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Management of Household Plastic Waste in Wollongong, Australia: The Role of Selective Waste Collection Systems

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Abstract: In addition to increasing requirements to adopt more circular economy approaches, Australian municipal waste management systems also face challenges due to the loss of capacity to export waste overseas. Accordingly, these systems will require effective sorting and collecting of waste. Selective Waste Collection (SWC) is the collecting and sorting of household recyclable waste. The study aimed at investigating how SWC systems in an Australian municipality (Wollongong) are organised and their role in the proper management of household plastic waste. For this purpose, we mapped the household plastic waste management system and characterised every SWC system in terms of, e.g., weight and type of plastic collected. We estimated that only about 20% of the household plastic waste generated in 2018–2019 was collected via the SWC systems. Our investigation enabled us to estimate Wollongong's household plastic waste generation, recycling rate, and final disposal; identify the gaps in knowledge and challenges faced by the systems; and offer recommendations to overcome them. The challenges include contamination, insufficient community awareness, and lack of consistent waste data. Our recommendations include a transition from a commingled to a non-commingled system. The results provide a useful approach and crucial information for performance evaluation, strategy, and planning purposes.

Keywords: household plastic waste; municipal waste management; selective waste collection; circular economy

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1. Introduction

The circular economy plays a vital role in the achievement of multiple Sustainable Development Goals (SDGs), including 8 on economic growth, 11 on sustainable cities and communities, and 13 on climate change. A circular economy model is based on reuse, recycling, and responsible manufacturing. When the creation of waste is unavoidable, the logistical starting point of a circular economy is the sorting and collecting of waste; critical activities in returning waste to the economy as a resource. Among all waste materials, plastic is the primary concern for many countries. Only nine per cent of the plastic waste generated worldwide so far has been recycled, ending up mostly in landfills, dumps or in the environment [1]. Lebreton and Andrady [2] estimated that globally around 80 million tonnes (Mt) of municipal plastic waste were inadequately discarded into the environment in 2015 and that this volume will nearly triple to 213 Mt by 2060.

The sorting and collecting of household plastic and other recyclable waste is called selective waste collection (SWC). SWC reduces the volume of waste sent to landfill and increases recycling rates, reducing the need for resource extraction to manufacture new materials [3]. Although SWC is imperative for the transition of waste management to a more circular approach, it presents a few challenges. One of them is that SWC is not always

cost-effective. It requires high initial investment and ongoing education and awareness campaigns, which, however, do not guarantee population participation. There are many ways that SWC can be implemented [4], and they are referred to as SWC systems. SWC systems can be classified by the types of recyclable waste material collected (accepted), when/how often the collection service is performed, and the method of collection/transport [5]. The main types of SWC systems found in the literature are door-to-door, voluntary drop-off points (VDPs), and deposit schemes. SWC systems are organised at a local level, managed mainly by the local government authority, whereas SWC agents are people and organisations who perform the selective collection [6]. One municipality can have more than one SWC system/agent, and possible agents are private service providers, not-for-profit organisations, waste pickers and their cooperatives, and/or residents. A SWC system can also include the informal sector. The term informal refers to individuals, families, micro-enterprises, or companies that perform selective waste collection and are not sponsored, financed, contracted, recognised, managed, and reported upon by public authorities [7].

To achieve the SDGs and attain more circular waste management systems, SWC systems must be sustainable. Accordingly, SWC systems need evaluation and performance monitoring to identify strengths and weaknesses. However, studies of SWC systems are scarce, and there is insufficient and/or dispersed data available. To assess the performance of different SWC systems in the State of Espírito Santo, Brazil, Nogueira Zon et al. [8] focused on waste pickers' role in these systems. The authors evaluated the SWC systems' sustainability by using ten indicators of the sustainability of SWCs and 16 indicators of the sustainability of waste pickers' organisations. Iba nez Forés et al. [9] analysed the performance of the door-to-door SWC system implemented in Jo ao Pessoa, Brazil, in terms of the collected volume and composition of the waste received at the material recovery facility (MRF). Ferreira et al. [10] introduced a performance evaluation framework for finding the best SWC system for a municipality and then applied the framework to compare the two SWC systems in Oporto, Portugal. To investigate the performance of the SWC systems, their framework compares variables related to collection route and collected waste volume and composition. Pasiecznik and Leoniewska-Gogola [11] assessed the SWC system in suburban detached housing areas in Wrocław, Poland, based on residents' participation behaviour. Finally, Gallardo et al. [12] evaluated and compared the efficiency of the SWC systems in all Spanish cities with over 50,000 inhabitants. The efficiency was determined based on many indicators which essentially provided information about the quantity and quality of materials that were recovered by each system.

Australia is facing challenges to its waste management practices because of changed policies overseas that almost halved Australia's exports of mixed plastic waste for reprocessing overseas between 2016 and 2020 [13]. Australia has historically relied on export markets, particularly China, to export certain waste materials. However, in January 2018, China introduced the National Sword policy, which banned the import of 24 types of solid waste, including many types of plastics [14]. These materials were displaced to other south-eastern Asian countries, many of which have now implemented their own restrictions. In response, in 2019 Australia announced that bans would be established on the export of waste plastic that has not been processed into a value-added material [13]. Nevertheless, Australia's ability to export recycled materials has led to an SWC policy and education centred on the quantity rather than the quality of the collected recyclable waste [15]. Recent policy responses have accentuated the necessity to progress waste management into a more circular economic model , which includes SWC systems, where (plastic) waste is seen as a resource [16–18]. Additionally, one of the targets defined in the 2025 National Packaging Targets (released in 2018) is that 70% of plastic packaging will be recycled (or composted) by 2025. To achieve this target, SWC systems will need to be improved with regard to the quality and quantity of the collected plastic waste. There have been Australia-based studies about reducing e-waste, construction waste [19,20], contamination [21], container deposit schemes [22], and improving development of waste management practices [23].

However, to the best of the authors' knowledge, there has been no systematic evaluation of the management of household plastic waste in an Australian city.

The objective of this study is to investigate how SWC systems in the city of Wollongong, Australia are organised and their role in the proper management of household plastic waste. Accordingly, the different SWC systems which accept plastic waste (plastic-related SWC systems) as well as the household plastic waste management system in Wollongong are categorised in this study. This research provides valuable knowledge to facilitate and guide decision-making for SWC systems by relevant authorities, as well as explaining the SWC systems adopted in an Australian municipality and comparing them with other systems. There was previously no mapping of Wollongong's household plastic waste management system, and this study introduces one from generation to collection, transfer, recycling, and disposal. The mapping is helpful for not only strategy and planning purposes, but also for monitoring and performance evaluation against outcomes. It can allow the targeting of areas for additional investment or help identify service providers that are failing to support the realisation of the waste policy objectives and therefore may need additional support or other responses [17].

2. Case Study

The focus area of this study was the local government area (LGA) of Wollongong, including the city centre with the same name. Wollongong is one of the most liveable regional cities in Australia [24], located about 80 km south of Sydney, in the state of New South Wales (NSW), as shown in Figure 1. It is the third largest city in NSW and the 11th largest in Australia, with an area of 1296 km^2. In 2019, Wollongong's population was 218,076 inhabitants residing in 73,953 households [25]. The study area contains both rural and residential areas.

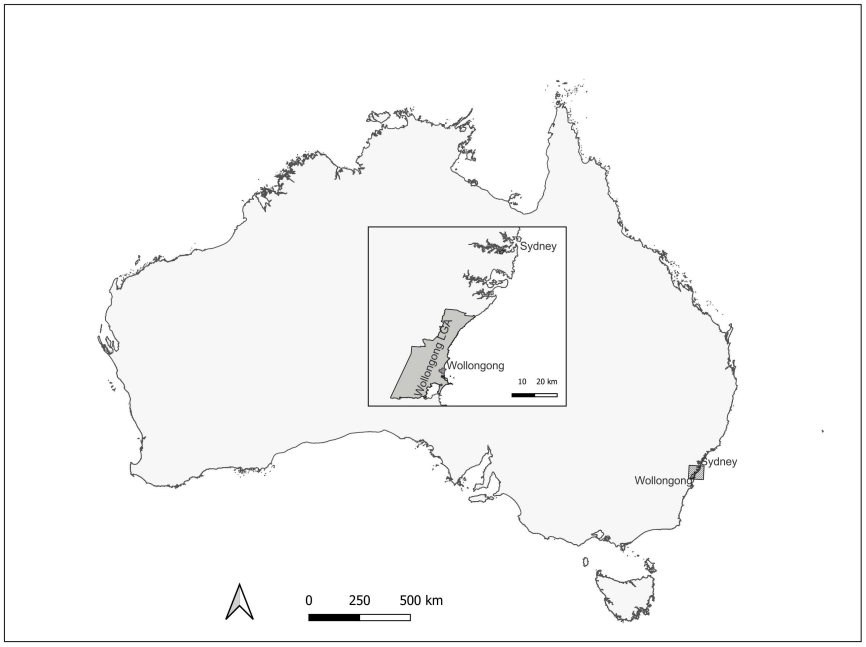

Figure 1. Case study area, Wollongong local government area (LGA) and city centre on the southeast coast of Australia.

Waste management facilities within Wollongong consist of a landfill, transfer station, a resource recovery centre, a material recovery facility (MRF), and a composting facility. Wollongong City Council (WCC) outsources the majority of waste collection services to an external contractor (private service provider). Three types of waste collection service are offered to residents: kerbside, self-haul, and on-call household clean-up. Kerbside and self-haul collections include three types of household waste: residual, recyclable,

and food and garden organics (FOGO), whereas on-call clean-up collection covers only residual and recyclable household waste. The external contractor provides kerbside and on-call household clean-up collections, and the self-haul drop-off is offered at a Community Recycling Centre (CRC), operated by the Council.

In the last five years, the Council has implemented programs designed to decrease the volume of household waste going to landfill, pollution and diminish its environmental impacts. One of these programs is the Regional Waste Education Program, which has increased community awareness of alternatives to 'single use' plastic items and helped develop and trial of community driven initiatives, such as the Rise & Shine community clean-up initiative. Some of the main waste management challenges faced by Wollongong are related to population distribution and seasonal tourism. The population is spread along a narrow coastal corridor, resulting in travel distances being cost prohibitive for some regional waste management solutions. The seasonal influx of tourists into Wollongong can cause a strain on all domestic services and waste generation can increase by up to 50% [26].

3. Methodology

The study was carried out in three stages between August 2020 and December 2021 (Figure 2). The goal of the study was to identify and describe Wollongong's plastic-related SWC systems, and then analyse how these systems contribute to the proper management of household plastic waste. The aim of the first stage was to identify the municipal plastic-related SWC systems. The main outcome was the mapping of the household plastic waste management system in Wollongong (Figure 3), explained in detail in Section 4.1. The objective of the second stage was to characterise each SWC system in terms of type of collection, agent, managing authority, sector, accepted items, and collected amount. In this study, it was assumed that residents act as SWC agents when they, for example, organise a community collection program or participate in a VDPs SWC program by transporting their recyclable waste to VDPs. With regard to SWC sectors, the present study follows the most widely adopted definition for the informal SWC sector in the literature, proposed in [7]. According to this definition, individuals, families, or businesses working without recognition of the managing authority are part of the informal sector. In the second stage, firstly other municipal waste collections were identified and the household plastic waste weight that is carried through each of them was determined. Then, the household plastic waste weight that is transported through its whole management system was computed. The characterisation of the plastic-related SWC systems together with that of the other waste collections are described in Section 4.2. The third stage aims to identify the challenges present in the plastic-related SWC systems, and then presents possible solutions for overcoming those challenges (Section 5).

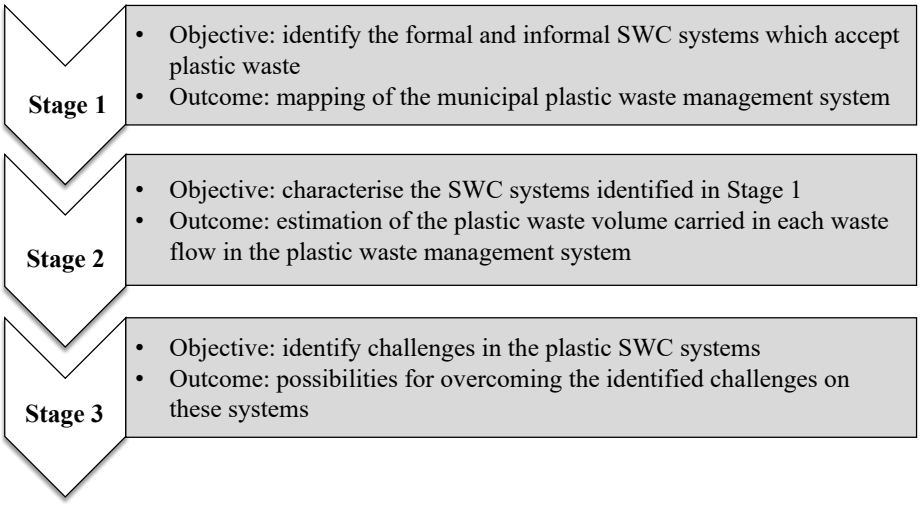

Figure 2. Work stages and their main outcomes.

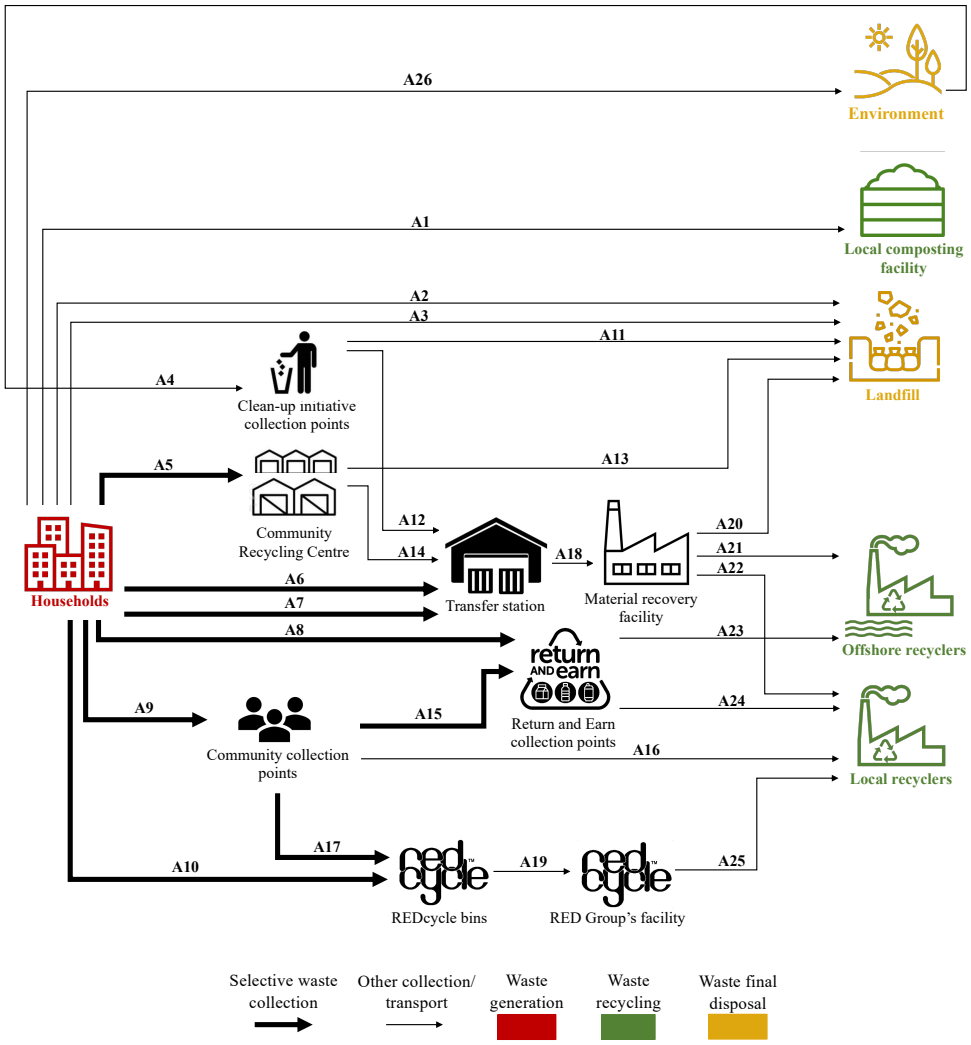

Figure 3. Mapping of the waste management system in Wollongong (refer to Tables 1 and 2 for explanations of the arrows).

Data were drawn from different sources: informal meetings with waste management stakeholders, field visits to the CRC and private service provider's facility, and desktop research (academic research journals, government documents, consultancy reports, and managerial records), for 2018–2019. The data sources used for the household plastic waste weight estimations are highlighted in the description of each plastic waste collection/transportation.

4. Results

This section introduces the outcomes of the first and second stage of the study, which are the mapping of the household plastic waste management system and the characterisation of the plastic-related SWC systems and of the other waste collections in Wollongong.

4.1. Mapping of the Waste Management System

The mapping is a representation of the waste management system in Wollongong, and it was validated by waste management stakeholders. Figure 3 illustrates Wollongong's household waste generation through to recycling and final disposal activities. The icon in red depicts the household waste generation points and the icons in green and in yellow represent the waste recycling and disposal activities, respectively. The mapping includes 26 arrows that represent the collection and transport of the household waste generated

within Wollongong metropolitan area. The arrows with thicker lines represent plastic-related SWC systems, while the other arrows show SWC systems which do not accept plastic waste and collection/transportation of residual waste.

4.2. Estimation of Plastic Waste Weight That Is Transported Through the Waste Management System

Once the waste management system in Wollongong was mapped, the amount of household plastic waste transported through the whole system was estimated. Firstly, the household plastic waste generation was calculated. The weight of household plastic waste generated in Wollongong was estimated based on the Australian plastic waste generation data for 2018-19 [27] and per capita allocation [25]. It was estimated that 10,317.30 tonnes of plastic waste were generated by households in Wollongong in 2018–2019. Part of it was collected and transported via SWC systems (Figure 3, A5–A10), which are described in Section 4.2.1. The remainder was either collected/transported via other waste collections (A1–A3) or leaked to the natural environment (A26). These other waste collections are presented in Section 4.2.2. The Data Availability Statement provides a document with all calculations, assumptions, and references adopted in this study for estimating the household plastic waste weights carried through each collection/transportation in the waste management system in Wollongong.

4.2.1. Selective Waste Collection Systems of Plastic

Wollongong has all the main SWC systems found in the literature (Figure 3): door-to-door, VDPs, and (a container) deposit scheme. There are six SWC systems in the study area (A5–A10). However, the SWC system illustrated by A7, which is the on-call household clean-up service of recyclable waste, does not accept any sort of plastic waste. Therefore, the aforementioned system is not characterised in this section. The plastic-related SWC systems are described as follows and summarised in Table 1.

Table 1. Selective household waste collection systems in Wollongong that include plastic.

Name	Arrow ID	Type	Agent	Management	Sector	Items	Weight
Self-haul collection	A5	VPDs	Residents	WCC	Formal	Items listed above, especially those which will not fit the door-to-door collection bin (e.g., outdoor plastic furniture)	2038.87
Kerbside recycling collection	A6	Door-to-door	Private provider	WCC	Formal	Polyethylene terephthalate (PET), high density polyethylene (HDPE), and polyvinyl chloride (PVC), plastic film/bags, polystyrene (PS), expanded polystyrene (EPS) foam, plastic furniture, plastic composite	1827.53
Return and Earn	A8 & A15	Deposit scheme	Residents	NSW Government	Formal	PET, HDPE, and Low-density polyethylene (LDPE) drink containers (e.g., water and beer containers)	267.94
Community collection programs	A9	VPDs	Residents	Community program operator	Informal	Conditional to the donation site operator	-
REDcycle program	A10 & A17	VPDs	Residents	RED Group	Formal	Soft plastic (e.g., biscuit packets, fresh produce bags)	16.12

A5—*Self-haul collection*

A5 shows the *self-haul collection*. In the *self-haul collection*, residents transport their own eligible waste to the CRC. The CRC is a drop-off facility managed by WCC where residents and businesses can dispose of their waste. The CRC accepts regular and recyclable waste, especially those waste items which do not fit into the household bins such as outdoor plastic furniture. Items should not be larger than 20 kg or 20 L, except for larger fridges and freezers. The present study classifies this service as a formal VDP SWC since the local

authority provides it and residents transport their own-sorted waste to the drop-off facility without any economic incentive. To estimate the weight of plastic waste that is received at the CRC, first, the amount of waste dropped off at the CRC is estimated by using the Australian plastic waste generation data for 2018–2019 [27] and per capita allocation [25]. Then, the proportion of plastic in the total dropped-off waste is calculated by adopting the proportions in the 2019 Wollongong City Council Audit Report.

A6—*Kerbside recycling collection*

This arrow represents the *kerbside recycling collection* offered by the Council. The service is a commingled and formal door-to-door selective waste collection system. In the *Kerbside recycling collection*, plastic waste—together with paper, cardboard, glass, and metal waste—is first disposed of by residents in household yellow-lidded wheeled waste bins. Then, the commingled recyclable waste is collected from the bins, and transported to the MRF, every 2 weeks by the private service provider. This municipal service does not accept all types of plastic waste. In Australia, plastics are classified into two groups: soft (flexible) and hard (rigid). Polystyrene foam is considered separately and is only accepted for recycling in some areas, but not in Wollongong. Soft plastics are generally defined as plastics that can be scrunched into a ball, unlike hard plastic, such as bottles and tubs, which are moulded and hold their shape [28]. Soft plastics are not collected via the door-to-door SWC system because they become caught in machinery at the MRF, causing failures or damage. They can be disposed of either in the residual waste bin (see A2 in Table 2) or through a specialised soft plastic recycling program (see A10 & A17). Using the results presented in the Wollongong Kerbside Audit Report 2019, it was estimated that 1827.53 tonnes of plastic were collected in the *Kerbside recycling collection* in Wollongong in 2018–2019.

Table 2. Details of arrows in the mapping of the waste management system not shown in Table 1.

ID	Optr	Mng	P_i	P_w	Description
A1	Private	Council	Polypropylene non-packaging, plastic bags, plastic film and plastic composite	35.24	The FOGO collection is illustrated in A1. This service is performed weekly by the service provider and collects food and garden waste (e.g., kitchen scraps, leaves, small branches and weeds). Residents are offered green-lidded wheeled bins which they must use only for food and garden waste disposal. Nevertheless, the 2019 Wollongong City Council Audit Report, provided by the service provider to the research team, shows that there is plastic contamination in this waste stream. The plastic waste contamination collected by FOGO was determined based on the results of this audit report.
A2	Private	Council	Any	5249.06	This arrow represents the residual waste collection performed weekly by the private provider. Residents are provided with red-lidded wheeled bins for their residual waste. Acceptable items are most items that cannot be recycled or placed in the green-lidded wheeled bins (FOGO collection). Household bulky waste items (see A3 & A7) are not collected via regular waste collection. The plastic waste collected via the regular waste collection was determined based on the 2019 Wollongong City Council Audit Report.
A3	Private	Council	PET, HDPE, PVC, plastic film/bags, PS, EPS foam, plastic furniture, plastic composite	271.09	A3 & A7 depict the on-call household clean-up service of residual waste and recyclable waste, respectively. This service manages household bulky waste and is available to residents within Wollongong. Residents are entitled to use the service twice yearly and must separate regular and recyclable waste into two piles. Although A7 represents a formal door-to-door SWC collection system, this system does not accept plastic waste. The accepted items are mattresses, tyres, metal, and e-waste. The amount of plastic waste in A3 was estimated based the NSW Local Government Waste, Resource Recovery Data report 2018–2019 [29] and the On-call Household Clean-up Audit Report prepared by the service provider in 2021. As there was no previous audit report for this service, we adopted the 2021 On-call Household Clean-up Audit Report.
A7	Private	Council	None	-	

Table 2. *Cont.*

ID	Optr	Mng	P_i	P_w	Description
A4	Volunteers	Council	Any	0.52	A11 & A12 represent the transportation of the litter items after they are collected and sorted into recyclable and residual waste by community-led environmental clean-up initiatives (A4). Volunteer community groups and individuals pitch in with the Council to remove litter from public areas such as parks, creeks and beachfront reserves. The private service provider transports the collected recyclable items to the transfer station (A11), whereas the collected residual items are transported to the landfill (A12). The weight of plastic in A4 was provided by the Council waste management officer (L. Hickson, personal communication, 10 May 2021). The proportions of the plastic weight in A4 sent to the transfer station and landfill were unknown by the Council. Although the plastic waste collected by community-led environmental clean-up initiatives has been sent to the transfer station (A11) in previous years, there was an indication that in 2018–2019 all weight collected was sent to the landfill (A12).
A11	Volunteers	Council	PET, HDPE, and PVC drink containers and packaging and PS, LDPE, and polyethylene (PP) packaging	0	
A12	Volunteers	Council	All apart from the ones listed in A11	0.52	
A13	Private	Council	No data available	1121.37	A13 & A14 depict the transportation of residual and recyclable waste from the CRC to the landfill and the transfer station, respectively. Recyclable, and residual, waste items are collected at the CRC via the *self-haul collection* which we classified as a VDP SWC system. Accordingly, *self-haul collection* is explained in detail in Section 4.2.1. According to [29], 45% of the material from CRC in NSW was recycled. In this way, it was assumed that 45% of the plastic waste that arrives at the Wollongong's CRC (2038.87 tonnes, see A5 in Table 1) was transported to the transfer station to be recycled (A14) and that the remaining weight was sent to landfill (A13).
A14	Private	Council	No data available	917.49	
A16	Program operator		It varies based on the community program operator	-	A16 illustrates the transportation of recyclable waste from community collection points to local recyclers. There is no data available on the amount of (plastic) waste collected through *community collection programs*. So, the amount of waste transported from community collection points to local recyclers is also not available. Accordingly, this study classifies *community collection programs* as an informal VDP SWC. More details about *community collection programs* can be found in Section 4.2.1
A18	Private	Council	PET, HDPE, and PVC drink containers and packaging and PS, LDPE, and PP packaging	1898.38	The transportation of recyclable waste from the transfer station to the MRF is shown in A18. The materials gathered at the transfer station are the recyclable materials collected via *kerbside recycling*, on-call household clean-up, and *self-haul collections*. The amount of plastic waste in A18 was estimated based on the per capita allocation of the waste amount received at MRFs in Australia [13].
A19	RED		Soft plastic	16.12	A19 displays the transportation of soft plastic waste from *REDcycle* drop-off bins to the RED Group's facility. *REDcycle program*, which is a VDP SWC system, is presented in detail in Section 4.2.1 together with the definition of soft plastics. The soft plastic waste weight in A15 is equal to A10 plus A17 (see Table 1).
A20	MRF		PET, HDPE, PVC, and LDPE non-beverage/packaging; PP, PS and EPS non-packaging; EPS packaging; plastic film/bags	221.47	A20 represents the transport of waste items from the MRF to landfill. These items include residual waste or recyclable material that cannot be recovered in the MRF. The amount of plastic waste transported from the MRF to landfill was estimated based on Australian disposal data from 2018–2019 [13].
A21	MRF		PET, HDPE, LDPE, PP, PS, PVC, acrylonitrile butadiene styrene (ABS)	752.75	A21 & A22 illustrates the transport of baled recycled materials from the MRF to offshore and local recyclers, respectively. Wollongong, like other Australian municipalities, sends part of its household waste to south-eastern Asian countries for reprocessing. After the waste ban, only plastic waste that has been sorted into a single resin or polymer type can be exported. Local recyclers are either in NSW or interstate. For estimating the amount of baled plastic recycled transported to offshore and local recyclers, it was adopted the proportion of Australian plastic waste reprocessed offshore and locally in 2018–2019 [28].
A22	MRF		PET, HDPE, LDPE, PP, PS, PVC, ABS	815.47	

Table 2. *Cont.*

ID	Optr	Mng	P_i	P_w	Description
A23	Cleanaway	NSW EPA	PET, HDPE, and LDPE drink containers	128.62	A23 & A24 display the transportation of plastic drink containers collected via the *Return and Earn* scheme to offshore and local recyclers, respectively. *Return and Earn* scheme is a type of SWC, more precisely, a deposit scheme, described in Section 4.2.1. To estimate the amount of baled plastic recycled waste collected via *Return and Earn* that is transported to local and offshore recyclers, this study used the amount of plastic waste collected by the scheme and the proportions of Australian plastic waste reprocessed locally and offshore in 2018–2019 [28].
A24	Cleanaway	NSW EPA	PET, HDPE, and LDPE drink containers	139.32	A24 represents the transportation of soft plastic waste from the RED Group's facility to local recyclers. Soft plastic collected by *REDcycle program* is reprocessed only onshore. The soft plastic waste amount transported from the RED Group's facility to local recyclers is the same as the amount of soft plastic waste collected from the *REDcycle* drop-off bins (see Table 2).
A25	RED		Soft plastic	16.12	A25 represents the transportation of soft plastic waste from the RED Group's facility to local recyclers. Soft plastic collected by *REDcycle program* is reprocessed only onshore. The soft plastic waste amount transported from the RED Group's facility to local recyclers is the same as the amount of soft plastic waste collected from the *REDcycle* drop-off bins (see Table 1).
A26	-	-	Any	133.40	A26 shows the leakage of plastic waste into the natural environment. That is, plastic waste that ends up as litter in the marine and terrestrial ecosystem. To estimate the amount of plastic waste litter generated in Wollongong, the present study utilised the NSW Litter Report 2016–2020 [30] and the composition of the beverage containers supplied to NSW in 2018–2019 [31]. Part of the plastic waste which is leaked into the environment is collected by community-led environmental clean-up initiatives (see A4).

A8 & A15—*Return and Earn*

The *Return and Earn* scheme is a container deposit scheme, illustrated by A8 and A15. This scheme was implemented in 2017, and it is an NSW Government initiative funded by contributions from the beverage industry. The NSW EPA is responsible for regulating the scheme. *Return and Earn* captures a broad range of beverage containers (bottles, cans, and cartons) that contribute to the litter stream but excludes plain milk and wine in glass containers. In this system, residents can obtain a 10-cent refund for every eligible beverage container. There are four types of *Return and Earn* points: reverse vending machine (RVM), automated depot (AD), over-the-counter, and donation station. RVMs are self-service machines that read the container barcode and either accept or reject it based on its eligibility. ADs are specialist return and recycling centres. Over-the-counter return points are local businesses, such as news agencies or corner stores. Donation stations are RVMs that only accept plastics, cartons, and cans and donate the 10-cent refund to a charity. In both, ADs and over-the-counter return points, staff issue the refund. A total of 23 *Return and Earn* points operate in Wollongong. A8 illustrates the beverage plastic containers which are returned by residents to *Return and Earn* points, while A15 presents those which are returned to *Return and Earn* points by *community collection programs* (see A9). Based on the reports on the weights collected through the scheme [32,33] 267.94 tonnes of plastic waste was collected via *Return and Earn* in Wollongong in 2018–2019. It is important to highlight that no distinction can be made between plastic drink containers returned by residents and by *community collection programs*. Therefore, the estimated weight refers to both A8 and A15.

A9—*Community collection programs*

A9 illustrates the transportation of recyclable waste by residents to community collection points. An example of *community collection programs* is the Scouts Recycling Scheme [34]. Scout Recycling Scheme sets up donation sites where residents can give their eligible drink containers to the Scout Group (donation site operator). The donation site operator can then return the containers to a *Return and Earn* point for refund. This study classifies *community collection programs* as VDPs SWC systems because they rely on residents transporting their

recyclable waste to the community-led collection points without any economic incentive. The recyclable waste gathered by *community collection programs* is then taken to a *Return and Earn* point (A15), local recyclers (A16) or *REDcycle* bins (A17). Unlike all the other SWC systems in Wollongong, *community collection programs* are categorised as informal. Authorities do not collect data on the weight of plastic waste collected via *community collection programs*.

A10 & A17—*REDcycle program*

A10 and A17 depict the *REDcycle program*. The national *REDcycle program* is a formal SWC system managed by the RED Group. Like *community collection programs* and *self-haul collection*, this study labels the *REDcycle program* as a VPDs SWC because there is no economic incentive for residents to participate in the program. The program was implemented nationwide in 2011 through a partnership between the RED Group—a consulting and recycling organisation—and some manufacturers and retailers in Australia. It is an example of product stewardship, which primarily enforces producers to cover a proportion of costs associated with the management of waste at the end of a product's useful life [20]. This program accepts only soft plastic waste, and a list of the accepted soft plastic waste items is shown on the program's website. The program's partners have adopted 'Return to Store', 'Store Drop Off' or *REDcycle* logos (see Figure 4) on-pack to help consumers identify the eligible soft plastic waste items. Residents must sort their eligible soft plastic waste at home, and then dispose of it either at one of the *REDcycle* VDPs located at a partner grocery store or at a community-led collection point. There are 22 *REDcycle* VDPs located across Wollongong. An example of community-led collection point is the soft plastic collection bins located at local schools. A10 represents the transportation of soft plastic waste directly from households to *REDcycle* bins, whereas A17 displays the transportation of soft plastic waste by *community collection programs*. Using information provided by the program via email (R. Gleghorn, personal communication, 29 January 2022), it was estimated that *REDcycle* collected about 16.12 tonnes of soft plastic waste generated in Wollongong in 2019. This amount represents the soft plastic waste collected at the *REDcycle* drop-off points (A10 and A17). The soft plastic waste collected via the *REDcycle* bins is returned to the RED Group's facility in Melbourne for initial processing, and then it is delivered to recyclers.

Figure 4. 'Return to Store' and 'Store Drop Off' *REDcycle* logos on-pack for the consumers.

4.2.2. Other Waste Collection/Transportation

The remaining arrows (A1–A4, A11–A14, A16, A18–A26) represent SWC systems that do not accept any sort of plastic waste and other waste collections/transport. These arrows are described in Table 2, every arrow includes an operator (Optr), a managing authority (Mng), acceptable plastic waste items (P_i), and a plastic waste weight (P_w), in tonnes.

5. Challenges in the SWC Systems under Study

This investigation estimated that:

- about 20% (2111.59 tonnes) of the household plastic waste weight generated in Wollongong in 2018–2019 (10,317.30 tonnes) was collected via the municipality's plastic-related SWC systems. This was estimated by summing the weights in A5–A10 (see Table 1).
- approximately 17% (1852.28 tonnes) of the household plastic waste generated in the municipality was recycled. The recycling rate was calculated based on the weights in A16 and A21–A25.

- over 55% (5741.62 tonnes) of the household plastic waste generated in Wollongong was sent to landfill. To estimate the amount of household plastic waste sent to the landfill, the weights in A2, A3, A11, A13 and A20 were summed.

The estimated recycling rate overstates the recycling rate since some exported material might have been contaminated or 'off-spec', and therefore likely to have been used as a fuel or disposed of. Accordingly, it is important to note that the estimated recycling rate is based on the share of plastic waste sent for recycling—not on the portion that is truly used as raw material. Although Wollongong's estimated household plastic recycling rate is higher than the estimated 2018–2019 Australian recycling rate for plastic waste from municipal, commercial, and industrial and construction and demolition waste streams (13%) [13], Wollongong's estimated recycling rate is far from the National plastic packaging recycling rate target of 70% by 2025 [35].

The municipal SWC systems can enhance Wollongong's recycling rate, supporting the achievement of the 2025 plastic recycling target, as well as promote a shift towards a more circular plastic waste management system—when avoiding the generation of plastic waste is impracticable. For that, however, these systems need to be evaluated and their performance assessed. Accordingly, the next section identifies the main challenges in Wollongong's plastic-related SWC systems and makes recommendations. The focus is on how the plastic-related SWC systems can overcome these challenges mainly through enhanced rates of recycling, as there is a lack of support by WCC for other circular economy actions such as reuse. Once households book an on-call household clean-up service of residual waste and/or recyclable waste (see A3 and A7, Figure 3 and Table 2), they can place waste items out by the kerbside by 6:00 a.m., but no more than 24 hours before the service is booked. This time-frame allows for informal reuse of disposed items by residents. However, reuse is not encouraged by WCC, though some other nearby councils (such as Shellharbour and Shoalhaven) do offer the service.

5.1. Contamination Levels

One of the most significant challenges in the SWC systems under study was contamination. Contamination results in a reduction in the value of the recyclable materials and reduces the amount of recyclable materials that can be recovered. The Australian National Waste Policy 2018 signals different policy interventions that may depend on reducing contamination levels to reach their goals [36]. According to the 2019 Wollongong City Council Audit Report, about 10% of the recyclable materials collected via *kerbside recycling collection* in Wollongong are lost to contamination, and among the main contaminants are non-recyclable hard plastic and soft plastic. It may then be inferred that about 182 tonnes of the plastic waste collected via the door-to-door SWC system is soft plastic waste and non-recyclable hard plastic that ends up in landfill. While this may be the only option for non-recyclable hard plastic, (part of or all) the soft plastic waste could be returned to the economy as a resource via the *REDcycle* program. In Australia, kerbside recycling contamination rates (based on states' data) vary from 4 to 16% [13], showing the potential for Wollongong to reduce the contamination level in *kerbside recycling collection*.

Reducing contamination is an outcome, not a single behaviour. The desired outcome of eliminating contamination depends on many preferred behaviours, which vary across different municipalities [37]. Wollongong's *kerbside recycling collection*, for example, does not accept soft plastic waste, whereas other councils do. Therefore, instead of focussing solely on behavioural change, other means of reducing contamination should be investigated. One way of reducing recycling contamination is to convert the *kerbside recycling collection* into a non-commingled SWC system. In a non-commingled SWC system, recyclable materials are separated in different containers at the point of generation. In a commingled SWC system, where recyclable items are mixed in the same bin, contamination is more likely, resulting in the value degradation of the recyclable materials. A report comparing six kerbside collection systems, varying from fully commingled (single bin) to three-bin systems, in NSW [38] concluded that the non-commingled systems achieved the lowest

contamination rates. Further source separation at the point of generation (i.e., household)—not only separating recyclable and non-recyclable but also into paper, plastic, metal, and glass—may result in a much lower contamination rate. Therefore, in a non-commingled system, the collected materials will always be of higher quality than the materials collected by a commingled system. Additionally, the former will have lower separation cost compared to the latter. Although the recyclable materials collected by a commingled selective collection can be sorted in a MRF, this will lead to cost-intensive separation. Using data from 223 Canadian provincial municipalities over a 10 year period, Lakhan [39] found that municipalities who implement commingled SWC systems face higher material management costs than those that opt for non-commingled systems. Regarding behavioural change, it is believed that building perceptions of personal efficacy as well as communication of *kerbside recycling collection* attributes can increase compliance. Australia's earlier ability to export recycled materials resulted in an education focus on the quantity rather than the quality of recycling which has led to the contamination of recycling waste [15]. Information provided by councils around NSW demonstrated that enforcement strategies, such as encouraging a recycling champion for each block of flats and bin inspectors carrying out door visits to households, can reduce contamination greatly [40].

5.2. Community Awareness

Another main challenge identified in the Wollongong's SWC systems, which is closely related to contamination, is the lack of community awareness about what waste items are accepted in a SWC system. Community awareness is a critical factor for increasing both the quality and quantity of the plastic waste collected via a SWC system. This is supported by the study presented in [41]. The study proposed a technique which considers a panel of experts to identify contamination causes in commingled SWC systems. The paper concluded that the lack of community awareness is one of the major causes of recycling contamination.

In Australia, the SWC managed by local governments vary between different councils and depends on the regulatory framework of their state or territory. These variations together with the complexity of plastic waste can be confusing to residents. Defining the scope of soft plastic, for instance, can be difficult due to the wide variety of resins, polymers and formats used [42]. Consequently, households become confused about what plastic items can be disposed via *kerbside recycling collection*—and which plastic items should be disposed of in *REDcycle* bins. According to the Australian Packaging Covenant Organisation, the *REDcycle* scheme has contamination levels of up to 20% [43]. This challenge can also lead to the problem of recyclable plastic waste being disposed into FOGO and the regular waste bins. In 2018–2019, incorrectly placed plastic waste comprised about 0.12% (35.24 tonnes) of the collected FOGO waste (see A1, Table 2) and more than 12% (5249.06 tonnes) of the regular household waste (see A2, Table 2). In 2020–2021, about 1% of FOGO waste (10.27 tonnes) and 2% (1282.28 tonnes) of the residual waste was recyclable plastic. Measures to mitigate contamination include a communication and engagement program—which is provided by WCC and has been highlighted in many studies. Another initiative that could be used to increase community awareness about what is/is not accepted in SWC systems is a waste bin app. A waste bin app could advise residents on the correct use of bins. Additionally, at a higher level, the implementation of a consistent national approach to education could result in a well-informed community. In Australia, education is often left to poorly resourced individual councils or service providers. The communication is thus often inconsistent and less effective than it could potentially be through a coordinated national approach. According to the review presented in [37], a national mass communication and education program could create an environment for local behaviour change efforts. The review evaluated published literature and practitioner reflections on the effectiveness of interventions for reducing recycling contamination in Australia.

5.3. Lack of (Consistent) Waste Data

The last main challenge recognised in the SWC systems under study was the lack of (consistent and complete) data about the recyclable waste collected via these systems as well as waste weight/volume which is carried through the other waste collection streams in the household plastic waste management system. Data on (plastic) waste generated in Wollongong is currently not compiled in a standardised manner across the different waste facilities, and there is no comprehensive data strategy in place that supports timely data collection. Consequently, there is limited visibility of the collection of waste between service providers and waste facilities and gaining an accurate picture of waste generation, recycling and final disposal becomes laborious. Additionally, once (plastic) waste material leaves Australia, little is known about the share that is actually recycled to new materials. As discussed by [44], the lack of data on waste volumes/weight is a barrier to enhancing circularity. Measuring the progress of a waste management system towards a circular approach starts with knowing how the system is performing. In terms of Wollongong's household plastic waste system, this means knowing what types and how much plastic waste is returning to the cycle through reuse and/or recycling, much of which is currently unknown or unavailable. The research team had to utilise different data sources to determine the weights that are transported through the household plastic waste management system, and then estimate the household plastic waste recycling rate and final disposal. These data sources are from various jurisdictions and are often not aligned because of the differences in the geographic coverage, scale, time frames, and scope of the data. For each waste collection, it was included the type of plastic waste accepted and collected. However, for most of the collections there is no information on the actual composition of the collected plastic waste. For example, there is no data on the proportion of soft plastic in the 1852.28 tonnes of plastic waste sent for reprocessing, and this study thus could not estimate the recycling rate for soft plastic versus hard plastic waste.

It is important to highlight that due to its nature, i.e., informal SWC systems, there is currently no data available on the amount of plastic waste collected by individual *community collection programs* (see A9, Table 1). Nevertheless, these systems are integrated with the household plastic waste management system as these programs return containers to the deposit scheme (*Return and Earn*) and/or soft plastics to the *REDcycle program*. Therefore, although their individual contribution to the household plastic waste management system cannot be computed, part of the plastic waste collected by *community collection programs* is recorded and made available by the *Return and Earn* report, and the figures could potentially be disaggregated.

A possible initiative to address the challenge of a lack of consistent data about waste is to implement monitoring and control tools for the management of (plastic) waste. If such tools are shared between SWC management entities, it could lead to more accurate and consistent performance data allowing timely changes to improve effectiveness. Reports with greater details could inform management entities about changes to plastic waste management (generation, recycling, and disposal) over time and help evaluate responses to government initiatives and regulatory changes and community education programs. According to the National Plastic Plan 2021 [35], the Australian Government has invested AUD 20.6 million to develop a waste data visualisation platform. The customer-facing data hub will gather data from different sources to supply nationally consistent real-time information on waste. The first release of the data hub presents interactive visualisations of the National Waste Report database time series from 2006–2007 to 2018–2019 and Australia waste and resource recovery infrastructure database. However, to date the data hub is yet to display any data about (plastic-related) selective waste collections.

6. Conclusions

This study presented the mapping of Wollongong's household plastic waste management system, describing each plastic waste collection from generation, through the collection, transfer, recycling, and final disposal. The goal was to determine the size and

effectiveness of the municipality's plastic-related SWC systems. This research is relevant not only considering the necessity to progress waste management into a more circular economy but also in a context where studies about SWC systems are scarce and there is a lack of consistent data reported on these systems. This data is a key requirement if local governments are to pursue a circular economy approach and achieve the SDGs. The description and analysis of the plastic-related SWC systems allowed the research team to identify gaps in knowledge and challenges faced by these systems, and then propose recommendations to overcome them. The main challenges identified are: 1. contamination in the collected plastic waste content, 2. insufficient community awareness about what materials are accepted in the SWC systems and in other waste collection services, and 3. lack of consistent data on (plastic) waste. Among the proposed recommendations are the transition from a commingled to a non-commingled door-to-door SWC system and initiatives that raise community awareness about plastic waste items accepted in the waste collection services, such as more communication/engagement programs or the development of a waste bin app. Moreover, collecting consistent plastic waste data not only allows the improvement of community engagement/education programs and planning of SWC services, resources, and infrastructure, but also enables the establishment of targets based on reliable data and comparison with SWC systems in other Australian municipalities. The analysis of these challenges and recommendations are pertinent to plastic-related SWC systems. However, they could be extended to other recyclable waste materials. This investigation also showed that in Wollongong there is a lack of support for other circular economy actions such as reuse. Reuse could be encouraged through communication and engagement with residents. It should be noted that apart from overcoming the challenges associated with Wollongong's plastic-related SWC systems, there is an urgent need to enhance the recycling capacity in Wollongong, and other Australian municipalities, to decrease the transfer of plastic waste's negative impacts to lower-income countries. In 2021, the Australian Government announced an AUD 190 million investment in the Recycling Modernisation Fund to support the states and territories to increase the capacity of recycling facilities around Australia. Finally, although this study presents important results, ithas certain limitations. For example, the level of uncertainty in some of the adopted data is likely to be high and the lack of consistency across the adopted data sources affects the accuracy of quantitative results presented. For future research, consideration should be given to understand and quantify the economic, environmental, and social impact of waste plastic not being recycled or reused and leaking to the environment and/or being sent to landfill.

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Abbreviations

The following abbreviations are used in this manuscript:

SWC	Selective waste collection
SDG	Sustainable Development Goals
VDP	Voluntary drop-off point
MRF	Material recovery facility
LGA	Local government area
NSW	New South Wales
WCC	Wollongong City Council
FOGO	Food and garden organics
CRC	Community Recycling Centre
RVM	Reverse vending machine
AD	automated depot
PET	Polyethylene terephthalate
HDPE	high density polyethylene
PVC	polyvinyl chloride
PS	polystyrene
EPS	expanded polystyrene
LDPE	Low-density polyethylene
PP	polyethylene
ABS	acrylonitrile butadiene styrene

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