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Post-consumer plastic packaging waste in England: Assessing the yield of multiple collection-recycling schemes

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ABSTRACT

The European Commission (EC) recently introduced a 'Circular Economy Package', setting ambitious recycling targets and identifying waste plastics as a priority sector where major improvements are necessary. Here, the authors explain how different collection modalities affect the quantity and quality of recycling, using recent empirical data on household (HH) post-consumer plastic packaging waste (PCPP) collected for recycling in the devolved administration of England over the quarterly period July-September 2014. Three main collection schemes, as currently implemented in England, were taken into account: (i) kerbside collection (KS), (ii) household waste recycling centres (HWRCs) (also known as 'civic amenity sites'), and (iii) bring sites/banks (BSs). The results indicated that: (a) the contribution of KS collection scheme in recovering packaging plastics is higher than HWRCs and BBs, with respective percentages by weight (wt %) 90%, 9% and 1%; (b) alternate weekly collection (AWC) of plastic recyclables in wheeled bins, when collected commingled, demonstrated higher yield in KS collection; (c) only a small percentage (16%) of the total amount of post-consumer plastics collected in the examined period (141 kt) was finally sent to reprocessors (22 kt); (c) nearly a third of Local Authorities (LAs) reported insufficient or poor data; and (d) the most abundant fractions of plastics that finally reached the reprocessors were mixed plastic bottles and mixed plastics.

1. Introduction

Since the Packaging and Packaging Waste (PPW) Directive came into force (Directive 94/62/EC), European Union (EU) member states have made major investments in their recycling systems, e.g. collection schemes, sorting and reprocessing equipment and infrastructure. However, although the recovery and recycling targets set in the PPW Directive are similar for all member states, the operational strategies for achieving them vary considerably from country to country (da Cruz et al., 2014a, 2014b; European Commission, 2006; Marques et al., 2014). According to the extended producer responsibility (EPR) principle (an overriding principle of the PPW Directive), all economic operators placing packaging on the market are responsible for its management and recovery (OECD, 2001). Producers of packaging waste can transfer this responsibility to another entity (e.g. a Green Dot company) and by paying a financial contribution earn the right to put a "Green Dot" trademark on their packaging.

The PPW Directive and associated recycling targets updated in 2004 (European Commission, 2004), to encourage packaging re-use and recycling, do not stray from the original objectives. In particular, the Directive specifies essential requirements for the design, production, and commercialization of packaging that enable their reuse, recovery and recycling, minimizing their impact on the environment.

Abbreviations: approx, Approximately; AWC, Alternated weekly collection; BSs, Bring sites; C&I, Commercial & industrial; ca., Circa (Latin term for "approximately" or "about"); Coll, Collected; Cx, Commingled with a separate stream of glass (g), fiber/paper (q), plastic (p) within the commingled; Cxx, Commingled with two separate streams within the commingled; DEFRA, Department for environment, food and rural affairs; EC, European Commission; EfW, Energy from waste; EPR, Extended producer responsibility; EU, European Union; FCM, Food contact materials; HDPE, High-density polyethylene; HH, Household; HWRC, Household waste recycling centres; KS, Kerbside; KSS, Kerbside sort; kt, Kilotonnes; LAs, Local authorities; MBT, Mechanical-biological treatment; MC, Multi-commingled (more than three streams within the commingled); MRFs, Material recovery facilities; NPP, Nuclear power plant; PCPP, Post-consumer plastic packaging; PET, Polyethylene terephthalate; PO, Polyolefins; PPW, Packaging and packaging waste directive; PRFs, Plastic recovery facilities; PTTs, Pots, tubs and trays; RCV, Refuse collection vehicle; RECOUP, Recycling of used plastics (Limited); UK, United Kingdom; WCAs, Waste collection authorities; WDAs, Waste disposal authorities; WDF, Waste data flow; WFD, Waste framework directive; WRAP, Waste and resources action programme; wt%, percentage by weight.

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Furthermore, the EU Waste Framework Directive 2008/98/EC (WFD) requires member states to apply the EU Waste Hierarchy and achieve two recycling and recovery targets by 2020: (a) reuse and recycle at least 50% of household (HH) waste and (b) prepare for reuse, recycling and other recovery at least 70% of construction and demolition waste (European Commission, 2008; Gharfalkar et al., 2015; Waite et al., 2015).

The recycling of plastic packaging waste is regarded to be an important prerequisite for its diversion from landfill and the biosphere, and the generation of a recognizable high-quality secondary material (PlasticEurope, 2012). Although, there is a general agreement that the 'clean' fractions of plastic polymers should be recycled, there is still debate on how to properly manage the mixed and/or contaminated ("dirty") waste plastics found in waste (Astrup et al., 2009; Lazarevic et al., 2010; Rigamonti et al., 2014). To achieve mono-material flows of secondary raw material from post-consumer plastic packaging (PCPP) waste, such fractions need to be sorted out of the HH waste (Groot et al., 2014). Matching the large variety of materials and substances that constitute PCPP (and the impurities it may contain) with the correct combination of available sorting and processing technologies to deal with them, render its effective recycling complex and challenging (Feil et al., 2017; Thoden van Velzen et al., 2013; Thoden van Velzen et al., 2016; Velis and Brunner, 2013; WRAP, 2013).

Recognising the need for high quality recycling as an effort to increase circularity and recovery of resources from waste, the present work focuses on the various collection schemes that are implemented in England, and in particular how current practices affect the recovery of PCPP waste (Feil et al., 2017; Ragossnig and Schneider, 2017; Velis, 2015).

The aims of the present study are: (a) to analyse the collection performance of the different schemes adopted by the waste collection authorities (WCAs) (mostly known as local authorities (LAs)) that operate in England, with specific focus on PCPP waste; (b) to compare the quantities of PCPP recovered from the various collection schemes and examine the proportion that reach material recovery facilities (MRFs) and reprocessors (plastic recovery facilities, PRFs) and (c) determine the final quantity and most abundant types of plastics that are, in fact, recycled, as a function of the collection scheme implemented.

2. Background on UK recycling collection schemes

Three main collection schemes, currently in use in the UK, are: (a) kerbside collection (KS), (b) household waste recycling centres or civic amenity sites (HWRCs) and (c) bring sites/banks (BSs). A detailed description of the collection schemes is presented below.

2.1. KS collection

KS collection involves LAs, paid contractors or permitted private business/charity collecting waste intended for recycling directly from HHs. Recently, there has been a degree of convergence in the detailed practical operations (e.g. how waste is sorted by the householder and the frequency with which it is collected). This can be mainly attributed to the government-funded Waste and Resources Action Programme (WRAP) creating performance benchmarks and guides for LAs (Defra, 2013). Jenkins et al. (2003) reported that LAs doubled their collection rate (by weight) with the introduction of KS collection as opposed to relying on householders to take recyclable materials to a specified collection point (Jenkins et al., 2003). It is also reported that the degree of effective source separation is a critical factor in achieving targets such as "50% recycling of HH waste by 2020" (Cole et al., 2014). It is noteworthy that the majority of English LAs operate separate collections of recyclables and residual waste (the fraction of waste that cannot be recycled) (WRAP, 2009a, b).

There are three broad subsets of this type of collection, as follows:

- KS sort (KSS), where the collection of dry recyclables takes place in containers (mostly boxes, bags or sacks) which is then hand sorted by collection operatives into a refuse collection vehicle (RCV) that has multiple compartments for the various collected materials.
- KS single stream commingled or fully commingled (C), where the collection of all dry recyclables occurs together in one container and then transferred into a standard RCV with only one compartment. In turn, there is subsequent sorting at a MRF and in some cases there is an intermediate stop at a transfer/bulking station. After sorting, the final destination is the reprocessors, though part of the stream can be converted to energy, depending on the quality (Cimpan et al., 2015).
- KS dual or three (multi) stream commingled (Cx, Cxx, MC), where the collection of commingled materials takes place in one stream, while a separate stream is used for one or more other dry recyclates (Cimpan et al., 2015). Usually, two containers with two compartments in the RCV are used to maintain separation (split body RCV). The commingled stream is then sent to a MRF for sorting.

More details on the various collection modes (abbreviations also defined) that operate under the KS collection scheme are also shown in Table 1.

2.2. HWRCs

HWRCs serve as an alternative and/or support to KS collection. They are large facilities that usually reside within a community to which householders can take their waste. Items that are too costly for LAs to collect routinely via KS are often received at the HWRCs. These include building waste, green (garden) waste and even dry recyclables not collected via KS owing to omissions by householders or contractors.

Limited relevant literature is available regarding the collection rate performance of HWRCs. Parfitt et al. (2001) assessed the effects of container use on refuse and recycling collection in rural and urban classified areas in the UK and suggested that the contribution of HWRCs to collection was 16%, and was mostly attributed to green waste (Parfitt et al., 2001). Other studies on recycling via HWRCs focused on the collection of bulky waste, optimisation of parameters involved in this kind of collection scheme, or the

Table 1
Code description for the various collection streams that operate under the KS collection scheme.

Symbol	Terminology	Description
C	Commingled	(Single stream)
g	Separate Glass Stream	Separate Glass Stream, within the commingled dual or 3 stream collection scheme
p	Separate Plastic Stream	Separate Plastic Stream, within the commingled dual or 3 stream collection scheme
q	Separate Paper/ Fiber Stream	Separate Paper/Fiber Stream, within the commingled dual or 3 stream collection scheme
MC	Multi Stream Commingled	Either 2 or more commingled collection separated according to fiber and containers or other
KSS	Kerbside Sort	Collection of dry recyclables in containers (mostly boxes, bags or sacks) with further hand sorting into a RCV with multiple compartments for the various collected materials

responsiveness of the staff on site and how this affects collection/drop-offs (Curran et al., 2007; Maynard et al., 2009; Williams and Taylor, 2004; Woodard et al., 2004). Detailed data on the relevant legislation, up to date statistics on HWRCs provision and evidence-based approaches to assessing and improving their performance can be found in the relevant WRAP reports (WRAP, 2012, 2014a).

2.3. BSs

BSs are smaller, strategically located in target areas with high foot traffic like supermarkets or leisure facilities, where the public can place recyclables in an effortless manner. These sites collect recyclable materials such as cans, glass bottles, plastic bottles, plastic carrier bags etc. They can be commingled, but the amendment on collection set by the WFD restricts it (European Commission, 2008).

As with HWRCs, limited literature is available on BSs, regarding particular amounts on the breakdown of their contributions or quantifying any rejections due to contamination. Again, WRAP annual reports are the most relevant data source (WRAP, 2009a, b, 2014b, 2015a).

2.4. Frequency of collection

Another factor that critically affects the amount of PCPP waste collected is the frequency of collection. Most LAs that operate in England use alternate weekly collection (AWC) across all schemes (also known as ‘fortnightly collection’). Residual waste destined for landfill or energy from waste (EfW) plants or mechanical-biological treatment (MBT) plants, is collected on the one week and dry recyclables the week after (European Parliament, 2013; Parfitt and Bridgewater, 2011). However, some LAs maintain fortnightly collection of refuse, but collect recyclables on a weekly basis (WRAP, 2009a). Restricting refuse collection in this way has been shown to promote recycling activities and increase recycling rates (Williams and Cole, 2013).

2.5. Contamination, quality and types of recyclables

Recycling efficiency is highly dependent on the quality of the dry recyclable input materials (Velis and Brunner, 2013). In general, high quality secondary materials can support “closed loop” recycling, as they can directly substitute virgin materials, while lower quality materials will normally be “cascaded” into lower value applications. However, the quality of materials collected can be easily affected by contamination introduced at various stages of the segregation at source, collection and sorting/recycling processes (e.g. food contact materials (FCM) and/or cosmetics plastic packaging). In some cases, as it happens with polyolefins (PO), contamination can also occur during the first use (e.g. food component sorption by the packaging) and/or during storage (prior to the implementation of any recycling process), thereby making closed loop recycling for PO rather impossible.

WRAP (2015b) defines contamination during recycling as “unwanted or non-target material within the commingled recycling including liquids and food within target material” (WRAP, 2015b). This broad definition generally manifests one of the following:

- Contamination with non-recyclable materials that should be in the residual waste stream (i.e. black bin);
- Contamination with non-targeted materials being erroneously collected, e.g. by householder putting glass in recycling containers even though their WCA does not collect this material;
- Targeted materials collected but contaminated with liquids, oils or putrescibles, e.g. food residues.

Contamination during KS processes is usually associated with incorrect segregation by householders, who are then encouraged to re-segregate their waste for the next collection. Contamination noticed post-KS, HWRC or BS i.e. during the offloading of a RCV may potentially lead to rejection of the whole load either to landfill or to another MRF (“dirty” MRFs) that can sort the waste. Finally, contamination that evades the MRFs pre-sorting procedures can not only affect the quality of the dry recyclables, but also damage facilities (mechanical sorting equipment), leading to further rejection by the reprocessors.

The quality of the recyclates obtained from the various collection schemes is debated by many parties involved in recycling. KS is normally considered to produce the highest quality recyclables in comparison to other schemes. The Department for Environment, Food and Rural Affairs (Defra) advises that source separation of recyclables increases the value of recycling and lowers costs and environmental impact (Defra, 2005). This view is mirrored by WRAP who identify that: the quality of recyclates obtained with KS is more reliable compared to other schemes; there is a lower net cost involved (WRAP, 2009a) and have lower rejection rate in MRFs than commingled waste (WRAP, 2009b). Other advantages of KS collection scheme, include higher portion of collected recyclables that are, actually, recycled and ability to diversify to collection of other types of materials.

Other investigators come to different conclusions. Some report that source-separated and commingled collection produce comparable quality recyclates (Feil et al., 2017; Luijsterburg and Goossens, 2014), or that higher total collection yields of dry recyclables are obtained via commingled rather than separate collection (WYG, 2011).

Consequently, LAs are often left with an unclear choice regarding how quality vs. quantity of recyclables can be optimised so as to achieve their recycling targets. The purpose of this study is to provide some clarity and shed some light regarding the effect of the various collection methods on the quantity and types of recyclates obtained.

3. Methodology and data sources

The waste data flow (WDF) database (WasteDataFlow, 2015) that archives quarterly data reported by all LAs and waste disposal authorities (WDAs) on waste collected and processed in the UK, was used as the primary source of data. WDF contains data on population, number of HHs and weight of all materials collected from HH and non-HH sources in each LA. Annual plastic waste arisings were calculated based on Defra latest statistics on packaging waste for years 2012–2014, assuming an even quarterly distribution throughout the year 2014, which was estimated at 555 kt (Defra, 2016). The total amounts of plastics collected in England during the examined period were calculated at 131 kt (for KS), 8 kt (for HWRCs) and 2 kt (for BSs), respectively; thus a total of 141 kt. This amount accounts for only 25.5% of the plastic waste generated in England; the majority of plastics (approx. 55%) end up in the residual waste stream, for disposal to landfills, EfW and/or MBT plants;, with the remaining 19.5% estimated to be disposed as litter (street or marine litter).

Data was obtained for 320 LAs in England, including the 6 unitary counties and the City of London (WasteDataFlow, 2015). Further details on the type of plastic recyclables collected, materials collected commingled with plastics, containers used to store plastic recyclables for collection and frequency of collection were obtained from the LA’s individual websites.

The collection methods considered here were KS, BSs and HWRCs. Waste data obtained also included information on waste flows from street recycling bins, but their contribution to the overall collected amount was found to be negligible.

The compositional analysis of commingled material input and output in MRFs, performed by WRAP, was used to determine the amount and distribution of plastics in the commingled stream for each of the LAs commingled weight; thus, approx. 17% of the commingled stream consists of plastics; 7% plastic bottles, 4% pots, tubs and trays (PTTs), 3% plastic films (WRAP, 2015b), 2% plastic fines (plastic particles < 45 mm) and 1% non-packaging plastics and liquids (WRAP, 2015b). However, given that approx. 75% of inputs to MRFs come from HH waste, and 25% from commercial and industrial (C&I) waste (Tolvik-Consulting, 2011; WRAP, 2007), for every 100 t of waste presented at a MRF (rounding to the nearest 1 t), the HH waste stream was estimated to consist of 7 t of bottles, 4 t of PTTs, 3 t of films and 62 t of other waste, while the C&I stream will consist of 2 t plastic fines, 1 t NPP and 21 t of other waste; i.e., the HH waste stream is enriched in plastics compared to the C&I stream. Thus, a fully commingled HH waste stream intended for MRF will be 9.2% bottles, 5.3% PTTs and 3.9% films; a total of 18.4% plastics. This is the calculation basis followed in the detailed methodological approach of the descriptive statistics presented in Section 4.2.1.

Descriptive statistics were performed for various examined variables along with comparisons by relevant categorical factors (e.g. per type of collection scheme) and groupings of cases (e.g. regional overviews). Results were analysed in order to reveal patterns and to formulate any hypotheses on the interdependence of waste plastics collection schemes and their potential to increase the amount of PCPP waste collected for recycling. All the major findings are presented and discussed in Section 4.

4. Results and discussion

4.1. Distribution of collection schemes in LAs in England

Out of the 320 LAs in England, 315 operate a KS collection (either individually or in combination with HWRC and/or BSs), which represents approx. 98% of all the LAs that operate in England. About 19% operate only KS, while the rest operate together with either BS or HWRC or with the combination of all three schemes (see Fig. 1a). The remaining 5 LAs either specified that they do not collect plastics of any kind or did not publish the details of materials collected on their websites. However, these 5 LAs operate BSs and/or HWRCs, thus making up for the 1.5% (sum of 0.9%, 0.3% and 0.3%) of the combined collection systems that is depicted in Fig. 1a. This accords with previous UK-focussed analyses, from major English organizations, e.g. RECOUP (RECycling Of Used Plastics), WRAP or WYG (global consulting and advisory company), where the whole of the UK is accounted, providing similarly high contribution of the KS scheme (Recoup, 2014).

As it was explained in Section 2.1, various modes of collection are implemented within the KS collection (Fig. 1b). Over half is simply fully commingled collection (C), a third involves commingled collection with a separate stream of glass, paper and/or plastic (Cx), while the remainder involves other combinations of commingled collection with either two separate material streams (Cxx) or even more streams (multi-commingled, MC) (Table 1). The most prevalent combination of collection system types is the KS and HWRC collection (42.8%), (Fig. 1a). More specifically, 315 LAs have reported to use KS collection, 233 LAs to use HWRC and 122 LAs to use BSs. Furthermore, it was calculated that approx. 99% of total plastics collected came from KS and HWRCs, with the remainder coming from BSs (Fig. 1a).

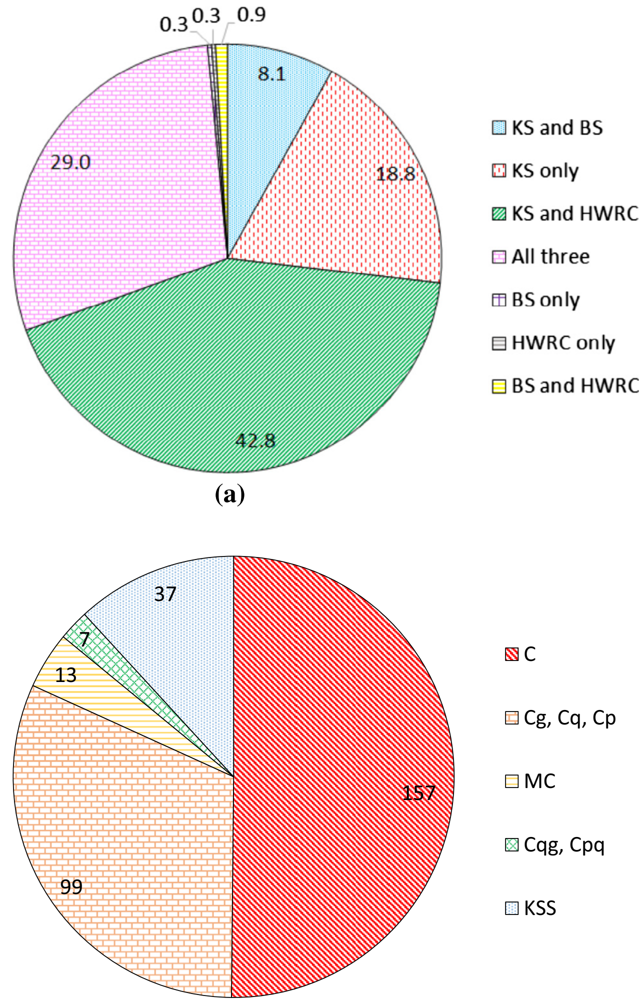

Fig. 1. Distribution percentages of 320 LAs operating (a) with various collection systems and (b) under the KS collection scheme and its variations. The dominance of the KS scheme and the commingled way of collection are obvious. Key: KS: kerbside, HWRC: household waste recycling centres, BS: bring sites, C: commingled, Cg: separate glass stream within the commingled dual or 3 stream collection scheme, Cq: separate fiber/paper stream within the commingled dual or 3 stream collection scheme, Cp: separate plastic stream within the commingled dual or 3 stream collection scheme, Cxx: schemes with 2 separate material streams and a commingled stream under the multi commingled stream, MC: multi commingled stream with either 2 or more commingled collection separated according to fiber and containers or other.

The distribution of the different containers used for the collection of plastics, as well as the distribution of the frequency of collection is shown in Fig. 2. It is apparent that most LAs collect bottles, PTTs and films via wheeled bins (primarily) and sacks (secondarily). Fortnightly collection is the most common.

4.1.1. KS collection

The three main schemes under the KS collection (described in Section 2.1.), as well as any other combination of schemes within this category, were identified and classified using the abbreviations presented in Table 1.

Information on collection schemes for the 313 (out of the 315) LAs were accounted in the present study, since necessary information were missing from the other 2 LAs' websites. As shown in Fig. 1b, about 50% of the LAs (157 out of the 313) collected their plastics fully commingled, while KS sort collection accounted for

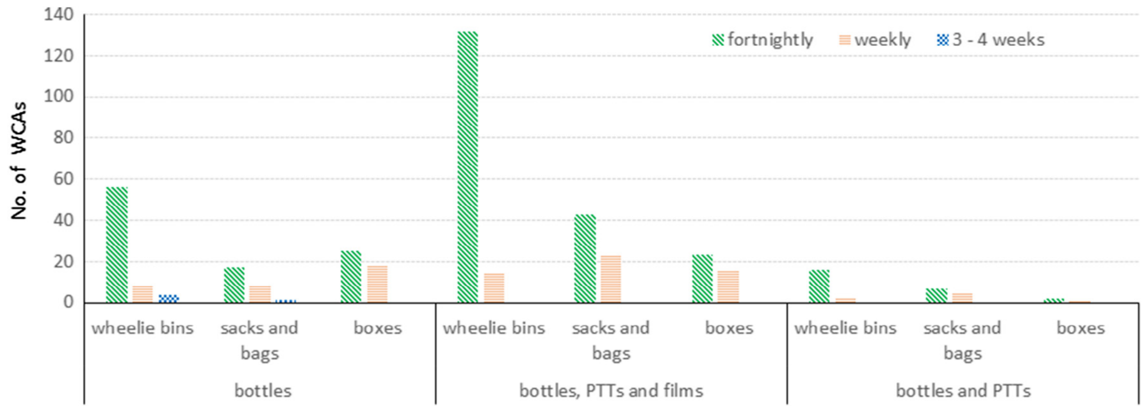

Fig. 2. Distribution of type of containers used, frequency of collection and number of LAs. It is clear that the majority of the LAs collect bottles, PTTs and films, by the use of wheeled bins and sacks, whereas similar number of LAs use boxes for the same type of collection, both fortnightly and weekly.

ca. 12% (37 out of the 313). Overall, 87% of LAs collect their plastics commingled, whereas a mere 13% accounts for a separate collection. This data "reality" is in contrast to the debate statement of "quality vs quantity" that KSS supporters use over commingled collection. Even considering that KSS is a much cheaper option, the final choice, as described in Fig. 1b, would still be commingled collection, most likely because it is more convenient for both HH residents and collection crews.

4.1.2. HWRCs

The 233 LAs that reported operating HWRCs contributed thereby a total of approx. 8 kt of plastics collected over the examined period, around 6% of the grand total. Data on the performance of HWRCs was almost non-existent before the report from the National Assessment of Civic Amenity Sites in 2004, the findings of which (summarised in a WRAP report) indicated 31% recycling rate for English HWRCs, excluding rubble recycling (WRAP, 2012). Later WRAP studies in 2013/2014 report that 697 HWRCs were identified in England (7 less than in previous year), with 76.3% targeting plastics collection and an average recycling rate of 60.1% (WRAP, 2014a).

The contribution of HWRCs is expected to be significant mainly due to their acceptance of items that are not accepted in KS collection, such as bulky items and other plastic items like film and hard plastics (Suffolk Coastal, 2015).

4.1.3. BSs

A total of 122 LAs reported BSs collection quantities, with a recorded number of 1444 BSs operating, collecting plastics either commingled and/or source separated. Some LAs reported only quantities, but omitted the number of existing BSs in their area. The plastic quantities in the commingled collection could not be determined in detail, since this data was not reported; therefore, in order to estimate the amount of plastics, the assumption of the 18.4% of the commingled stream was again adopted. The amount of plastics collected source-separated for the period of the collection was approx. 1 kt, while the amount of the total plastics collected was estimated at almost 2 kt. This amount represents only a mere 1% of the overall collection of plastics (see Fig. 1a). WRAP's BS guidance indicates that the general contribution to collection of BSs has reduced by 31% from 2007 to 2011, with a simultaneous reduction to the contribution to recycling (from 8.1% to 4.7%) during the same period (WRAP, 2014b). Thus, it can be speculated that the contribution of BSs in plastics collection might have reached a plateau and might have become irrelevant to the increased KS collection, unless LAs proceed to a major change in their strategy.

4.2. Descriptive statistics on plastics collection

4.2.1. Detailed methodological approach

Table 2 summarises the amount of plastics sent to recycling by LAs, grouped by collection scheme for the 320 LAs reporting. The 'collected' (Coll) plastics column is taken directly from our database and adds together that collected at the KS and that collected via other schemes (HWRC, BS, etc.), the median and mean values of the latter being 15.8% and 27.3% of the total respectively. This material is assumed to be sent directly for recycling.

The 'MRF' column is calculated using the reported total commingled input (KS plus other, the median and mean of the latter being <1% and 3.2% of the total respectively) sent to a MRF facility in the following manner. As it has already been stated, the total input to MRF is reported by WRAP (2015b), to consist of 17% plastics; 7% bottles, 4% PTTs, 3% films, 2% plastic fines and 1% non-packaging plastics (WRAP, 2015b). However it is known that bottles, PTTs and films overwhelmingly dominate the plastics fraction of HH waste and are largely absent from commercial and industrial

Table 2
Amount of plastics (kg HH^{-1} y^{-1}) sent to recycling by LA reported collection scheme (C, Cg, Cp, etc.) reported via direct collection (Coll) and estimated from MRF inputs and MRFs rejection rates with supporting statistical data (95% confidence in the mean; maximum and minimum; Total = total number of reporting LAs by collection scheme; No data = number of LAs not reporting sufficient data for analysis; Data = number of LAs submitting sufficient data for analysis).

	C		Cg		Cp		Cpq		Cq		Cqg		KSS		MC		Mcg		Other	
	Coll	MRF	Coll	MRF	Coll	MRF	Coll	MRF	Coll	MRF	Coll	MRF	Coll	MRF	Coll	MRF	Coll	MRF	Coll	MRF
Mean	3.1	34.4	1.6	25.6	30.7	n/a	24.9	n/a	4.3	20.2	11.2	5.6	16.7	4.1	4.9	6.6	6.9	n/a	4.0	38.9
±95%	0.8	2.2	0.9	3.7	n/a	n/a	3.7	n/a	1.2	3.2	10.0	1.5	2.5	3.9	2.3	3.8	n/a	n/a	3.1	36.3
Max	24.4	63.4	6.0	48.2	n/a	n/a	26.8	n/a	18.2	43.8	19.9	6.4	33.9	15.6	10.7	17.8	n/a	n/a	9.0	57.4
Min	0.1	5.4	0.1	9.9	n/a	n/a	23.0	n/a	0.1	2.1	2.2	4.9	0.6	0.2	0.3	1.7	n/a	n/a	0.8	20.4
Total	157	157	33	33	1	1	2	2	65	65	5	5	36	36	12	12	1	1	9	9
No data	61	23	14	2	0	1	0	2	25	25	2	3	0	29	3	4	0	1	4	7
Data	96	134	19	31	1	0	2	0	40	40	3	2	36	7	9	8	1	0	5	2

waste, and vice versa (WRAP, 2015b). However, if only certain plastic types are collected for recycling in the commingled stream and the rest are either separated at source or enter the residual waste stream, then the corresponding percentage of plastics in a given commingled stream must be reduced accordingly, e.g. in an authority where only bottles and PTTs are collected in the commingled stream, the percentage of plastics will be 9.2% + 5.3% = 14.5% and so on.

When analysing across multiple LAs with a variety of approaches to collecting plastics, these percentages must be increased by a correction factor so that the overall average composition of the commingled HH waste remains at 18.4% in plastics. This correction factor is equal to 18.4% divided by the average percentage of plastics determined as described above according to the collection practices, and thus will depend on the particular group of LAs analysed (i.e. it is not intrinsic to the model); in this case, the average was 13.2% giving a correction factor of 1.40.

For each LA, the total reported commingled input to the MRF is multiplied by the plastics percentage appropriate to the reported collection details, corrected accordingly, and then multiplied by the pass-through rate (i.e. 1 minus the reported reject rate) for the appropriate facility in each case.

4.2.2. Collection efficacy of the various schemes

The proportion of LAs reporting sufficiently complete data for analysis in accordance with their stated collection scheme is mixed, varying among the four major schemes from over 90% (MRF inputs from Cg, plastics collected for recycling from KSS) to around 60% (MRF inputs from Cq). In total, 97 out of 320 LAs did not report sufficient data to be included in the analysis.

Plastics collection is dominated by a small number of schemes; over half of LAs report collections as fully commingled (C) and a further 40% by just three schemes (Cq, Cg, KSS). Many LAs reported data that might not be expected given their stated collection scheme, e.g. 55% of those reporting as using collection schemes that do not collect plastic at the KS reported data for the amount of plastics sent for recycling, and 29% of those reporting as using fully separated collection reported sending some commingled materials to MRF. In most cases, these are small amounts associated with the non-KS collection schemes. However, 10 of the LAs reporting as collecting fully commingled, reported figures for KS collection of separated plastics, 4 of these in significant amounts over 50 t in the reporting quarter. Similarly, 7 of the LAs reporting as collecting using the KSS scheme, reported collecting significant amounts of commingled waste. This suggests either that LAs are using mixed methods for collecting waste that are not properly characterised by the reporting categories available, and/or that LAs are reporting under the wrong headings. In most cases, it is possible by examining the contextual information associated with the data to infer which of these has occurred, but this requires a subjective assessment and has, thus, not been carried out in this analysis.

The efficacy of the various schemes with regard to plastics recycling (i.e. the plastics recycling yield achieved, in kg HH^{-1} y^{-1}) is also extremely variable, by over two orders of magnitude in many cases. The highest reported yield for direct collection of plastics for recycling was approx. 40 kg HH^{-1} y^{-1} (Royal Borough of Kingston upon Thames, KSS) and the highest estimate for plastics derived from commingled waste sent to MRF was approx. 63 kg HH^{-1} y^{-1} (Ashford Borough Council, C). LAs reporting very low recycling rates are often – but not always – associated with one or more instances of missing data, or again potentially reporting under the wrong categories (see above).

Fig. 3 summarises the efficacy of the various schemes contributing in the recycling of plastic under three categories; those LAs that report KS separation of plastic (*group 1*), those that report collecting fully commingled (*group 2*), and those that report KS separation but not of plastic (*group 3*), with the data split according to whether the plastics sent for recycling is directly collected or derived from a MRF. While those LAs in *group 1* unsurprisingly send the most directly for recycling, the total amount of plastics recycled is exceeded by both other groups. Arguments as to which collection scheme is the most appropriate therefore depend on whether it is preferable to maximise the direct (source separated) collection of plastic (which is perceived by some to provide a better quality recyclate) (Defra, 2005; WRAP, 2009a, b) or the total amount of plastic recycled (commingled collection) (Feil et al., 2017; Luijsterburg and Goossens, 2014; WYG, 2011).

Based on the premise that plastics collected separately from KS and those from BSs and HWRCs provide a better quality recyclate than those derived from MRFs, it was considered useful to look at the distribution of plastics recyclate that is generated via these three options, i.e. KSS, BSs and HWRCs, and via MRFs. Fig. 4

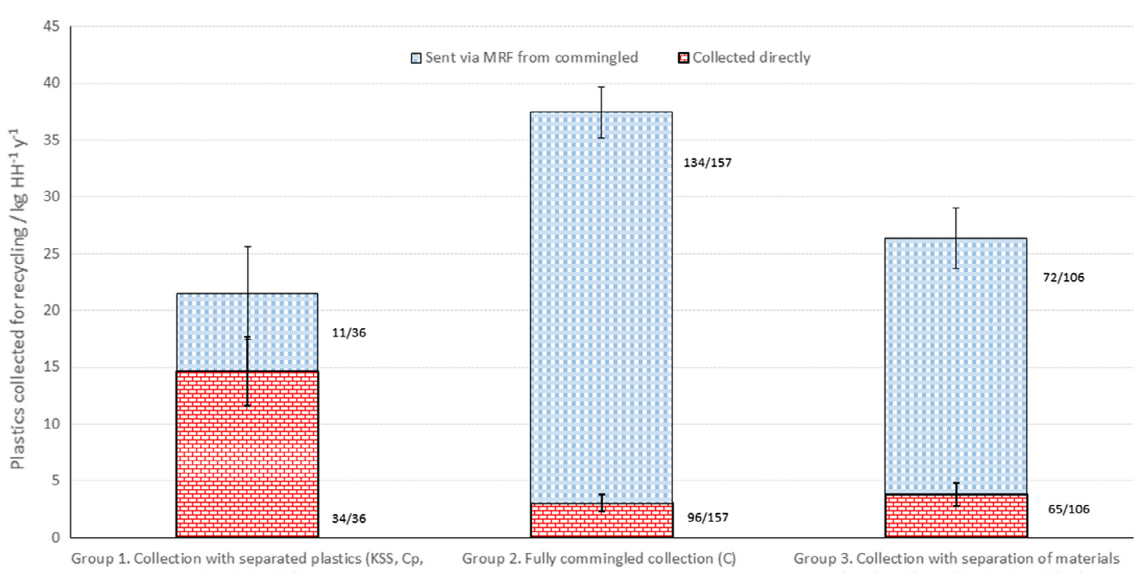

Fig. 3. Plastics collected for recycling by LAs grouped according to collection group scheme. Error bars = 95% confidence in the mean. Legend adjacent to top of columns is number of LAs reporting sufficient data / total number of LAs reporting under each group of collection schemes.

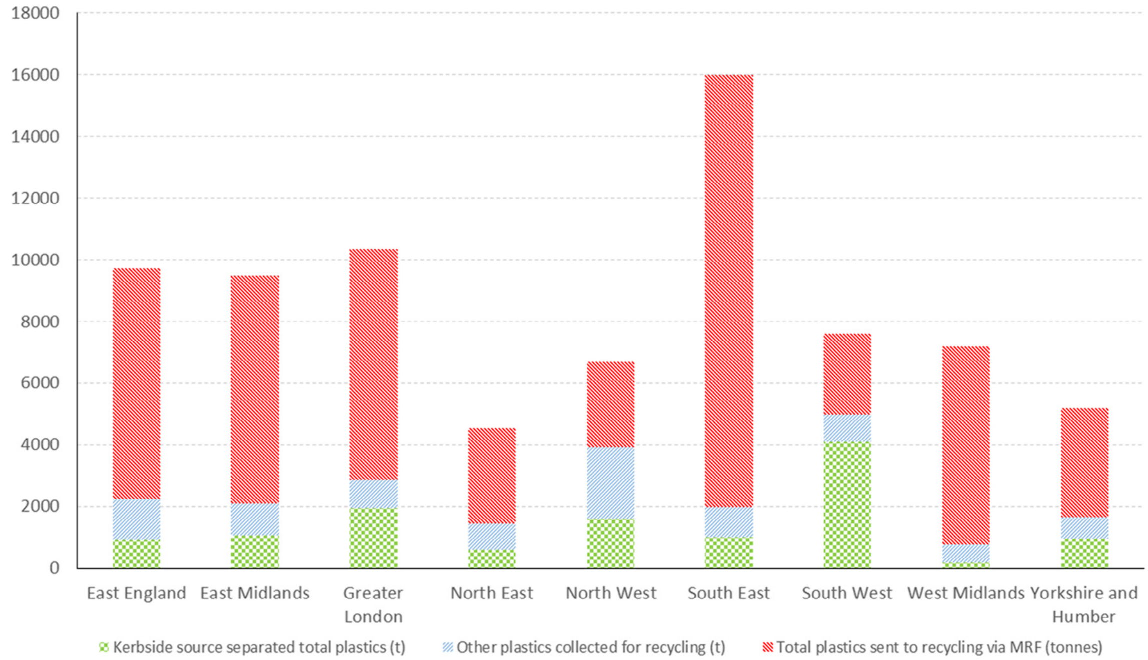

Fig. 4. Distribution of collected plastics per region in England via the KSS scheme, via other-BSs and HWRCs- schemes, and the commingled via MRFs scheme. The abundance of the commingled collection is obvious.

illustrates the quality of plastic recyclate generated in each region via the aforementioned options. The abundant stream of plastic recyclate in most regions is the one derived via MRFs, with the exception of North and South West regions where plastic recyclate was mostly derived from KSS, BSs and HWRCs. This can be attributed to the prevalence of LAs operating in these regions by using a high number of KSS and, BSs and HWRCs (e.g. South West involves 14 LAs that provide KSS collection plastics, 23 LAs that also have HWRCs and 16 LAs providing BSs). North West region, on the other hand, has only 4 LAs that provide KSS, but 26 LAs with HWRCs and 10 LAs with BSs.

Fig. 5 plots the total amount of plastic sent for recycling against the number of HHs in a WCA for each of the groups described above. Little correlation or clustering is apparent, other than that the largest 3% of LAs tend to perform relatively poorly regardless of the collection scheme adopted.

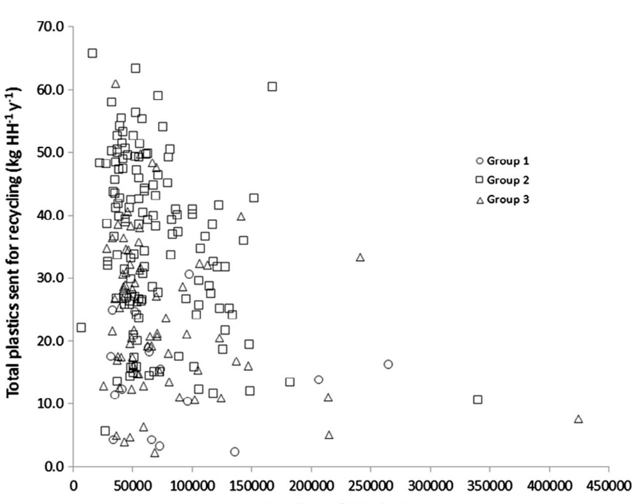

Fig. 5. LA size (with regards to number of HHs) vs. total amount of plastics collected for recycling. Key: *Group 1*. Collection with separated plastics (KSS, Cp, Cpq, MC, MCg), *Group 2*. Fully commingled collection (C), *Group 3*. Collection with separation of materials other than plastic (Cg, Cq, Cqg, Other).

4.3. Sorting of recyclables and plastics

The recyclables collected from the 320 LAs are reportedly going to MRF for further sorting. According to the quarterly data from the WDF, only 275 LAs have reported amounts of recyclables sent to MRFs, and these were selected for the analysis in regards to the MRFs input. From the WDF and the information provided in WRAP's Material Facilities Portal and operator's websites, it was possible to identify the MRFs where LAs send their recyclables. As shown in Fig. 6, LAs use MRFs mostly situated within their region, but the use of nearby MRFs is also shown to be quite prevalent. This can be explained by the fact that contractors responsible for the collection of recyclable materials from the LAs, may also have respective contracts with MRF operators which lead to this wide distribution of recyclables in the variety of existing MRFs. Capacity aspects could also be another factor that governs the final destination of the recyclables collected, but due to the limited range of data and lack of analysis on the C&I waste, that is also accepted in the MRFs, makes it difficult to derive any robust data with regards to capacity.

Based on the reported data, the amount of recyclables (not just plastics) that went into 52 MRFs for the examined period was just over 687 kt; 556 kt of these were diverted for further reprocessing (either nationally or elsewhere), while the rest were either rejected to landfill (∼20 kt) and/or diverted to EfW plants (∼36 kt) for energy recovery. This resulted in an overall rejection rate of approx. 9%, which is close to the 8.5% reported by WRAP (WRAP, 2009b) and to the 10.8% reported by the Environment Agency (WRAP, 2006b). However, a detailed scrutiny into the available reported data in combination with the analysis on the size (capacity) of MRFs in which they are diverted to, has indicated that rejection rates may vary widely depending on the size (capacity) of the MRF (Fig. 7).

These results are in contrast with the reported speculations that rejection rate is inversely proportional to the size of the plant, with

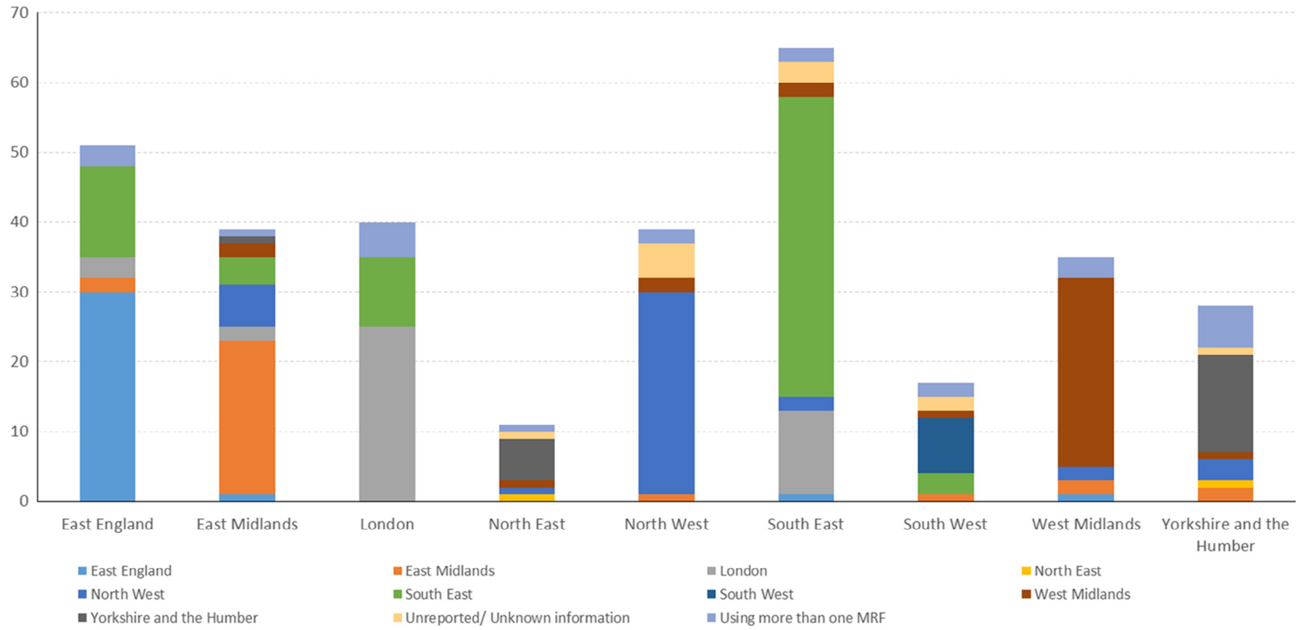

Fig. 6. Distribution of MRFs used by LAs per region in England.

Fig. 7. MRFs efficiency and rejection rate (per category, according to their capacity).

the smaller MRFs having a higher rejection rate and the bigger MRFs having the smallest rejection rate (WRAP, 2006c). This speculation is supported on the fact that larger MRFs are expected to have a more sophisticated sorting technology (e.g. manual vs. sensor based sorting) and thus be more effective in sorting recyclables into their nature (i.e. glass, plastic, paper/card, and metals). Especially in the case of plastics, large MRFs are considered to be technically capable to address challenges associated with black-coloured polymers, plastic containers with film attachments that cannot be recycled, and the presence of organic materials (contamination or non-recyclable bio-based polymers) (WRAP, 2006b). As reported by WRAP (2006a), a 2–5% rejection rate could apply on the most efficient MRFs whereas a 12–15% on the less efficient (WRAP, 2006a). Nonetheless, the analysis performed in this study (based on the reported data) demonstrated that MRFs with capacity between 25 kt and 50 kt, (11 MRFs were accounted in this category) were the most efficient with a rejection rate of 6.7%, followed by MRFs with a capacity of 10–25 kt (4 MRFs in this class) and >100 kt (16 MRFs in this range), with 7.2% and 10.2% rejection rates, respectively. The MRFs with the highest rejection rate were

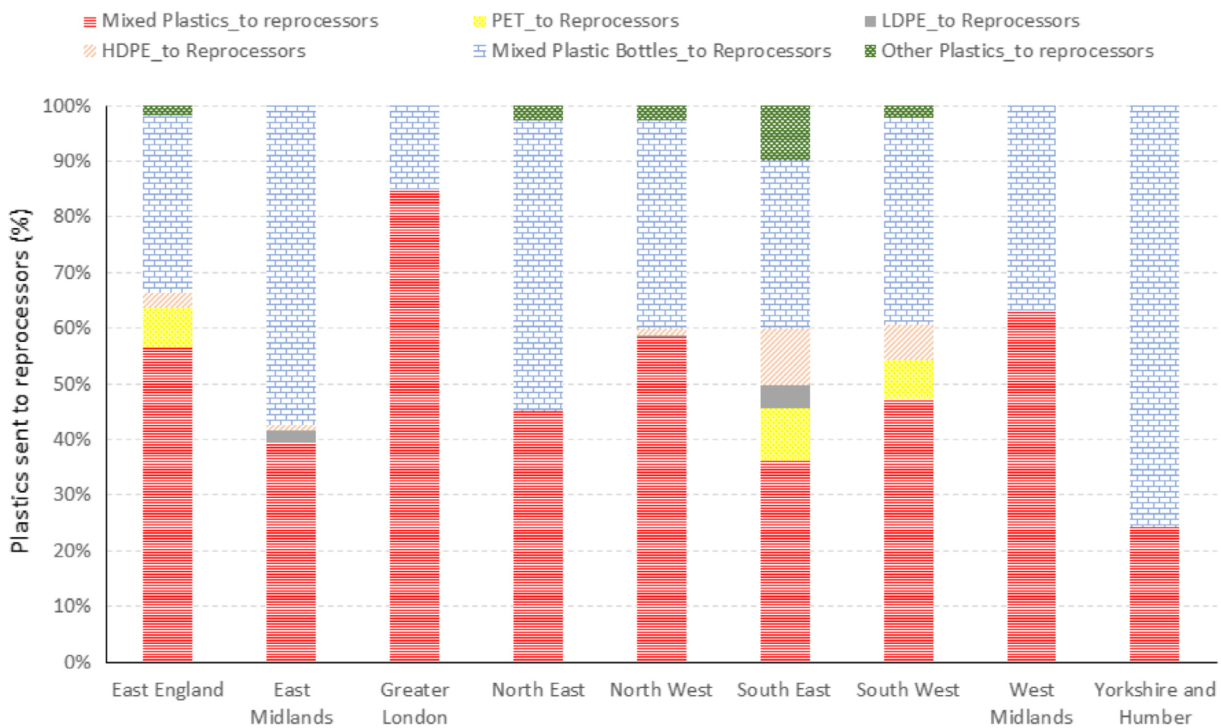

Fig. 8. Distribution of plastics sent to reprocessors, from July-September 2014, per region in England, UK. The prevalence of mixed plastics and mixed plastic bottles fractions is clear in all regions.

those in the range of 50–100 kt (20 MRFs in this range) with a 12.5% rejection rate and the smaller MRFs (<10 kt) (just 1 MRF in this class) with a rejection rate of 17.5% (Fig. 7). Apart from the rejection taking place within the MRFs, there is also a minor rejection at their gate, but this differentiation was not possible to be made based on the data that were available from WDF.

4.4. Reprocessing of plastic materials and recycling rate

Some have expressed concerns that sorting plastics is not a sustainable business in the UK. According to Ellen MacArthur Foundation, the global plastic economy has to be redesigned completely (Ellen MacArthur Foundation, 2016). Best practices for recycling plastics require that they are separated appropriately and washed to be further reprocessed, even though washing is not considered a sufficient enough decontamination process for FCM and/or cosmetics. Moreover, different polymers (and combinations of additives) contained are a major issue for sorters, as well as reprocessors. From the WDF the names of the reprocessors are given, but tracing their location and/or the fate of the recyclables after being reprocessed is beyond the aims and scope of the present research. In the end, considerable amount of both high and low quality recyclables (almost 60% of the amount reaching at MRFs–low quality- and reprocessors–high quality-) will end up being exported mostly to China, Hong Kong and other Asian countries (WRAP, 2016).

The amount finally sent to reprocessors was estimated at approx. 22 kt and Fig. 8 presents the distribution percentages of the plastics reprocessed per region. The prevalence of mixed plastics and mixed plastic bottles fractions in all regions is clear. It is also noteworthy that South East region and East England displayed high amounts of PET and HDPE sent to reprocessors, mainly due to the higher number of LAs that operate with a plastic collection system in these areas (63 out of 67 LAs and 47 out 47 LAs, respectively). There are still quantities of plastics further rejected from the reprocessors which were reported to be approx. 11 t. The recycling rate, according to the most commonly used definition shown below, was calculated at around 23% based on the ratio of the amount of waste plastics collected for recycling (excluding rejects at MRFs-PRFs) divided by the amount of waste plastic packaging generated in England during the examined period (waste arisings).

$$\text{Recycling rate} = \frac{\textit{amount of PCPP waste collected for recycling (excluding rejects at MRFs—PRFs)}}{\textit{Total amount of PCPP waste generated}}$$

Nonetheless, the authors acknowledge that there are various other definitions reported both in "grey literature" and in scientific research, as well as several other uncertainty issues involved. However, these are outside the focus of the present work, but will be discussed in another upcoming work of the same team of authors.

5. Conclusions

The present research has focused on evaluating the effect that different collection schemes have on the quantity of PCPP waste collected for recycling, using empirical serial data from HH dry recyclables collection in England, in 2014. Three main collection schemes were analysed: (i) KS recycling collection, (ii) HWRCs, also known as 'civic amenity sites', and (iii) BSs. The main conclusions drawn from the data analysis are as follows:

(1) Across all collection schemes, most LAs (203) use the AWC and collect PTTs and plastic bottles by the use of wheeled bins and sacks.
(2) The KS collection scheme was found to be the dominant one amongst BSs and HWRCs, contributing to the amount of PCPP waste collected for recycling. The efficacy of schemes varies widely between authorities. In general, fully commingled collection (C) is estimated to produce the highest yield of plastics collected for recycling in terms of kg HH^{-1} y^{-1}. There is no overall correlation between the size of a LA (measured in number of HHs) and its plastics recycling yield.
(3) At that point in time, nearly a third of LAs did not report sufficient data to be included in the analysis. Many LAs reported data that suggest they operate mixed schemes, or that plastics collection is being reported under the wrong categories. Some LAs that report very low plastics recycling rates, may not be reporting them correctly. The quality of the data could be greatly improved by simplifying or clarifying the reporting process, or examining the categories under which LAs must report.
(4) Out of the approx. 141 kt of plastics collected for recycling (reported on an 'as received' basis and accounting for almost 25.5% of the total plastic waste generated, that is 555 kt) (Defra, 2016), only a mere 22 kt (ca. 16%) were reported to be finally sent to reprocessors (PRFs) (either directly or after being processed in MRFs). Mixed plastics and mixed plastic bottles are the most abundant fractions of this amount, accounting for ca. 50% and 40%, respectively.
(5) A recycling rate of approx. 23%, based on the most commonly used definition, was calculated for PCPP waste, in England, in 2014 (quarterly figure).

To the authors' best knowledge, the existing academic literature on the impact of different collection schemes on the recyclables quantity and quality is rather limited (Kranzinger et al., 2017; Pfeisinger, 2016; Snell et al., 2017). The present work is merely a first step towards this direction. The fact that EC has recently introduced a 'Circular economy package', setting ambitious recycling targets and identifying waste plastics as a key area where major improvements and focus is necessary (European Commission, 2015; European Parliament, 2014), solidifies the significance of this research and highlights the need for further investigation. As a future proposition, the authors would recommend that in order to maximise the total amount of recyclables collected per household a commingled collection should, perhaps, be implemented. Besides, based on the findings of the present work, this is the scheme that produced the highest yield of plastic recyclates, in terms of kg HH^{-1} y^{-1}.

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