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Full circle: Challenges and prospects for plastic waste management in Australia to achieve circular economy

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ABSTRACT

Plastic manufacturing accounts for 6% of global oil consumption and is one of the world's fastest-growing waste streams. As the global supply of fossil fuels becomes critical, it is important to quantify how virgin plastic made from fossil fuel sources is recovered, reused, and remanufactured. In this study, the authors undertook the first systematic literature review of Australia's plastic waste (PW) management system to assess challenges and opportunities in moving towards a circular economy. Sources included government reports, industry survey reports, academic research articles, and national household and waste data. Results of the study showed that despite the sharp exponential growth in consumption of plastics (3.5 million tonnes (Mt) in 2018–19), Australia's national recovery rate is only 11.5%, which leaves substantial room for improvement. From 2007 to 2019, average PW generation was just over 2.6 Mt and in 2019, the generation was close to 2.55 Mt. In terms of polymer types, high-density polyethylene (HDPE) generated the most, followed by polyethylene terephthalate (PET) and low-density polyethylene (LDPE). Close to half (47%) the volume of plastic waste is generated by households (specifically, PET and HDPE). Market growth was of biodegradable plastics is much slower than expected. Most recycling facilities use mechanical recycling as the main processing technology, and more facilities are required to process PET (especially in NSW and Victoria). The construction (built environment) sector consumes the largest quantity of recycled plastics; however, local recycled material use was only 10% in all the Australian sectors. Plastic waste is also used for energy recovery, with polyethylene (PE), polypropylene (PP) and polystyrene (PS). This study also discusses the benefits of implementing state-of-the-art processing facilities using diversified recycling technology; vertical integration of plastic manufacturers and pre-processors; regulatory and structural reform; and development of local manufacturing industries using recycled plastics. It is incompetent to efficiently resolve the Australian plastic waste problem with simply bans, it is a global cross-sectoral issue that calls for cross-departmental cooperation. The future of plastic waste management not only relies on the effectiveness of local government and recyclers, but also on community involvement, and initiatives on national, regional, and global level. Numerous stakeholders including industry insiders, governments, customs agencies, regulators, intergovernmental organizations, non-governmental organizations, and civil society need to be involved.

1. Introduction

Each year, globally, approximately 90 billion tonnes (Bt) of plastic materials are extracted and used to manufacture goods. Only 9% of this material is recycled. This pattern creates an unsustainable environment for the natural ecosystem, and most importantly, human health (CSIRO, 2020a). The characteristics and type of waste generated by each country largely depends on its income level and consumption patterns. This is true for almost all waste streams. Fossil fuel production and use is critical to the global economy. Plastic production from fossil fuel resources represents 6% of global oil consumption (Walker, 2021). Plastic manufacturing also consumes other non-renewable resources including gas and coal (Commonwealth of Australia, 2020). Globally, between 1950 and 2015, the volume of plastic produced increased almost 200-fold. In 2020, the plastics consumption was estimated to be 367 million tonnes (Mt) which is 0.3% less than the plastic consumption in 2019 (368 Mt) due to COVID-19 outbreak (Uddin et al., 2022). In the built environment, production and consumption of plastic is

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continuously increasing, due to large application areas in agriculture, construction and infrastructure, packaging, automobile manufacture, and electrical and electronic equipment. According to Arim (2019), globally total plastic production reached in the last 70 years as 9.2 Bt, and cumulative waste generation was approximately 6.9 Bt. Due to the short lifespan of plastic products, plastic waste (PW) represents a relatively high proportion of the world's municipal solid waste (MSW) (Ayeleru et al., 2020). Globally, plastic accounts for 12% of total waste generation (by weight) (World Bank, 2021). According to Tulashie, Boadu, Kotoka, and Mensah (2020), approximately 300 Mt of PW is being generated globally each year. Between 1950 and 2020, around 6.8 Bt of PW was generated. Less than 10% of this waste was recycled, and an additional 15% was incinerated. This leaves significant room for improvement in terms of waste diversion of PW from landfills and recovery of reusable materials. There is potential for a much greater proportion of material to PW to be recovered from PW and fed into the forward supply chain to create a circular economy (CE). The supply chain and recycling and disposal routes of plastic are presented in Fig. 1.

From a holistic point of view, the CE model integrates the operational activities of waste management into the forward supply chain as well as emphasising resource recovery through reuse and recycling (CSIRO, 2020a). The model also supports responsible manufacturers by developing new industries and jobs, reducing emissions, and increasing the efficient use of natural resources in a closed-loop supply chain environment. Most importantly, by viewing waste as a resource, the circular economy model creates a missing link between circulating material resources and waste management. However, Geyer, Jambeck, and Law (2017) predicted that with the current pace and structure of the waste management trend, by 2050, approximately 9000 Mt of PW will be recycled, 12,000 Mt will be incinerated, and 12,000 Mt will be landfilled (Fig. 2). At present, a large portion of PW is being landfilled, and it takes minimum of 450 years for plastic to fully biodegrade. This could cause substantial damage to the environment and human health (Arim, 2019). For example, PW escaping from landfill, bin or street litter into the marine environment is already harming marine creatures and their ecosystem. The volume of marine plastic pollution is reaching concerning levels. Kilvert (2019) estimates that the 'great Pacific garbage patch' in the North Pacific Ocean contains approximately 78,000 tonnes of PW.

Among developed economies, Australia is a major player in the area of sustainability and has committed to achieving the United Nations Sustainable Development Goals (UNSDGs) by 2030 (United Nations, 2021). Like other high-income nations, Australia is facing a tremendous challenge in keeping up with the infrastructure development and recycling technology adoption needed to effectively manage solid waste. Resources such as plastics, paper, glass, metals, textiles, masonry, food and other organic materials are generally lost to landfill as waste (Australian Government, 2018). In 2020, total waste generation (all types) in Australia was 76 Mt, which increased by 10% since 2016–17 (ABS, 2020). Annual per capita waste generation was estimated to 2.7 tonnes (Australian Government, 2018). The Australian PW recovery rate is of particular concern. Landfilling is considered as the main method of plastic waste disposal in the Australian waste recycling landscape (Australian Government, 2018). As shown in Table 1, Australia's PW recovery rate is lower than many countries with lower per capita GDP. However, the Australian Government is reviewing the National Waste Policy to incorporate CE principles and the UNSDGs. This review will focus on PW, due to market conditions (achieving recycling targets), community concern and policy-related operating environment for companies (Australian Packaging Covenant Organisation, 2019).

PW is a critical waste stream that received closed attention recently, due to the Chinese ban on waste import sin 2018 (Huang et al., 2020). The established process for Australian waste disposal at that time was for local governments to sell kerbside recycling to companies who then exported the recycled material to China (Arim, 2019). China's ban on waste exports created an unexpected interruption to this PW disposal chain. Another important issue is the serious impact of improper disposal of PW on the aquatic environment. Each year, around 130,000 tonnes of Australian PW end up in waterways and oceans. It comes from various sources, including littering, flushing wet wipes, and plastic which blows away during processing in landfills (Murray-Atfield, 2019). From a triple bottom line perspective (social, economic and environmental), the Australian Government clearly understands the necessity of formulating immediate measures and management strategies to combat the harmful effects of this critical waste stream.

This review article aims to investigate the present status of PW

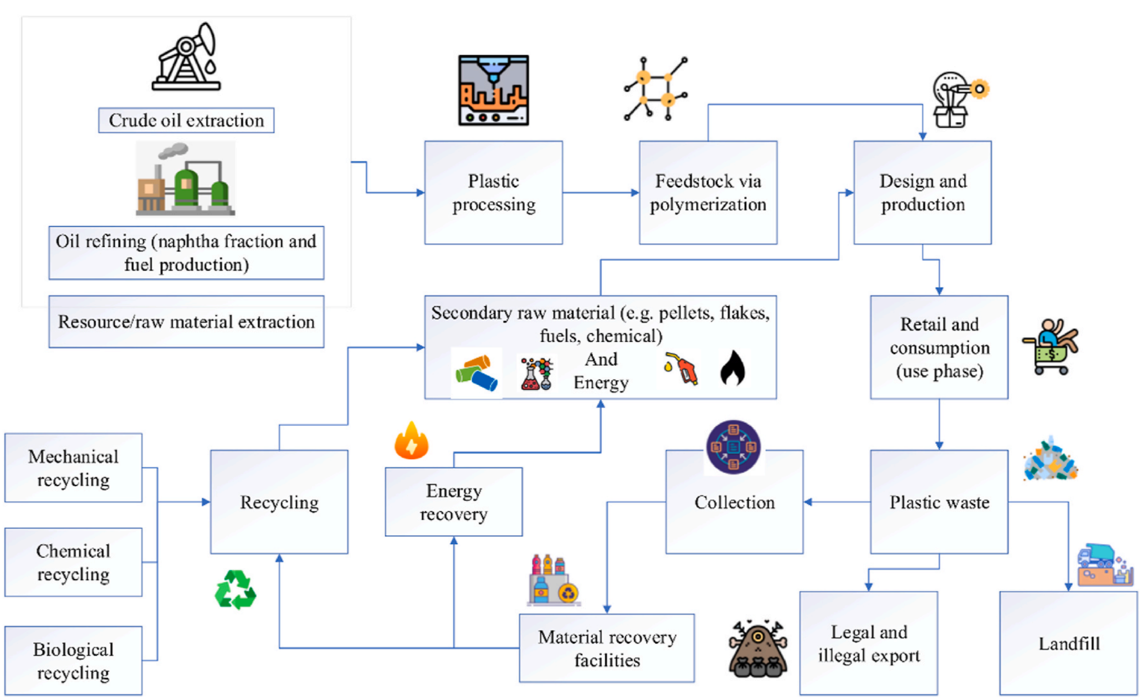

Fig. 1. Plastic production, disposal, and recycling routes.

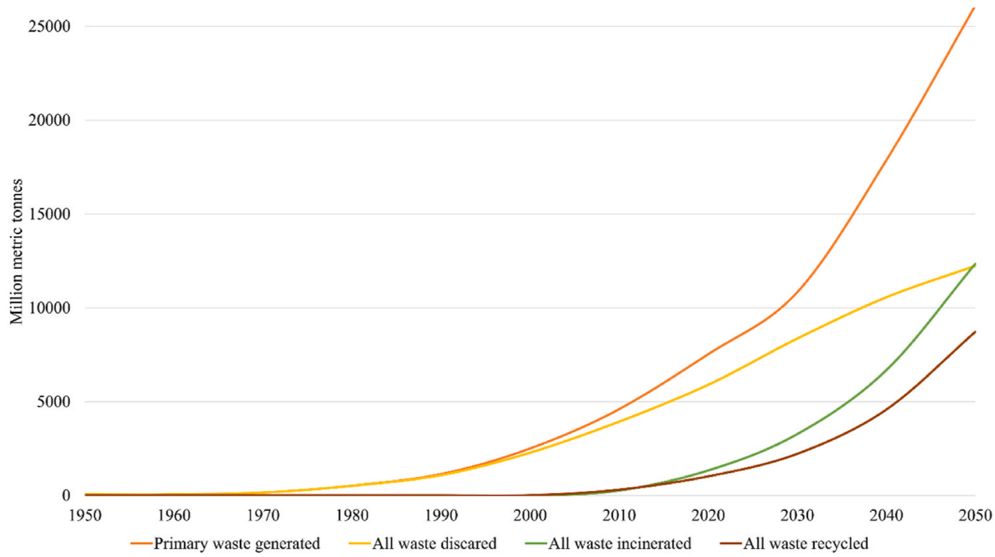

Fig. 2. Projected cumulative plastic waste generation and amounts in various disposal routes (global) [Data source: (Geyer et al., 2017)].

Table 1
PW recycling rate, per capita GDP, and per capita PW generation in selected countries (Envirotech online, 2020; eurostat, 2013; Kilvert, 2019; McCarthy, 2019; Misicka, 2018; D. Ng, 2018; O'Farrell, 2020; Parker, 2020).

Country	Recycling rate (%)	Per capita GDP (USD)	Per capita plastic waste generation (kg)
Germany	56.10	46,445.25	81
Austria	53.80	50,137.66	34.1
Wales – United Kingdom (UK)[a]	52.20	32,980	40
Switzerland	49.70	81,993.73	100
South Korea	53.70	31,846.22	98.2
Australia[b]	11.50	55,060.33	53

[a] Average value of UK generation was used.
[b] Defined as recovery rate rather recycling rate.

management and recycling in Australia (in terms of consumption, waste generation and recovery rate from various sources and types of plastics). It will also investigate how the circular economy model can help mitigate the impact of unrecovered and improperly disposed PW. To assess the resource efficiency of the existing national PW stream, this article also assesses the current reprocessing capabilities to manage polymer consumption and PW generation in each Australian state. To assist policy makers, the review will examine existing government policies and strategies and suggest avenues to incorporate informed decision-making on technology deployment and CE business models. Finally, this paper will discuss existing challenges and roadmaps to move towards a circular plastic economy. As well as informing future Australian PW management strategies, this discussion may be useful for similar developed economies, as well as developing countries initiating sustainable processes for the PW management.

2. Literature review

Table S1 in appendix summarises previous review articles focusing on Australian PW (published in international peer-reviewed journals). The search term "plastic waste" identified 16,464 articles in the research database, including 1171 review articles. The articles were selected from the Web of Science core collection database using the keyword "plastic waste", along with the selection of "review article" and "Australia" in the database's Refine Research window. This search identified 18 articles. Table S1 shows that most previous review articles by Australian researchers focused on material substitution (use of plastic waste as a substitute for virgin material), bioplastic production to mitigate impact of synthetic plastics, microplastics, and processing- and treatment-related issues. The literature review found no previous studies which examined issues related to plastic consumption, PW sources and types of PW generation, or current processing capabilities across PW recycling industries and sectors that are considering PW as a secondary source of raw material. This demonstrates the gap in research which furthers understanding of how PW can be used as a resource to feed CE supply chains, and highlights strategies to alleviate the current PW crisis in Australia. The academic papers reviewed did not examine recent Australian data on PW management and recycling. In most cases, published data in articles, government reports, and white and grey papers did not further understand of the potential opportunities to use PW resources in a closed-loop supply chain (informed by a CE model) to mitigate current negative environmental and health impacts.

This review article is the first systematic approach to unveiling some of the critical issues in managing PW management and recycling in Australia. The main research questions are:

RQ1: What is the consumption pattern of plastics in Australia (in terms of polymer types, sector, and main application areas, at state-level demand)?
RQ2: What are the current recycling process and technology widely applied in Australian recycling industries?
RQ3: What are categories of waste currently generated in Australia and the amount of waste generation (quantitative assessment of plastic waste generation in terms of polymer types, sector, and state-level of generation)?
RQ4: What is the rate of recovery of various types of plastic waste, availability of recycling facilities at various states, main applications of the recycled plastics across sectors and economic implications of the recovered plastics in Australia?
RQ5: What are the main challenges for plastic waste management in Australia?
RQ6: What are the prospects and opportunities achieving circular plastic economy in Australia?

3. Research methodology

This review article made use of several research databases. These included Google Scholar, Web of Science and Science Direct. PW consumption, generation and recovery-related data included in this review was sourced mainly from government reports (primarily white and grey papers) published by the Australian Government. In this case, to identify all the relevant articles (including some research articles) the authors used keywords in Google search engines. Initially, the search expression "'plastic waste recycling" OR "Plastic waste management" AND "Australia"' was used in the Google search engine. This retrieved government websites, reports, and other sources. From the search results, the authors selected, analysed, and reviewed all relevant documents. Articles found in the Web of Science core collection database which focused on Australian PW were also reviewed. In addition to the literature review, the authors used Microsoft Excel's "TREND" function to estimate historical Australian plastic consumption patterns. Finally, the authors outlined and discussed the challenges and opportunities for more sustainable PW management in Australia. The searching was also done by manually in order to prevent word limitations and elimination the errors to collect the appropriate information. This searching was taken care to cover all the relevant information was collected and was not overlooked. The searching was covered to topics relevant to the plastic waste generation, consumption, recycling capabilities, and the challenges associated to achieve the circular economy of the plastic waste in the Australian context. The common manufacturer and recyclers of the Australia for the plastic waste was identified and a discussion has been done each of them to understand whether they are in the pilot stage and in full scale commercialisation stage. Many of them have been scanned and were learned that they did not meet the criteria of inclusion. At first, we identified the suitable standards and measures for the research to select the appropriate peer reviewed papers and reports and relevant government reports, patents and industry white papers. Then we have explored and identified the other relevant papers which could suitable and supporting to the research. At the next stage, we assessed all the papers and reports and ascertained whether the information in the documents is relevant and covers the scope of this research. At the final stage, we examined the collected papers and noted down all the papers' information in the date of publication, context and major findings.

The main research components of this study to identify comprehensively the plastic waste management in Australia and the challenges and prospects towards achieving the circular economy for plastic waste. For this we have studies the trend of plastic waste generation and consumption. The major types of plastics is consumed by Australia at different state, their quantitative assessment, the major sources of waste, etc. was assessed to figure out the plastic waste problems in Australia. We discovered the current waste recycling capabilities where we have studies the state and national processing facilities, Australian plastic recycling routes and their performance, the plastic waste recovery rate at different state and the potential consumption sectors for the recycled materials. We have included and summarise the laws and regulation around plastic waste management in Australia and extended producer responsibilities (EPR). We have also studied the plastic waste flows in landfills and aquatic environment. With all these information, we have outlined the challenges and recommendations to reducing PW for a circular economy for Australia.

4. Results

4.1. Plastic consumption and plastic waste generation

O'Farrell (2020) mentioned the following classifications (Table 2S) of plastics available in the Australian PW stream. Australian polymer classification follows the same pattern as global polymer classification, but the identification code has a different name. Globally, polymers are classified by resin identification code, while in Australia they are classified by plastic identification code (PIC). According to Chemistry Australia (2017):

> *The Plastics Identification Code continues to be one of the most successful and enduring Product Stewardship programs run by industry. The simple, effective "1 to 7" numbering system identifies the resin composition of plastic containers (and other items intended for recycling). This voluntary coding system has been a key element in the successful collection, recovery, and management of used plastics in Australia.*

Other aggregated polymer types (denoted by PIC 7) are also present in the categorisation that include acrylics, acetals, polyethylene oxide, polyisobutylene and other polymers of propylene (other than PP), and polymers of styrene (other than PS, expanded polystyrene (PS-E) and acrylonitrile butadiene styrene (ABS)/acrylonitrile styrene (SAN).

4.1.1. Plastic consumption

Consumption of plastic in Australia has increased exponentially over the years (Department of Agriculture., 2020). Using the data provided by O'Farrell (2020), the historical pattern of Australian plastic consumption between the 2000–01 and 2018–19 financial years can be estimated as shown in Fig. 3. In 2000, plastic consumption was 1.5 Mt. By 2018–19, it increased by over 166% and reached 3.5 Mt. Since 2000, the estimated annual per capita plastic consumption has been recorded as 53 kg (Kilvert, 2019). In contrast to the rapid and growing consumption of plastic, the plastic recovery rate has been slow to increase. In 2000–01 0.15 Mt of plastic was recovered, rising to 0.4 Mt in 2018–19. However, according to 2020 Australian Bureau of Statistics (ABS) data, plastic consumption in Australia is starting to decrease, with a 3% decline in PW tonnage since 2016–17 (ABS, 2020).

4.2. Plastic consumption by polymer types

In 2018–19, 60% of plastic consumed in Australia was in the form of finished and semi-finished goods, while only 36% of consumption was associated with local manufacturing using virgin resins (either locally manufactured or imported). Surprisingly, the national consumption of locally processed recycled polymers was only 4% in the 2018–19 financial year (O'Farrell, 2020). Fig. 4 shows Australian plastic consumption by polymer type for 2018–19. According to Unknown polymers (generally imported as finished and semi-finished products) were the main source of polymers entering the Australian plastic product market (O'Farrell, 2020). However, in terms of total consumption, HDPE made up the bulk of consumption for the year. Local polymer manufacturing industries sourced mainly imported resins, followed by PP. This trend of importation was also valid for PET, PVC, and LDPE. For all the polymer types recorded in Fig. 4., local use of Australian-recycled polymers is relatively low. Despite the global progress in production and consumption of bioplastics, the Australian market has not reported any significant local penetration.

Fig. 5(A) shows the total consumption of polymers in various Australian application sectors during 2018–2019. It demonstrates that consumer packaging (24.6%), other application areas (23.5%), and the built environment (18.5%) accounted for the bulk of polymers consumed. In terms of the types of polymers consumed, HDPE, PP, PVC and PET were the main known polymer types consumed by the application sectors examined, while the share of unknown polymer consumption was 15% in 2018–19 (Fig. 5(B)).

Fig. 6 shows which types of polymers were used in each application sector. PET was widely used in the packaging sector, as well as the 'other applications' sector. HDPE and PP were widely consumed in all the application sectors. HDPE and LDPE were the two main polymers consumed in packaging applications, but a quarter of total HDPE consumption for 2018–19 was in the built environment sector. The built environment sector was also the main consumer of PVC polymers. PP was consumed mainly through imported automobiles, packaging, and other applications. A large portion of total PS consumption is used by the electrical and electronic sector. The electrical and electronic sector is also the highest consumer of ABS/ASA/SAN and EPS polymers. Almost 50% of EPS consumption in 2018–19 was in the built environment sector, with the other main sectors were packaging and electrical and

Table 2
Common re-processors and their performance, based on data available from ENF (2021), O'Farrell (2019), and Department of Agriculture Water and the Environment (2013a).

	Industry	State	Types of plastics recycled	Main processing technology	Specific process features	Recycled materials	Processing capacity (tonnes/yr)
1	Polymer Processors	Victoria	PP, HDPE, LDPE, LLDPE, ABS, HIPS	Not specified	Not specified	Granules/ pellets	≥2500
2	Advanced Circular Polymers	Victoria	PET, PP, HDPE	Not specified	Sorting and shredding/granulation (polymer identification and flake manufacture plant)	Flakes	up to 70,000
3	Advanced Plastic Recycling	South Australia	HDPE	Mechanical recycling	Extrusion	Granules/ pellets	
4	Astron Sustainability	Victoria	PET, PP, HDPE, LDPE, LLDPE	Mechanical recycling	Sorting, shredding/granulation, and pelletising (extrusion, injection and washing equipment)	Granules/ pellets	30,000
5	Australian Recycled Plastics Pty Ltd	NSW	PET, PP, PS, PVC, HDPE, LDPE	Mechanical recycling	Not specified	Flakes	
6	CLAW Environmental	Western Australia	PP, HDPE, EPS, PS	Mechanical recycling	Shredding, granulating, washing and pelletising	Granules/ pellets	
7	Corex Recycling Pty Ltd	Victoria	HDPE, LDPE, PP and HIPS, ABS, GPPS	Mechanical recycling	Extrusion, filtration systems, contamination detection	Granules/ pellets	
8	GT Recycling	Victoria	PP, HDPE	Mechanical recycling	Decontamination and size reduction process	Granules/ pellets	1500 (flexible PP packaging), overall, ≥ 2500
9	iQRenew Pty Ltd	NSW	PET, HDPE and mixed plastic (residues of PET, HDPE and soft plastics and multilayer packaging)	Mechanical and chemical recycling	Optical sorting and processing for physical recycling and (Cat-HTR™ platform – catalytic hydrothermal reaction	Flakes, fuels, chemicals and new plastics	
10	Olima Fibre Processors Pty Ltd	Victoria	PET, PP, PA, PS, PC, HDPE, MDPE, LDPE, ABS, HIPS	Mechanical recycling	Granulation lines	Granules/ pellets	
11	Olympic Polymers	Victoria	Post-industrial plastic	Mechanical recycling	Film extrusion, profile extrusion and injection moulding, granulation	Granules/ Pellets	≥2500
12	Plastic Forests Pty Ltd	NSW	Soft plastics (food industry flims, agricultural flims, woven PP, post-industrial film)	Not specified	Dry-Cleaning Technology		
13	Poly Pipe Recyclers	Western Australia	LLDPE	Not specified	Not specified	Granules/ pellets	
14	Recyclecare Pty Ltd	NSW	HDPE	Not specified	Not specified	Granules/ pellets, Flakes	
15	Repeta Pty Ltd	NSW	PP, HDPE, LDPE	Mechanical recycling	Injection moulding, blow moulding, film and other extrusion processes, as well as rotational moulding applications	Granules/ pellets	
16	Valera Recycling Pty Ltd	NSW	PP, PVC, HDPE, LDPE, LLDPE	Mechanical recycling	Not specified	Flakes	
17	JK Plastics Pty Ltd	NSW	PP, PE	Mechanical recycling		Flakes	
18	Martogg Group of Companies	Victoria	PET, HDPE, LDPE	Mechanical recycling	Sorting, shredding/granulation and pelletising (bottle to bottle recycling – 'Vacurema' processing line)	Granules/ pellets	10,000–20,000
19	Resitech Industries Pty Ltd	Queensland	PP, HDPE, LDPE	Not specified	Not specified	Granules/ pellets shredded	8000
20	YCA Recycling	South Australia	PET, PP, PA, PS, PC, PVC, HDPE, LDPE, ABS, POM	Not specified	Not specified	Not specified	
21	Dunlop Flooring	Victoria	Foam underlay	Not specified	Not specified	Not specified	≥2500
22	Cryogrind	Victoria	PVC	Not specified	compounding and melt filtration equipment, Cryogenic processing technology (reagent - liquid nitrogen)	Not specified	≥2500
23	Action Products	Queensland	Not specified	Not specified	Not specified	Not specified	≥2500
24	Visy Recycling	New South Wales	PET and HDPE	Mechanical recycling	Sorting, shredding/granulation and pelletising and bottle production	Granules/ pellets	101,000
25	Recycled Plastics Australia	South Australia	Not specified	Mechanical recycling	Sorting, shredding/granulation, and pelletising	Granules/ pellets	40,000
26	Microfactories™	New South Wales	E-waste plastics	Microrecycling	Sorting, shredding/granulation, pelletising, high temperature transformation	3D plastic filaments	

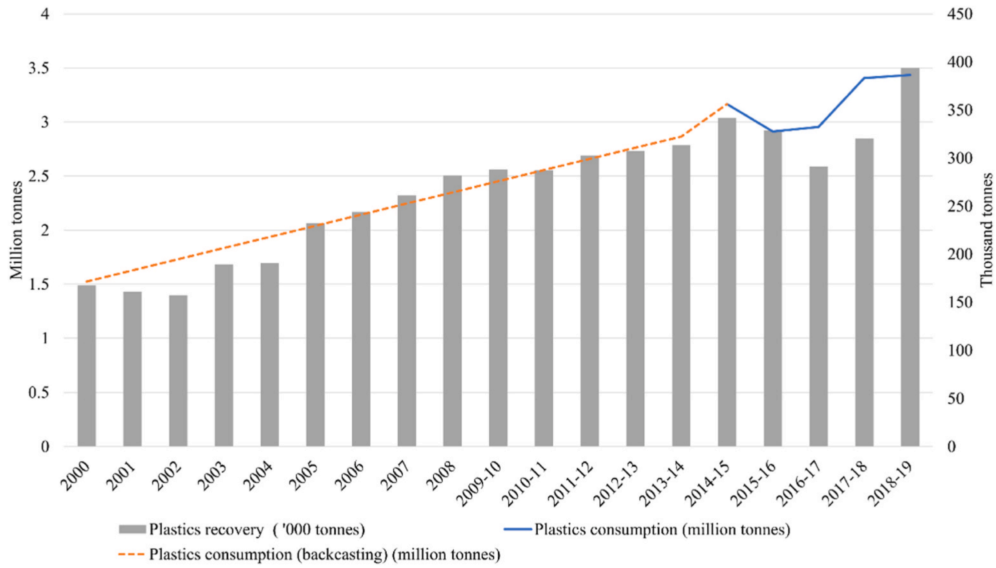

Fig. 3. Plastic consumption and recovery trend in Australia.

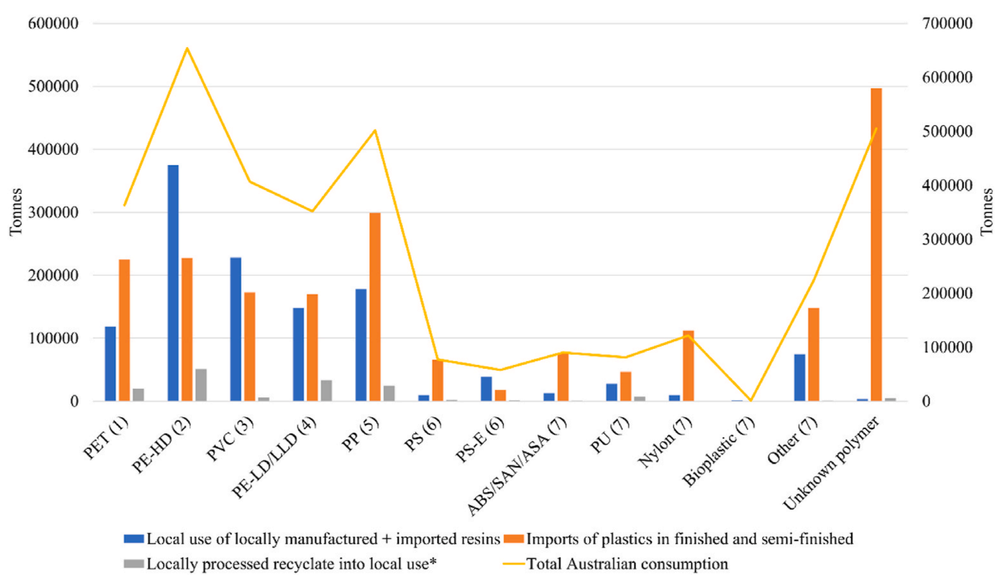

Fig. 4. Australian plastics consumption by polymer type and source in 2018–19 (tonnes).

electronic applications.

4.2.1. Australian plastic consumption by state

Fig. 7 (A) shows plastic consumption in the year 2018–19, and Fig. 7 (B) shows plastic consumption in each state by polymer type. The highest amount of polymer consumption was recorded in NSW, followed by Victoria and Queensland. This is in line with the expected result of greater total polymer consumption for states with a larger population. The data presented in Fig. 7. (b) was sourced from O'Farrell (2020) who mentioned that "consumption data for each jurisdiction is estimated based upon the jurisdiction's population as a proportion of the national population". From here, it can be inferred that more populous states consumed more of each type of plastic. At a state level, PET, PE-HD, PVC, PE-LD and PP are the main known polymers consumed. In NSW, the most highly consumed known polymers were PE-HD (209,200 tonnes) and PP (160,600 tonnes). Victoria also consumed a greater amount of PE-HD and PP than other known polymers. NSW and Victoria also consumed significantly more PVC than other states. A significant volume of unknown polymers was consumed in NSW (161,600 tonnes), Victoria (131,300 tonnes) and Queensland (101,300 tonnes). A significant amount of Australian PW comes from single-use items. About 40 per cent of plastics consumed are single-use objects such as cutlery, plates, food containers, electronics packaging (Kilvert, 2019). In South Australia, 255 million straws and 210 million disposable coffee cups are used each year (Arim, 2019).

Plastic bags are another notable source of Australian PW. Each year, 6.9 billion plastic bags are consumed nationally, and more than half of these bags are used for shopping.

4.3. Plastic waste generation

4.3.1. Quantitative assessment of plastic waste generation

Fig. 8 shows the PW generation in Australia from the year 2007–2019. Between the years, the average annual generation was over 2.6 Mt. The highest amount of PW generation was over 2.75 Mt in 2010, while in 2018, the generation was just under 2.5 Mt (Blue Environment, 2020). On the other hand, based on the annual per capita consumption of 53 kg, Kilvert (2019) estimated that since 2000, cumulatively PW

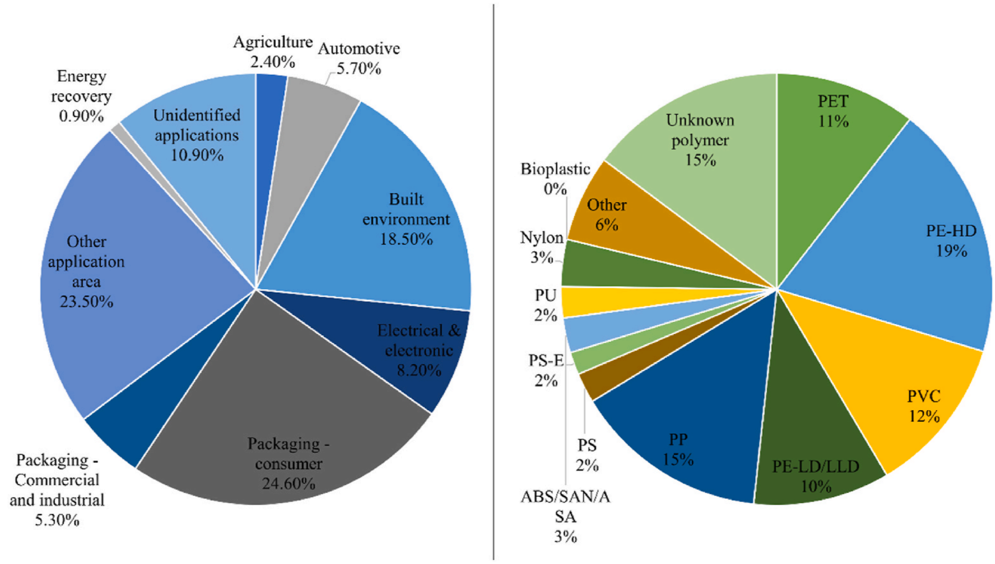

Fig. 5. (A) Plastic demand by application sector and **(B)** types of polymers consumed by Australian application sectors in 2018–19.

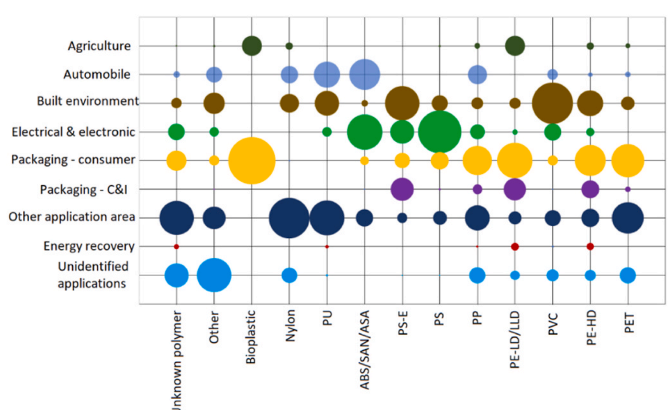

Fig. 6. Application area destinations of all plastics by polymer type in 2018–19.

generation in Australia reached 300 Mt. In 2018–19, PW generation represented 3% of total waste generation (all types) in Australia (ABS, 2019). Nevertheless, Commonwealth of Australia (2020) reported that less than 10% of PW generated in 2016–17 was recycled.

Huang et al. (2020) mentioned that from demand-side dependency perspective, Australia was largely dependent on China and the USA for its' waste export. For example, in 2015, Australia's PW that represented 4.6% and 6.2% of the global PW import went to China and the USA, respectively (Huang et al., 2020). This shows that the Australian PW trade network connects to both the US and China, which are the main supply-side controllers, but independent from other economies on the demand side. On the other hand, 70% of the world's recyclable commodities exported to China (World Wide Fund for Nature (WWF), 2019). However, from March 1, 2018, China has enforced scrap-import contamination standards which specify a contamination threshold requirement of no more than 0.5% impurities for both scrap paper and scrap plastics. As of 2015, 34% of Australian PW was exported to China (Huang et al., 2020).

The supply chain flows of plastic in Australia (imports, exports, manufacturing, recycling, and disposal) are illustrated in Fig. 9. Waste exports have remained steady at 6%, and in 2020, the national spending on waste services was more than $17 billion, which was an increase by 18% since 2016–17 (ABS, 2020). In 2018–19, 393,800 tonnes of plastic waste was recovered (approximately 11.5%), while more than 50 million tonnes were accumulated to landfills (84%) (ABS, 2020). PW has the lowest recovery rate of any waste stream in Australia (11.5%), followed by textiles, leather and rubber (26%), and hazardous waste (27%) (ABS, 2020). In 2018, Australia exported 4.5 Mt of waste (mainly to China, Vietnam, and Indonesia), at an approximate cost of $3 billion (A. W. M. Ng, Ly, Muttil and Nguyen, 2021).

4.3.2. *Sources of plastic waste*

Fig. 10 shows the sources and relative proportions of various types of PW from the sources for the year 2018–19. Households produced the largest volume, with a total generation volume of 1.2 Mt. This included 446,695 tonnes of PET and 441,976 tonnes of HDPE. Additional ABS data (2020) shows that households contributed 47% of total PW, and since 2016–17, household PW has remained stable between 1.1 and 1.2 Mt. Other sources of HDPE were construction (61,810 tonnes), manufacturing (100,766 tonnes) and other industries (16116 tonnes). In 2018–2019, the total generation of LDPE PW was 0.42 Mt, which came mainly from construction (54,996 tonnes), manufacturing (121,746 tonnes) and all other industries (187,593 tonnes). The plastic designated as others is a matter of concern and is currently going to landfilling. One of the major difficulties of this criteria is the multilateral associated to the plastic waste, such as metal laminated plastics in the packaging waste. This kind of multimaterials is difficult to identify and standardised for recycling and remanufacturing. The plstics comes from the household is comprised of PET, PP, PE, PVC and others. Industrial and manufacturing sectors and the construction sectors have all kind of plastics such as PET, PP, PE, PVC, PS and other where the major share is HDPE and LDPE (Fig. 10).

4.3.3. *Plastic waste generation by polymer type*

Fig. 11 shows the PW generation trends of various plastic types. In 2016–17, HDPE constituted around 32% of total PW (ABS, 2020). The amount of HDPE PW peaked (among the known categories of plastics) in 2018–19 at just over 800,000 tonnes. Similarly, generation of LDPE PW increased from around 300,000 tonnes in 2016–17 to just over 400,000 tonnes in 2018–19. In 2017–18, the generation of PET and HDPE plastic PW were similar, at approximately 600,000 tonnes. Historical PW generation from 'other plastic' (mainly category 7) types reached an all-time high of over 900,000 tonnes in 2016–17, which then decreased to just below 500,000 tonnes. PVC and PS PW generation has remained relatively low (under 100,000 tonnes). Overall, if 'other plastics' are

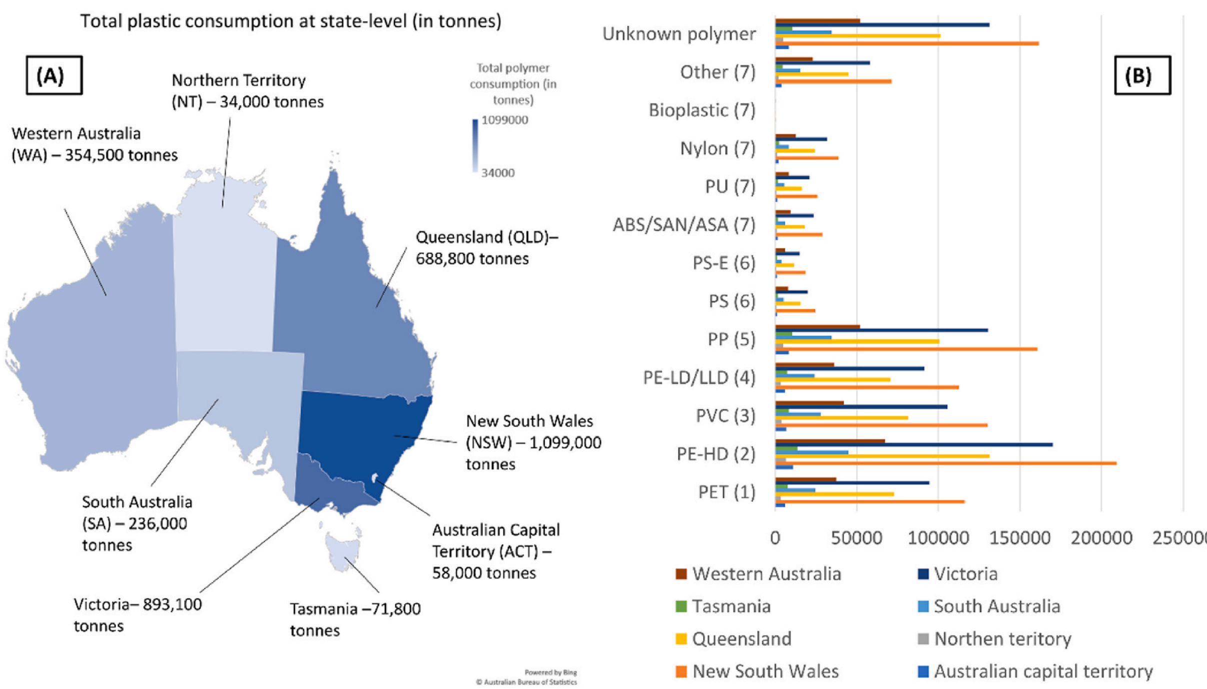

Fig. 7. (A) Australian polymer consumption by state in 2018–19 and **(B)** types of plastic consumed in each state.

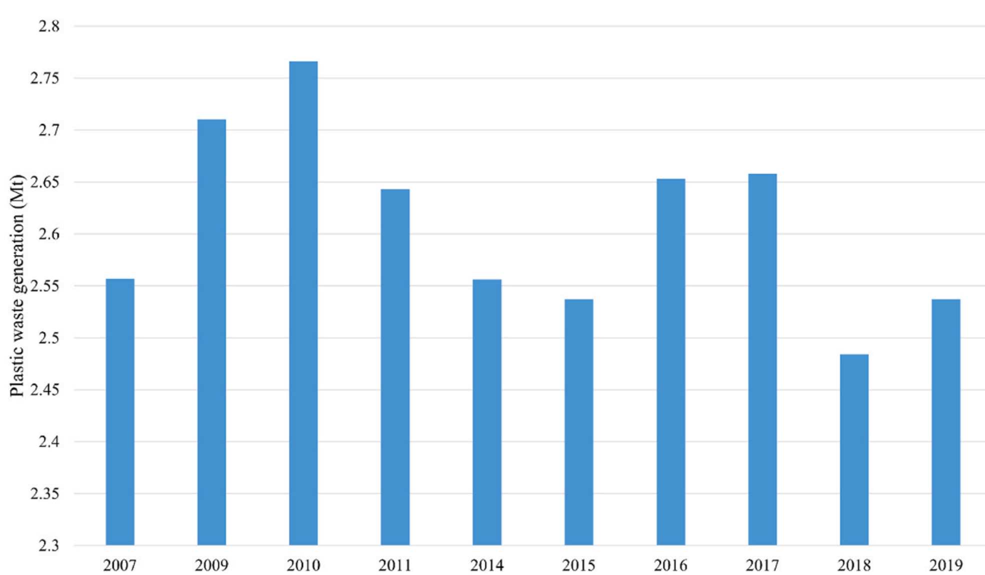

Fig. 8. Plastic waste generation from 2007 to 2019 (Blue Environment, 2020).

excluded, HDPE, PET and LDPE were the three dominant types of PW, with generation varying between 400,000 tonnes (LDPE category) and 800,000 (HDPE).

4.4. Plastic waste recycling capabilities

4.4.1. State and national reprocessing facilities

In Australia, main types of resource recovery facilities are categorized as alternative waste treatment (AWT) facilities, garden organics processing facilities, thermal waste technologies, material recovery facilities (MRF) and recycling facilities (Department of Agriculture Water and the Environment, 2013a). Transfer stations are considered as separate part of waste management infrastructure (Department of Agriculture Water and the Environment, 2013b). In the plastic industry, the term recycling is broadly applied to several activities such as collection, sorting, reprocessing, export for reprocessing and new product manufacturing (O'Farrell, 2019). Thus, the term "reprocessing facilities" referred as a part of the broader definition of recycling facilities. These facilities use mechanical, biological and thermal technologies for sorting and processing discarded waste from a number of sources (Department of Agriculture Water and the Environment, 2013a). The number of reprocessing facilities in each Australian state, and the corresponding recovery rate and proportion of specific PW handling facilities are shown in Fig. 12. Fig. 12 shows that Victoria has the highest number of plastic reprocessing facilities (27), followed by NSW (18), and Queensland (11). Despite the relatively high number of facilities available in Victoria, the state's resource recovery rate is only slightly higher (16%) than that of South Australia (13.7%) and NSW (13.6%). In 2017–18, South Australia and Queensland processed around 61% and 53% (respectively) of recyclate generated within their state (O'Farrell,

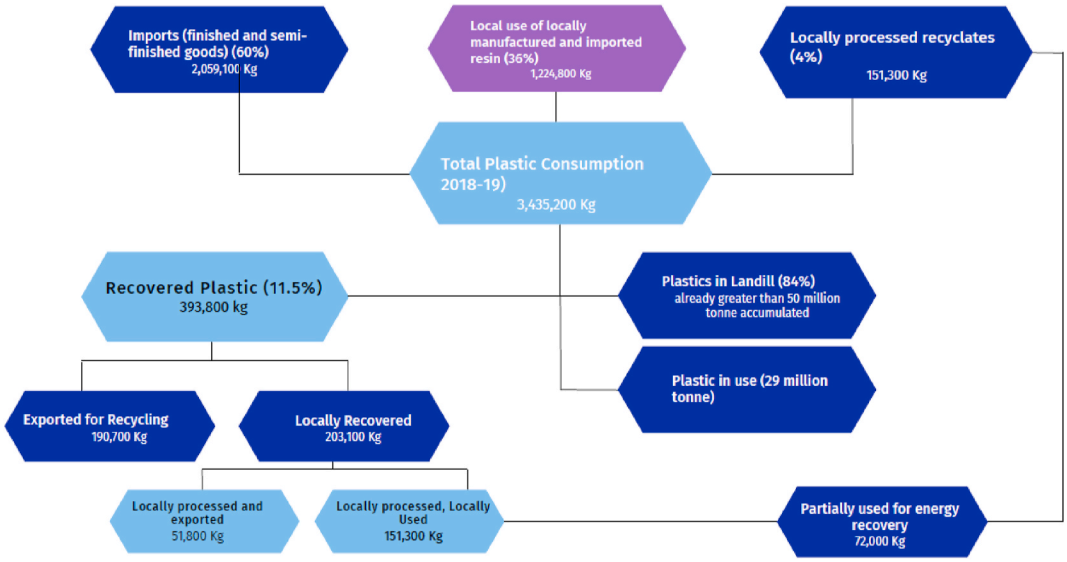

Fig. 9. Plastic supply chain flows in Australia, 2018–19 (Blue Environment, 2020).

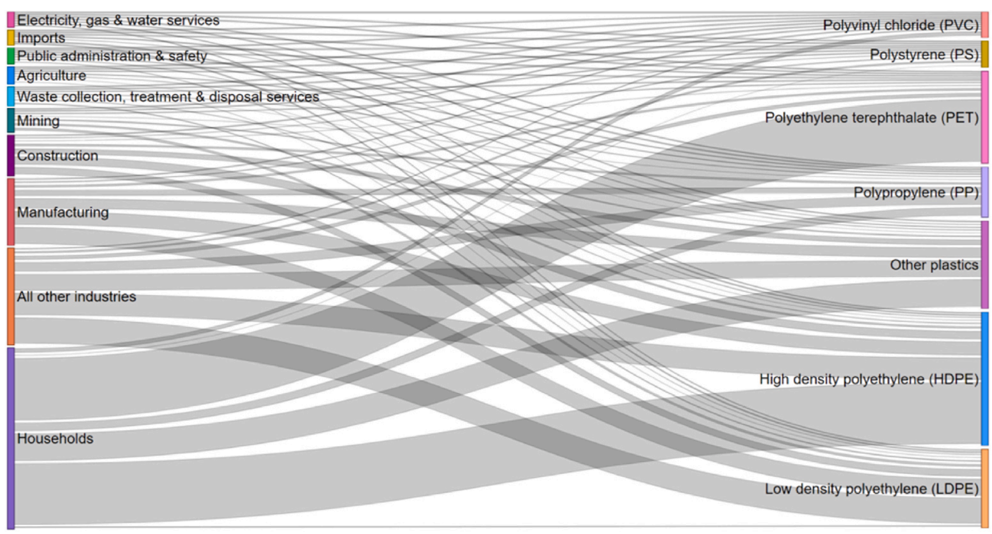

Fig. 10. Sources and types of plastic waste in Australia (Data source: ABS (2019)).

2019). Surprisingly, although no recovery facilities were reported in the Australian Capital Territory (ACT) or Northern Territory (NT), their PW recovery rates waste were reported as 7.9% and 3%, respectively. This might be due to reprocessing of waste generated in neighbouring states (e.g., PW generated in NT is processed in Queensland and ACT's PW in NSW facilities). However, other statistics from the Department of Agriculture Water and the Environment (2021) showed that there has been one recovery facility established in each of these territories in recent years. However, the source did not report the specific polymer handling capabilities established in the territories. The Department of Agriculture Water and the Environment (2021) also reported that, in June 2021, the number of PW processing facilities in NSW, Victoria, Western Australia, and in South Australia reached 22, 40, 11 and 13, respectively. However, what types of facilities they are (e.g., MRF or polymer recycling facilities) and what kinds of polymers they process was not detailed.

In terms of specific polymer processing capabilities, South Australia has two facilities which specialise in handling EPS PW, and three which specialise in PS. Victoria has developed diverse range of plastic processing capabilities. The state's facilities can handle HDPE (total 17 processing facilities), LDPE (12), PP (12) and PS (8). Therefore, it can be inferred that Victoria has the highest number of facilities that deal with different types of plastic. Unlike other states, Victoria also has facilities which handle nylon and engineering plastics such as ABS, SAN and ASA. Victoria also has the highest number of PET processing facilities (6). In Queensland, the highest number of facilities (7) are allocated to HDPE plastic waste recycling. Surprisingly, there is only one reprocessing facility for PET in NSW, which is lower than the number of HDPE, LDPE/LLDPE and PP reprocessing facilities. Facilities located in NSW can handle up to 30 different types of polymers (O'Farrell, 2019). The range of specialized reprocessing facilities in Western Australia and Tasmania are relatively low, specialising only on HDPE and PP. None of the states have developed bioplastic processing facilities. Despite large-scale generation of 'other' and unknown polymers, NSW, Victoria, Western Australia, and South Australia had a limited focus on handling these two problematic plastic waste streams. In 2017–18, Victoria and NSW reprocessed 37% and 30% of PW into recyclates, respectively (O'Farrell, 2019).

The overall number of facilities in Australia dealing with specific polymer waste types is shown in Fig. 13. The current national reprocessing landscape is dominated by the recycling of HDPE-type polymers

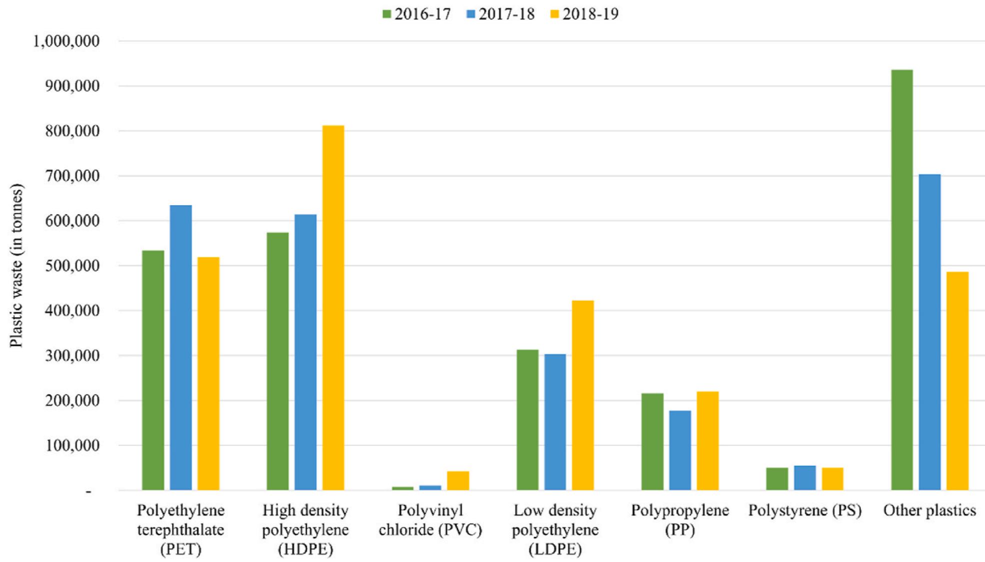

Fig. 11. Plastic waste generation as per polymer type between 2016–17 and 2018–19 [Data source: ABS (2019)].

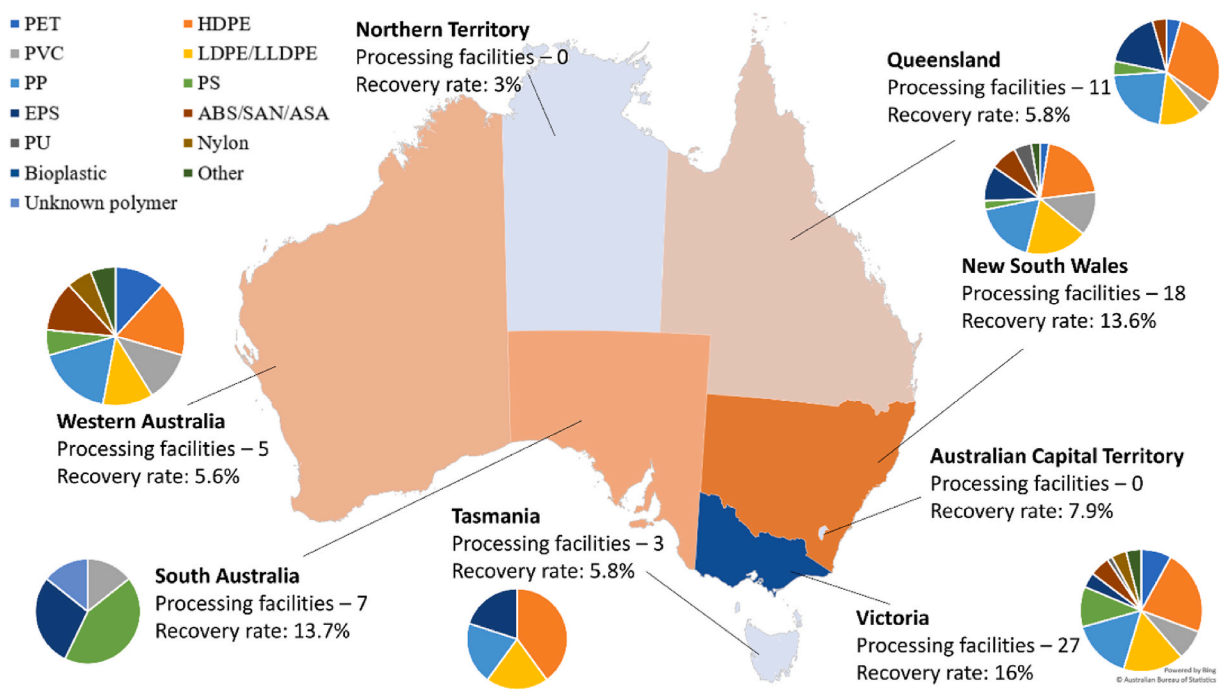

Fig. 12. Australian polymer reprocessing facilities and recovery rates by state [Data source: O'Farrell (2020)].

(37 facilities) followed by PP (28 facilities), LDPE (25 facilities) and PVC (14 facilities). Only 10 facilities can process PET plastic waste, and there are also a few PS and EPS processing plants (14 facilities, each). This study identified limited capabilities for handling nylon and polyurethane (PU). As discussed above, there are no bioplastic processing facilities in Australia, and only six of the facilities can deal with unknown and other types of plastics. Industry analysis also found a lack of processing facilities for other plastics, such as 1 facility in Victoria for general purpose polystyrene (GPPS), 1 facility for medium-density polyethylene (MDPE) processing in Victoria, 2 facilities for polycarbonate (PC) plastic processing (one in Victoria, other in SA), and 1 facility for polyoxymethylene (POM) in SA ENF (2021).

4.4.2. Australian plastic recycling routes and performance

Globally, there are several technology options for PW recycling and processing facilities, including mechanical, chemical, and biological recycling, as well as energy recovery. The broad categorisation of available PW recycling routes can be represented in Fig. 14. According to PlasticsEurope (2019), mechanical recycling is "a method by which PW is recycled into 'new' (secondary) raw materials without changing the basic structure of the material". Mechanical recycling is also known as secondary material recycling, material recovery, or back-to-plastics recycling. Using a multistep process (including collection, sorting, and heat treatment), this process can produce recycled materials such as plastic granules, pellets, and flakes for substitution of virgin plastic material (Faraca and Astrup, 2019). However, mixed plastic recycling using mechanical processes is often challenging as the waste stream must be separated effectively to reduce the polymer mixture (Qureshi et al., 2020). The technique is a labour intensive activity (Larrain et al., 2021). In contrast, chemical recycling involves the transformation of

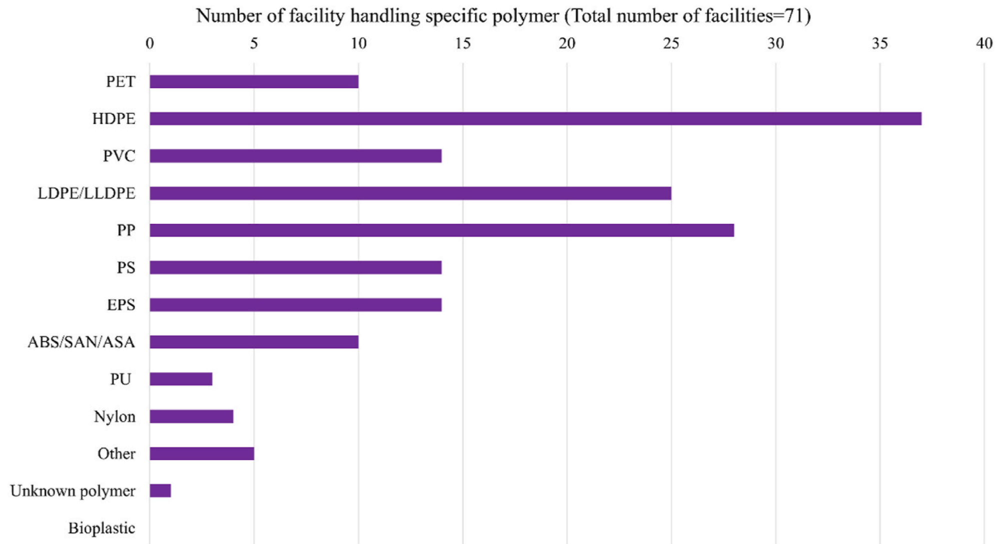

Fig. 13. Number of processing facilities handling specific polymers [Data source: O'Farrell (2020)].

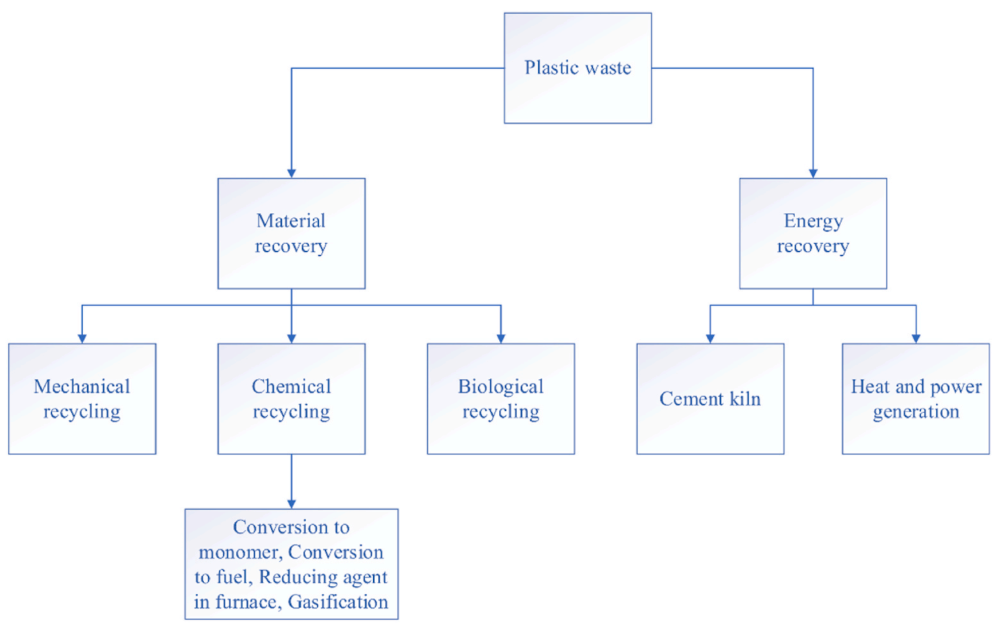

Fig. 14. Globally available plastic recycling routes (FICCI, 2014).

polymers into their monomer (simple chemical) structure to produce fuels, chemical products, and new plastic products (Sri Sasi Jyothsna and Chakradhar, 2020). Energy recovery is a subset of chemical recycling. Pyrolysis, gasification, and hydrothermal treatment are some commonly used for energy recovery options. Biological recycling processes use microbes (such as bacteria) and fungi to degrade both synthetic and natural plastics. According to Koshti, Mehta, and Samarth (2018), biodegradation of PET using an enzymatic approach is economically viable option.

Table 2 shows the common routes and technologies used by Australian PW recyclers. It shows that mechanical processing is the most frequently used technology. Table 2 also categorises recycling processes based on the definitions and information available in each recycling company's website. The table confirms that no biological recycling processes have been implemented in the Australian reprocessing industry (as noted in the last two sections). Only one company (iQRenew) uses chemical recycling processes. iQRenew integrates both mechanical and chemical recycling processes in their plant in New South Wales, with a catalytic hydrothermal process that represents and investment of approximately $75 million (iQRenew, 2021). Plastic Forests is specialized processing soft plastic waste from food, agricultural and post-industrial waste streams. This company implements a proprietary Dry-Cleaning Technology developed by GreenMongrel, which does not use water or chemicals. This technology is used to process soft plastics in association with the REDcycle and Simply Cups programs. iQRenew Pty Ltd is also capable of recycling soft plastics and multilayer packaging. Chemical recycling processes (including chemolysis, pyrolysis, fluid catalytic cracking, hydrogen technology and gasification) are particularly efficient in processing multilayer packaging and mixed plastic waste streams (Lahtela, Silwal and Kärki, 2020). Microfactories™ have also targeted to recycle the packaging and mixed plastic waste streams (Al Mahmood, Hossain and Sahajwalla, 2019), the pilot trials are ongoing now. They have adopted newly invented thermal disengagement technology (Al Mahmood, Hossain and Sahajwalla, 2020) for this purpose.

Another challenging PW stream is foam underlay, which consists of various types of polymeric foams including PU, PS, PVC, and PE. The only recycling facility that handles this waste stream is Dunlop Flooring in Victoria, but no information on the specific recycling process used was found in the available information sources.

Australia has a few very large plastic processing groups capable of processing more than 30,000 tonnes/year. These include Visy Recycling, the Martogg Group, Advanced Circular Polymers, Astron Sustainability, and Recycled Plastics Australia. Although O'Farrell (2019) mentioned that Martogg Group has the capacity to processing up to 20,000 tonnes/year; however, the company recently stated that its total annual capacity for recycling and compounding have increased to 100,000 tonnes (Martogg and Company, 2020). O'Farrell (2019) also identified that half of the PW generated in 2017–18 was processed by eight reprocessing facilities that had processing capacity greater than 5000 tonnes/year. Total 66,800 tonnes of PW were processed by the facilities. The facilities with processing capacity between 2000 and 5000 tonnes/year reprocessed a total of 33,200 tonnes of PW in the same year. The output of these processing plants was used locally (approximately 80,800 tonnes in 2017–18).

Mechanical recycling processes produce products such as granules, flakes and pallets which are used as secondary raw material in the manufacturing industry. These processes consist of several processing stages, including sorting (both manual and optical), shredding, and granulation and pelletising using various means such as extrusion and injection moulding equipment. Despite widespread application of mechanical recycling processes in Australian facilities, only around 12% of total PW generated was processed using mechanical recycling in 2016–17 (Blue Environment, 2018). Lack of efficient recovery of material could be one of the reasons (O'Farrell, 2019). In a survey, O'Farrell (2019) found that the recycling industry commonly uses mechanical recycling techniques such as sorting, chipping, grinding, washing and extrusion to manufacture new products. The use of mechanical recycling is justified due to the consistent high economic value of the polymer recyclate and reduced energy requirements (in processing the recyclate) for new product manufacturing. The economic viability of PW recycling processes is also affected by reasonable access to recycling facilities, the availability of large quantities of PW and the possibility of obtaining clean, sorted and homogeneous output after processing (O'Farrell, 2019). In 2017–18, 60,800 tonnes of PW were processed by 31 facilities, with "sorting/shredding/granulation and product manufacture" as the primary processing methods. A further 42,500 tonnes was recycled in 16 facilities, using "sorting/shredding/granulation". Another 29,100 tonnes of plastic were processed by five facilities employing "compaction, extrusion and product manufacture" as their primary process. Of the recycled plastic produced in 2017–18, 20% was intended for internal use (within the processing facilities). Another 65% was "processed and sold to local manufacturing companies" (36 out of 55 facilities initiated this specific process) and 15% was "sold to export market" (O'Farrell, 2019).

Bottle recycling schemes are popular among recycling companies considering recycling PET and other types of polymers (e.g., HDPE and LDPE). This interest has been generated in light of all Australian states (other than Tasmania and Victoria) passing container deposit legislation (CDL) to implement container-deposit schemes. In Tasmania and Victoria, container deposit schemes are proposed to start from 2022 to 2023, respectively (Australian Associated Press, 2020). While South Australia has had a container deposit scheme since 1977, the initiation of similar schemes in other states has greatly increased the number of available return points around the country. For example, NSW has established 619 return points. The process of remanufacturing bottles from waste plastics using blow moulding process (as used by VISY) is shown in Fig. 15.

4.4.3. Plastic waste recovery rate

In the Australian PW management system, there is a distinct difference between the terms 'recovery rate' and 'recycling rate'. O'Farrell (2020) defines recycling rate as the recovery (at a defined point) as a percentage of end-of-life disposal. The recovery rate includes material sent to composting and energy recovery. In addition, the recovery rate includes not only post-consumer plastic but also pre-consumer packaging manufacturing scrap. In contrast, the recycling rate excludes both materials sent to energy recovery (burning in cement kilns) and reused products but includes composting. Another key term is 'recovery amount'. O'Farrell (2020) explained that "typically, recovered material includes some contaminated materials and also materials intended for reprocessing, but which are lost during the overall recycling process".

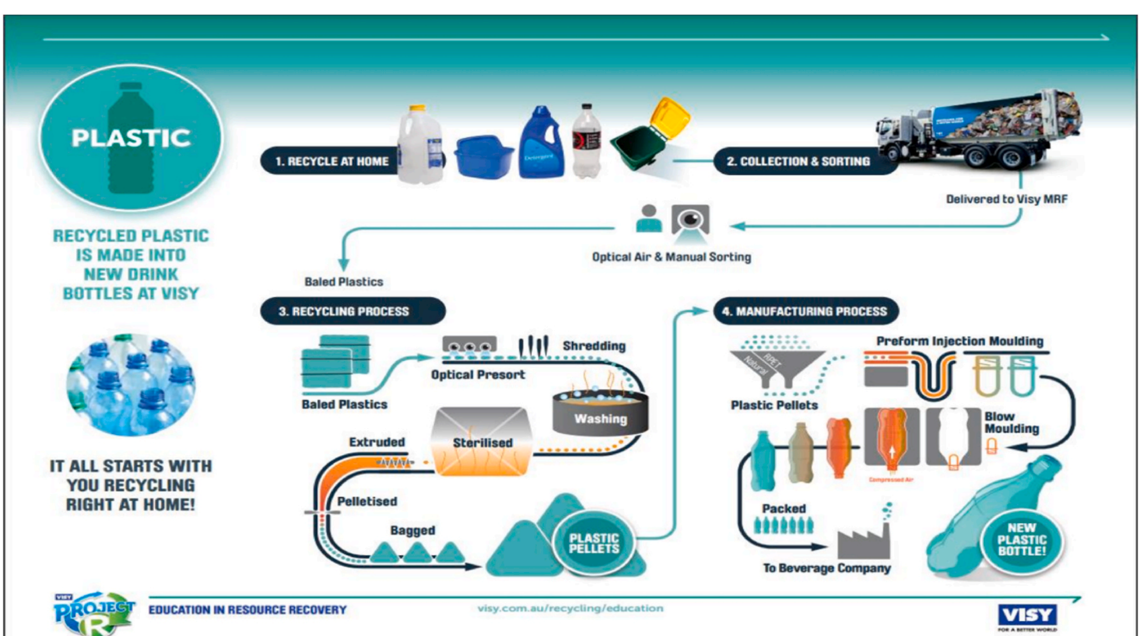

Fig. 15. Plastic recycling process for bottle manufacturing (VISY, 2021).

The reporting scheme presented by O'Farrell (2019) and O'Farrell (2020) adopted "recovery rate" as the main interpreting performance indicator rather "recycling rate".

In 2017–18, the national plastic recovery rate was 9.4% (O'Farrell, 2019) which increased to 11.5% in 2018–19, mainly because of increased implementation of energy recovery" route. The recovery rate is currently dominated by municipal packaging, and packaging related to commercial and industrial applications. The Australian Packaging Covenant is the national product stewardship scheme for packaging which underpins the polymer recovery rate. Packaging from consumer and commercial and industrial (C&I) sources represents the main source of recovered PW, with recovery rates of 58% and 13% of total recovery, respectively. Other recovery routes are construction and demolition (C&D) waste material recovery (into energy recovery), e-waste recycling (Islam et al., 2021), and the export of used clothing. All these sectors represented 29% of the total recovery (O'Farrell, 2020). In terms of polymer types, in 2018–19, 21.0% and 19.7% of plastic were recovered from PET and HDPE, respectively (mainly from packaging sources).

From 2014–15 to 2018–19, the PW recovery rate was relatively stable between 10.8% and 11.5% (O'Farrell (2020). Energy recovery in cement kilns is restricted in NSW and South Australia; however, national energy recovery activities increased from 10,000 tonnes in 2017–18 to 75,000 tonnes in 2018–19. Fig. 16 shows the trends of local and export reprocessing of recovered plastics between 2000 and 2018–19. Between 2000 and 2018–19, export reprocessing increased by over 338% (from around 43 to 191 kilotonnes). Local reprocessing was relatively stable between 2005 and 2017–18, then increased sharply in 2018–19 to exceed export reprocessing, reaching just over 203 kilotonnes. In 2000, the proportion of export reprocessing was only 26%. O'Farrell (2020) found that the proportion of export reprocessing was 54.5% in 2017–18, which decreased to 48.4% in 2018–19. This decrease was due to the development of local plastic reprocessing industries and local energy recovery from scrap plastics. It is expected that local reprocessing will continue to increase in the coming years, due to China's 'National Sword' policy that restricts Australian PW imports, and the regulatory requirements of the domestic PW market in Australia. This is backed up by Australian Government and industry targets. For example, the 2025 National Packaging Targets set the goal to recycle or compost 70% of plastic packaging by 2025 (Australian Packaging Covenant Organisation Limited, 2017).

The recovery amount and recovery rate of various polymers is presented in Fig. 17. HDPE was the only polymer that had a recovery amount greater than its recovery rate. Despite the high consumption (Shown in Fig. 4), recovery rate at the end of life for unknown polymers was approximately 5%. The recovery rate of PVC was even lower (close to 1%), despite its widespread use in the built environment (mainly in the building and construction industries). Although lifespan of PVC related products is generally between 2 and 15 years (Vinyl Council Australia, 2021), which might be the reason for low level of waste generation. This data shows that further assessment is required, to integrate plastic waste management, construction and demolition waste management, and recycling.

4.4.4. Resource recovery and per capita recovery at state-level

The Waste Management and Resource Recovery Association (WMRR) of Australia now have an investment of $14 billion in waste and resource recovery. This organisation has called for national policy and regulations "to ensure the certainty of volumes to build infrastructure, create jobs and grow domestic processing" (World Wide Fund for Nature (WWF), 2019). The PW collection system in Australia consists of kerbside recycling collection by contractors or local Council employees, who transfer the waste stream to MRFs where it is sorted, compacted and baled for sale. In South Australia, NSW, and Queensland, selected plastic drink containers (made of PET and HDPE plastics) are collected via container deposit schemes. Under the collect and return to store scheme, soft plastics returned by consumers at major supermarkets are transferred by REDcycle to Replas, which are the on-sold. In a larger-scale version of kerbside collection, commercial and industrial waste plastics are collected by contractors, then transferred to MRFs (World Wide Fund for Nature (WWF), 2019).

Municipal kerbside collection of rigid-plastic packaging and C&I packaging are the dominant types of recovered plastics, accounting for 51% and 20% of recovery, respectively. The main components of C&I packaging are pallet film (mainly LDPE/LLDPE), pre-consumer packaging manufacturing scrap, HDPE and PP plastic drums and other rigid forms of business-to-business packaging, and EPS foam packaging. The rigid plastic packaging is sent to MRFs for processing, either in single streams (PIC1 1–7) or multiple streams containing three grades. Multiple stream rigid plastics could include polymer types such as PET (PIC 1), HDPE (PIC 2) and mixed plastic grades (PIC 3–7, including LDPE, with some residual PIC 1 and 2) (O'Farrell, 2019).

The state-level recovery of various polymers is illustrated in Fig. 18.

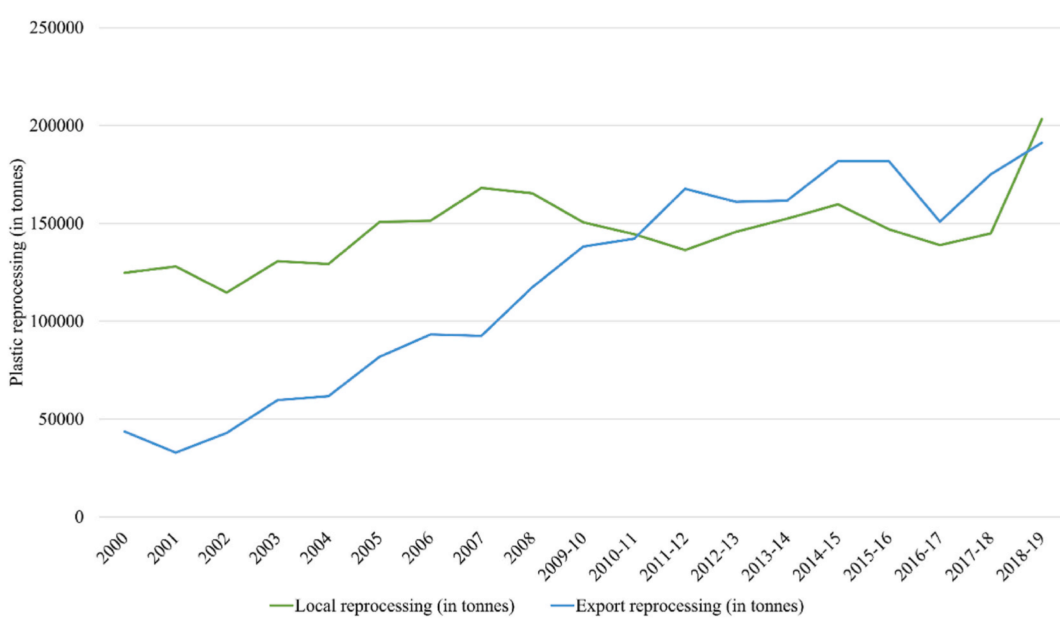

Fig. 16. Trend of local vs. overseas plastic reprocessing [Data source: O'Farrell (2020)].

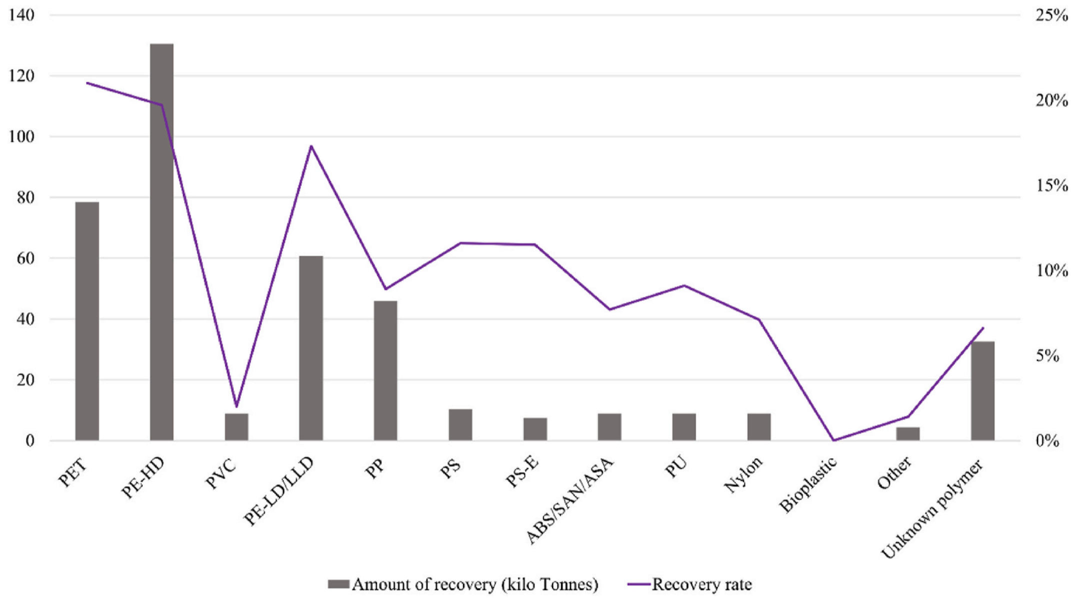

Fig. 17. Plastics recovery amount (in tonnes) and recovery rate (in %) by polymer type in 2018–19 [Data source: O'Farrell (2020)].

Fig. 18. Recovery of polymer types by states in 2018–19 (tonnes).

The figure shows that NSW and Victoria are the major resource recovery hubs. Queensland and South Australia are also recovering a considerable amount of PW. In NSW, PET, PE-HD, PE-LD and PP are the critical plastic resource recovered. A similar pattern is observed for Victoria, with a slight change in PP recovery. Victoria's resource recovery rate was 16%, whereas NSW and South Australia had 13.7% and 13.6%, respectively. Interestingly, the greatest amount of unknown polymer was recovered in South Australia (13,100 tonnes) followed by Victoria (8900 tonnes) and NSW (7900 tonnes). Victoria and NSW could adopt technology know-how from South Australia handle unknown polymers.

According to O'Farrell (2020), "Victoria has the highest recovery rate at 16.0%, followed by SA on 13.7%. The Victorian rate is contributed to by the relatively large amounts of manufacturing scrap generated in and recovered from Victoria". Despite the high plastic consumption in NSW, the recovery percentage is small. Per capita recycling amounts in Victoria and NSW were 18.5 and 21.5 kg/person/year, respectively. Although recycling total as well as consumption were limited, per capita recycling was higher in South Australia (O'Farrell, 2020). The national average of recovery for recycling was 15.5 kg/person in 2018–19 (compared with 12.8 kg/person in 2017–18) (O'Farrell, 2020).

In 2018–19, per capita recycling was highest in Victoria at 21.5 kg/person.year, followed by NSW with 18.3 kg/person.year. However, other statistics showed that despite low recycling amounts (in tonnes), per capita recycling was significantly higher (18.5 kg/person.year) in South Australia (O'Farrell, 2020). The national recycling average in 2017–18 was 12.8 kg/person that increased to 15.5 kg/person in 2018–19. Further assessment to identify sources, and other technology-specific dialogue and discussion around the plastic manufacturing and distribution supply chain would assist in understanding these trends more fully and improving performance. One possible strategy could be to use network analysis (open loop or closed loop) to develop an efficient reverse logistic supply chain.

Between 2016–17 and 2018–19, there was a 10% increase in resource recovery, and a total of 320,000 tonnes of plastics were recycled (O'Farrell, 2019). The most recent available statistics on

(2017–18), of the total 320,000 tonnes of plastics collected for reprocessing 145,700 tonnes (46%) was reprocessed in Australia and 174,300 tonnes (54%) was exported for reprocessing (O'Farrell, 2019). In 2018–19, total 393,800 tonnes of plastics were recycled, out which 72, 000 tonnes sent to energy recovery. Thus, it is estimated that over 18% of the recovered and recycled plastics is going to energy recovery path. In terms of percentage increase, there is a 23% increase of the resource recovery (O'Farrell, 2019).

4.4.5. Recycled plastic sources and potential consumption sectors

Among the sources of polymers suitable for reprocessing within the context of the Australian PW scenario, consumer packaging is the most dominant waste category. As shown in Fig. 19 (A), this waste stream is composed of a diverse range of polymers. This study analysed data for the year 2018–19. In this year, PET, HDPE, PP, LDPE, and EPS were the main polymer types recorded in consumer packaging used for recycling. For 'other applications', (i.e., household products, furniture, clothing and footwear, rope, cable, twine and thread and textile) the most significant types of polymers were nylon and PU. The C&I packaging sources mostly consisted of PVC, EPS, and LDPE type plastics. The electrical and electronic product sector mainly produced PS, ABS/SAN/ASA, and other plastic types (mainly category 7). The main sources of unknown polymer were consumer packaging, other applications, and unidentified applications.

Fig. 19 (B) shows the destination sectors of recycled polymer in local manufacturing industries. The figure shows that the consumer packaging industry only accepted recycled PET-type plastics. The energy recovery route was the endpoint for several types of polymers, including HDPE, PVC, LDPE, and all locally processed unknown polymers. In 2017–18, 7% of locally processed plastics went to the energy recovery sector. The proportion increased to 35% in 2018–19 (O'Farrell, 2019). The built environment sector accepted the most known polymer recycling streams, including HDPE, PVC, LDPE/LLDPE, PP, PS, EPS, and PU. An important observation is that although consumer packaging was the main source of recoverable plastics, the sector only accepted recycled PET-based plastics for product manufacturing. On the other hand, despite representing limited types of polymer uptake, the built environment sector consumes a wide range of recycled polymers for re-manufacturing. Around 19% of processed scrap plastics were consumed by the built environment sector (O'Farrell, 2019).

Another important consideration is the economic value of recovered plastics in Australia, which can be estimated from the decrease in market value of recycled materials. Before 2015, the estimated percentage decrease of market value for recovered PET was 83.75%, and 87% for HDPE. Between 2015 and 2017, the price of mixed plastic (categories 1 to 7) was \$300–\$350/tonne which decreased to around \$65/tonne for the recycled mixed plastics.

4.5. Laws and regulation around plastic waste management in Australia

Australian legislative requirements for PW management and recycling vary substantially between local government areas, states and territories, and the Federal level. For example, some local governments have the capacity to process recycled material (in kerbside recycling bins) themselves, while others rely on contractors (World Wide Fund for Nature (WWF), 2019). However, the Federal Government has recently made inroads into establishing a nationally co-ordinated plastic recycling framework. March 2020 marked the first National Plastics Summit, which was followed by the release of Australia's first national plastic plan in 2021.

The history of intergovernmental cooperation on environmental protection is also relevant to the national regulation of PW. In 1992, an intergovernmental agreement on the environment was established between the Commonwealth, state and territory, and local governments to

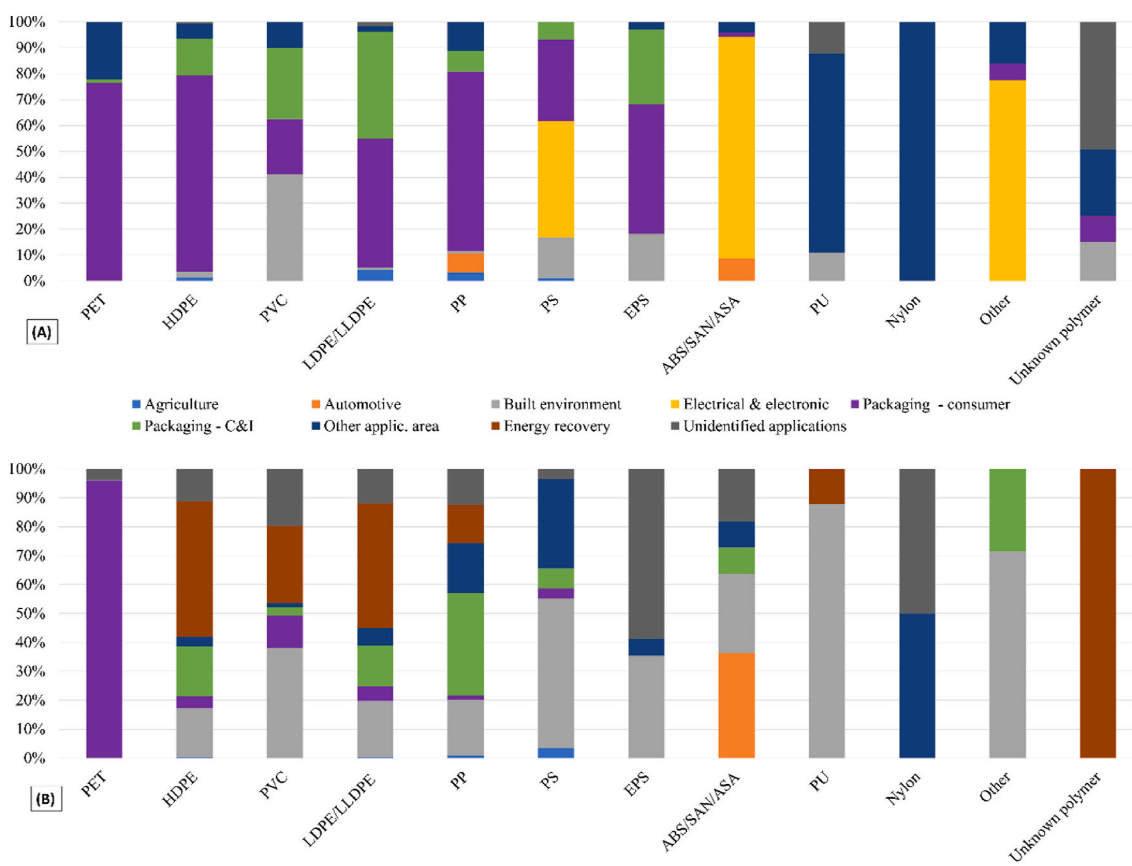

Fig. 19. (A) Sources of recyclates and (B) destination of recycled plastics in local manufacturing sector.

facilitate a national approach to protecting the environment. This agreement defined the roles and responsibilities of the respective levels of government, and dispute resolution procedures. It also provided greater clarity on government and business decision making, and improved environmental protections (Australian Packaging Covenant Organisation Limited, 2017). Later in 1999, the Australian Packaging Covenant Organisation (APCO) was established to reduce the environmental impacts of consumer packaging. APCO is an independent, not-for-profit company established under an agreement between the Australian Government, state and territory governments, and the packaging industry. It is underpinned by the National Environment Protection (Used Packaging Materials) Measure 2011 (NEPM). APCO administers the Covenant on behalf of government and Covenant signatories. In 2018, the Covenant had been signed by over 950 industry stakeholders (mainly companies those have an annual turnover of $5 million or more) (Department of Agriculture, 2018). Fig. 20 shows the actors, stakeholders activities roadmaps for achieving the 2025 target. APCO plays a critical role in achieving these targets, along with other stakeholders. However, recent SWOT analysis showed that for enhanced reporting, commitments and financial contribution-related requirements, many companies feel reluctant to participate or may withdraw their engagement from APCO.

The signatories of the Covenant work collaboratively to achieve sustainable national packaging outcomes. Under the NEPM, stakeholders engaged in producing and selling packaging and packaged products are required to propose more recyclable, compostable or reusable packaging designs (Department of Agriculture, 2018). Fig. 21 shows the legislative framework for the Covenant. Laws and arrangements of participating states and territories implement the NEPM compliance obligations for business entities. The NEPM provides free-rider protection for signatories, to ensure that participants in the Covenant are not competitively disadvantaged (Department of Agriculture, 2018). Furthermore, APCO mandates the product stewardship principle, which supports environmentally-sound management of products and materials over their lifespan. Product stewardship is a national approach to policy and regulation in Australia, and it creates an environment for shared responsibility in reducing negative impacts on environmental and human health. The nature of the arrangement of the scheme could be voluntary, mandatory or shared with industry (Department of Agriculture, 2021).

In November 2016, a new Australian Packaging Covenant and five-year (2017–2022) strategic plan were endorsed by the National Environment Protection Council after consulting environment ministers in the Australian, state and territory governments, as well as APCO. The strategic plan (which is carried out by APCO) focuses on number of issues such as "resource efficiency through sustainable packaging design, diverting packaging from landfill through consumer education and packaging disposal labelling, and improving packaging sustainability performance through research and sharing of knowledge across industries" (Department of Agriculture, 2018). However, APCO members have expressed concerns about competitiveness (under current regulatory settings) due to the existence of free riders in the Australian market and the global supply chain (Australian Packaging Covenant Organisation, 2019).

In July 2019, South Australia was one of the first states in Australia to ban some single-use plastics. The ban included straws, cutlery, and stirrers, and will eventually be expended to encompasss other items, such as coffee cups and bags (Keane, 2019). A special recommendation from the Australian Government's Senate Environment and Communications References Committee has also proposed that petroleum-based single-use plastics should be phased-out by 2023. The committee also recommended that the Australian Government should establish a Plastics Co-Operative Research Centre (CRC), to investigate techniques for PW reduction, cleaning up our oceans and finding end-markets for recovered plastic (Commonwealth of Australia, 2018). In August 2019, the Australian Government announced a ban on waste exports which specifically addressed the issues related to plastics in oceans (England, 2020). In November of the same year, the government initiated the National Waste Policy Action Plan, with seven targets for waste streams including plastic, paper, glass and tyres (Murray-Atfield, 2019). Fig. 22 shows the seven targets set by the Federal Government for all waste streams. Targets 1 and 5 are directly related to PW. Nationally accepted definition and standards of waste and recycled products and defining the scope of export bans, developing legislative framework, market for recycled products, industry and infrastructure capacity and capabilities enhancement for recycling and remanufacturing of the recycled materials, manufacturing of products with recycled content with the help of Australian recycling investment funds through Clean Energy Finance,

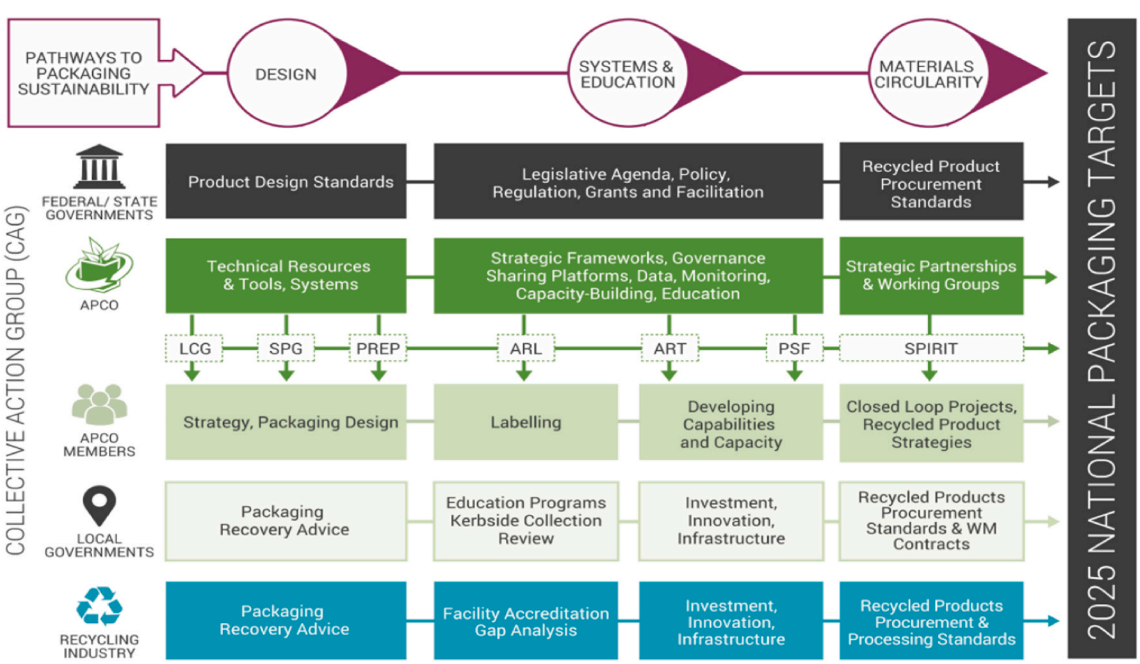

Fig. 20. Sustainable packaging pathway and stakeholder activities (Australian Packaging Covenant Organisation, 2019).

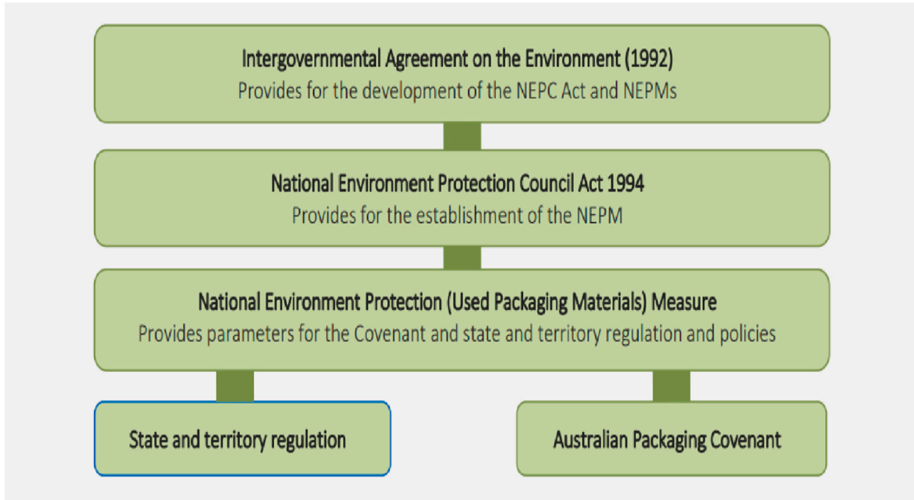

Fig. 21. Legislative framework for the Australian Packaging Covenant (Australian Packaging Covenant Organisation Limited, 2017).

Fig. 22. Targets of 2025 national packaging target in Australia.

reporting, sustainable procurement policies, exploring and improving environmentally responsible trade within the Asia-Pacific region and finally, avoiding landfilling of recyclable material. Target 5 comprises an action plan related to the reduction and clean-up of plastic litter, lower dependance on problematic plastics, and sound management of chemicals and hazardous waste.

The other targets are also associated with waste-reduction and avoidance strategies, and further reinforce the need for sustainable PW management. For example, action components under Target 2 include avoid food waste (linked with food packaging), avoid business waste, improve reuse and reparability, encourage innovation and sustainable design, improve consumer awareness and support consumer choices. The Australian government, business sector (mainly waste and resource recovery industry) and research organizations, state and territory governments, local government, non-government organizations (NGOs) are the major stakeholders involved achieving the specific target. Under Target 3, strategic orientation of the resource recovery rate has been highlighted. For instance, the main action areas under the target are to implement effective product stewardship for priority products, set national standards and specifications, establish cross-border waste transportation and waste levies, provide access to waste management and processing services, and support waste industry transformation via incentives. End-market development and enhancement of the use of recycled products by the government and industry are the main objectives of Target 4. This target also includes sustainable practice models for government, and sustainable procurement practices among businesses and individual entities. Target 6 is associated with organic waste reduction-related strategies and finally Target 7 focuses on informed decision making of policymakers, consumers and business entities based on comprehensive and time-demanded data to discover market development and research opportunities with a particular emphasis on waste.

4.5.1. *Extended producer responsibilities (EPR)*

In Europe, the European Commission actively considers all types of waste management and product lifecycle issues under the producer responsibility principles. Importantly, the extended producer responsibilities (EPR) encourages, or even legally binds, producers to bear the cost of waste management and clean-ups for the entire product lifecycle (Kilvert, 2019). However, there are few financial incentives for manufacturers to use recycled materials (World Wide Fund for Nature (WWF), 2019). Administrative complexity and compliance risk are complicating factors of the increased application of NEPM obligations, and there are inconsistencies in the interpretation between jurisdictions. As mentioned previously businesses have expressed concerns about the additional administrative burdens, compliance and varying decisions by state and local government on how to apply the NEPM obligations. For example, legal and administrative barriers may affect waste collection, use of recycled materials in manufacturing, and reuse of packaging. In the case of packaging design and materials, sector-specific manufacturing greatly influences the efficacy of the legal framework within a jurisdiction. At national level, there are also inconsistencies in regulatory approaches waste management and recycling that might affect innovation opportunities (Australian Packaging Covenant Organisation, 2019).

4.6. Plastic waste flows in landfills and aquatic environment

In 2015, the level of plastic pollution in the marine environment reached approximately 150 Mt (Ocean Conservancy, 2015). Each year, this increases by around 6–12 Mt. This is roughly equivalent to 15 plastic shopping bags for every meter of the world's coastline (CSIRO, 2020b). In Australia, plastic makes up approximately three quarters of total waste. This equates to between several thousand and 40,000 pieces of plastic per square kilometre. There area no outside sources for PW in Australia – all PW generated arises form consumption within the country (CSIRO, 2020b). This has dire consequences, particularly in the marine environment, For example, an estimated 5000–15,000 turtles have become ensnared in derelict fishing nets in the Gulf of Carpentaria. To address this issue, the WWF's global plastic report recommended establishing a strong national strategy with legal obligations for reduced plastic use and flow into the marine ecosystem. A major portion of plastic waste originates from used packaging which goes directly go to landfills, along with other products such as plastic-lined paper, tissues and glassware (Murray-Atfield, 2019). Plastic shopping bags are also a major problem. Each hour, approximately 200,000 plastic checkout bags are disposed of in landfills (RecyclingNearYou, 2020). The Australian Government has mapped the nation's existing has specific capabilities to handle plastic pollution (shown in Fig. 23). These capabilities should be used to tackle the present plastic crisis.

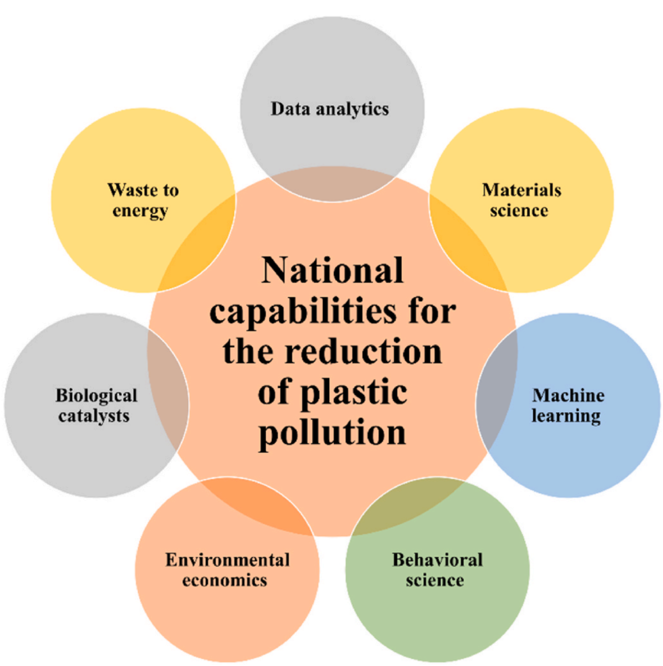

Fig. 23. National capabilities of Australia for plastic waste pollution.

4.7. Comparison of plastic waste management in different countries

The current main recycling method for PW is mechanical recycling, and the total recycling rate is still very low. The reason behind this phenomenon is most of Australia's materials recovery facilities lack technical capacity to sort co-mingled, highly contaminated municipal waste into many specific material types that have low levels of contamination. Large volumes of recycled materials end up in landfill due to contamination.

In comparison to global scenario, Australia has low recycling and recovery rate (Table 3S). As shown in the following comparison table between Germany, Japan, USA and China, we can see that Japan and Germany have comparatively very high recycling rate and the recovery rate is very high. Japan has adopted energy recovery techniques and chemical feedstock recovery, profusely since most of the plastic cannot be recycled. They have recycling rate of around 25% and recovery rate of 57%. Among its total recycling process, majority of recycling is done by chemical (feedstock) recycling, comprising 60% (Sharma, Shekhar, Sharma and Jain, 2021). Plastic wastes are used as coal alternatives with cokes oven, syngas generation, and as blast furnace reducing agents. Likewise, the remaining 40% is recycled using mechanical recycling technique (Okuwaki, 2004). Unlike Australia, where majority of recycling relies in mechanical recycling (de Mello Soares, Ek, Östmark, Gällstedt and Karlsson, 2022). It is based on recycling thermoplastics such as PET, HDPE, LDPE, and PVC and not used for thermosets and multilayered plastics. The mechanical recyclates, usually cannot be used with virgin plastics and so are downcycled to make into different products.

Australia has set target to recycle 70% of plastic packaging by 2025 and resource recovery of 80% from all waste stream by 2030; as of 2019–20 data the recovery rates are 17% and 36% respectively, for packaging for business to consumer and business to business category ("AUSTRALIA'S 2025 NATIONAL PACKAGING TARGETS," 2022). The majority of recycling loads are being carried out by mechanical process, and there has been plans to expand the capacity by expanding the infrastructure to accommodate around 145,000 tonnes per year within 2025, but still, that does not help to achieve the set target by Australia (GOVERNMENT, 2020).

To increase the plastic waste recycling rate, there needs to be more advancement in the recycling technologies and the industries, currently being used. There are recycling facilities which process around 70000 tonnes of plastic waste per year, but the product they produce can only be downcycled, due to the mixture of plastic waste, and the preciseness required to sort all the wastes. This only delays the end-of-life of the plastic, producing only cascading recycling system. In order to achieve a closed loop system, which is required to support the circular economy principle, the recyclate needs to be able to reuse in the plastic ecology.

5. Challenges and recommendations to reducing PW

5.1. Data and method of estimation and standardisation

Plastic-specific consumption data is generally collected from Australian-based resin manufacturers, Australian-based resin importers, Customs import and export data, and plastic reprocessors (O'Farrell, 2020). However, one gap in available data is the high level of consumption of unknown polymers, which is greater than all known polymer types (in 2018–19, it was 500,000 tonnes). From Fig. 4, it is observed that unknown polymer is entering in the Australian market as import of finished and semi-finished items. Lack of identification of plastic type (e.g., mismatching PIC code or no code present on the product) used in the imported products could be one of the reasons. Better control and monitoring at the Australian border for imported products should be enforced with the help of APCO members (mainly importers) who should be responsible declaring exact plastic type.

Before 2014-15 plastic consumption estimation methodology only took into account virgin plastics (O'Farrell, 2019). In 2015, the methodology was updated to include packaging on imported goods and imported finished and semi-finished plastic goods. Proper standardisation of the plastics in the future product design to achieve circular plastic design is needed. Further incorporation of the extended EPR is needed to encourage producers to change production toward products that are easier to keep within the circular value chain, and thus, reduce loss to the environment. There is a lack of testing and certification facilities to assess the quality of recycled plastic products. Research funding should be directed towards quality, performance, and the inclusion of environmentally benign additives leading to the development of novel products. Mapping of waste streams is essential to concentrate on commodity plastics and their tonnage in the recycling streams which may lead to a circular economy for Australian plastic waste. Worth noting that the only reported method of recovery of unknown polymers was energy recovery (Fig. 19). This could be avoided if government and regulatory bodies mandate that industrial manufacturers and importers declare the specific polymer types that they bring into Australia. The PIC code should be clearly marked on foreign products and imported resins, to facilitate appropriate downstream collection and recycling. The authors also recommend that a standardised industrywide polymer identification method and estimation methodology is developed. This initiative should also be extended to the estimation of PW generation.

5.2. Recovery rate and infrastructure

The low recovery rate in the reverse supply chain is one of the critical challenges of the Australian PW management and recycling system. Existing gaps in the collection, recycling and reprocessing value chain limit positive environmental outcomes and lead to material leakage from landfills. At present, national collection efficiency is only 17%. Lack of investment in R&D; commercialisation program for improved recycling outcomes; and infrastructure for collection, sorting and recycling are much less advanced in Australia compared to other countries (Australian Packaging Covenant Organisation, 2019). This reduces the likelihood of meeting the nation's recycling and recycled material use targets (Australian Packaging Covenant Organisation, 2019). A further challenge is that Australia is yet to develop sustainable markets for recycled plastic products. Generally, the waste collection and resource recovery industries are very fragmented (World Wide Fund for Nature (WWF), 2019). At national level, there are also inconsistencies in regulatory approaches waste management and recycling that might affect innovation opportunities (Australian Packaging Covenant Organisation, 2019). Furthermore, it was observed that eight of the processing facilities with greater processing capacity, processed half of the PW generated in 2017–18. The activities of large reprocessing facilities could be viewed as natural monopoly and they have the capabilities to overcome high barriers such as competitive location of the processing plant in a region, access to feedstock and technology (Department of Sustainability Environment Water Population and Communities, 2012). Small processing facilities might have difficulties in these areas which might be reason for limited overall recovery rate. Victorian government mentioned that distribution of power in the waste and recycling industry is not healthy (Parliament of Victoria, 2019). Ventola, Brenman, Chan, Ahmed, and Castaldi (2021) identified that contamination, technology limitations, and the availability of recycled product markets are the influencing factors for sorting and selling plastics. Convergence of environmental standards, R&D support, and incentives for processing technologies would lower the cost of recovery that eventually trigger a higher recover rate (OECD, 2018). Public behavior, large-scale initiatives, and clever inventions are examples of areas in which significant changes are required (Arim, 2019). For example, better plastic labelling (i.e., Australasian Recycling Label) and increased consumer education will help increase the return rate in the container deposit scheme (O'Farrell, 2019). Karmakar (2020) also recommended separate bins for different plastic types, and international quality certification with a transparent monitoring process. Lessons can also be learned from research conducted in other countries. For the PW management system in USA, Thomas Hundertmark, Manuel Prieto, Andrew Ryba, Theo Jan Simons, and Wallach (2019) proposed a number of initiatives, including increasing the demand for recycled materials, improving consumer behavior, and secondary bag programs (collection scheme for specific plastics). The same study recommended enhanced sorting with upgraded MRFs, advanced recycling technologies that can deal mixed plastics, and coordination across value chains. Measures initiated by industry and retailers can also help divert PW from landfill. For instance, the recent establishment of soft plastic collection and separation at supermarkets has been a positive step. To reach the minimum standard to support collection and sorting, substantial investment in the areas of collection, sorting and recycling, R&D, commercialisation and infrastructure have to be taken (Australian Packaging Covenant Organisation, 2019). Hahladakis and Iacovidou (2019) suggested that potential collaboration among industries could lead to effective solutions, and that all involved parties must work together.

5.3. Problems related to regional circular economy solution

NSW and Victoria generate the greatest share of the national HDPE and PP type PW. These two states also generate LDPE from the construction (built environment), manufacturing, and other industries. A similar pattern was also seen in terms of plastic consumption. In Victoria, most processing facilities can deal with the above-mentioned types of plastic waste, however, increasing the state's PET processing capabilities would help improve the plastic recovery rate. In NSW, there are opportunities to improve the rate of resource recovery. For example, greater number of processing facilities for HDPE, PP and PET. NSW has the highest number of households in the nation, and households are the main source of PET and HDPE. However, the number and capacity of reprocessing facilities focusing these waste streams are restively low in NSW compared to Victoria. Although most of the reprocessing facilities in NSW and Victoria implement mechanical recycling technology, it is found that decontamination process (mainly volatile organic compound removal) for quality improvement has remained largely unreported by industry. A comprehensive stakeholder assessment should be performed for each state to understand the existing industry-level PW management strategies and barriers to change. The assessment should also identify regulatory reforms to encourage industry to use more recycled plastic materials. The Federal and state governments should also provide incentives to manufacturers that use recycled material in the production process, and mandate recycling-oriented product design (where recyclability is considered at the beginning of the product design stage). Governments should also work to raise industry-wide awareness of the growing opportunity to use recycled material in the built environment sector. Another effective mechanism would be to introduce government procurement quotas for recycled items or products made from recycled materials. This was one of the goals set in the 2025 National Plastic Strategy (Australian Packaging Covenant Organisation, 2019).

5.4. Closed-loop supply chain and local manufacturing industries

There is currently a limited scope for local use of locally recycled polymers, and the local recycled material utilization rate is only 10% (0.13 Mt). In Australia, there are few financial incentives for manufacturers to use recycled materials (World Wide Fund for Nature (WWF), 2019). Further assessment is needed to investigate how to increase the intake of recycled HDPE, PP, PVC, PS, and nylon plastic in the packaging and built environment sectors. This will need to involve coordination of stakeholder across both the sectors. One of the main difficulties is that the output generated by mechanical recycling of plastic is generally in the form of flakes, pellets and granulated products prepared for foreign buyers. If an interruption to 'business as usual' occurs (e.g., the COVID-19 pandemic, a decrease in oil prices, or a regulatory ban on exports), then the outputs of the recycling industry became unprofitable. This further emphasises the need to implement diversified recycling and waste management strategies. For example, industry could make use of more blow-moulding and injection-moulding processing equipment in conjunction with mechanical recycling which targets HDPE, LDPE, and PET for both high- and low-value product development. APCO members (product manufacturers and plastic importers) and plastic reprocessors should collaborate in developing products using the 'design for recycling' principle and single polymer-based product design (i.e., avoid multilayer packaging). To increase the amount of PET recycling, chemical recycling techniques such as chemolysis could be applied. Ragaert, Delva, and Van Geem (2017) stated that to make the chemolysis process economically viable, throughput of 15000 tonnes/year is required. This recycling technique could be applied for recoverable PET polymers in NSW and Victoria, which produce 30,200 tonnes and 26, 200 tonnes per year, respectively. Chemical recycling is also suitable for multilayer plastic packaging, PE, PS, PP, and fibre-reinforced composites; however, further assessment is required to assess economic viability. One opportunity for the output of chemical recycling techniques is tapping into Australia's healthy demand for batteries. Saito et al. (2020) have developed sustainable polymer electrolytes from PW for solid-state batteries using chemical recycling techniques.

Instead of focusing solely on recycling, Australia should also target reuse and remanufacturing as effective waste-reduction strategies. The electrical and electronic equipment (EEE) sector should be considered as a source for reuse and remanufacturing schemes. EEE is the main source of PS-related plastics in Australia. Pyrolysis/microwave pyrolysis is a viable disposal solution for such type of plastics (Thomas Hundertmark et al., 2019). Pyrolysis and gasification are the most popular energy recovery techniques; however, further field-level assessment is required of the types of processes implemented their associated contribution for carbon dioxide (CO2) emissions. In Europe, plastic production, and plastic waste incineration (mainly for energy recovery) are responsible for approximately 400 million tonnes of CO2/year. This has attracted heavy criticism, and led to energy recovery being considered as an unsustainable means of PW management (Walker, 2021). Currently, PE and PS are the two main plastic types used for energy recovery, along with limited PVC, as seen from Fig. 19. To reduce the need for energy recovery, PVC use should be limited (due to toxic elements), and industry should consider increasing the use of PP to replace PVC, with PE and PS polymer products. Thomas Hundertmark et al. (2019) suggested establishing market for sort bales might be necessary for PVC waste due to small volume generation, and MRFs often do not sort or accept them.

A huge number of studies have been done on the chemical recycling of plastics and are in laboratory and pilot trial stage. iQRenew and Licella proposed plastics to chemically converted fuels and chemicals by Cat-HTR technology. It is a advanced hydrothermal liquefaction technology (Licella). Cat-HTR™ technique was developed by a venture named Licella which uses water at near or super-critical temperatures to convert plastic into oil from which it was made. The recovered oil can be used as a substitute of fossil oil. Licella has been working in this project for 13 years and now they have perfected the technology and launching a commercial project in England to process 80000 tons of plastic. In Australia, a planning is going on to stablish in Victoria (Licella). Samsara has proposed a technology which employs a computer-designed enzyme to break down the plastics into monomers at room temperature (SAMSARA). It is suitable for rigid plastics, coloured plastics and mixed plastics. The technology is still at the research stage. IQ Energy Australia has designed a modular and scalable technology through their IQ Advanced Recycling units (Australia). These units can take waste and dirty plastics and transform these into a plastic derived crude oil or gas which can be further processed into variety of industrial and consumer products. This research is at the trial stage.

5.5. Monitoring and tracing of material use and waste sectors

A high proportion of unknown polymers are consumed as semi-finished and finished products and of known polymers, the most consumed are HDPE and PP. To maximise recovery, diversified recycling solutions should be considered. Purified polymers could be developed using an advanced recycling route such as 'purification', which employs dissolution technology (Thomas Hundertmark et al., 2019). In most cases, 'other application areas' consume and dispose of a large volume of waste and contribute to landfill diversion. A clearer definition of the sectors and areas included in the unknown category should be formulated to understand the materials entering the supply chain as well as the flow of waste materials. Another important step will be the detailed assessment of hard-to-recycle materials, such as PVC from the built environment, nylon from other applications, and PS from the EEE sector. Further investigation should also be performed to understand how textile waste contributes to PW in Australia. Globally, over 50% of total textile consumption comes from polyester products (Stanes, 2021). Polyester is a synthetic fibre which falls into the same category as PET. This can cause significant environmental impacts. For example, microplastic pollution is mainly caused by textile waste (Henry, Laitala and Klepp, 2019).

5.6. Challenges of future PW stream and recycling strategy

There is a need to develop Australia's capability for bioplastic production, development, and subsequent recovery and recycling. Despite bioplastic consumption being shown as zero percent in Fig. 5 (B), in 2018–19, approximately 15.4% of bioplastics was consumed by agriculture sectors. With the pace global bioplastic production, and prediction made by Michael and Holdings (2004) for Australia (domestic market of 40,000 tonnes by 2020), bioplastic intake will continue to increase, and as mechanical recycling is the dominant process in Australia, reprocessors should enhance their processing capabilities to accommodate bioplastics. For bio-based PET and bio-based PE, mechanical recycling is considered an enabler for closed-loop polymer recycling (Cruz Sanchez, Boudaoud, Camargo and Pearce, 2020). There is an opportunity to expand the use of bioplastic in the food packaging/consumer packaging sector. However, this should be balanced by establishing separate collection facilities and anaerobic digestion plants to provide a long-term waste management solution. Chemical recycling opportunities such as pyrolysis and gasification should also be developed for bio-based PW. Households contribute 47% of the PW, mainly in the PET and HDPE categories. Further attention should be given to bio-based alternatives to these polymer types, as well as consumption incentives and recycling solutions. Education programs should specifically address consumer awareness and knowledge gaps about polymer types, recycling labels, and appropriate disposal methods. The Australian Government has mapped specific capabilities to handle plastic pollution. These include data analytics, material science, machine learning, behavioural science, environmental economics, biological catalyst, and waste to energy (CSIRO, 2021). The capabilities should be used to tackle the present plastic crisis. In future, detailed technology options will be investigated in the Australian PW recycling context. Currently, Australasian Recycling Label is operational that provides information to customers disposing of components of a product in appropriate bins (e.g., recyclable in yellow bins, non-recyclable in red bin and soft plastics at designated store). The design aspects and consumer knowledge and awareness regarding the labelling should be further assessed through survey for effective communication and developing waste collection strategy.

Australia has traditionally shipped most of its recyclable waste to China (with smaller amounts shipped to Indonesia, Vietnam, India, Malaysia, and Thailand), in shipping containers that would otherwise return empty to their country of origin. The 2019 National Waste Policy will introduce bans on the export of waste materials, including tyres, glass, paper, and plastic. This promises to be a challenge as well as an opportunity to develop new science, commercialise technologies, and take advantage of favourable economic and social conditions. The environmental, economic and health complexities of the waste challenge facing urban, regional, and Indigenous communities have been brought into focus by the COVID-19 pandemic, 2019/20 bushfires, floods, and protests.

5.7. Regulatory and structural reform

Along with the waste export ban and policy action plan, the Australian Government has set four goals as part of the 2025 National Packaging Target. These goals are in conjunction with the circular economy principles, and are listed below (Arim, 2019):

- 100% of all Australia's packaging will be reusable, recyclable, or compostable by 2025 or earlier
- 70% of Australia's plastic packaging will be recycled or composted by 2025
- 30% average recycled content will be included across all packaging by 2025
- Problematic and unnecessary single-use plastic packaging will be phased out through design, innovation, or the introduction of alternatives.

Container deposit schemes, plastic bag bans, and phasing out of single-use plastics are some of the critical interventions to be carried out by local governments (APCO, 2019). To achieve these goals, more vertical integration is necessary among the stakeholders. For example, a direct relationship between APCO members and the recycling industry is currently missing. Federal or state governments should also develop researchdevelop research wings or hubs to collaborate between product manufacturers and downstream industries in the recycled material flow, including end-user industries (e.g. energy recovery, the built environment, packaging, and agriculture) to identify low- and high-value applications of recycled PW materials.

5.8. Bioplastic opportunities

The projected bio-plastic production for 2024 is 2.43 MT worldwide which is only 15% growth from 2019, with 2.11 MT recorded production capacity (Afolalu, Yusuf, Emetere, Ongbali and Ademuyiwa, 2022). This slow growth can be accounted to the low awareness within the consumer as shown by the nationwide online survey done in Australia with 2518 participants (Filho et al., 2022). Despite the lack of knowledge towards the bioplastic, the consumer sentiments towards the use of bioplastic seemed positive. The same survey showed that, though around 68% of the people would support the use of biodegradable plastics, many of the participants (58%) (Dilkes-Hoffman, Ashworth, Laycock, Pratt and Lant, 2019) were unaware of the kind of impact biodegradable plastic can cast on environment. So, considering this positive sentiment of people to use the bioplastic, with same survey showing that 62% of people decision to dispose the plastic in recycling bin (Dilkes-Hoffman et al., 2019), we can predict the growing plastic waste contamination by the addition of the bioplastic stream. This plastic waste contamination can be negated by an effective system of standards, labelling and waste management options developed and implemented by the governments and local councils, preceding the widespread adoption of bioplastic.

The government and local council need to be proactive so that the uncertainty among the consumers regarding the nature of bioplastic and their readiness to use it would not invite unforeseen consequences. The impact of bioplastic contamination can be countered in two stages: introduction of standards and labelling for bioplastic and development of waste management system for the it.

The standards and regulations for the labelling of the bioplastic must be well defined, so that the customer can identify them easily. This will help in public awareness and prevent false (intentional and unintentional) labelling, from the manufacturers. Also, from the organisational level, there needs to be development of waste management facilities to incorporate the bioplastic stream. These facilities can be effectively implemented by having sorted and labelled bioplastics, which results in pure plastic waste stream.

5.9. Small scale regional solution for PW

The researchers of UNSW has invented MICROfactories™ (Veena Sahajwalla, 2018), which are engineered modules that utilise waste materials to manufacture value-added products (V Sahajwalla and Hossain, 2020). They are founded on the science of Microrecycling being developed at the SMaRT@UNSW Centre, where complex material interactions, transformations, and properties are investigated and extracted at a micro-level. Each module encapsulates the science and technology required to reform hard-to-recycle materials, such as problematic waste glass, e-waste, and plastics into new materials or value-added fit-for-purpose products. The modules are designed to function at appropriate locations, for example locating them at the source of waste materials or at the manufacturing site, to maximise commercial feasibility. UNSW's modular microfactories can operate on a site as small as 100 square metres and, because they are free from connection to inflexible international raw material supply chains, are able to exploit multiple input streams, dealing with waste wherever it may be found, and creating demand for jobs through various ripple effects in regional centres and communities. The modules can accept diversity and variability in the waste material input and create a technical, controlled output product. This is critical in meeting industrial feasibility criteria. Lab testing showed a new green filament made from 100% waste plastic displayed outstanding physical properties and potential. This led to the development of a Filament MICROfactorie™ at UNSW that has shown it can produce commercial scale filament output, made from waste. SMaRT has worked with numerous industry and community partners on filament research and development. Reforming waste plastic into filament as a feedstock resource for manufacturers and other users who do 3D printing holds promise for a new era in manufacturing (Veena Sahajwalla and Gaikwad, 2018).

5.10. Prospects of sustainable growth of plastics in a circular economy in Australia

While humans become increasingly reliant on plastics and demand for them continues to rise, plastic waste is predicted to continue to grow immensely worldwide. Simply enforcing prohibitions will not be enough to tackle Australia's plastic waste problem. It is a global, cross-sectoral problem that necessitates inter-departmental collaboration. Plastic waste management's future depends not only on the efficiency of local governments and recyclers, but also on community participation and national, regional, and global strategies. Many parties must be involved, including industry professionals, governments, customs agencies, legislators, intergovernmental organizations, non-governmental organizations, and civil society. To tackle plastic waste, we need a combination of interventions, global cooperation, and goal-oriented measures.

5.10.1. Futuristic management strategy for PW

It is becoming widely apparent that top-down restrictions have minimal impact on domestic and global plastic waste management. To overcome the problem, it will take significant regional, national, and international cooperation, economic incentives, and a management structure that reduces the negative impact on the environment and human health. To begin, an official international protocol on plastic waste trade has been implemented in conformity with the Basel Convention, with both developed and developing nations having to participate. During the Basel Conference of the Parties, which took place from April 29 to May 10, 2019, governments modified the Basel Convention to encompass plastic waste in a legally binding framework, making global plastic waste trade more transparent and governed, as well as trying to ensure that its management is safer for humans. Plastics management associations should be constituted around the world, with a stringent categorisation standard established and a framework built around durability, usability, and safety to ensure that plastics are circulated, utilised, and disposed of in a controlled manner. The extended producer responsibility approach has the potential to effectively reduce plastic waste output. By extended producer responsibility, manufacturers must undertake environmental obligations throughout the product's life cycle, including waste recycling and disposal. However, Australia is taking a different approach because the cost is significant and legislation varies by country, while a large number of plastic products are imported from abroad. As a result, implementing extended producer responsibility is difficult. To further adopt and improve the extended producer responsibility approach, Australia and other nations will need to strengthen enforcement under the supervision of international bodies in the future.

Moreover, the government must establish a comprehensive framework for the recycling, usage, and treatment of plastic waste. Governments must improve existing rules and regulations regarding the management of plastic waste, as well as promote plastic waste recycling through extended producer responsibility. Environmental effects, mitigation strategies, and extended producer responsibility are all factors to be considered in a sustainable plastic product life cycle system. When it comes to international plastic waste pollution, the adoption of expanded producer responsibility serves as the platform for preventing transboundary plastic waste flows. Transboundary movements and discarding of plastic waste can be efficiently avoided by having numerous parties monitor its trading routes and putting in place strong preventative measures. They do, however, necessitate collaboration between Australia and other developed and developing countries. To achieve a controlled plastic waste cycle, all countries should reinforce law enforcement, engage closely, support safe repatriation of unlawfully trafficked items, and boost global and regional collaboration. However, these necessitate collaboration between Australia and other developed and developing countries. To achieve a controlled plastic waste cycle, all countries should reinforce law enforcement, engage closely, support safe repatriation of unlawfully trafficked items, and boost global and regional collaboration.

5.10.2. *Advanced recycling for used plastics*

Problematic plastic waste collection, which is also contaminated with multimaterials including packaging waste, e-waste, as well as other waste, is a widespread issue in both developed and developing nations. Creating an online and offline waste recycling system could be the key to solving the problem. Developing an online/offline PW drop-off service system, especially for challenging PW, recycling logistics system, monitoring and tracing system, credit system, and disposer management system might result in a circular loop plastic waste cycle from producers to disposers and back to producers. The government provides funding and incentives to encourage money from the general public to the business, hence, increasing merchant and manufacturer PW recycling rates. Producers, merchants, and sorting businesses must all be engaged to come up with novel solutions. Modern plastic products, such as those used in e-waste, the built environment, and other applications, are becoming increasingly fragile, and traditional recycling techniques are no longer capable of producing satisfactory results. Recycling and treatment of waste result in loss of a lot of useful materials. More than half of the materials generated by these tricky waste streams are likely to be buried. The regeneration of various plastic waste categories and units is challenging to achieve with a single strategy. As a result, the next big accomplishment will be in well-designed processes that enable close-loop recycling and repurposing of e-waste using a multi-technique approach.

The efficient recyclability of the plastic wastes needs to achieve technological advancement to know the thermal properties, mechanical properties, and morphology of different available specimens. Chemical recycling, including liquefaction and naphthalizing, as well as thermal and energy recovery, will play important roles in the efficient utilization of used plastics both for bioplastics and fossil-based plastics. This will be strengthened by an innovative development of carbon dioxide capture and utilization and carbon dioxide capture and storage.

5.10.3. *Green product design to achieve sustainability*

The eco-friendly design of products is conducive to addressing the recycling issue after they become scrap. So, we must incorporate eco-friendly design, manufacturing and environmental protection, environmental behaviours, and consumer psychology while designing plastic products in the future. The environmental attributes of the product, removability, recyclability, maintainability, reusability, etc., should be carefully considered in product design from the beginning to the final disposal of e-waste. In R&D, manufacturers must give importance to the selection of sustainable materials, product structuring, and eco-friendly design so that the products can be easily recycled when they become scarp. Plastic product producers should be encouraged by the government to carry out eco-friendly design and production to extend the lifespan of plastic goods, reducing plastic waste at the source.

The production, use, and disposal of some of the problematic plastic waste, like e-waste, and packaging are all inevitable. Recycling plastic waste is necessary, but it must be done in a safe workplace with high standards. If possible, plastic waste can be refurbished as new products instead of used for resource purposes. If not refurbished able, it should be sorted and processed by well-paid and sufficiently equipped professionals. The unstandardized additives, persistent organic pollutants, fumes contained, and contamination level in the surrounding environment of plastic waste garbage, should be strictly monitored and controlled. Eco-friendly, and green plastic waste collection and disposal techniques should be developed for recycling.

5.10.4. *Integrating recycling, manufacturing and business*

Business models for all kind of plastics including the bio based should be constructed keeping in mind the current problems that the society is facing. The virgin materials, waste plastics, additives, used in the plastics, application and waste also need to be scrutinized during product design.

Bio-based plastics need to solve some critical issues like efficient utilization of non-edible resources, and food wastes before getting acknowledgment. However, a closed-loop system where biodegradable and non-biodegradable plastics can be treated by a variety of waste management methods can increase the social and environmental impact of Biodegradable plastics.

The manufacturer and the researchers should collaborate with governments, stakeholders, and society to tackle social, economic, and environmental issues. A holistic approach should be taken where every stage of the value chain should be considered, and necessary steps will be deployed together which can emphasise on the innovative approach to attain meaningful development concerning the challenges and opportunities of bioplastics and fossil-based plastics.

In spite of extensive development, the market growth of biodegradable plastic was slower than the expectation. The lack of infrastructure and social system to collect, sort, and treat compost waste and biodegradable plastics products worked as one of the major factors behind this slow growth. Economic feasibility and the advancement of the infrastructure is another factor. Some developed countries like Japan and some of the EU countries has adopted the controlled eco-friendly advanced incineration technology which could be a feasible solution for the problematic mixed waste plastics like packaging waste for Australia (Kuan, Low and Chieng, 2022). These improvements seemed to solve the landfill issues which Australia could also adopt.

To remain sustainable, we need to change our throw away mentality and adopt the principles of circular economy which needs fundamental efforts. To achieve sustainable future for medium to long term goals for the plastic waste should be defined keeping in mind the three most important issues: (i) no leakage of waste to the environment, both the soil and aquatic environment; (ii) technological innovation to recycle and transform the problematic plastic waste into resources, either product or sustainable feedstock, and (iii) reducing the carbon footprint. The full circle of the plastic waste economy is not only dependent on the circulation of the materials, but also a meaningful business model, which consist of the circularity of the material, reduced carbon footprint and social awareness.

6. Conclusion

This is the first holistic systematic review to provide an overview of plastic consumption and waste generation in Australia. Targeted material-specific product design should be the highest priority among product manufacturers, as poor-quality mixed polymer does not have a market, and this discourages reprocessors from handling such waste. Bioplastic consumption has not been officially recorded, but some sources have reported minimal use. In future, the PW processing industry should adopt market dynamics using appropriate recycling techniques, such as mechanical recycling. The PVC material flow for energy recovery should have further environmental impact assessment due to the presence of toxic chorine and other substances. Wastewater treatment plants should adopt microplastic handling to avoid leakage into water bodies and oceans. For effective plastic waste management in Australia, collection systems should be improved, and incorporate emerging recycling technology, such as biological and chemical recycling.

The future of Australian plastic waste management heavily for a full circle relies on the efficacy of local government, recyclers, and community involvement. Along with efficacy, it is necessary to take initiatives on national, regional, and global levels. It is time to stand together and initiate international cooperation, interventions, and goal-oriented actions against plastic waste. The chemical community, both industry and academia should collaborate with governments, stakeholders, and society to tackle social, economic, and environmental issues. Taking a holistic view that considers each step of the value chain and implementing integrated approaches that highlight innovation should achieve meaningful progress toward addressing the challenges and issues of bioplastics and fossil-based plastics.

In a diverse country like Australia, it is very important to build the regional solution based on small scale recycling unit where every region and community can handle their own waste regionally and the consumer should be also trained and encouraged to use their own local product. An example of this is the newly invented MICROfactorie™ solution which Australia has already started embracing. This will empower the local businesses by recycling their local waste, reduce the transportation cost and will also create local job opportunities for the small, large or regional cities and communities.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.133127.

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