnes) calculated for 2018.

(C&I: Commercial and industrial, C&D: Construction and demolition, ELV: End-of-life vehicles, WEEE: Waste electrical and electronic equipment, Other: Rugs, mattresses, sports and leisure equipment, cutlery, shoes. The import and export of plastic products and waste were not computed and are therefore not shown in system boundary.)

Stock changes relate to the in-use period of plastic products. The difference between input and output, i.e. between the waste production and plastics consumption stages, was 67 ± 16 kt, representing a net increase in stocks of 31% of incoming plastic products. The packaging sector had the lowest stock change, as these plastics typically have an average service life of only six months (Bucknall, 2020). The construction sector showed the largest build-up of stocks, with 32% of the total.

Total plastic waste production in 2018 was 149 ± 11 kt of which 68% was attributed to the packaging sector. The next sector generating significant waste quantities was commercial and industrial with 16.6 ± 0.7 kt. All other sectors contributed less plastic waste, varying from 0.5% to 7% of the total. A minor amount (2%) of the total plastic waste was reused (clothing textiles, and construction and demolition waste). About 33% of total plastic waste was recovered for recycling. Plastic waste disposed of using landfill and incineration accounted for 62% and 3% of the total, respectively.

3.2 Uncertainty analysis

Systematic data quality analysis was carried out based on Laner et al. (2015) to estimate the uncertainties associated with plastic flows (**Supplementary Material: Table S4**). The uncertainties in the plastic products consumption stage ranged from 4% to 41%. Placed-on-the-market data for electrical and electronics equipment (Environment Agency, 2020), led to an uncertainty of 7%. Construction and automotive sectors accounted for 4% of uncertainties each (data from Domenech et al., 2020).

Generally higher uncertainties, ranging from 4% to 125%, were observed in the waste generation stage. This is because of the difficulties associated with estimating plastic waste flows due to uncertainties in: (1) estimation of mass of waste produced; and (2) quantification of plastic content percentage in the waste generated in a sector. Lower uncertainties were present in the waste sectors with tighter regulations which require regular reporting, such as packaging (7%), waste electrical and electronic equipment (7%), and end-of-life vehicles (12%). Highest uncertainties were observed in furniture (125%) and other sectors (72%). Focusing on the waste treatment stage, uncertainty computed for waste recovered for recycling and reuse was computed as 8%, while 10% was calculated for landfilling and 13% for incineration.

3.3 Recycling destination of recovered municipal plastic packaging waste

The present study evaluated overall recovery of plastic waste for recycling as 33%. However, only 6809 tonnes out of a total of 25313 tonnes of municipal plastic packaging waste (with recorded destination) gets recycled within Northern Ireland and the remaining 73% is exported (**Fig.3)**. An additional 103 tonnes of municipal plastic packaging waste were sent for recycling with no destination recorded (categorised as 'other/exempt' in WasteDataFlow (n.d.)). It was observed that Armagh City, Banbridge and Craigavon Borough, Causeway Coast and Glens Borough, Fermanagh and Omagh District, Mid Ulster, and Newry, Mourne and Down district councils recycled less than 16% of municipal plastic packaging within Northern Ireland (**Fig.3**). It was assumed that municipal plastic packaging waste recovered for recycling purposes was recycled. However, there can be sorting losses or illegal dumping and burning of exported plastic packaging waste from the UK (Greenpeace, 2021). Relatedly, ICPO-INTERPOL (2020) has highlighted an increase in plastic waste crime worldwide.

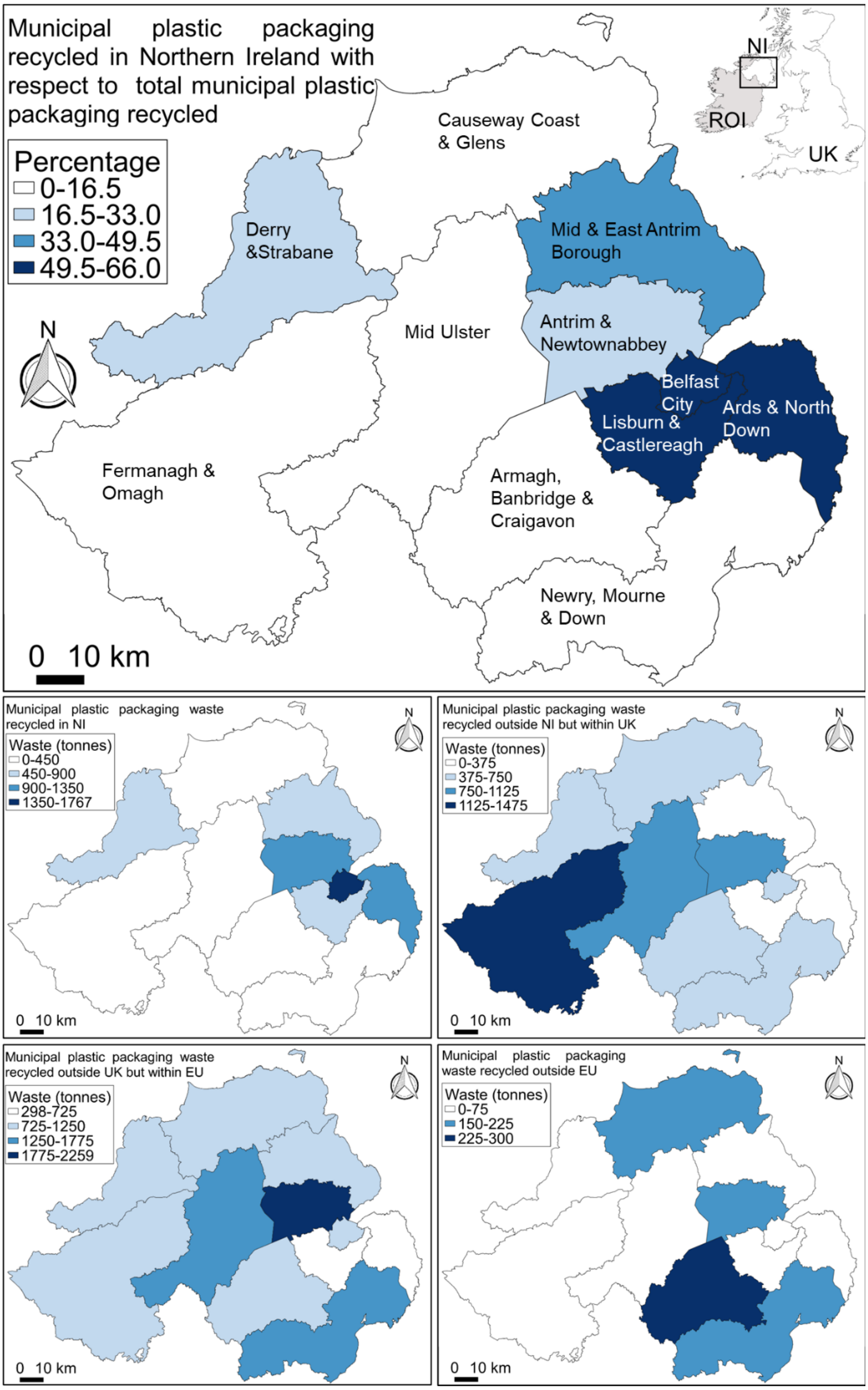

Fig.3. Geographic maps showing the recycling destination of municipal plastic packaging waste for the year 2018. Local government district boundaries are based on Ordnance Survey of Northern Ireland published in 2012, reproduced with permission from Land and Property Services, Open Government Data Licence v3.0.
(EU: The European Union, ROI: Republic of Ireland, UK: The United Kingdom)

3.4 Comparison with other regions

Quantitative comparison of studies of plastic flows across various regions and timescales is challenging, due to the complex nature of plastic streams and different assumed boundary conditions. Nevertheless, plastic waste generation in Northern Ireland of 79 kg/capita-year is comparable to the findings for other regions (**Table 2**). The exceptions are the United States and Austria, which had higher throughput of plastics, and South Africa, which is still in the developing stages of the plastics economy.

When it comes to plastic waste treatment (**Table 2**), recycling accounted for 33% in Northern Ireland, which is comparable to rates in Austria, Denmark, Japan and the UK (which range from 22-34%). In contrast, Trinidad and Tobago and South Africa had the lowest recycling rates; this is likely due to the "developing economies" of these countries (IMF, 2019) compared to the others in **Table 2**. The United States also recorded lower recycling rates, which are attributed to single-stream mixed waste collection. Incineration rates vary widely and were lowest in Northern Ireland (3% of plastic waste). Conversely, Northern Ireland had the fourth highest rate of landfilling of plastic wastes after Trinidad and Tobago, the United States and South Africa. Both landfilling and incineration are undesirable routes from a circular economy perspective as explained in the zero waste hierarchy (Simon, 2019) (hereafter referred to as the waste hierarchy). The preferred routes for resource conservation follow the trend: Refuse/rethink/redesign > Reduce and reuse > Preparation for reuse > Recycling/composting/anaerobic digestion > Material and chemicals recovery > Residuals management (including biologically stabilised materials to landfill) > Unacceptable (e.g. landfill/incineration) (Simon, 2019). Therefore, incineration should only be considered when the valuable plastic components have been reused and recycled (Papineschi et al., 2019).

Possible reasons for reliance on landfilling are: (1) differences in population distribution, underlying geology and land use patterns, and the impact of regional bans. Denmark, for example, was the first country globally to ban landfilling of incinerable wastes in 1997 due to potential contamination of drinking water from groundwater sources and limited space for landfills (IVL Report E006, 2012); and (2) the allocation of plastic waste management costs. In Northern Ireland, these are mainly borne by local councils rather than the polluter, which hinders innovation in the recycling and energy recovery sector. In fact, the current implementation of Extended Producer Responsibility (EPR, a policy approach under which producers are given a significant responsibility for the treatment or disposal of post-consumer products (OECD, 2016)) has been criticised in the UK, as it has been stipulated that only up to 10% of the financial responsibility of plastic packaging is borne by industries (Eunomia, 2018).

Table 2. Comparison of plastic waste generation and treatment in Northern Ireland with other regions.

Region	Year	Plastic waste generation		Reuse[a]	Recycling[b]	Incineration[c]	Landfill	Reference
		kt	kg/capita	%	%	%	%	
Northern Ireland	2018	149	79	2	33[d]	3	62	This study
United Kingdom	2016	5300	81	-	34[e]	35[e]	31[e]	Domenech et al. (2020)
Austria	2015	920	106	-	28[f]	71	1	BMNT (2017)
Denmark	2016	440	77	-	22[g]	78	<1	DEPA (2019)
Japan	2013	9400	74	-	25[h]	57	18	MOE Japan (2018)
South Africa	2017	2247	40	-	15[i]	-	85	Olatayo et al. (2021)
Trinidad and Tobago	2016	96	70	-	0	0	100	Millette et al. (2019)
United States	2015	35200	110	-	9[j]	14	77	Di et al. (2021)

[a]Reuse: Studies compared here did not quantify reuse %.
[b]Recycling: Chemical and mechanical recycling.
[c]Incineration: Incineration with/without energy recovery.
[d]The present study reports plastic waste recovered for recycling and did not compute sorting losses.
[e]The waste treatment proportions reported for the UK were for 2690 tonnes of plastic waste.
[f]BMNT (2017) recorded recovered plastic waste.
[g]DEPA (2019) reported recycling rates after considering sorting losses.
[h]MOE Japan (2018) did not mention if the estimates accounted for losses.
[i]For South Africa the proportion of plastic waste recovered for recycling was reported as 15%.
[j]The recyclables collected in United States in 2015 corresponded to 9% while the recycled quantities amounted to 6.2%.

4. Discussion: Supporting the transition to a circular economy

4.1 Monitoring and data management

What gets measured gets managed. However, available data for plastics management in Northern Ireland are patchy (**Table 1** and **Section 3.2**). This results in: (1) absence of identification of opportunities for recycling and reuse by industry and consumers; and (2) lack of baseline or year-on-year plastic flows and stocks data, which could be used to measure the impacts of upcoming legislation and innovations in plastics management systems. To eliminate this shortage of data, policymakers with input from various government and non-governmental organisations should: (1) improve data monitoring so that it goes beyond municipal waste and includes other sectors e.g. construction; (2) foster the dialogue between stakeholders; and (3) invest in research where needed to analyse current use of plastics across various sectors.

A potential solution is trans-sectorial collaboration between the manufacturers and waste collectors, as statutory bodies are demanding higher recycling rates from local councils (Gent, 2020) and legislation is driving manufactures to use greater amounts of recycled polymer within products (Rhein and Sträter, 2021). Poor capture and quality rates are of concern to both parties, therefore mechanisms that allow a greater flow of data between them may provide effective measures to deal with the rapidly evolving polymer packaging/product marketplace, decrease the cost of recovery and reduce the need for additional legislation. It is recommended that government engages with clusters like the Northern Ireland Polymers Association, which has membership from polymer companies across the region (NIPA, 2021) and could support manufacturers to track their plastic footprint through regular consultation, place-based initiatives, and stakeholder engagement workshops.

4.2 Science and engineering

The current economic system has focused on a produce-use-dispose model (**Fig.2**). In this study, only 31% of plastic materials contributed to stock changes for a year, indicating high throughput and the disposable characteristics of current plastic use. Standardisation and simplification of design could increase circularity, as differences in polymer chemistries, grades, colour, shape, size, and branding of products present challenges for both recycling and reuse.

Designed-in contamination is another barrier to effective resource management, as it may render the product unsuitable for further processing. Examples include additives like colour pigments, lacquers, layering of different polymers, and labels. Designed-in contamination is an issue both for short service-life plastics (e.g. packaging) and long service-life plastics (e.g. in the construction sector). Construction accounts for the largest increase in plastic stocks in Northern Ireland (**Fig.2**). The use of plastics in construction has been rising due to their versatility (TEPPFA, 2019). As construction plastics can have a service life of up to 35 years (Bucknall, 2020), and construction practices and legislation change over time, end-of-life management can be challenging. For instance, despite a recent ban on phthalates (UK GOV, 2019), these plasticisers are likely to be present in long service life products (Pivnenko et al., 2016) and measures to limit their toxicity during end-of-life management will be required for decades to come.

The design phase determines up to 80% of a product's environmental impacts (European Commission, 2014), so to ensure product circularity and to avoid being restricted to the bottom of the waste hierarchy, changes at the design stage are key. While the aim is to move to circular economy designs that are at the top of the waste hierarchy, it is recognised that plastics are used in a variety of products with different service lives. Tailored solutions are therefore needed. Reuse, for example, is higher up the waste hierarchy than recycling, but may not always be possible due to logistical, hygiene or practical reasons (highlighted by the fact that only 2% of total plastic waste was reused **(Table 2)**). Refilling schemes for packaging have not become widespread due to similar reasons. Currently only 1.8% of plastic packaging is made reusable by manufacturers globally (Ellen MacArthur Foundation, 2020), and a step-change would be required to support a transition to reusability.

There are also technological barriers to be overcome in the recycling sector. Performance can be a problem when there are high levels of recycled plastics. Plastic moulders usually incorporate 20-25% of recycled content with virgin, as blending regrind into virgin resin beyond 25% can significantly affect material performance (Getor et al., 2020). Plastics degrade during reprocessing due to crosslinking and chain scission. Mixed waste streams can also cause problems; a polypropylene recycling flow contaminated by PET can result in formation of spherical drops of PET reducing the overall quality of the product (Ragaert et al., 2017).

This study recorded that 33% of total plastic waste is recovered for recycling (**Table 2**). This is because recovered plastics are a valuable resource (e.g. plastic bottles can sell for over

£400/t (WRAP, 2017)), however, many plastic items are small, insufficient in volume and made of difficult to recycle polymers, e.g. plastic films (WRAP, 2019). For difficult to recycle plastics (e.g. due to logistics, contamination, and deterioration of product functionality), chemical recycling could improve resource efficiency. Polymers in plastic waste can be broken down to basic molecules that can be used to synthesise new plastics (Häußler et al., 2021), but the process is still not available at commercial scale anywhere in the world (Hatti-Kaul et al., 2020). Other methods of chemical recycling are pyrolysis and gasification, which produce fuels (Benavides et al., 2017) but are near the bottom of the waste hierarchy and sensitive to feedstock quality (Sophonrat et al., 2019). Moreover, the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) registration should be carried out to standardise the liquid oil as a product, before commercial adoption of pyrolysis as a recycling method (Qureshi et al., 2020).

Changes in the plastics economy may be challenging, but they are both possible and essential. Proposed changes need to be examined carefully to assess potential environmental and social impacts over the whole life cycle and minimise unintended negative consequences. An example of unintended negative consequences can be found in the current regime for disposal of biodegradable plastics. In Northern Ireland, and more widely (Kakadellis and Harris, 2020), managed disposal routes for compostable plastics are limited (Hutchings et al., 2021), meaning that such plastics are often sent to landfill/incineration and the intended environmental benefits are not therefore realised.

It should be recognised that a circular approach does not necessarily translate to a sustainable one (Walker et al., 2021). Gregson et al. (2013) highlighted that trials to prevent waste which aim to move up the waste hierarchy should be compared to existing and projected performance of recycling and energy from waste. Life cycle assessment of planned changes is required to avoid negative consequences. Life cycle assessment is a comprehensive tool (ISO 14040:2006; ISO 14044: 2006) that sits at the interface of science, engineering, and policy (Jeswani et al., 2020) and is used to assess environmental and human health impacts of products and processes (Osman et al., 2021). It has also been suggested that life cycle assessment should be used to evaluate and substantiate sustainability claims of plastics produced using renewable sources (i.e., biobased plastics) (Lynch et al., 2017; Moshood et al., 2021). The primary objective should be to use less in the first place and that perverse incentives do not increase waste production to meet recycling targets.

4.3 Policy and behaviour

The material flow analysis supported the identification of policies and behaviours that both enable and act as barriers to circularity in the plastics economy. This is exemplified by the fact that only 27% of municipal plastic packaging waste is recycled within the region and the remaining 73% is exported for recycling **(Fig.3)**. Identification of the regional hotspots provides important information to help local councils understand the development needs for plastic waste management infrastructure **(Fig.3)**. The barriers to a more advanced recycling infrastructure in Northern Ireland are:

(1) The limited demand from manufacturers for recycled content unless there is a significant price advantage for recycled over virgin feedstocks. The use of recycled content by manufacturers is inextricably connected to the price of virgin polymer. The volatile prices of virgin feedstock and recyclate, due to oil price fluctuations and/or UK government subsidies in the oil and gas sector (CIEL, 2017; European Commission, 2019), caused a disinclination among recycling companies to develop infrastructure (Burgess et al., 2021); and

(2) The current implementation of EPR has unintentionally incentivised export of unsorted plastics rather than developing recycling capacities locally. This is attributed to the volatility in the prices of Packaging Recovery Notes (PRNs) and Packaging Export Recovery Notes (PERNs) (Eunomia, 2018), which disincentivises investment in recycling infrastructure. A further barrier is that PRNs are issued by a reprocessor when the polymer has been recycled, but after removal of contaminants and processing, there could be weight loss compared to original tonnage of plastics processed. In contrast, PERNs are issued by plastic exporters based on original tonnage of unsorted plastic. As PRNs and PERNs are issued to businesses at the same prices (BPF, 2021), this leads to distortion of the market in favour of export rather than reprocessing in the UK.

Up until recently, Northern Ireland, and more widely the UK was heavily reliant on China as an end market for recovered plastics. Starting in early 2018 China introduced tighter restrictions on imports and other countries quickly became overwhelmed with shipments of recovered plastic (WRAP, 2019), with reports of mismanagement of exported plastic waste (ICPO-INTERPOL, 2020). The challenge now is ensuring that end markets for recovered plastics are commercially and environmentally sustainable. Wherever exports continue in the future, it is important that plastics exported from Northern Ireland are recycled to equivalent standards as here in Northern Ireland. Primarily, however, there should be emphasis on increasing the breadth and depth of end markets closer to home and ensuring that there is a quality stream of plastics for recovery and recycling; policies also need to be carefully designed to promote lower overall resource use. The longer-term challenge will be to ensure that policy across different nations moves in the same direction to minimise the risk of plastics mismanagement.

Moving from national level, there are also barriers at citizen level, as discarded plastic is often recognised by consumers as valueless (Green Alliance, 2020), resulting in loss of plastics in residual bins. This adds to the existing challenges caused by the public who often place the wrong items into recycling bins/bags/boxes or do not participate at all (Mehta et al., 2021). This is further complicated by the multiple collection systems currently in operation in Northern Ireland, and throughout the UK (BBC, 2018). This results in difficulties for material recovery facilities in providing high-quality recyclate.

At the extreme end of personal behaviours surrounding plastic waste are illegal dumping and fly-tipping which arise partly from a lack of strict enforcement of existing policies (EU IMPEL, 2019). An investigation of illegal dumps from 2006 to 2015 estimated they contained around 725 kt of waste with associated landfill costs of £22 million (NICVA, 2016). Further investigations focusing on composition analysis of illegal dumps could provide information about **mismanaged plastic waste flows** in Northern Ireland. Similar research needs have been highlighted by Hsu et al. (2021) at the EU level. Illegal waste sites contain plastics and household waste along with other categories of waste (Brennan, 2016). The problem of illegal waste disposal is exacerbated by policy and regulatory differences between Northern Ireland and the Republic of Ireland (Cave, 2016), highlighting the need for a holistic all-island approach to waste management and, in the context of this paper, a circular approach to plastics.

There has, however, been progress with policy, both in Northern Ireland and beyond, to support moves towards a circular economy, including: (1) Internationally, the Norway amendment to the Basel convention on transboundary movement of hazardous wastes has changed to include mixed plastic wastes in the category of waste which mandates full administration since 1 January 2021 (Basel Convention, 2019); and (2) The Single-use Plastics Directive (European Parliament, 2019) is to be implemented in Northern Ireland, as due to the Good Friday Agreement (The Agreement, 1998), the region continues to follow EU waste management rules and regulations (The Northern Ireland Protocol, 2020). The

Good Friday Agreement calls for greater coordination between Northern Ireland and the Republic of Ireland in an all-island approach to environmental issues, including plastics (rx3, 2011), which could alleviate illegal waste transport between the two regions.

At a national level, progress with policy in the UK includes: (1) Consultation on reforming the EPR by 2023 (DEFRA, 2019); (2) A £200/t tax from April 2022 on plastic packaging containing less than 30% recycled content, which could increase demand for recycled plastic. This is regardless of polymer type or the technical difficulty of achieving the target (HMRC, 2020); and (3) Plans for a Deposit Return Scheme (DRS) to incentivise consumer recycling and improve recovered plastic quality (WRAP, 2020b). Such a scheme could see a significant rise in the quality and quantity of plastic diverted from existing waste streams, but this would lead to reduced income for collectors and, therefore a suitable funding mechanism would need to be implemented.

We can also learn from existing systems that support "circular" behaviours, as there is potential for these to be implemented in other sectors. The current study recorded the highest proportion of reuse (48%) in the clothing textiles category (**Section 3.1, Supplementary Material: Table S4**), which could be due to the presence of charity shops selling pre-owned clothes (WRAP, 2012b). Charity shops or sharing schemes could improve reuse of other consumer products as well. WRAP (2012a) notes that nearly 30% of mattresses and underlay are reusable because they are identified as very clean, but the actual reuse observed in the MFA in the present study (other sector) was only 5% (**Supplementary Material: Table S4)**. Consumer behaviour and a consistent approach to collection could play a strong role in enhancing reuse of plastics.

In summary, the barriers to closed loop management of plastics are multifaceted: plastics are cheap (**Section 1**), there is insufficient infrastructure to produce high quality recyclate, and waste management and regulation systems are financially constrained and reliant on export of plastic waste (**Fig.4**). A transition to a circular plastics economy would not only include reuse (**Section 4.3**) and recycling but also design and manufacturing for circularity (**Section 4.2**). It is crucial that this transition is supported by robust scientific data and systems analysis to ensure sustainable design.

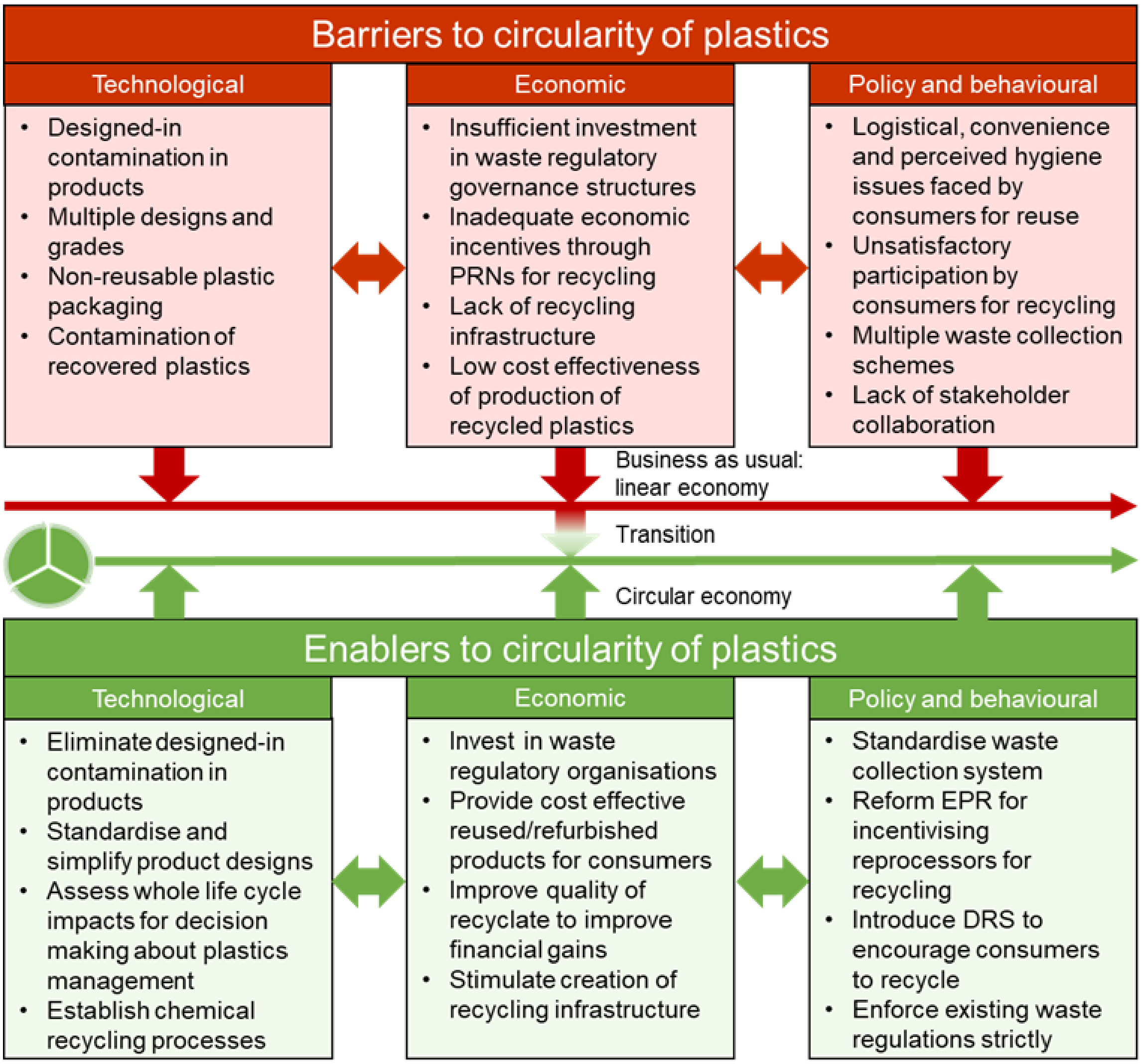

Fig.4. Barriers and enablers for transition to a circular economy for plastics.
(DRS: Deposit Return Scheme, EPR: Extended Producer Responsibility, PRN: Packaging Recovery Note)

4.4 Contribution and limitations of the study

With an overarching aim to make recommendations for supporting the transition to a circular plastics economy, this study used: (1) quantitative uncertainties to conduct MFA, and (2) geospatial mapping to identify local hotspots requiring development of advanced plastic waste management infrastructure. In this study, Northern Ireland was presented as an example region, however, the approach used is universal and could be applied elsewhere. For the first time, research including plastic product consumption was conducted in Northern Ireland, providing information on long-term plastic stocks locked in various sectors. This supports a number of United Nations Sustainable Development Goals including Responsible Consumption and Production (SDG 12), Industry, Innovation and Infrastructure (SDG 9), and Climate Action (SDG 13).

The main limitation of the present study is the system boundary considered for plastics. Future studies would benefit from consideration of trade and manufacture of plastics across Northern Ireland. Nevertheless, the UK wide plastic trade flows are in Domenech et al. (2020). It would also be interesting to see the change in overall uncertainties, when data specifically for Northern Ireland (rather than UK wide) and updated reports recording plastics content in products across various sectors are available. Coupled with this is the need for an all-island approach to data management, so that waste flows with the Republic of Ireland can be better managed. Finally, it should be noted that, this study computed recovered plastics for recycling and did not account for losses in the system such as sorting losses.

5. Conclusions

This study investigated plastic stocks and flows using MFA for plastic products consumption, plastic waste generation and plastic waste treatment stages in Northern Ireland for 2018. The results indicated that 217 ± 11 kt of plastics are consumed, with packaging contributing 47% of total consumption. The commercial and industrial (33 ± 5 kt) and construction (25 ± 1 kt) sectors accounted for 15% and 12% of total consumption, respectively.

The difference in the input and output contributed to stock changes, which amounted to 67 ± 16 kt per year (31% net increase in stocks of the incoming quantity of plastic products). Total plastic waste production in 2018 was 149 ± 11 kt, of which about 68% was attributed to the packaging sector. Only a minor amount (2%) of the total plastic waste flow was reused, 49 kt (33%) of plastic waste was recovered for recycling, and plastic waste disposed of using landfill and incineration accounted for 96 kt (65% of the total). The findings from the present study support the following recommendations:

- Implement effective collection and sorting to improve mechanical recycling yields. However, where mechanical recycling processes are not feasible, application of chemical recycling should be considered.
- Standardise material designs, refilling and sharing schemes, and waste collection systems, to increase plastic reuse and recycling.
- Develop a holistic all-island approach for transition to a circular economy for plastics in Northern Ireland and the Republic of Ireland.
- Going forward, it is important that manufacturers, consumers, government, waste collectors and regulators, and non-governmental organisations do not act in isolation, but that their united efforts co-create the future of plastics in a circular economy.

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CRediT authorship contribution statement

Neha Mehta: Formal analysis, Investigation, Methodology, Software, Writing - original draft. **Eoin Cunningham:** Co-supervision, Funding acquisition (Co-Principal Investigator, ACCEPT Transitions), Writing - review & editing. **Martin Doherty:** Writing - original draft (Section 4.3). **Peter Sainsbury:** Writing - original draft (Section 4.3). **Ife Bolaji**: Writing - review & editing. **Behnam Firoozi-Nejad:** Writing - review & editing. **Beatrice M. Smyth:** Funding acquisition (Co-Principal Investigator, ACCEPT Transitions), Supervision, Writing - review & editing.

References

Alam, O., Billah, M., and Yajie, D. (2018). Characteristics of plastic bags and their potential environmental hazards. Resources, Conservation and Recycling 132, 121–129.

Anthesis (2018). Toxics in the carpets in the European Union. Anthesis Consulting Group. https://circulareconomy.europa.eu/platform/sites/default/files/knowledge_-_toxics_in_carpets_eu_review_anthesis_final_study.pdf (accessed 23 December 2020).

Apricod (2004). Towards sustainable plastic construction and demolition waste management in Europe.

Basel Convention (2019). BC-14/12: amendments to Annexes II, VIII and IX to the Basel Convention. Basel. basel.int/Implementation/Plasticwaste/PlasticWasteAmendments/Overview/tabid/8426/Default.aspx (accessed 10 May 2021).

BBC (2018). Why plastic recycling is so confusing? The British Broadcasting Corporation. https://www.bbc.co.uk/news/science-environment-45496884 (accessed 10 May 2021).

Benavides, P.T., Sun, P., Han, J., Dunn, J.B., and Wang, M. (2017). Life-cycle analysis of fuels from post-use non-recycled plastics. Fuel 203, 11–22.

BMNT (2017). Plastic waste in Austria. https://www.bmk.gv.at/en/topics/climate-environment/plastics/waste-Austria.html (accessed 10 May 2021).

Borrelle, S.B., Ringma, J., Law, K.L., Monnahan, C.C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G.H., Hilleary, M.A., et al. (2020). Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science 369, 1515–1518.

Bosker, T., Bouwman, L.J., Brun, N.R., Behrens, P., and Vijver, M.G. (2019). Microplastics accumulate on pores in seed capsule and delay germination and root growth of the terrestrial vascular plant Lepidium sativum. Chemosphere 226, 774–781.

BPF (2021). Recycling roadmap. British Plastics Federation. https://www.bpf.co.uk/roadmap (accessed 10 May 2021).

Brennan, C. (2016). The Enforcement of Waste Law in Northern Ireland: Deterrence, Dumping and the Dynamics of Devolution. Journal of Environmental Law 28, 471–496.

Brouwer, M.T., Thoden van Velzen, E.U., Augustinus, A., Soethoudt, H., De Meester, S., and Ragaert, K. (2018). Predictive model for the Dutch post-consumer plastic packaging recycling system and implications for the circular economy. Waste Management 71, 62–85.

Bucknall, D. (2020). Plastic Sustainability Challenges. Plastics Research Innovation Fund Conference: Creative Circular Economy Approaches to Eliminate Plastics Waste - Online, Sheffield, United Kingdom, June 2020. https://www.ukcpn.co.uk/wp-content/uploads/2020/08/PRIF-Conference-Brochure-Final-1.pdf (accessed 23 December 2020).

Burgess, M., Holmes, H., Sharmina, M., and Shaver, M.P. (2021). The future of UK plastics recycling: One Bin to Rule Them All. Resources, Conservation and Recycling 164, 105191.

Cave, S. (2016) Background paper on Waste Management in Northern Ireland. Research and Information Service Briefing Paper 10/17 NIAR 435-16. Northern Ireland Assembly. http://www.niassembly.gov.uk/globalassets/documents/raise/publications/2016-2021/2017/aera/1017.pdf (accessed 15 June 2021).

Ciacci, L., Passarini, F., and Vassura, I. (2017). The European PVC cycle: In-use stock and flows. Resources, Conservation and Recycling 123, 108–116.

CIEL (2017). Fueling plastics. Fossils, Plastics & Petrochemical feedstocks. Center for International Environmental Law. https://www.ciel.org/wp-content/uploads/2017/09/Fueling-Plastics-Fossils-Plastics-Petrochemical-Feedstocks.pdf (accessed 23 December 2020).

DAERA (2019). Statistical Review of Northern Ireland Agriculture 2018. Department of Agriculture, Environment and Rural Affairs. https://www.daera-ni.gov.uk/sites/default/files/publications/daera/stats-review-2018-final.pdf (accessed 10 May 2021).

DAERA (n.d.). End of life vehicles. Department of Agriculture, Environment and Rural Affairs. https://www.daera-ni.gov.uk/articles/end-life-vehicles (accessed 10 May 2021).

DEFRA (2014). Materials facilities: how to report on mixed waste sampling. Department for Environment, Food and Rural Affairs. https://wrap.org.uk/sites/default/files/2020-10/WRAP-pb14150-mrf-guide.pdf (accessed 18 August 2021).

DEFRA (2019). Consultation on EPR: Reforming the UK Packaging Producer Responsibility System. Department for Environment, Food and Rural Affairs. https://consult.defra.gov.uk/environmental-quality/consultation-on-reforming-the-uk-packaging-produce/supporting_documents/packagingeprconsultdoc.pdf (accessed 10 May 2021).

DEPA (2019). Preliminary assessment of plastic material flows in Denmark. Technical Report. The Danish Environmental Protection Agency. https://www2.mst.dk/Udgiv/publications/2019/06/978-87-7038-082-9.pdf (accessed 23 December 2020).

Di, J., Reck, B.K., Miatto, A., and Graedel, T.E. (2021). United States plastics: Large flows, short lifetimes, and negligible recycling. Resources, Conservation and Recycling 167, 105440.

Domenech, T., Casas-Arredondo, M., and Hsu, W. (2020). How circular are plastics in the UK?: Findings from Material Flow Analysis. Plastics Research Innovation Fund Conference: Creative Circular Economy Approaches to Eliminate Plastics Waste - Online, Sheffield, United Kingdom, June 2020. https://www.ukcpn.co.uk/wp-content/uploads/2020/08/PRIF-Conference-Brochure-Final-1.pdf (accessed 23 December 2020).

Ellen MacArthur Foundation (2020). Upstream Innovation: a guide to packaging solutions. https://plastics.ellenmacarthurfoundation.org/upstream?gclid=CjwKCAiA_9r_BRBZEiwAHZ_v18D5Rp6z4LjzvFAYbmXyR2Wn1mvJ1F7HxocIX2VMAgzApOG9GkURrRoCYksQAvD_BwE&utm_source=twitter&utm_medium=organic_social&utm_term=-&utm_content=&utm_campaign=UIG#introduction (accessed 10 May 2021).

Environment Agency (2019). WEEE collected in the UK. https://www.gov.uk/government/statistical-data-sets/waste-electrical-and-electronic-equipment-weee-in-the-uk (accessed 18 August 2021).

Environment Agency (2020). Electrical and Electronic Equipment (EEE) placed on the UK market. https://www.gov.uk/government/statistical-data-sets/waste-electrical-and-electronic-equipment-weee-in-the-uk (accessed 18 August 2021).

EPA Ireland (2020). Waste packaging statistics for Ireland. Environmental Protection Agency Ireland. https://www.epa.ie/nationalwastestatistics/packaging/ (accessed 10 May 2021).

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., and Reisser, J. (2014). Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea. PLOS ONE 9, e111913.

Eriksen, M.K., Pivnenko, K., Faraca, G., Boldrin, A., and Astrup, T.F. (2020). Dynamic Material Flow Analysis of PET, PE, and PP Flows in Europe: Evaluation of the Potential for Circular Economy. Environmental Science and Technology 54, 16166–16175.

EU IMPEL (2019). Making the circular economy work: Guidance for regulators on enabling innovations for the circular economy (prevention and recycling of waste). European Union Network for the Implementation and Enforcement of Environmental Law. https://www.impel.eu/wp-content/uploads/2019/08/Guidance-Making-the-Circular-Economy-Work.pdf (accessed 10 May 2021).

Eunomia (2018). Plastic packaging: shedding light on the UK data. https://www.eunomia.co.uk/reports-tools/plastic-packaging-shedding-light-on-the-uk-data/#:~:text=By%20analysing%20what%20is%20known,higher%20than%20the%20official%20figure (accessed 23 December 2020).

European Commission (2008). Directive 2008/98/EC on waste (Waste Framework Directive) of the European parliament and of the council of 19 November 2008. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098 (accessed 29 May 2020).

European Commission (2014). Ecodesign Your Future How Ecodesign can help the environment by making products smarter. https://op.europa.eu/en/publication-detail/-/publication/4d42d597-4f92-4498-8e1d-857cc157e6db (accessed 16 June 2021).

European Commission (2018). A European strategy for plastics in a circular economy. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1516265440535&uri=COM:2018:28:FIN (accessed 23 December 2020).

European Commission (2019). Report from the commission to the European Parliament, the council, the European economic and social committee and the committee of the regions. Energy prices and costs in Europe. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=COM:2019:1:FIN&from=EN (accessed 23 December 2020).

European Commission DG Env (2011). Plastic waste in the environment https://ec.europa.eu/environment/waste/studies/pdf/plastics.pdf (accessed 23 December 2020).

European Parliament (2019). Directive (EU) 2019/904 of the European Parliament and of the council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32019L0904&from=EN (accessed 24 May 2021).

Gent, T. (2020). Councils must continue recycling collections to avoid negative environmental impact. https://www.localgov.co.uk/Councils-must-continue-recycling-collections-to-avoid-negative-environmental-impact/50439 (accessed 10 May 2021).

Getor, R.Y., Mishra, N., and Ramudhin, A. (2020). The role of technological innovation in plastic production within a circular economy framework. Resources, Conservation and Recycling 163, 105094.

Green Alliance (2020). Fixing the system. https://www.green-alliance.org.uk/resources/Fixing_the_system.pdf (accessed 29 May 2020).

Greenpeace (2021). What really happens to your plastic recycling? https://www.greenpeace.org.uk/news/plastic-recycling-export-incineration/ (accessed 7 June 2021).

Gregson, N., Crang, M., Laws, J., Fleetwood, T., and Holmes, H. (2013). Moving up the waste hierarchy: Car boot sales, reuse exchange and the challenges of consumer culture to waste prevention. Resources, Conservation and Recycling 77, 97–107.

Hatti-Kaul, R., Nilsson, L.J., Zhang, B., Rehnberg, N., and Lundmark, S. (2020). Designing Biobased Recyclable Polymers for Plastics. Trends in Biotechnology 38, 50–67.

Häußler, M., Eck, M., Rothauer, D., and Mecking, S. (2021). Closed-loop recycling of polyethylene-like materials. Nature 590, 423–427.

HMRC (2020). Policy Paper: Plastic Packaging Tax. Her Majesty's Revenue and Customs. https://www.gov.uk/government/publications/introduction-of-plastic-packaging-tax/plastic-packaging-tax (accessed 10 May 2021).

HTM07-01 (2013). Health technical memorandum: safe management of healthcare waste. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/167976/HTM_07-01_Final.pdf (accessed 25 August 2021).

Hsu, W.T., Domenech, T., and McDowall, W. (2021). How circular are plastics in the EU?: MFA of plastics in the EU and pathways to circularity. Cleaner Environmental Systems 2, 100004.

Hutchings, N., Smyth, B., Cunningham, E., Yousif, M., and Mangwandi, C. (2021). Comparative life cycle analysis of a biodegradable multilayer film and a conventional multilayer film for fresh meat modified atmosphere packaging – and effectively accounting for shelf-life. Journal of Cleaner Production, 327, 129423.

ICPO-INTERPOL (2020). Strategic Analysis Report: Emerging criminal trends in the global plastic waste market since January 2018. The International Criminal Police Organization-INTERPOL. https://www.interpol.int/en/News-and-Events/News/2020/INTERPOL-report-alerts-to-sharp-rise-in-plastic-waste-crime (accessed 15 June 2021).

IMF (2019). World Economic Outlook, October 2019. Global Manufacturing Downturn, Rising Trade Barriers. International Monetary Fund. https://www.imf.org/en/Publications/WEO/Issues/2019/10/01/world-economic-outlook-october-2019 (accessed 10 May 2021).

ISO 14040:2006. Environmental management-Life cycle assessment-Principles and framework. https://www.iso.org/standard/37456.html (accessed 25 August 2021).

ISO 14044:2006. Environmental management-Life cycle assessment-Requirements and guidelines. https://www.iso.org/standard/38498.html (accessed 25 August 2021).

IVL Report E006 (2012). National waste management review Sweden Germany Denmark Finland. RECO Baltic 21 Tech project. https://www.ivl.se/download/18.34244ba71728fcb3f3fb34/1591706118944/E006.pdf (accessed 10 May 2021).

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., and Law, K.L. (2015). Plastic waste inputs from land into the ocean. Science 347, 768–771.

Jang, Y.-C., Lee, G., Kwon, Y., Lim, J., and Jeong, J. (2020). Recycling and management practices of plastic packaging waste towards a circular economy in South Korea. Resources, Conservation and Recycling 158, 104798.

Jeswani, H.K., Chilvers, A., and Azapagic, A. (2020). Environmental sustainability of biofuels: a review. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 476, 20200351.

Jiang, X., Wang, T., Jiang, M., Xu, M., Yu, Y., Guo, B., Chen, D., Hu, S., Jiang, J., Zhang, Y., et al. (2020). Assessment of Plastic Stocks and Flows in China: 1978-2017. Resources, Conservation and Recycling 161.

Kakadellis, S., and Harris, Z.M. (2020). Don't scrap the waste: The need for broader system boundaries in bioplastic food packaging life-cycle assessment – A critical review. Journal of Cleaner Production 274, 122831.

Kawecki, D., Scheeder, P.R.W., and Nowack, B. (2018). Probabilistic Material Flow Analysis of Seven Commodity Plastics in Europe. Environmental Science and Technology 52, 9874–9888.

Klinglmair, M., Lemming, C., Jensen, L.S., Rechberger, H., Astrup, T.F., and Scheutz, C. (2015). Phosphorus in Denmark: National and regional anthropogenic flows. Resources, Conservation and Recycling 105, 311–324.

Laner, D., Feketitsch, J., Rechberger, H., and Fellner, J. (2015). A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and its Application to Plastics Flows in Austria. Journal of Industrial Ecology 20, 1050–1063.

Llatas (2011). A model for quantifying construction waste in projects according to the European waste list. Waste Management 31 1261–1276.

Lloyd, S. M. and Ries, R (2007). Characterizing, propagating, and analyzing uncertainty in life-cycle assessment: a survey of quantitative approaches. Journal of Industrial Ecology, 11(1):161179.

Lombardi, M., Rana, R., and Fellner, J. (2021). Material flow analysis and sustainability of the Italian plastic packaging management. Journal of Cleaner Production 287, 125573.

Lynch, D.H.J., Klaassen, P., and Broerse, J.E.W. (2017). Unraveling Dutch citizens' perceptions on the bio-based economy: The case of bioplastics, bio-jetfuels and small-scale bio-refineries. Industrial Crops and Products 106, 130–137.

Maisel, F., Chancerel, P., Dimitrova, G., Emmerich, J., Nissen, N.F., and Schneider-Ramelow, M. (2020). Preparing WEEE plastics for recycling – How optimal particle sizes in pre-processing can improve the separation efficiency of high quality plastics. Resources, Conservation and Recycling 154, 104619.

Mashek, W., Holmes, K., Martin, K., 2016. Automotive Recycling: Devalued is now Revalued. SPI: The Plastics Industry Trade Association. https://www.plasticsindustry.org/sites/default/files/2016-03256-SPI-PMW-Auto-Recycle-web.pdf (accessed 25 August 2021).

Mehta, N., Cunningham, E., Roy, D., Cathcart, A., Dempster, M., Berry, E., and Smyth, B.M. (2021). Exploring perceptions of environmental professionals, plastic processors, students and consumers of bio-based plastics: Informing the development of the sector. Sustainable Production and Consumption 26, 574–587.

Millette, S., Williams, E., and Hull, C.E. (2019). Materials flow analysis in support of circular economy development: Plastics in Trinidad and Tobago. Resources, Conservation and Recycling 150, 104436.

MOE Japan (2018). Japan's Resource Circulation Policy for Plastics. Ministry of the Environment, Japan. https://ec.europa.eu/environment/international_issues/pdf/S2-02-Yusuke%20Inoue.pdf (accessed 10 May 2021).

MOE Japan (2019). Japan Ministry of the Environment Establishing a Sound Material-Cycle Society and Measures to Address Marine Litter V.20 Japan Environment Quarterly.

Moshood, T.D., Nawanir, G., Mahmud, F., Mohamad, F., Ahmad, M.H., and Abdul Ghani, A. (2021). Expanding Policy for Biodegradable Plastic Products and Market Dynamics of Bio-Based Plastics: Challenges and Opportunities. Sustainability 13, 6170.

Nakashima, E., Isobe, A., Kako, S., Itai, T., and Takahashi, S. (2012). Quantification of Toxic Metals Derived from Macroplastic Litter on Ookushi Beach, Japan. Environmental Science and Technology 46, 10099–10105.

Nakatani, J., Maruyama, T., and Moriguchi, Y. (2020). Revealing the intersectoral material flow of plastic containers and packaging in Japan. PNAS 117, 19844–19853.

National People's Congress (2021). The Fourteenth Five-Year Plan for National Economic and Social Development of the People's Republic of China and the Outline of Long-Term Goals for 2035. In Chinese. http://www.xinhuanet.com/fortune/2021-03/13/c_1127205564.htm (accessed 31 August 2021).

NICEI (2020). NI Composite Economic Index. Northern Ireland Statistics and Research Agency. https://www.nisra.gov.uk/statistics/economic-output-statistics/ni-composite-economic-index (accessed 18 May 2020).

NICVA (2016). Details of illegal dumps investigated by NIEA Environment Crimes Unit 2006-15. Northern Ireland Council for Voluntary Action, Belfast. https://data.nicva.org/dataset?query=illegal+dumps&sort_by=created&sort_order=DESC (accessed 15 June 2021).

NIPA (2021). The Northern Ireland Polymers Association. https://polymersni.com/our-members/ (accessed 18 May 2020).

OECD (2016). Extended Producer Responsibility: Updated Guidance for Efficient Waste Management, OECD Publishing, Paris. https://doi.org/10.1787/9789264256385-en (accessed 25 August 2021).

Olatayo, K.I., Mativenga, P.T., and Marnewick, A.L. (2021). Comprehensive evaluation of plastic flows and stocks in South Africa. Resources, Conservation and Recycling 170, 105567.

Osman, A.I., Mehta, N., Elgarahy, A.M., Al-Hinai, A., Al-Muhtaseb, A.H., and Rooney, D.W. (2021). Conversion of biomass to biofuels and life cycle assessment: a review. Environmental Chemistry Letters.

Papineschi, J., Hogg, D., Chowdhury, T., Durrant, C., and Thomaon A. (2019). Analysis of Nordic regulatory frame work and its effect on waste preven tion and recycling in the region. https://www.compostnetwork.info/wordpress/wp-content/uploads/EUNOMIA-study-on-Nordic-Nations.pdf (accessed 18 May 2020).

Percival, A. (2019). Not so fantastic plastic. https://nhsproviders.org/news-blogs/blogs/not-so-fantastic-plastic#:~:text=The%20NHS%20disposes%20of%20around,plastic%20waste%20being%20currently%20recovered.&text=It%20comes%20in%20the%20packaging,and%20the%20plastic%20products%20themselves (accessed 18 May 2020).

Picuno, C., Alassali, A., Chong, Z.K., and Kuchta, K. (2021). Flows of post-consumer plastic packaging in Germany: An MFA-aided case study. Resources, Conservation and Recycling 169, 105515.

Pivnenko, K., Eriksen, M.K., Martín-Fernández, J.A., Eriksson, E., and Astrup, T.F. (2016). Recycling of plastic waste: Presence of phthalates in plastics from households and industry. Waste Management 54, 44–52.

PlasticsEurope (2018). Plastics - the Facts 2018. https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf (accessed 18 May 2020).

Prata, J.C., da Costa, J.P., Lopes, I., Duarte, A.C., and Rocha-Santos, T. (2020). Environmental exposure to microplastics: An overview on possible human health effects. Science of The Total Environment 702, 134455.

QGIS (2019). QGIS version 3.4.5. https://qgis.org/downloads/

Qureshi, M.S., Oasmaa, A., Pihkola, H., Deviatkin, I., Tenhunen, A., Mannila, J., Minkkinen, H., Pohjakallio, M., and Laine-Ylijoki, J. (2020). Pyrolysis of plastic waste: Opportunities and challenges. Journal of Analytical and Applied Pyrolysis 104804.

Ragaert, K., Delva, L., and Van Geem, K. (2017). Mechanical and chemical recycling of solid plastic waste. Waste Management 69, 24–58.

RES148-001 (2011). Construction, demolition and excavation waste arisings, use and disposal in Northern Ireland 2009/10. Waste and Resources Action Programme. https://www.daera-ni.gov.uk/publications/construction-demolition-and-excavation-waste-arisings-use-and-disposal-northern-ireland (accessed 18 May 2020).

Resource Futures (2012). SPMT12_002: The Market Potential and Demand for Product Re-use. Product module: Furniture. https://www.furniturebank.org/the-market-potential-and-demand-for-furniture-re-use-in-uk/ (accessed 23 December 2020).

Rhein, S., and Sträter, K.F. (2021). Corporate self-commitments to mitigate the global plastic crisis: Recycling rather than reduction and reuse. Journal of Cleaner Production 296, 126571.

Ritchie, H., and Roser, M. (2018). Plastic Pollution. Our World in Data.

rx3 (2011). The Irish Recycled Plastic Waste Arisings Study. https://www.dccae.gov.ie/documents/The%20Irish%20Recycled%20Plastic%20Waste%20Arisings%20Study.pdf (accessed 23 December 2020).

Simon, J. M. (2019). A Zero Waste hierarchy for Europe. New tools for new times. From waste management to resource management. Zero Waste Europe. https://zerowasteeurope.eu/2019/05/a-zero-waste-hierarchy-for-europe/ (accessed 23 December 2020).

Sophonrat, N., Sandström, L., Svanberg, R., Han, T., Dvinskikh, S., Lousada, C.M., and Yang, W. (2019). Ex situ catalytic pyrolysis of a mixture of polyvinyl chloride and cellulose using calcium oxide for hcl adsorption and catalytic reforming of the pyrolysis products. Industrial and Engineering Chemistry Research 58, 13960–13970.

STAN (2012). subSTance flow ANalysis (STAN) software version 2.6.801. Published by Vienna University of Technology, Vienna, Austria. https://www.stan2web.net/

Statista (2021). Production of plastics worldwide from 1950 to 2019 (in million metric tons)*. https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/ (accessed 23 December 2020).

TEPPFA (2019). Plastic pipes combine flexibility and strength. The European Plastic Pipes and Fittings Association. https://www.teppfa.eu/latest-news/why-flexibility-is-essential-in-pipes/ (accessed 18 August 2021).

The Agreement (1998). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/136652/agreement.pdf (accessed 23 December 2020).

The Northern Ireland Protocol (2020). The Northern Ireland Protocol. https://www.gov.uk/government/publications/the-northern-ireland-protocol (accessed 18 May 2021).

The Waste Management Licensing Regulations (Northern Ireland) (2003). Statutory Rules of Northern Ireland 2003, no. 493. https://www.legislation.gov.uk/nisr/2003/493/introduction/made (accessed 18 August 2021).

The Waste Electrical and Electronic Equipment Regulations (2013). Statutory Instruments 2013 No. 3113 Environmental Protection https://www.legislation.gov.uk/uksi/2013/3113/contents/made (accessed 18 August 2021).

Thompson, R.C., Swan, S.H., Moore, C.J., and vom Saal, F.S. (2009). Our plastic age. Philosophical Transactions of the Royal Society B: Biological Sciences 364, 1973–1976.

Turner, A., and Holmes, L.A. (2015). Adsorption of trace metals by microplastic pellets in fresh water. Environ. Chem. 12, 600–610.

UKFPRS Ltd (2020). Company files. https://find-and-update.company-information.service.gov.uk/company/12591824 (accessed 25 August 2021).

UK GOV (n.d.). Population estimates. Annual data provided by Office for National Statistics https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates (accessed 23 December 2020).

UK GOV (2019). Restrictions to be extended on products containing plasticising chemicals. https://www.gov.uk/government/news/restrictions-to-be-extended-on-products-containing-plasticising-chemicals#:~:text=Restrictions%20to%20be%20extended%20on%20products%20containing%20plasticising%20chemicals,-Restrictions%20on%20phthalates&text=The%20changes%20also%20include%20the,market%20from%2022%20July%202019. (accessed 23 December 2020).

Van Eygen, E., Feketitsch, J., Laner, D., Rechberger, H., and Fellner, J. (2017). Comprehensive analysis and quantification of national plastic flows: The case of Austria. Resources, Conservation and Recycling 117, 183–194.

Van Eygen, E., Laner, D., and Fellner, J. (2018). Circular economy of plastic packaging: Current practice and perspectives in Austria. Waste Management 72, 55–64.

Walker, A.M., Opferkuch, K., Roos Lindgreen, E., Raggi, A., Simboli, A., Vermeulen, W.J.V., Caeiro, S., and Salomone, R. (2021). What Is the Relation between Circular Economy and Sustainability? Answers from Frontrunner Companies Engaged with Circular Economy Practices. Circular Economy and Sustainability.

WasteDataFlow (n.d.). Information validated by the WasteDataFlow team and the Environment Agency. https://www.wastedataflow.org/ (accessed 23 December 2020).

WRAP (2006). UK Plastics Waste – A review of supplies for recycling, global market demand, future trends and associated risks. Waste and Resources Action Programme. https://www.wrap.org.uk/sites/files/wrap/UK%20Plastics%20Waste.pdf (accessed 23 December 2020).

WRAP (2012a). Composition and re-use potential of household bulky waste in the UK. Waste and Resources Action Programme. https://www.wrap.org.uk/sites/files/wrap/UK%20bulky%20waste%20summary.pdf (accessed 23 December 2020).

WRAP (2012b). Valuing our clothes: the evidence base. Waste and Resources Action Programme. https://www.wrap.org.uk/sites/files/wrap/VoC%20FINAL%20online%202012%2007%2011.pdf (accessed 23 December 2020).

WRAP (2016). The Materials Recovery Facilities (MRFs) Sorting Guide. Waste and Resources Action Programme. https://wrap.org.uk/resources/case-study/materials-recovery-facilities-mrfs-sorting-guide#download-file (accessed 25 August 2021).

WRAP (2017). Materials Pricing Report. Waste and Resources Action Programme. https://wrap.org.uk/resources/report/materials-pricing-report (accessed 23 December 2020).

WRAP (2018). The UK Plastics Pact. Waste and Resources Action Programme. https://wrap.org.uk/content/the-uk-plastics-pact (accessed 23 December 2020).

WRAP (2019). Plastics market situation report. Waste and Resources Action Programme. http://www.wrap.org.uk/sites/files/wrap/WRAP_Plastics_market_situation_report.pdf (accessed 23 December 2020).

WRAP (2020a). National municipal commercial waste composition, England 2017. Waste and Resources Action Programme. https://wrap.org.uk/sites/files/wrap/National%20municipal%20waste%20composition_%20England%202017.pdf (accessed 23 December 2020).

WRAP (2020b). Recycling Tracker Report 2020: Behaviours, attitudes and awareness around recycling. Waste and Resources Action Programme. https://wrap.org.uk/resources/report/recycling-tracker-report-2020-behaviours-attitudes-and-awareness-around-recycling (accessed 10 May 2021).

WRAP CYMRU (2020). Commercial and industrial waste in Wales, prepared by Resource Futures. Waste and Resources Action Programme. https://www.wrapcymru.org.uk/reports/composition-analysis-commercial-and-industrial-waste-wales (accessed 23 December 2020).

WRAP-WEEE (n.d.). WEEE recovery in the UK: the current situation and the road ahead. Waste and Resources Action Programme. http://waste-prevention.gr/waste/wp-content/uploads/2015/10/WEEE%20recovery%20UK-The%20Current%20Situation%20Road%20Ahead_EN.pdf (accessed 23 December 2020).

Zero Waste Scotland (2020). A Market Analysis of Farm Film Plastics. Zero Waste Scotland. https://www.zerowastescotland.org.uk/sites/default/files/A_Market_Analysis_of_Farm_Film_Plastic_30072020%20Final%20to%20publish.pdf (accessed 25 August 2021).

Zoboli, O., Laner, D., Zessner, M., and Rechberger, H. (2016). Added Values of Time Series in Material Flow Analysis: The Austrian Phosphorus Budget from 1990 to 2011. Journal of Industrial Ecology 20, 1334–1348.