Journal of Material Cycles and Waste Management (2024) 26:755–775
https://doi.org/10.1007/s10163-024-01901-1

SPECIAL FEATURE: ORIGINAL ARTICLE

Plastic flow and its management

# Environmental potential of recycling of plastic wastes in Australia based on life cycle assessment

Can Soenmez[1] · Venkateshwaran Venkatachalam[1] · Sebastian Spierling[1] · Hans-Josef Endres[1] · Leonie Barner[2]

Received: 16 May 2023 / Accepted: 28 January 2024 / Published online: 16 February 2024

**Abstract**
Plastic consumption in Australia is steadily increasing and is estimated to reach 8.8 million tonnes by 2050. Alongside plastic consumption, plastic waste management (PWM) faces rising environmental challenges in Australia as most of them are currently landfilled. Therefore, the Australian government has published a policy to transition to a circular economy as well as a new strategy for PWM with higher recycling rates. To understand the implications of the policy changes and the environmental impacts of End-of-Life (EoL) options, life cycle thinking is necessary. This study evaluates and compares the environmental impacts of the Australian PWM for 2018–2019 to the policy envisaged for 2030 that includes higher recycling rates and waste export bans from a life cycle assessment (LCA) perspective. From the results, it can be seen that the current PWM is majorly linear (take, make, use and dispose) as most of the wastes gets landfilled and exported to other countries but the future PWM strategy for 2030 results in higher resource recovery and significant reduction in the environmental impacts. There is a reduction in Global Warming Potential (GWP) by a factor of almost 10, if the recycling rates increase from 13 to 70%. The state and the federal governments along with other stakeholders need to implement stringent measures to recover plastic wastes if a transition to a circular economy is to happen by 2030.

**Keywords** Plastics · Circular economy · Recycling · Life cycle assessment · Waste management · End-of-Life · Australia

## Introduction

The use of plastics plays a significant role in modern society. Due to its various properties such as lightweightedness, low cost and durability they are indispensable in both long- and short-term applications. For example, the medical sector uses plastic packaging to keep medical instruments such as syringes, tubes, and other items—also often made of plastics—sterile before they are utilized [1].

Over the past few years, the environmental impacts of plastics are more and more scrutinized including their production, use, and End-of-Life (EoL) phase. When plastics become waste, i.e., at the end of their use, they can have a negative impact on the environment due to littering and pollution and are also a substantial loss of resources if they are not properly recovered. Plastics have so far followed a linear economy approach, with less than 10% of the global plastics recovered and recycled after use [2]. Therefore, the development of a sound circular economy for plastics is needed to increase the resource efficiency and reduce the over-dependence of fossil resources.

### The plastics problem in Australia

The Australian Plastics Flows and Fates Study 2019–2020 (APFFS) reports that in the financial year 2019–2020 (July to June) approximately 3.46 million tonnes (Mt) of plastics were consumed in Australia, and 2.5 Mt of plastics reached the EoL stage [3]. During the same period, only 326,600 t of plastics was recovered resulting in an overall recovery rate for plastics of 13.1% and the rest being landfilled. In addition, the APFFS estimates that plastics consumption will

---

✉ Venkateshwaran Venkatachalam
venkatachalam@ikk.uni-hannover.de

[1] Institute of Plastics and Circular Economy, Leibniz Universität Hannover, An Der Universität 2, 30823 Garbsen, Germany

[2] Centre for a Waste-Free World, Faculty of Science, School of Chemistry and Physics, Queensland University of Technology, 2 George Street, Brisbane, QLD 4001, Australia

increase significantly over the next two decades i.e., from 3.46 Mt to 8.8 Mt in the year 2049–2050 [3].

## Plastic waste management (PWM) in Australia

Even though there exist different options for a functional plastic waste management (PWM), mismanagement of plastic wastes occurs across the world [4]. An approach that is discussed in this context is the concept of circular economy, in which material is kept in the lifecycle through recycling or reuse, unlike in the linear economy, where raw materials are used to manufacture products and as soon as their use phase is over, they are disposed as wastes [5]. Options for waste management are often assessed via a so-called waste hierarchy as shown in Fig. 1, where the best option (avoid) is depicted at the top followed by other options with the least preferable option at the bottom (disposal).

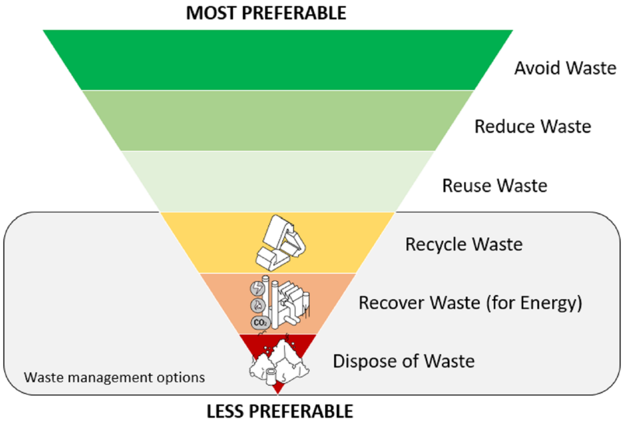


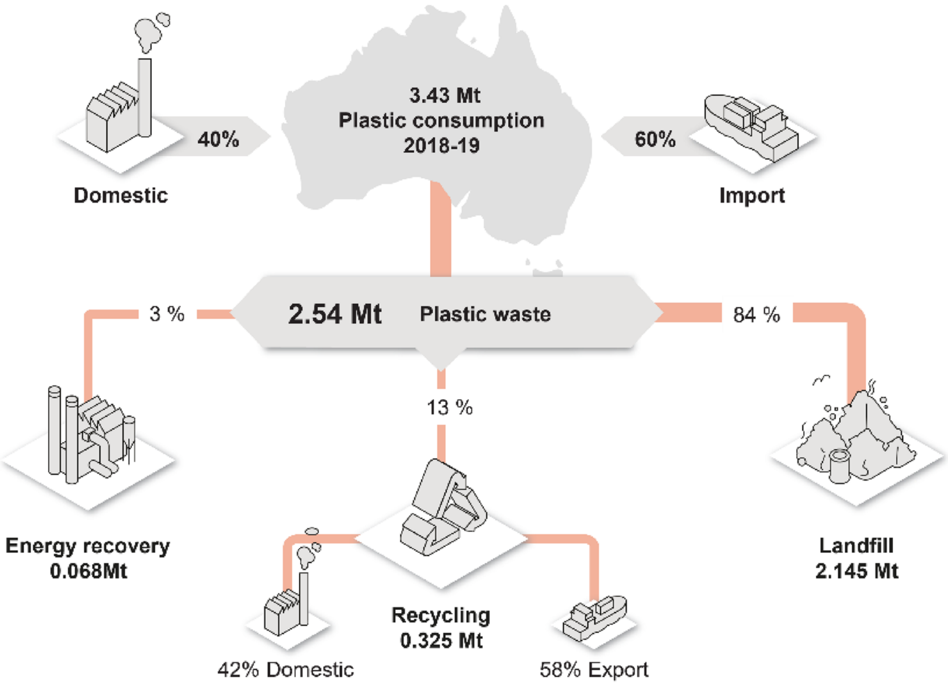
**Fig. 1** Waste Hierarchy (adapted from [6])

The Australian government strives to implement a circular economy approach and considers recycling as the most preferable EoL option. However, landfilling is still the dominant EoL option and the amount of plastic waste landfilled is nearly twice the quantity of plastics that are currently in use [6, 7]. Moreover, about 84% of plastic waste generated in 2018–19 is landfilled, further decreasing landfill capacity. Only 16% of the plastic waste is recovered and is either recycled (13%) or incinerated with energy recovery (3%). Of these 13% recovered for recycling, 58% of them are exported to other countries where they are recycled and the rest 42% of it are recycled locally [3, 7]. The source and fate of all plastics in Australia for the year 2018–19 is shown in Fig. 2.

## Australia´s roadmap to a plastic circular economy

The Australian government has set an ambitious goal for its transition towards a circular economy by 2030 [6]. Therefore, frameworks like the National Waste Policy 2018 [6], National Waste Policy Action Plan 2019 (NWPAP) [8], and the National Plastics Plan 2021 [9] are developed to set targets and policy measures. An overview of these measure is given in Fig. 3. Plastic waste export bans, increase in the average resource recovery rate to 80% (with a recycling rate of 70% and incineration 10%), and the gradual elimination of problematic plastics, such as expanded polystyrene (EXP) consumer food and

**Fig. 2** Source and fate of all plastics in Australia in 2018–2019 (adapted from [1])



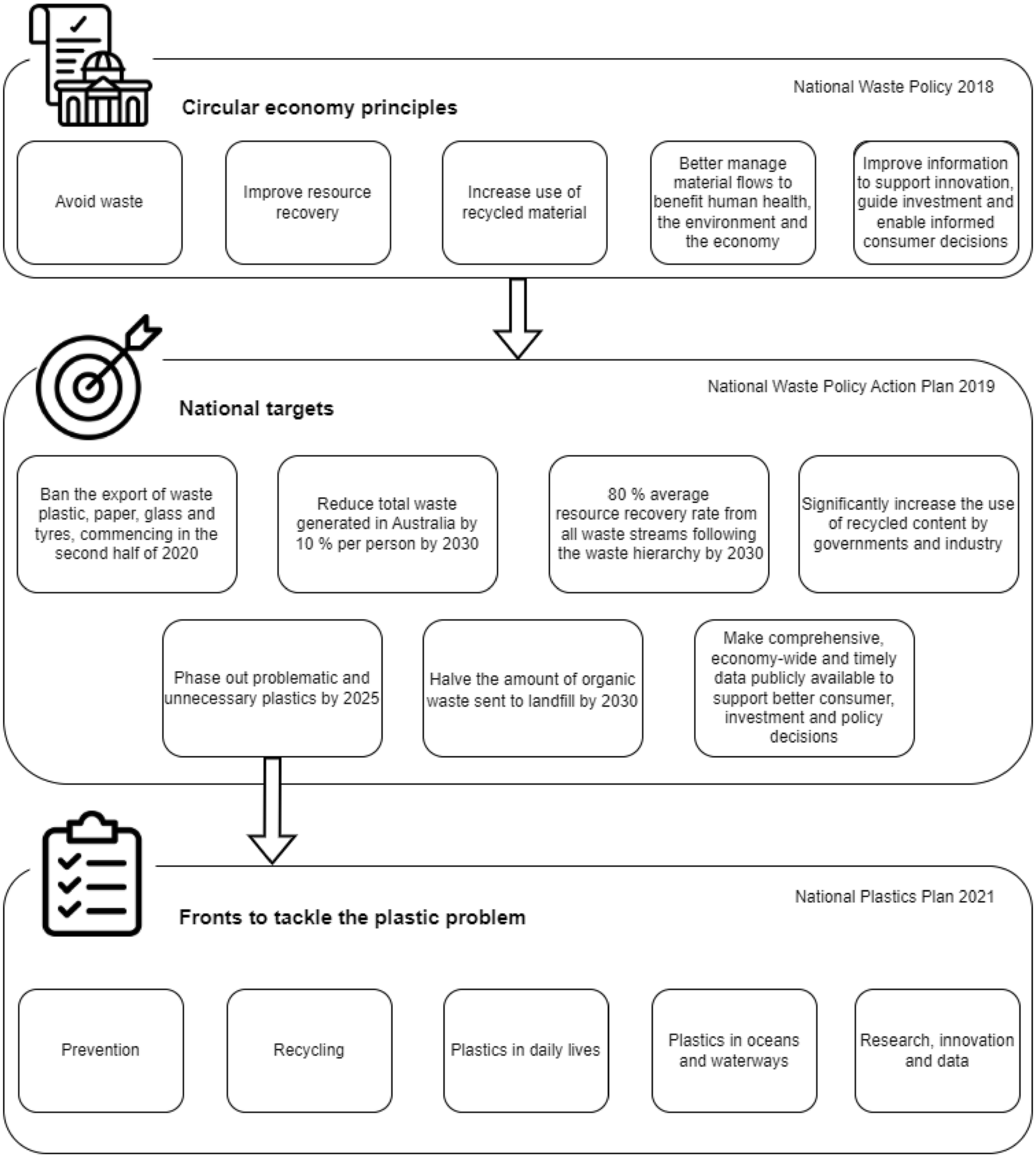


**Fig. 3** Australia's roadmap to a (plastic) circular economy

beverage containers or polyvinyl chloride (PVC) packaging labels, are some of important aspects of the NWPAP [6, 8–10].

The National Plastics Plan 2021 focuses on the EoL of plastic wastes, from which specific measures can be derived [8, 9]. The Recycling and Waste Reduction Act 2020 mandates an export ban of unsorted mixed plastics by July 2021, and unprocessed single polymer or resin plastics by July 2022 [9].

## Goal of the study

Although the Australian government has defined measures to transform the Australian PWM, neither the current nor the potential future impacts of PWM on the environment have been assessed from a life cycle assessment (LCA) perspective so far. Therefore, this study aims to quantify the environmental impacts of Australia´s PWM strategy using LCA. The LCA is a tool to analyse the potential environmental impacts of products or processes on the environment. First, a review on the previous LCA studies of the PWM in Australia is performed. Based on the findings of the review and the available inventory data on the PWM in Australia, LCAs for the current (2018–19) and planned (2030) PWM strategies in Australia are modelled. From the results of the LCA, the environmental performance of different EoL options and the environmental impacts of the future PWM scenarios are studied.

## Literature review on existing PWM LCAs in Australia

The literature review for this study is based on the approaches developed by Zumsteg [11] and Fink [12]. Zumsteg in his study "Systematic review checklist—A standardized technique for assessing and reporting reviews of LCA data (STARR-LCA)" conceptualized reviews in the context of LCAs [11]. For this study, the following review question was developed based on the STARR-LCA checklist:

> "How can the potential environmental impacts of current and future PWM scenarios in Australia that include mechanical recycling, energy recovery and landfilling as EoL options be quantified using LCA?"

The main objectives of this study are to provide an overview of LCA studies of PWM in Australia and assess the environmental impacts of different EoL options in Australia. To find suitable studies and to answer the research question, a search strategy including relevant search terms is defined. For this study, three categories of keywords and phrases are selected and combined by Boolean operators (AND, OR, NOT) as shown in Fig. 4. Truncations (*) and quotation marks ("") are used as tools to search for similar expressions with different endings.

For the literature review, two common online scientific search engines Scopus [13] and Web of Science [14] are used. Table 1 shows the results per search string from the two search engines and the search is limited to the article title, abstract, and keywords.

**Table 1** Number of results per search string and sources

| Search string combination | Scopus | Web of science |
|---|---|---|
| A | 1,718,363 | 959,994 |
| A AND B | 146,962 | 79,066 |
| A AND B AND C | 22,469 | 10,798 |
| A AND B AND C AND Australia | 208 | 65 |

The following screening criteria are defined to narrow down the suitable literature:

- Literature in English to ensure reproducibility
- No publication older than 10 years (> 2012) to reflect the current state of the art
- Geographic reference to Australia
- Literature published till September 2022

Figure 5 shows the results of the applying these criteria from both the search engines.

From these 181 studies, 34 publications are removed as they are duplicates. Further, 144 studies are excluded due to misleading titles and studies that are not relevant to the objectives of the review. At the end, only three studies fulfilled the search criteria. Table 2 lists the general characteristics of the three identified studies.

As Dastjerdi et al. published two similar studies in 2021 that rely on each other's data, these studies are considered as one study. Therefore, this review effectively includes only two studies. The main characteristics of both the studies are listed in Table 3.

The study of Demetrious and Crossin from 2019 evaluates the environmental impacts of mixed plastic and mixed paper recyclate in municipal solid waste (MSW)

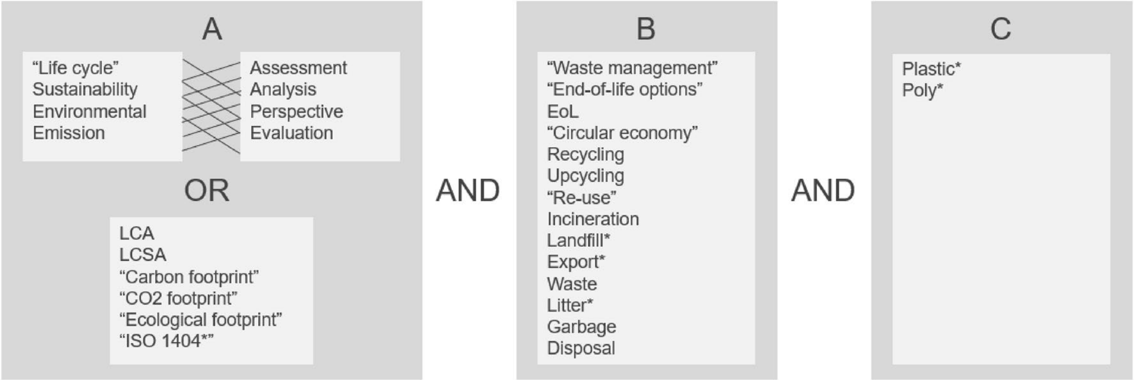


**Fig. 4** Selected and categorized search terms

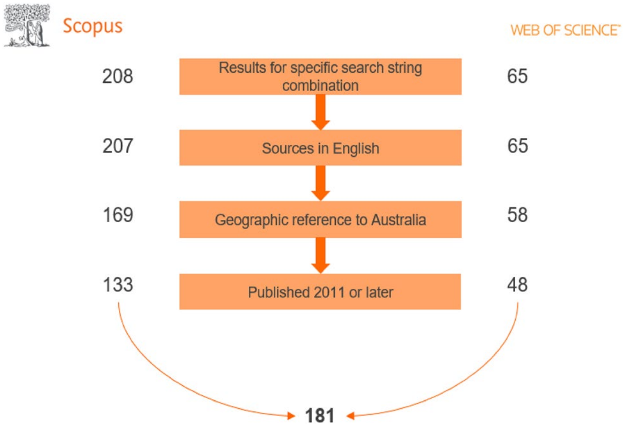


**Fig. 5** Number of identified studies from two search engines

in Victoria, Australia, considering three EoL scenarios: Landfill, incineration, and gasification-pyrolysis (GP). [17]

In contrast, the studies of Dasjerdi et al. from 2021 do not exclusively consider plastic waste streams individually. The approach of their studies is to analyze the opportunities of managing the residual municipal solid waste (waste, which is not recovered) in New South Wales (NSW). Therefore, five alternative scenarios are defined and compared to the baseline scenario, which represents the prevailing approach in NSW—landfilling. [15, 16].

The system boundaries include different EoL options such as recycling, incineration, gasification, anaerobic digestion, landfill as well as emissions, by-products, and credits for electricity [15].

However, these two studies do not contribute significantly to the review question for the following reasons:

- The base years are far in the past (2011 and 2015)
- Both studies do not cover the whole of Australia but focus on selected Australian states (Victoria and New South Wales)
- Dastjerdi et al. do not consider plastic waste streams individually
- Demetrious et al. do not evaluate plastic waste recycling
- No comparison between recycling, incineration and landfilling

From the review, a research gap can be identified when it comes to the comparative assessment of the environmental impacts of recycling, incineration and landfilling under the same conditions in Australia.

## Materials and methods

A LCA study based on ISO 14040/44 [18, 19] on the baseline and planned state of PWM in Australia is conducted. The specific aspects of LCA are defined based on Laurent

**Table 2** Information about the three relevant studies

| Title | Economic feasibility and sustainability assessment of residual municipal solid waste management scenarios in NSW, Australia [15] | Comparative life cycle assessment of system solution scenarios for residual municipal solid waste management in NSW, Australia [16] | Life cycle assessment of paper and plastic packaging waste in landfill, incineration, and gasification-pyrolysis [17] |
|---|---|---|---|
| Authors | Dastjerdi, B., Strezov, V., Kumar, R., He, J., Behnia, M | Dastjerdi, B., Strezov, V., Kumar, R., He, J., Behnia, M | Demetrious, A., Crossin, E |
| Year | 2021 | 2021 | 2019 |
| Type of study | Research publication | Research publication | Research publication |
| Region | New South Wales | New South Wales | Victoria |

**Table 3** LCA characteristics of the relevant studies

| Source | [15, 16] | [17] |
|---|---|---|
| Type of LCA | Attributional (comparative) | Attributional (comparative) |
| Impact assessment method | ReCiPe 2016 | CML baseline |
| Functional unit (FU) | 223,000 t plastic of residual MSW | 1 kg mixed plastic recyclate |
| Base year | 2011 | 2015 |
| Impact categories | Global warming, ozone formation, terrestrial acidification, (non-) human carcinogenic toxicity, stratospheric ozone depletion, fine particulate formation, fossil resource scarcity, freshwater ecotoxicity, and eutrophication | Acidification potential, climate change potential, eutrophication potential, photochemical oxidation potential |
| Software | OpenLCA 1.9 | SimaPro 8.0.4 |

et al., which analyzes the methodology of 222 published LCA studies of solid waste management systems [20].

In addition, a review of LCA of PWM by Alhazmi et al. [21] including 15 studies are considered in this study. Studies like Venkatachalam et al. [4], Kousemaker et al. [22], Franklin Associates [23], and Ekvall [24] are also considered for understanding EoL modelling approaches in LCA.

## Goal and scope

The main objective of this LCA study is the environmental assessment of different EoL options in Australia. The potential environmental impacts of different EoL options for the 2018–2019 baseline scenario and the planned Australian PWM strategy for their transition to a circular economy in 2030 (as discussed in Sect. Australia's roadmap to a plastic circular economy) are the major components of this current LCA study.

The data for the baseline PWM is taken for the year 2018–19 to understand the implications of exporting plastic wastes to other countries before the official ban of exporting plastics and unsorted resins come into force (July 2021 and 2022, respectively) [9]. The future of Australian PWM strategy includes measures such as higher recovery rates, less landfilling and avoided waste exports.

The EoL options considered for this study includes landfilling, mechanical recycling, and incineration with energy recovery. Although energy recovery covers several technologies such as waste-derived fuels, anaerobic digestion, and waste-to-energy (WtE) facilities, which are described in the National Waste Report 2020 by Pickin et al. [7], only incineration in WtE facilities is considered in this LCA in accordance to the study by Demetrious and Crossin [17].

The function of the system is to manage plastic waste generated annually in Australia. Therefore, the functional unit (FU) of this study is represented by the treatment of plastic waste generated in Australia in the financial year 2018–19 (July to June), which is 2,549,636 tonnes [25]. In addition, the specific composition of the waste in terms of polymer types is considered for the environmental credits of mechanical recycling, i.e. the substitution of virgin material for the production of different polymer types. The group of other polymers is not further specified and therefore credited with an average virgin polymer production of the remaining polymer types. Further explanations are carried out in Sect. Process inputs. The composition of the plastic wastes by polymer type is shown in Fig. 6.

The life cycle impact assessment (LCIA) method chosen for this study is the CML 2001—Jan 2016 [27], following the findings of Laurent et al. [20], as this method is the most used one among the over 200 reviewed studies in the field of waste management, which will help in the comparability of the results in the future. The impact indicators considered for this study are shown in Table 4:

However, the impacts indicators GWP, ADP fossil, AP and EP will be discussed in detail as these impacts are interpreted extensively across different LCA studies for PWM [28–32]. The results of other impact indicators are tabulated as well.

The system boundaries include all material and process inputs required to fulfil the function of the system. The main processes included are waste collection, waste sorting in material recovery facilities (MRF), transportation, and the three EoL options incineration, mechanical recycling, and landfilling. In addition, material inputs such as electricity, fuels, and auxiliary materials are also

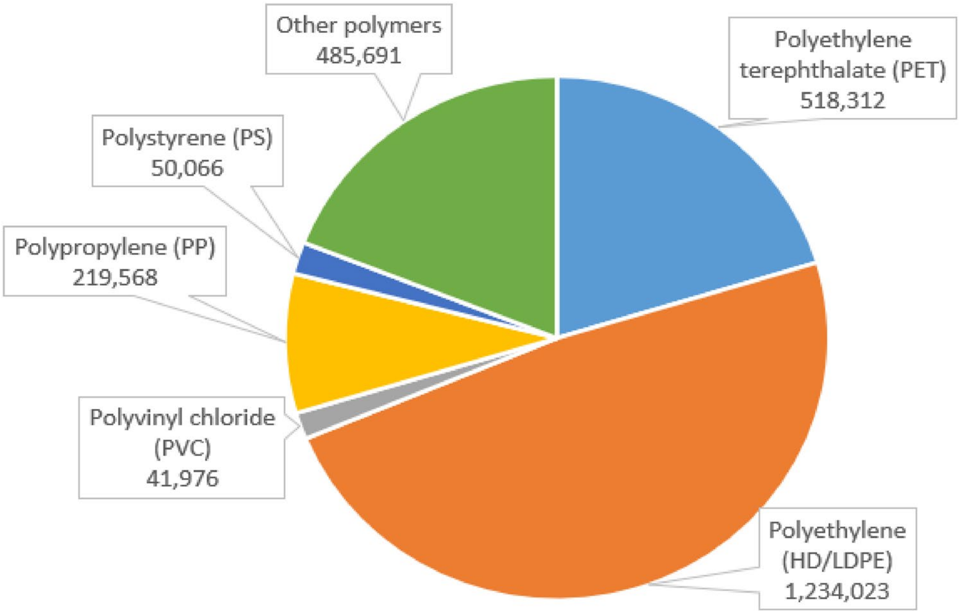


**Fig. 6** Composition of plastic waste (in tonnes) by polymer type [26]

**Table 4** Impact indicators considered for this study

| Impact indicator | Unit |
|---|---|
| Abiotic depletion (ADP elements) | kg Sb equivalents |
| Abiotic depletion (ADP fossil) | MJ |
| Acidification potential (AP) | kg $SO_2$ equivalents |
| Eutrophication potential (EP) | kg $PO_4$ equivalents |
| Freshwater aquatic ecotoxicity potential (FAETP inf.) | kg DCB equivalents |
| Global warming potential (GWP 100 years) | kg $CO_2$ equivalents |
| Human toxicity potential (HTP inf.) | kg DCB equivalents |
| Marine aquatic ecotoxicity potential (MAETP inf.) | kg DCB equivalents |
| Ozone layer depletion potential (ODP, steady state) | kg R11 equivalents |
| Photochemical ozone creation potential (POCP) | kg Ethene equivalents |
| Terrestrial ecotoxicity potential (TETP inf.) | kg DCB equivalents |

included as well as material substitution and energy credits, and emissions. Although steam is generated during incineration, credits are only accounted for electricity due to insufficient information on the market demand and use of heat generated by steam. This decision is supported by the findings of the reviewed study by Demetrious and Crossin [17]. Plastic production and use-phase of plastic are also excluded as this LCA study focuses only on the EoL of plastic. The system boundaries of the system are illustrated in Fig. 7 [7, 17].

The LCA study includes a baseline scenario (status-quo) and three sub-scenarios (based on the future Australian PWM in 2030). The description of each scenario is shown in Table 5.

In order to model the Australian PWM based on the available public data, following assumptions are required:

- All plastic waste is assumed to be post-consumer waste from municipal solid waste (MSW)
- Sorting and cleaning are required before they are recycled
- The plastic wastes that enter the EoL phase are assumed to be free of the inherent environmental impacts of the virgin material, which is also known as cut-off or recycled content approach [24, 33]. However, to show the differences in the impacts of the different EoL options, the credits obtained by recycling and incinerating these wastes (either in the form of substituted material credits or energy credits) are shown in the results
- All the recyclates resulting from the mechanical recycling are used to substitute virgin plastics (corresponding to a certain efficiency, which is also known as the material substitution potential or MSP)

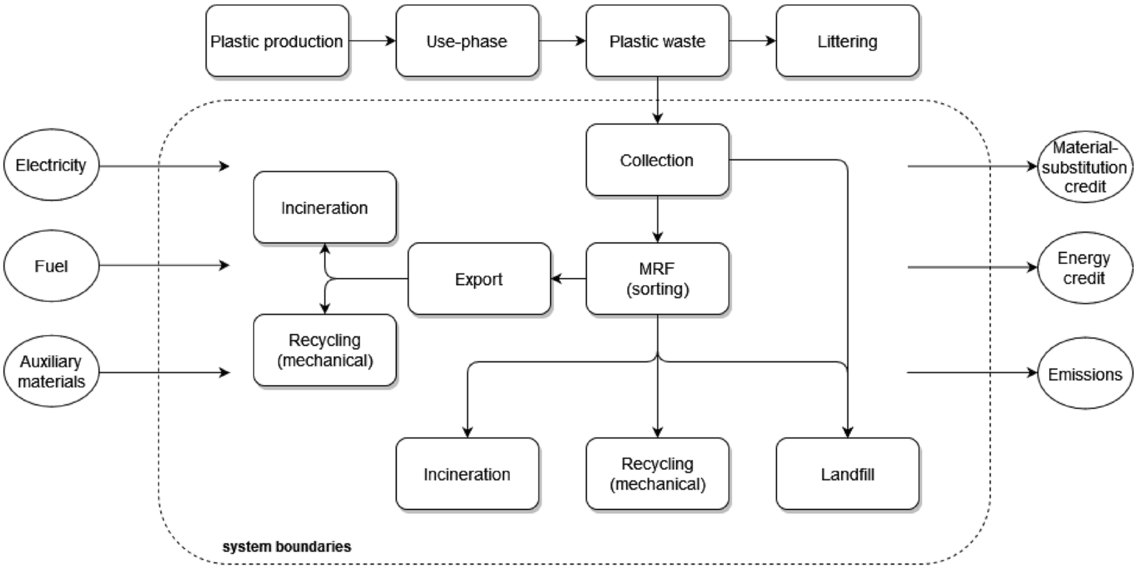


**Fig. 7** System boundaries for the LCA study

**Table 5** Description of different scenarios considered for this study

| Scenario | Identification | Description |
|---|---|---|
| Baseline scenario | S0 | Status Quo of PWM in Australia in 2018–19 that includes 84% landfilling, 13% mechanical recycling and 3% incineration with energy recovery (including exported wastes) |
| Sub-scenario A | S1A | Scenario for 2030 with 70% mechanical recycling, 20% landfill, 10% incineration with energy recovery but with exports included |
| Sub-scenario B | S1B | Baseline scenario but without exports of plastic wastes |
| Sub-scenario C | S1C | Scenario for 2030 but combines S1A, S1B—70% mechanical recycling, 20% landfill, 10% incineration with energy recovery but without any exports |

- Incinerating the plastic wastes are assumed to be with energy recovery, which will replace the electricity mix (need for producing electricity is reduced). However, credits obtained from generating heat from incineration are excluded because of a missing market demand for it in Australia
- The overall transport distances are not provided and are therefore estimated
- As Australia export plastic wastes to other Asian countries, the People's Republic of China (PRC) is selected as the destination country even though China has officially banned the import of plastic wastes in 2017 [34]. PRC is selected due to the availability of its LCI datasets
- Exported plastic waste is recovered (either mechanically recycled or incinerated) according to the official statistics although it can't be traced.

These assumptions cause uncertainties, which can be addressed by sensitivity analysis, in which significance of some of the process parameters towards the total environmental impacts are assessed. Parameters included in the sensitivity analysis are:

- Substitution potential of recyclates
- Inclusion of heat credits for incineration

## Life cycle inventory (LCI)

In the life cycle inventory (LCI) phase, data is collected for the foreground and background systems. Due to the unavailability of primary data, LCI data for this study is entirely based on literature and commercial LCI databases.

### Mass flows

The process parameters that are considered for the recycling process comes from Pickin et al. [7] and based on these values, mass flows of plastic wastes are modelled in the LCA for Experts software (GaBi) version 10.7.0.183 [35]. Database is used from Sphera (content version 2021.1) [36]. A list of datasets used can be found in the supplementary information. Table 6 describes the parameters considered for recycling. Potential cascading effects are not considered. However, the material substitution potential is considered for the first application of recyclates.

The mass flows (inputs and outputs) for the LCA model are based on the 2018–19 Australian Plastic Recycling Survey [1], Experimental Estimates by the Australian Bureau of Statistics [26], data on exports of Australian wastes [37] and the National Waste Report 2020 by Pickin et al. [7]. The mass flow of plastic wastes across different EoL options for the baseline scenario S0 is shown in Fig. 8.

From the mass flow diagram, it can be seen that there are significant losses in the sorting and recovery. The mass flow diagrams of scenarios S1A, S1B and S1C are shown in Figures S1-S3. The total amount of plastic wastes handled in the baseline scenario is shown in Table 7. The total amount of plastic wastes for the other scenarios (S1A, S1B and S1C) are shown in Figure S4–S6. Based on these mass flows and the share of different plastics in the Australian market, the environmental impacts of the total PWM for Australia in the year 2018–19 are calculated.

**Table 6** Parameters considered for the recycling

| Parameter | Description | Assumed value for the study (%) |
|---|---|---|
| Collection efficiency | Waste that is further processed (sorted) by MRF and not directly landfilled | 83 |
| Sorting efficiency | Waste that can be recovered and not sorted out to landfill | 93 |
| Reprocessing efficiency | Waste that is recovered and not lost in the reprocessing process (only applicable to local reprocessing) | 95 |

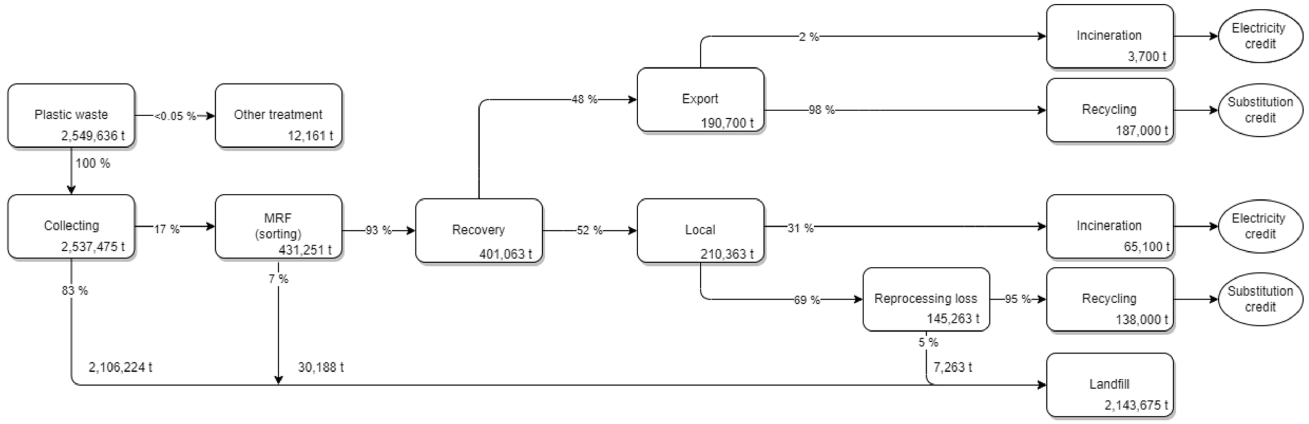


**Fig. 8** Mass flow of plastic wastes for the baseline scenario S0

**Table 7** Mass flows of plastic wastes for the baseline scenario S0

| Plastic wastes | Local [t] | Export [t] | Total [t] |
|---|---|---|---|
| Total recovery | 203,100 [1] | 190,700 [1] | 393,800 |
| Recycling | 138,000 [7] | 187,000 [7] | 325,000 |
| Energy recovery | 65,100 [7] | 3,700 [7] | 68,800 |
| Landfill | 2,143,675 | | 2,143,675 |
| Other treatment | 12,161 [26] | | 12,161 |
| Total | | | **2,549,636** [26] |

## Process inputs

The inputs required for the processes along with their sources are presented in this section. These process input data are independent of the scenario under consideration, as the process inputs are mass-based and therefore scalable for any scenario.

### Collection

This process includes the curbside collection of waste as well as the transport to the landfill site and the MRF. Within this study, specific data describing the overall collection of plastic waste in Australia is not applied due to insufficient data. The transportation is represented by truck dataset from the GaBi database [36].

### Transportation

Transportation datasets for truck and containership comes from the GaBi database [36]. The truck is diesel-driven and the default specification is used in this study due to insufficient data about the utilization rate. The local transport distances are assumed to be 50 km due to the unavailability of data.

Container ship, used for the export of plastic wastes, is powered by heavy fuel oil and the default specifications remain except for the travelling distance. The distance for the container ship is set to 10,000 km. The transport routes are presented in Fig. 9.

### Material recovery facility (MRF)

After commingled recyclables (including plastics) are collected, they are transported to a MRF and sorted. The required inputs for this process are electricity and liquefied petroleum gas (LPG) at 30 kWh and 1.2 L per ton of recyclables, respectively. These values are taken from Carre et al. as the data refer to an MRF in Melbourne [38]. Process output from the MRF consists of sorted waste for recovery and contaminated waste that is landfilled.

### Landfill

Landfilling is modelled based on an available dataset (Region—European Union) from the GaBi database [36]. This aggregated dataset includes processes such as surface and base sealing, a compacter, leachate and sludge treatment, and deposition. The process inputs are diesel, flocculation/precipitation agents, electricity, and thermal energy from natural gas.

### Incineration

Due to insufficient data for Australia, a dataset from the GaBi database representing WtE plants in Germany is used [36]. Incineration includes the thermal treatment of municipal waste, as there are no WtE plants that exclusively treat plastic waste. However, the dataset represents only the environmental impacts attributable to the plastic waste fraction. This dataset is partly aggregated and requires several process

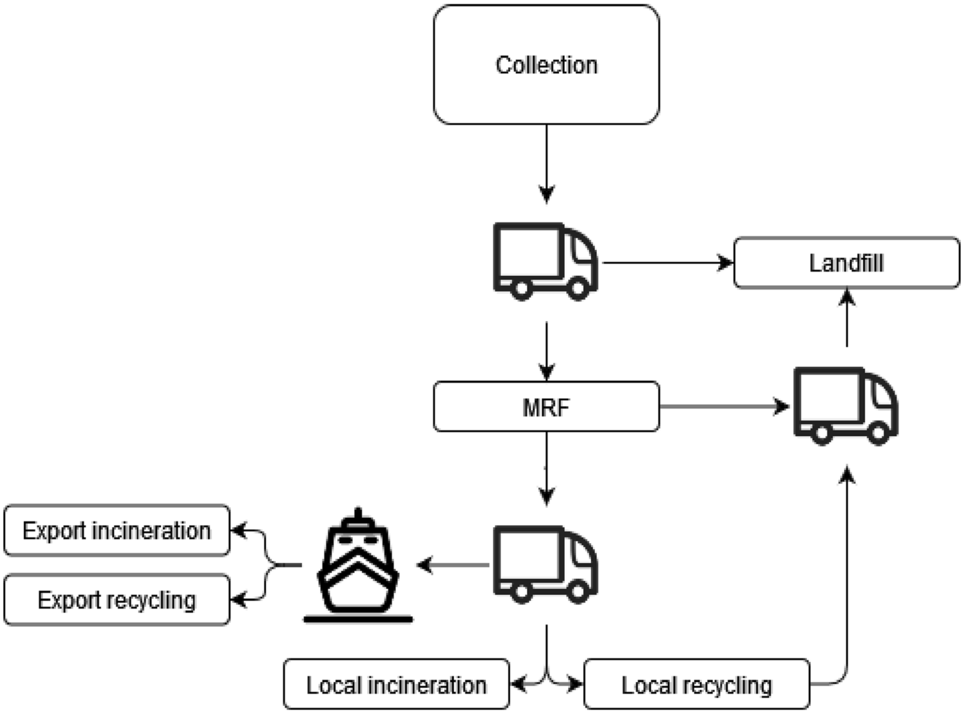


**Fig. 9** Transport routes after the collection of plastic wastes

inputs such as sodium hydroxide, coke, nitrogen, etc., which are included in the dataset. The output of the incineration are electricity and heat. The treatment of APC residues (boiler ash, filter cake, and slurries) are also included in the dataset. These residues are disposed of in underground salt mines, which are modelled as emission free. However, operations of the underground deposit as well as transportation is included. The datasets are specified to the regions under consideration (Australia & export nation) by applying the credits to the local electricity grid mix. The physical properties of the plastic wastes such as moisture and ash content along with the results of ultimate and proximate analysis are; however, not explained in detail within the documentation of the dataset, which is one of the major challenges when using the secondary inventory dataset to understand the environmental impacts of waste management. However, this dataset assumes a net calorific value for unspecified plastic waste of 30 MJ/kg.

### Mechanical recycling

The dataset from the GaBi database used for mechanical recycling is strongly simplified and partly aggregated with European Union as location [36]. It includes granulation, pelletizing, and compounding as the required steps to produce recyclates. The only process input is electricity, which is already included in the dataset. Therefore, the environmental impacts of the recycling process are based entirely on the electricity consumption. The greater the amount of recycled plastic waste, the higher the energy consumption and the resulting environmental impact. Credits and burdens are not included in this dataset. Therefore, in a further step, the residual waste (reprocessing loss) is landfilled according to mass flow models of the scenarios. The credits for the avoided production of granulates are accounted for by subtracting the environmental impacts for the production of the polymers according to their share in the specific waste composition [Fig. 6].

The recyclates do not replace virgin material completely as quality losses have to be compensated in the form of MSP. Dastjerdi et al. used a MSP of 91.3% for their study on waste management in New South Wales [16] supported by Merrild et al., who also assumed a material quality loss of 10% during the recycling, which corresponds to a MSP of 90% [39]. Therefore, an MSP of 91.3% is also used in this study for all the scenarios. However, a sensitivity analysis regarding the MSP is performed to assess the uncertainties regarding this assumption.

### Electricity grid mix

A dataset consisting of an electricity grid mix is required for processes such as the sorting and the electricity credits during the incineration process. For this study, the electricity grid mixes from Australia and PRC are used for the baseline and other scenarios. The composition and share of different energy sources in the grid mixes of Australia and PRC are shown in Figure S7. It can be seen that the Australian electricity grid mix has a higher share of fossil energy sources (about 84%) than the PRC dataset (about 74%), for the same reference year [36].

## Results and discussion

The LCIA results for the scenario and the sensitivity analysis are presented and discussed in this section. As mentioned in "Materials and methods" impact indicators GWP, ADP Fossil, AP and EP for different scenarios are discussed in detail.

Figure 10 shows the GWP for the baseline scenario (S0). Apart from showing the total GWP per FU, individual contributions from EoL options, credits, transport and sorting are shown separately. From the figure, it can be seen that the total GWP for handling the plastic wastes in Australia for the year 2018–19 is − 2.46E + 08 kg $CO_2$ equivalents. The negative value of total GWP is due to the fact that the credits for material substitution (− 5.74E + 08 kg $CO_2$ equivalents) and energy generation (− 6.72E + 07 kg $CO_2$ equivalents) in recycling and incineration offsets the combined environmental burdens of sorting, transport, recycling, incineration and landfill. In the case of incineration, the energy resources and the corresponding emissions during the incineration (1.45E + 08 kg $CO_2$ equivalents) is more than the credits they get out of generating energy during incineration (− 6.72E + 07 kg $CO_2$ equivalents).

The GWP of landfill is 1.45E + 08 kg $CO_2$ equivalents, which is higher than recycling and incineration, due to the fact that 84% of plastic wastes are currently getting landfilled and the wastes are landfilled without any energy recovery.

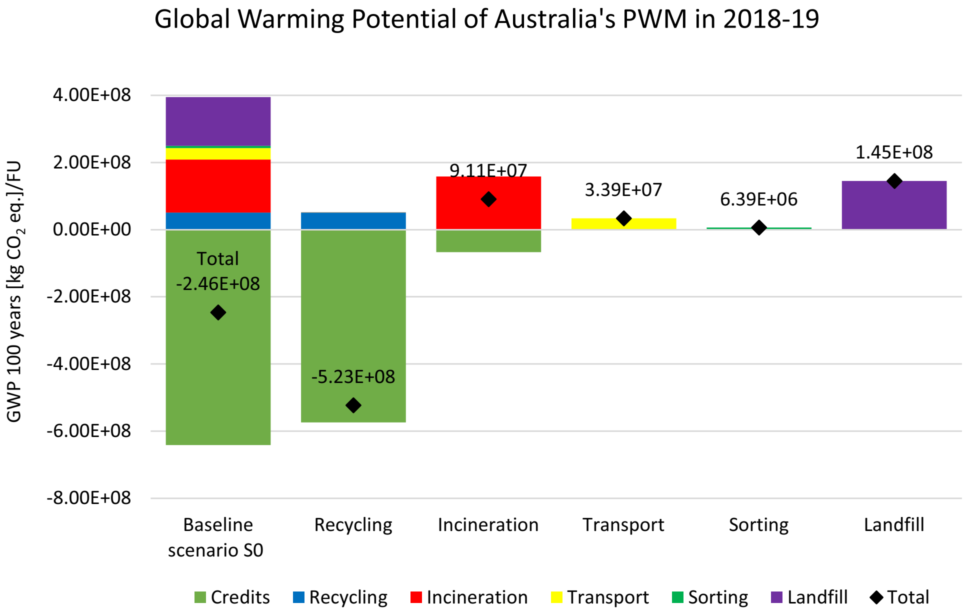
ADP Fossil of S0 is shown in Fig. 11. The total ADP fossil, similar to GWP, is expressed in negative and is − 1.78E + 10 MJ per FU, which is the resource depletion potential of PWM in Australia for the year 2018–19. Similar to GWP, most of the credits come from the material substitution in recycling and energy substitution in incineration. But in the case of incineration, the energy substitution credits offset the environmental burdens of the incineration process. Overall, landfill is the largest contributor to the total ADP causing as much as 2.17E + 09 MJ per FU.

In the case of AP, as shown in Fig. 12, the largest contribution comes from the transportation of wastes (4.95E + 05 kg $SO_2$ equivalents), which includes the use of fuel in transporting the wastes locally (to the collection, sorting and other facilities) and exporting them to PRC. Landfill is the second largest contributor to the total AP (3.76E + 05 kg $SO_2$ equivalents). The total AP (1.37 + 05 kg $SO_2$ equivalents), unlike GWP and ADP has a positive value i.e., environmental burdens from the system outweigh the credits obtained through material and energy substitution.

EP of S0 is 3.65E + 05 kg $PO_4$ equivalents and is shown in Fig. 13. The largest contribution of EP comes from the landfill, which is around 4.08E + 05 kg $PO_4$ equivalents and is due to the generation and treatment of leachates when the plastic wastes are landfilled. As the status quo involves 84% of the total wastes to be landfilled, most of the impacts come from the landfill. The second largest contributor to the total EP is the transportation (local + export) of plastic wastes (5.83E + 04 kg $PO_4$ equivalents).

The LCIA results of all the impact indicators for the baseline scenario S0 are shown in Table 8. From the results, it can be seen that the credits outweigh the environmental burdens in almost all of the impact indicators except for AP and EP, where the impacts due to transport and landfill contributes to higher impacts than the impacts/credits obtained during recycling/incineration.

**Fig. 10** Global warming potential of Australia's PWM in 2018–19 (S0)



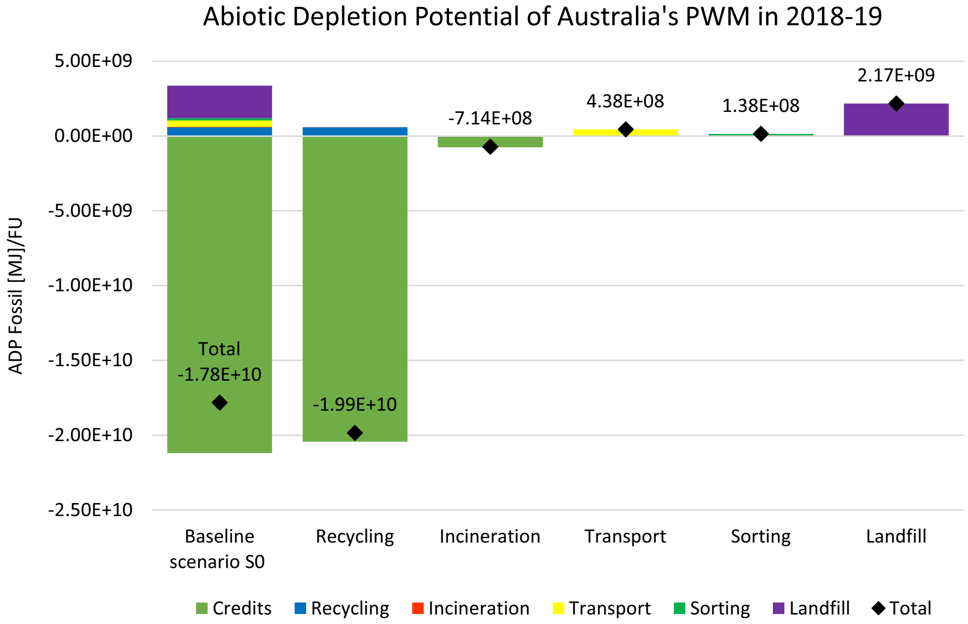


**Fig. 11** Abiotic depletion potential of Australia's PWM in 2018–19 (S0)

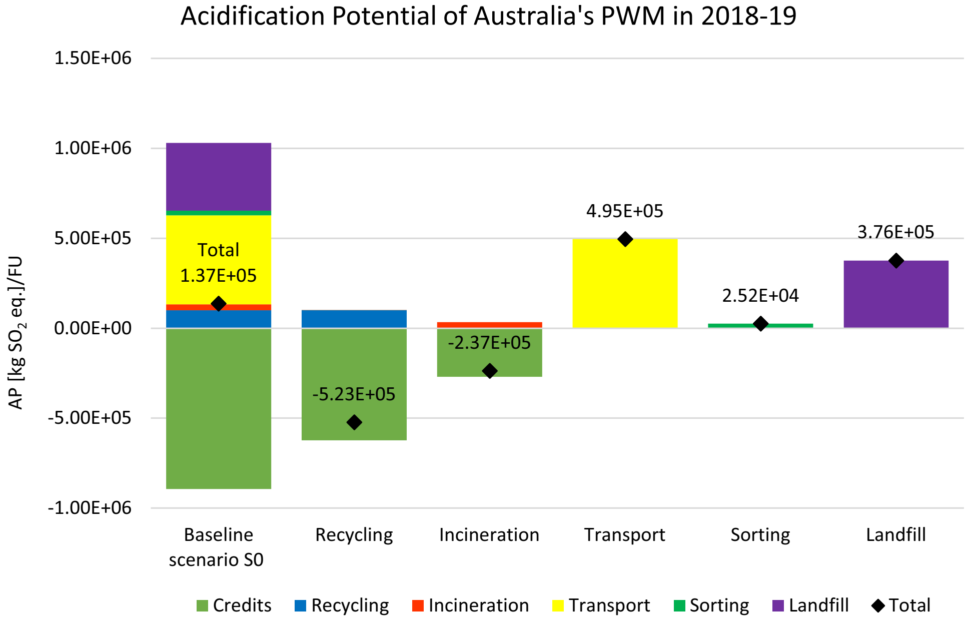


**Fig. 12** Acidification potential of Australia's PWM in 2018–19 (S0)

## Scenario analysis

Apart from the baseline scenario S0, three sub-scenarios, as defined in Table 5 are considered in the scenario analysis to understand the change in the impacts due to different strategies in the PWM in Australia. The results of these sub-scenarios are compared with the baseline scenario to understand the significance of different measures such as increased recycling rates or an export ban.

The GWP and ADP of PWM of Australia across different scenarios are shown in Figs. 14 and 15. In the case of GWP, an increase in the share of recycling (from 13 to 70%) increase the corresponding material substitution credits that reduce the need for the production of virgin polymers in S1A and S1C. In comparison to the baseline scenario, there is an 860% and 865% decrease in the total GWP for the scenarios S1A (70% recycling and export of wastes) and S1C (70% recycling and export ban), respectively and is due to the increase in the material substitution credits when increasing the recycling share. In the case of scenario S1B (Status quo and export ban), there is a 13% decrease in the total GWP, which could be a realistic scenario for the Australian

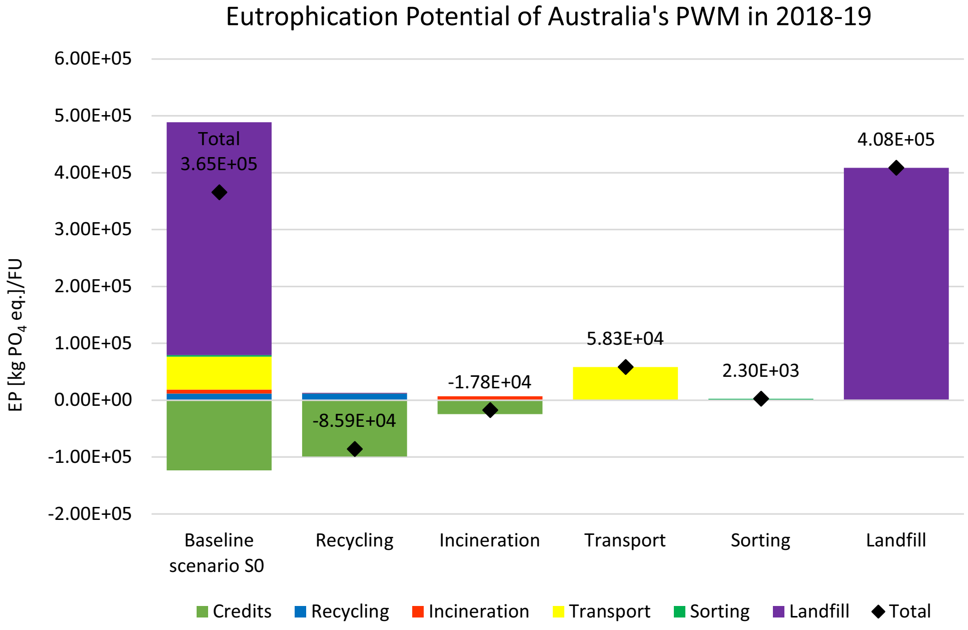


**Fig. 13** Eutrophication potential of Australia's PWM in 2018–19 (S0)

**Table 8** Impact assessment results of baseline scenario S0

| LCIA results per FU | Baseline scenario S0<br>Total | Recycling | Incineration | MRF (sorting) | Landfill | Transports |
|---|---|---|---|---|---|---|
| ADP elements [kg Sb eq.] | **− 1.50E + 02** | − 1.77E + 02 | − 1.48E + 00 | 6.26E−01 | 2.78E + 01 | 5.35E−01 |
| ADP fossil [MJ] | **− 1.78E + 10** | − 1.99E + 10 | − 7.15E + 08 | 1.38E + 08 | 2.17E + 09 | 4.38E + 08 |
| AP [kg $SO_2$ eq.] | **1.37E + 05** | − 5.23E + 05 | − 2.37E + 05 | 2.52E + 04 | 3.76E + 05 | 4.95E + 05 |
| EP [kg $PO_4$ eq.] | **3.65E + 05** | − 8.59E + 04 | − 1.78E + 04 | 2.30E + 03 | 4.08E + 05 | 5.83E + 04 |
| FAETP inf [kg DCB eq.] | **− 5.03E + 06** | − 5.68E + 06 | − 1.14E + 05 | 2.95E + 04 | 6.73E + 05 | 7.25E + 04 |
| GWP 100 years [kg $CO_2$ eq.] | **− 2.46E + 08** | − 5.23E + 08 | 9.11E + 07 | 6.39E + 06 | 1.45E + 08 | 3.39E + 07 |
| HTP inf [kg DCB eq.] | **− 2.53E + 07** | − 2.58E + 07 | − 5.48E + 06 | 5.98E + 05 | 4.40E + 06 | 9.37E + 05 |
| MAETP inf [kg DCB eq.] | **− 4.79E + 09** | − 1.97E + 10 | 3.19E + 08 | 4.35E + 08 | 1.38E + 10 | 3.24E + 08 |
| ODP [kg R11 eq.] | **− 1.09E-03** | − 1.09E-03 | − 4.85E−07 | 4.51E−08 | 4.92E−07 | 5.83E−09 |
| POCP [kg Ethene eq.] | **− 1.05E + 05** | − 1.47E + 05 | − 1.30E + 04 | 1.69E + 03 | 3.39E + 04 | 1.92E + 04 |
| TETP inf [kg DCB eq.] | **− 5.55E + 06** | − 8.54E + 06 | − 8.23E + 04 | 1.17E + 04 | 3.06E + 06 | 6.88E + 03 |

Bold refers to the total value of the baseline scenario, which was used to differentiate from the results of the individual processes, whose sum will give the total value

government moving forward in handling the plastic wastes locally before increasing the recycling share.

ADP of the different sub-scenarios are similar to that of GWP, wherein increase in the recycling share reduces the depletion of abiotic resources in S1A (512% decrease) and S1C (506% decrease due to a slight increase in the impacts of sorting) to manufacture and process virgin polymers. Only difference is that increase in the share of incineration (from 3 to 10%) in S1A and S1C increases the electricity credits obtained during the incineration which in turn reduces the overall ADP of the sub-scenarios (Fig. 15).

**Fig. 14** Global warming potential of different scenarios per FU

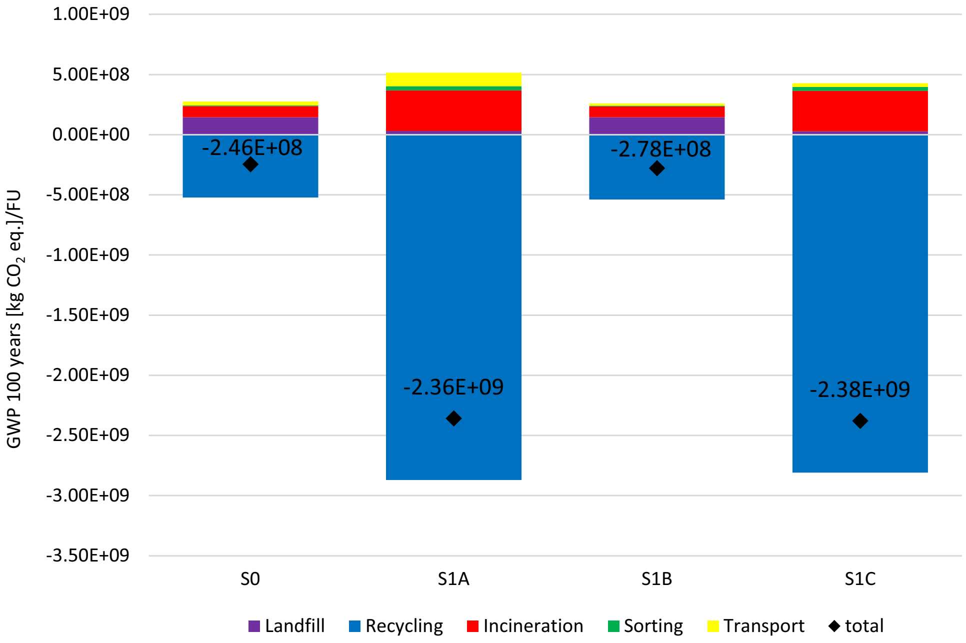
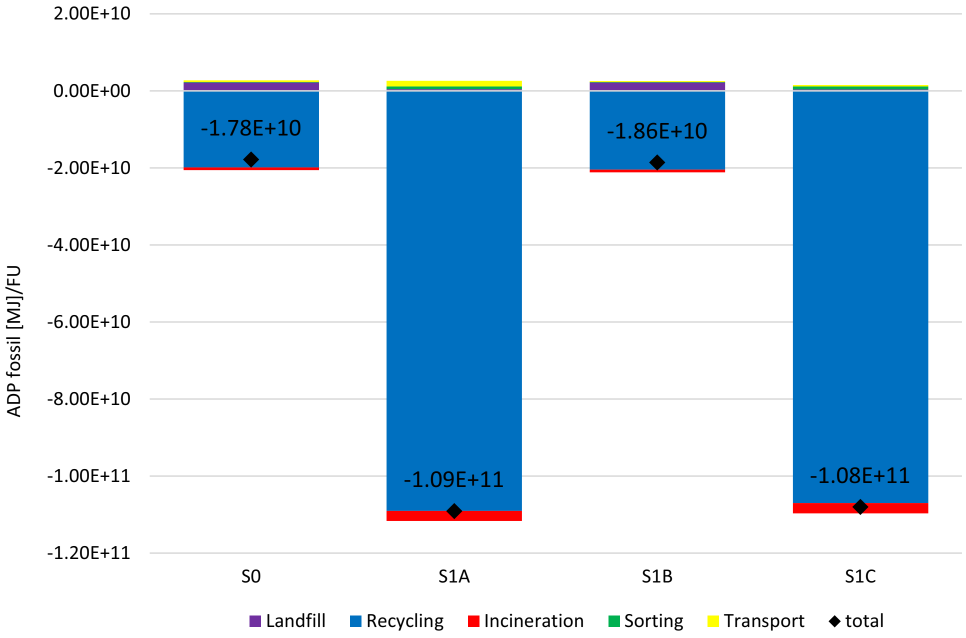


**Fig. 15** Abiotic depletion potential (fossil) of different scenarios per FU



The total AP and EP across different scenarios are shown in Figs. 16 and 17. In the case of AP, all the three sub-scenarios result in a negative value of AP in comparison to that of the baseline scenario S0 and is due to the share of incineration (and the corresponding credits) increase in S1A and S1C (from 3 to 10%) and a reduction in transport of the plastic wastes by banning the export of plastic wastes in S1B. However, in the case of S1A, even though there is a 788% decrease in the total AP in comparison to S0, the increase in the share of export in plastic wastes results in the higher contribution of AP due to the transportation and the fuel used in them. In the case of S1B, there is a 356% decrease in the total AP in comparison to S0 only by banning the export of plastic wastes.

The results of total EP in S1A (139% decrease) and S1C (215% decrease) are similar to that of AP, where the share of landfill is reduced and therefore the impacts of leachate treatment and transportation associated with them reduce significantly. There is a 15% decrease in the total EP for S1B in comparison to S0 and the decrease is due to the reduction in the impacts caused by export of plastic wastes.

**Fig. 16** Acidification potential of different scenarios per FU

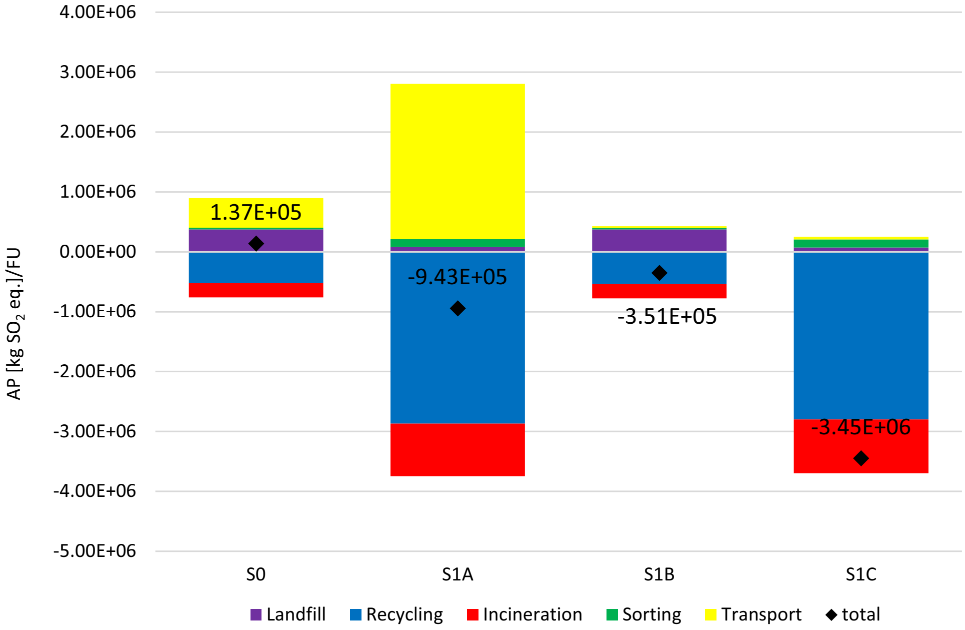
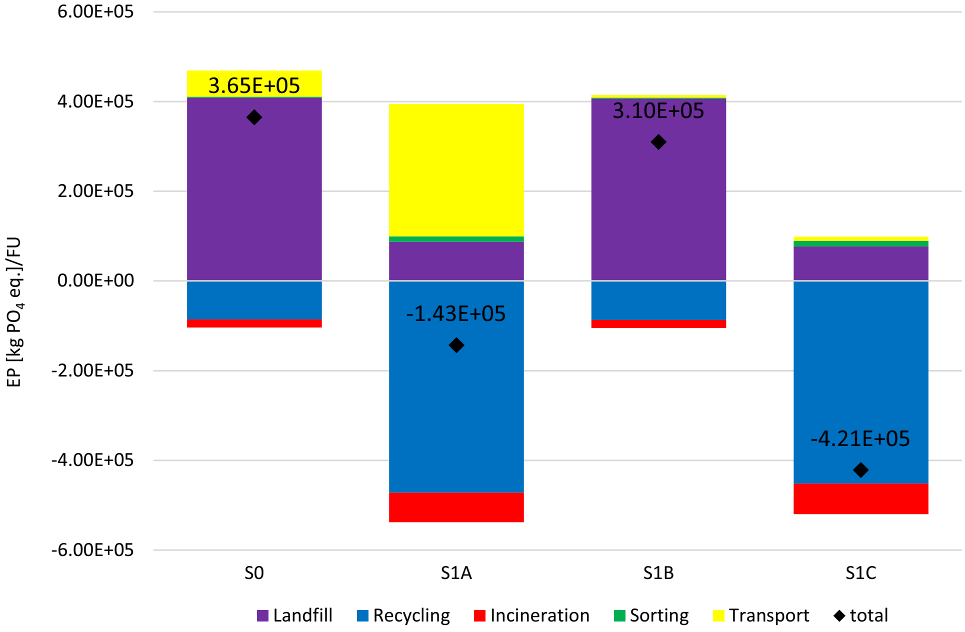


**Fig. 17** Eutrophication potential of different scenarios per FU



The LCIA results of other impact indicators across different scenarios are shown in Table 9. There is a slight decrease in the environmental impacts across all of the impact indicators for the scenario S1B in comparison to S0. Combining higher recycling (and incineration) rates along with the reduction in the landfilling and export of plastic wastes have resulted in a significant decrease in the environmental impacts for scenarios S1A and S1C in comparison to S0. There is also a slight decrease in six out of the eleven impact indicators for S1A in comparison with S1C, which can be attributed to the export of plastic wastes (S1A) and the electricity mixes used in the handling of them. The region-specific electricity grid mix and share of renewable energy sources in it are considered to be critical as with increasing recycling share (S1A or S1C), more waste will be sorted in MRF and processed, where the main process input is electricity.

Although the two sub-scenarios S1A and S1C are inclined towards the ambitious goals of Australian roadmap towards circular economy by 2030, the LCIA results of S1B shows that there is already a potential of reducing the environmental impacts only by banning the export of plastic wastes.

**Table 9** Impact assessment results of different scenarios

| LCIA results per FU | S0 | S1A | S1B | S1C |
|---|---|---|---|---|
| ADP elements [kg Sb eq.] | **− 1.50E+02** | − 9.67E+02 | − 1.55E+02 | − 9.47E+02 |
| ADP fossil [MJ] | **− 1.78E+10** | − 1.09E+11 | − 1.86E+10 | − 1.08E+11 |
| AP [kg $SO_2$ eq.] | **1.37E+05** | − 9.43E+05 | − 3.51E+05 | − 3.45E+06 |
| EP [kg Phosp. eq.] | **3.65E+05** | − 1.43E+05 | 3.10E+05 | − 4.21E+05 |
| FAETP inf [kg DCB eq.] | **− 5.03E+06** | − 3.11E+07 | − 5.22E+06 | − 3.06E+07 |
| GWP 100 years [kg $CO_2$ eq.] | **− 2.46E+08** | − 2.36E+09 | − 2.78E+08 | − 2.38E+09 |
| HTP inf [kg DCB eq.] | **− 2.53E+07** | − 1.54E+08 | − 2.68E+07 | − 1.54E+08 |
| MAETP inf [kg DCB eq.] | **− 4.79E+09** | − 1.01E+11 | − 5.39E+09 | − 9.86E+10 |
| OCP [kg R11 eq.] | **− 1.09E-03** | − 6.00E−03 | − 1.12E-03 | − 5.87E−03 |
| POCP [kg Ethene eq.] | **− 1.05E+05** | − 7.12E+05 | − 1.34E+05 | − 8.29E+05 |
| TETP inf [kg DCB eq.] | **− 5.55E+06** | − 4.65E+07 | − 5.81E+06 | − 4.55E+07 |

Bold values refers to the results of baseline scenario, in order to differentiate from the results of other scenarios considered for this study

Moreover, increase in the local recycling will open up the markets for recyclates and reduce the uncertainties associated with the fate of plastic wastes (downcycling, mismanagement) after exports.

## Sensitivity analysis

To investigate the uncertainties in the assumptions of certain process parameters and their significance to the total environmental impacts, a sensitivity analysis is conducted. As discussed in Sect. Process inputs, the MSP of recyclates and the inclusion of heat credits for the heat generated during incineration are considered for the sensitivity analysis. As the MSP (ability to replace the virgin polymers) of the recyclates in Australia is unknown, a value of 91.3% is taken from the literature [16] and is used to calculate the environmental impacts across different scenarios. To understand the uncertainty and significance of this parameter, the substitution potential is varied by having two MSPs of 75% and 50%. For incineration, the heat that is generated is assumed to replace the production of thermal energy from hard coal in Australia using an average dataset from the GaBi database [36]. The results of the variation of these process parameters are then compared with the baseline scenario per FU. However, it is assumed that the impacts of sorting, transport and landfill remain unchanged.

Figure 18 and 19 shows the results of the sensitivity analysis for GWP and ADP fossil respectively. It can be observed that lower the MSP, there is an increase in the total GWP of the PWM system. There is an 41% increase in the total GWP when the substitution potential changes from the assumed value of 91.3% to 75% and there is a 105% increase in the total GWP when the substitution potential is assumed to be 50%. This suggest that the downcycling and the losses associated with the quality and the processing of the material results in the increase in environmental impacts. In the case of incineration with heat credits included (and having a MSP of 91.3% for recycling), there is a 25% decrease in the total GWP which is attributed to the increase in the total energy substitution credits during incineration of the plastic wastes.

The results of sensitivity analysis for ADP fossil are similar to that of GWP, with a 20% and 51% decrease in total ADP for the MSP of 75% and 50% in recycling respectively. For the incineration with heat credits, there is a 8% decrease in the total ADP.

The results of sensitivity analysis for AP and EP are shown in Figs. 20 and 21. Similar to GWP and ADP, the results of AP follow the same pattern. For AP, there is an increase of 81% and 205% for the substitution potential of 75% and 50% respectively. For incineration with heat credits, there is a decrease of 435% in the total AP when the heat from the incineration is utilized along with the electricity.

In the case of EP, as the impacts of landfilling are kept constant for the sensitivity analysis, there is only a slight change in the total impacts when these parameters are considered and varied. There is an increase of 5% and 12% in the total EP for the substitution potential of 75% and 50%

**Fig. 18** Global warming potential of sensitivity analysis per FU

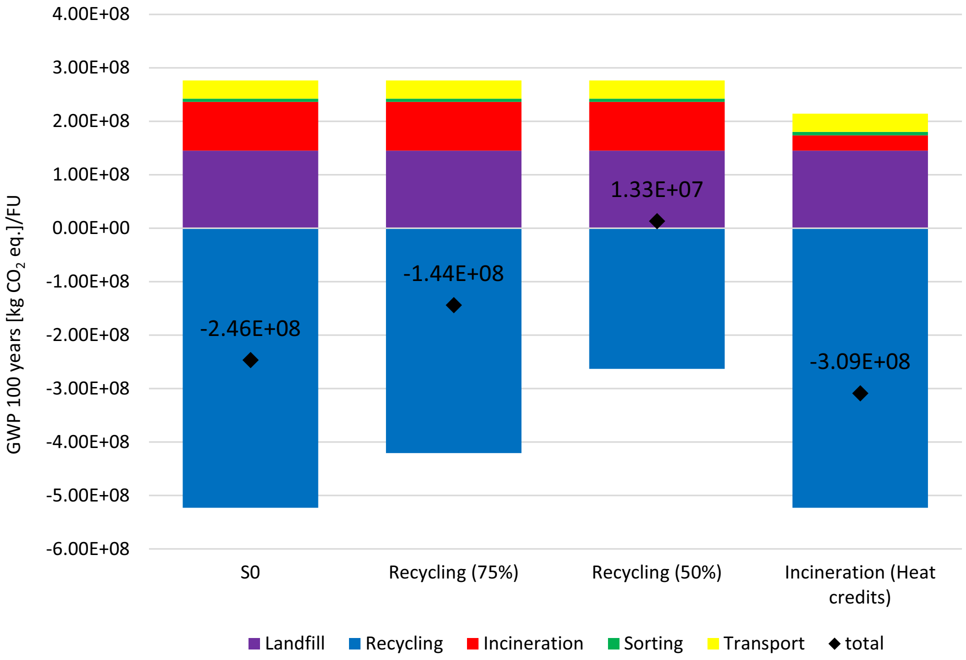
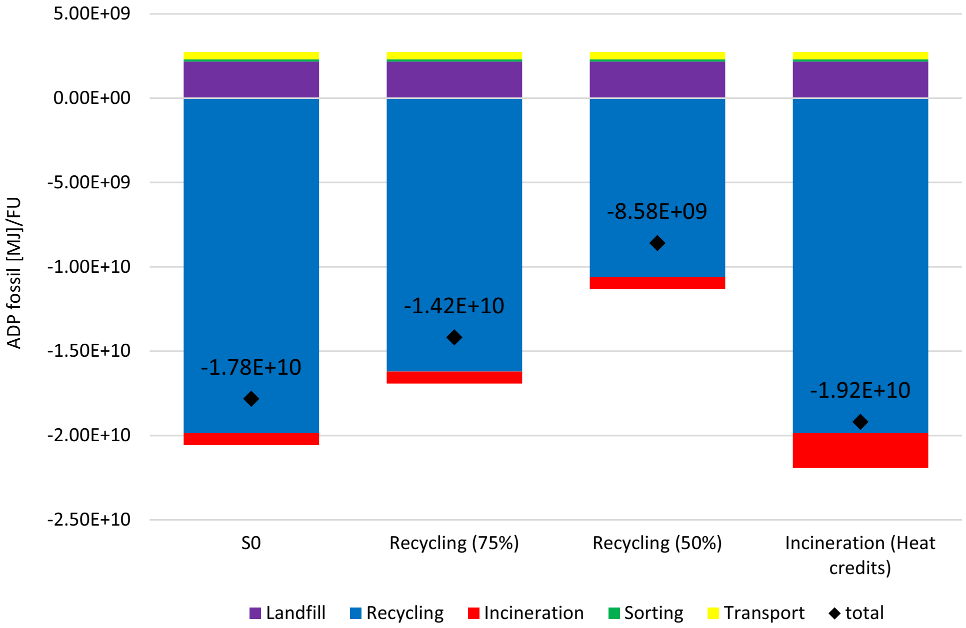


**Fig. 19** Abiotic depletion potential (fossil) of sensitivity analysis per FU



respectively. When it comes to the inclusion of heat credits in incineration, there is a 12% decrease.

## Limitations

Despite sensitivity analysis, it is necessary to identify limitations in performing this LCA study, which are as follows:

1. The current LCA focuses exclusively on potential environmental impacts associated with the different plastic waste management scenarios
2. Aspects such as the market for recyclates and their applications are not considered. According to Australian plastics reprocessors (2018–19), there is a lack of infrastructure for recycling. In addition, lower grade polymers are not recycled due to the high cost of recycling. Furthermore, the market demand for mixed polymers

**Fig. 20** Acidification potential of sensitivity analysis per FU

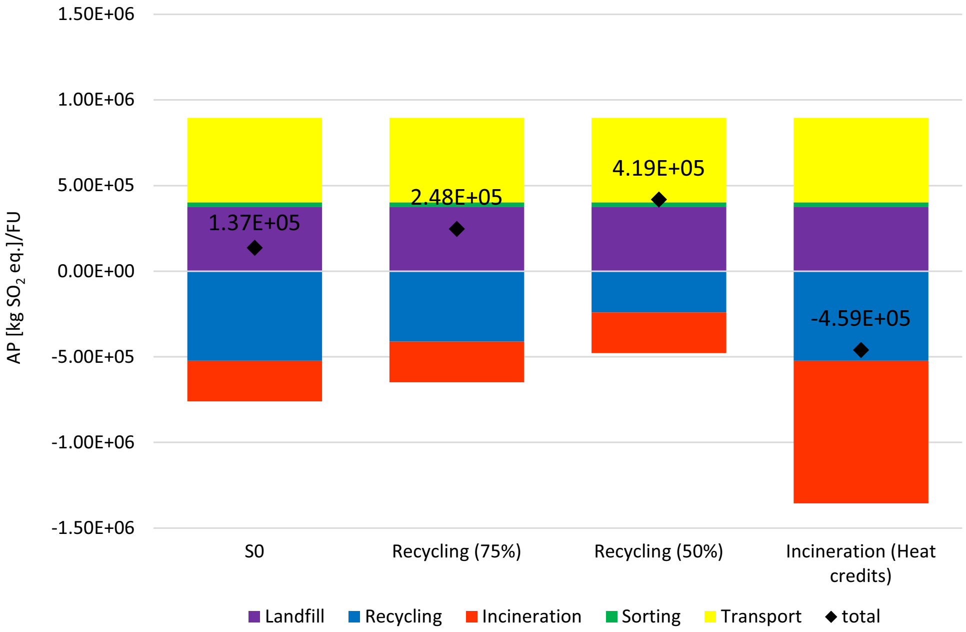
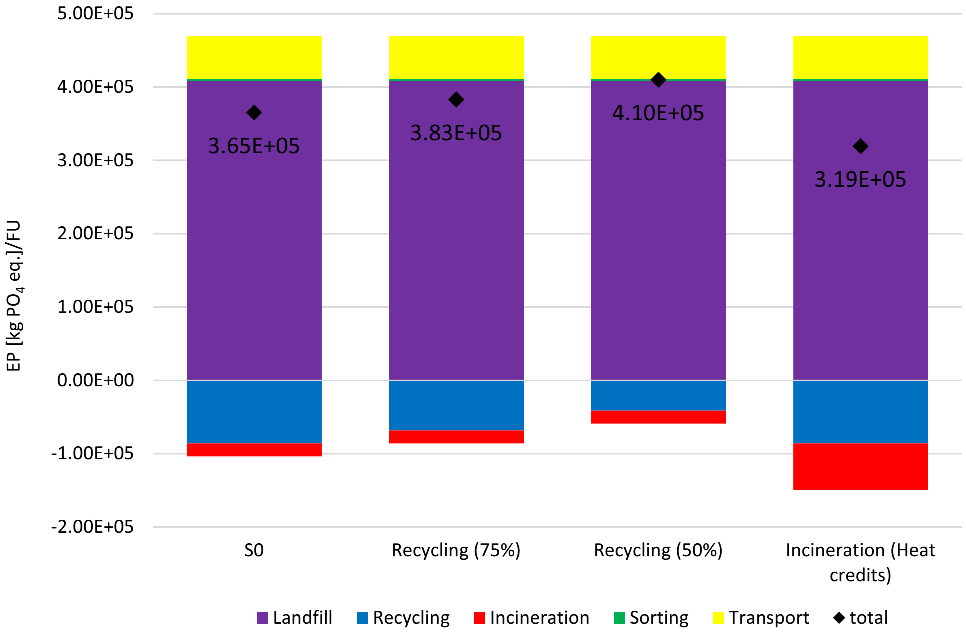


**Fig. 21** Eutrophication potential of sensitivity analysis per FU



is weaker than for single type polymers. The impact of these aspects is not considered in the current LCA [44]

3. Feasibility/scalability of the planned measures (i.e., increasing the recycling capacity, banning the exports) is not considered
4. As no sufficient distinction could be made between post-consumer and pre-consumer waste, all plastic wastes are considered as post-consumer waste from MSW. In addition, it is not possible to differentiate between different polymer types in terms of individual material substitution potential or the location of the recycling due to a lack of data and datasets. However, the environmental benefits of recycling, i.e., the reduction effects of environmental impacts, are considered separately for each polymer type (Fig. 6)
5. Foreground data for the EoL options (sorting, export, recycling, incineration and landfill) are not available for Australia. Therefore, datasets from other countries consisting of average and aggregated process data are used for calculating the environmental impacts. Therefore, regional specific data are not fully used

6. Transport routes and collection of plastic wastes are simplified and the share of export and local handling of plastic wastes are calculated based on the statistical data but the fate of the exported plastics is largely unknown

## Discussion

Most of the plastic waste generated in Australia in 2018–19 are landfilled, which is the main driver for the baseline PWM´s contribution to the impacts considered in this study. Although only 13% of plastic waste is recycled and 3% is recovered for energy, the credits awarded for these processes outweigh the potential burdens for the baseline scenario S0. Especially, when it comes to GWP, the credits given for the recycling and incineration result in the reduction of GHG-emissions equivalent to the annual emissions of about 14,000 average Australian households (~ 18 t $CO_2$ equivalents per average household) [40]

In general, the LCIA results highlight the advantages of recycling over incineration and in particular over landfilling. However, a high MSP of over 90% is selected in this study, which might not reflect the reality due to different parameters like colour of the recyclates, physical and chemical properties, contamination and most importantly the applications where these recyclates are used. The sensitivity analysis showed that a low MSP of 50% still leads to more credits than burdens in all impact categories. The LCIA results of recycling across scenarios have to be interpreted carefully due to the fact that the MSP for the plastic wastes change according to the plastic types and applications.

Even though the plastic wastes incinerated with energy recovery contributed positively towards the environmental impacts, heating value of the plastic wastes and market demand for the utilization of the energy are the critical factors that have to be considered when choosing incineration as an EoL option. From the sensitivity analysis, incineration including heat credits found to be more beneficial in all of the impact categories.

The planned Australian PWM, as modelled in this study, excludes plastic waste exports, and considers 70% recycling and 10% energy recovery. However, 20% of the waste will still be disposed of in landfill, which conflicts with the waste hierarchy. The LCIA results of the planned PWM strategies (S1A and S1C) show a drastic decrease in the total environmental impacts across the impact indicators. In particular, the potential savings in GWP category generated by the planned PWM (S1C) are nearly ten times greater than in the baseline scenario S0. The PWM in S1C has the potential to save GHG emission equal to the annual emissions of about 130,000 average Australian households [40]. Therefore, the results show that the higher rate of plastic waste recycling and the credits given for substituting virgin material are attributed for this improvement. In the case of scenario S1B, there is already a significant decrease in the total environmental impacts across different indicators only through banning the export of plastic wastes and handling them locally with the current recycling/disposal share.

However, in 2022 the Australian Auditor-General has undertaken an independent performance audit of the implementation of the national waste policy action plan and found that “the draft national resource recovery rate target (80 per cent by 2030) is not expected to be achieved, even under the high success scenario (in which existing state, territory and industry targets are met; recovery rates increase at the projected baseline trend rate of increase; and there is a significant increase in waste to energy)”. [25]

The National Waste Report 2022 found that the overall resource recovery rate sat at 63.1% in 2020–21 and only increased by 2.2% since 2016–17 [41]. The finding of the Auditor-General regarding the failure to meet the recovery rate target is concerning especially considering that Australia’s population is increasing (and therefore potentially the overall waste that is accumulated), and landfill sites are becoming more and more scarce. The Australian Plastics Flows and Fates Study 2019–20 states that based on the current trend the annual Australian plastic consumption might increase from 3.4 Mt to 8.8 Mt in the year 2049–2050 [3]. In other words, significant amounts of (plastic) waste will still have to be deposited into landfills by 2030.

## Conclusion

To understand the impacts of different EoL options of plastic wastes from an environmental perspective, this study was conducted for the Australia’s plastic waste management (PWM). The literature review identified the research gaps in quantifying the environmental impacts of current EoL options in Australia. Despite the unavailability of primary data for different EoL options, data from the official documents and literature sources were used to conduct this LCA. Based on the policy targets, status-quo and future targets of Australia’s PWM was found and a scenario analysis was done to understand the significance of policy measures on the total environmental impacts. Data quality and the regional data unavailability were found to be critical aspects in the LCA study. Further research should focus on collecting primary data on MRF, landfilling and waste composition in Australia.

From the results, it can be seen that increasing the share of recycling along with assuming a higher MSP for the recyclates to replace the virgin polymers contribute positively towards the environmental impacts. In the case of incineration, the utilization of electricity and heat credits contribute positively towards the environmental impacts. Landfilling and the transport associated with them contributes significantly towards the total impacts due to the large share of plastic wastes currently landfilled. From the scenario analysis, it can be seen that the future PWM strategies could reduce the total environmental impacts of the PWM and can increase the resource recovery, thereby transitioning towards circular economy. Even if the recycling targets are not met in the near future, banning the waste exports and treating them locally will significantly reduce the environmental impacts and facilitate in implementing other strategies.

With challenges like market demand for virgin plastics, mismanagement of plastic wastes, need for an effective (plastics) circular economy in Australia is constantly growing. In line with this, the Australian Government has announced the transition to a circular economy by 2030 and has recently established an advisory group on the Circular Economy [42]. Moreover, a new, national framework to understand waste prevention was developed in 2022, detailing distinct waste prevention activities [43]. These frameworks along with the environmental impacts of the current and future PWM strategies can definitely pave the way for Australia in making the difficult yet necessary transition towards the circular economy by 2030.

Beyond this study's sustainability assessment, further research should also address the challenges described in Sect. Limitations. The feasibility and scalability of the main measure envisaged (increasing recycling rates) in particular should be considered and investigated. The potential environmental benefits of the Australian waste management strategy depend on factors like recycling infrastructure, recyclability, and market demand for recycled plastics. While these challenges and limiting factors exist, it would also be interesting to investigate potential positive (economic) spillovers such as job creation when going for a transition from a liner to a circular economy for plastics.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s10163-024-01901-1.

**Acknowledgements** The publication of this article was funded by the Open Access Fund of Leibniz Universität Hannover.

**Funding** Open Access funding enabled and organized by Projekt DEAL.

## Declarations

**Conflict of interest** The authors hereby declare that there is no conflict of interest.

## References

1. Kyle O'Farrell (2020) 2018–19 Australian plastics recycling survey: national report, department of agriculture, water and the environment, Australian government. https://www.dcceew.gov.au/sites/default/files/documents/australian-plastics-recycling-survey-report-2018-19.pdf. Accessed 01 Dec 2022
2. Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. Sci Adv 3:e1700782. https://doi.org/10.1126/sciadv.1700782
3. O'Farrell K, Harney F, Chakma P (2021) Australian plastics flows and fates study 2019–20: national report. https://www.dcceew.gov.au/sites/default/files/documents/apff-national-report_0.pdf. Accessed 20 Feb 2023
4. Venkatachalam V, Pohler M, Spierling S et al (2022) Design for recycling strategies based on the life cycle assessment and end of life options of plastics in a circular economy. Macro Chem Phys 223:2200046. https://doi.org/10.1002/macp.202200046
5. Ellen MacArthur Foundation (2021) What is a circular economy?. https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview. Accessed 08 Mar 2023
6. Department of climate change, energy, the environment and water (2018) 2018 National waste policy: less waste, more resources. Commonwealth of Australia. https://www.agriculture.gov.au/sites/default/files/documents/national-waste-policy-2018.pdf. Accessed 28 Jan 2023
7. Pickin J, Wardle C, O'Farrell K et al. (2020) National waste report 2020: department of agriculture, water and the environment. https://www.dcceew.gov.au/environment/protection/waste/national-waste-reports/2020. Accessed 22 Mar 2023
8. Department of the environment and energy (2019) National waste policy action plan 2019: commonwealth of Australia. https://www.agriculture.gov.au/sites/default/files/documents/national-waste-policy-action-plan-2019.pdf. Accessed 17 Jan 2023
9. Department of agriculture, water and the environment (2021) National plastics plan 2021: commonwealth of Australia, Canberra. https://www.dcceew.gov.au/environment/protection/waste/plastics-and-packaging/national-plastics-plan. Accessed 19 Feb 2023
10. Schandl H, King S, Walton A, Kaksonen AH, Tapsuwan S (2020) National circular economy roadmap for plastics, glass, paper and tyres. CSIRO, Australia
11. Zumsteg JM, Cooper JS, Noon MS (2012) Systematic review checklist: a standardized technique for assessing and reporting reviews of life cycle assessment data. J Ind Ecol 16:S12–S21. https://doi.org/10.1111/j.1530-9290.2012.00476.x
12. Fink A (2019) Conducting research literature reviews: from the internet to paper, 5th edn. SAGE, Los Angeles, CA
13. Elsevier (2023) How scopus works. https://www.elsevier.com/solutions/scopus. Accessed 16 Apr 2023
14. Clarivate web of science platform. https://clarivate.com/products/scientific-and-academic-research/research-discovery-and-workflow-solutions/webofscience-platform/. Accessed 16 Apr 2023
15. Dastjerdi BH, Strezov V, Kumar R et al (2021) Economic feasibility and sustainability assessment of residual municipal solid

waste management scenarios in NSW. Australia Sustain. 13:8972. https://doi.org/10.3390/su13168972

16. Dastjerdi B, Strezov V, Kumar R et al (2021) Comparative life cycle assessment of system solution scenarios for residual municipal solid waste management in NSW. Australia Sci Total Environ 767:144355. https://doi.org/10.1016/j.scitotenv.2020.144355
17. Demetrious A, Crossin E (2019) Life cycle assessment of paper and plastic packaging waste in landfill, incineration, and gasification-pyrolysis. J Mater Cycles Waste Manag 21:850–860. https://doi.org/10.1007/s10163-019-00842-4
18. International organization for standardization (2020) ISO 14040:2006/Amd 1:2020: environmental management—Life cycle assessment—Principles and framework—Amendment 1. https://www.iso.org/standard/76121.html. Accessed 20 Jan 2023
19. International Organization for Standardization (2020) ISO 14044:2006/Amd 2:2020: Environmental management—Life cycle assessment—Requirements and guidelines—Amendment 2. https://www.iso.org/standard/76122.html. Accessed 20 Jan 2023
20. Laurent A, Clavreul J, Bernstad A et al (2014) Review of LCA studies of solid waste management systems–part II: methodological guidance for a better practice. Waste Manag 34:589–606. https://doi.org/10.1016/j.wasman.2013.12.004
21. Alhazmi H, Almansour FH, Aldhafeeri Z (2021) Plastic waste management: a review of existing life cycle assessment studies. Sustainability 13:5340. https://doi.org/10.3390/su13105340
22. Kousemaker TM, Jonker GH, Vakis AI (2021) LCA practices of plastics and their recycling: a critical review. Appl Sci 11:3305. https://doi.org/10.3390/app11083305
23. Franklin Associates (2018) Life cycle impacts for postconsumer recycled resins: PET, HDPE and PP. https://plasticsrecycling.org/images/library/2018-APR-LCI-report.pdf. Accessed 13 Mar 2023
24. Ekvall T (2020) Attributional and consequential life cycle assessment. In: José Bastante-Ceca M, Luis Fuentes-Bargues J, Hufnagel L et al (eds) Sustainability assessment at the 21st century. IntechOpen
25. Australian national audit office Australian government implementation of the national waste policy action plan: commonwealth of Australia. https://www.anao.gov.au/work/performance-audit/australian-government-implementation-the-national-waste-policy-action-plan. Accessed 04 Mar 2023
26. Australian Bureau of statistics (2020) Waste account, australia, experimental estimates 2018–19. department of the environment and energy, Canberra. https://www.abs.gov.au/statistics/environment/environmental-management/waste-account-australia-experimental-estimates/latest-release#data-downloads. Accessed 14 Jan 2023
27. Institute of environmental sciences (CML)—Leiden university CML-IA characterisation factors. https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors. Accessed 17 Mar 2023
28. Aryan Y, Yadav P, Samadder SR (2019) Life cycle assessment of the existing and proposed plastic waste management options in India: a case study. J Clean Prod 211:1268–1283. https://doi.org/10.1016/j.jclepro.2018.11.236
29. Gear M, Sadhukhan J, Thorpe R et al (2018) A life cycle assessment data analysis toolkit for the design of novel processes—a case study for a thermal cracking process for mixed plastic waste. J Clean Prod 180:735–747. https://doi.org/10.1016/j.jclepro.2018.01.015
30. Hossain MU, Ng ST, Dong Y et al (2021) Strategies for mitigating plastic wastes management problem: a lifecycle assessment study in Hong Kong. Waste Manag 131:412–422. https://doi.org/10.1016/j.wasman.2021.06.030
31. Hottle TA, Bilec MM, Landis AE (2017) Biopolymer production and end of life comparisons using life cycle assessment. Resour Conserv Recycl 122:295–306. https://doi.org/10.1016/j.resconrec.2017.03.002
32. Jeswani HK, Azapagic A (2016) Assessing the environmental sustainability of energy recovery from municipal solid waste in the UK. Waste Manag 50:346–363. https://doi.org/10.1016/j.wasman.2016.02.010
33. Allacker K, Mathieux F, Pennington D et al (2017) The search for an appropriate end-of-life formula for the purpose of the European commission environmental footprint initiative. Int J Life Cycle Assess 22:1441–1458. https://doi.org/10.1007/s11367-016-1244-0
34. Brooks AL, Wang S, Jambeck JR (2018) The Chinese import ban and its impact on global plastic waste trade. Sci Adv 4:eaat0131. https://doi.org/10.1126/sciadv.aat0131
35. Sphera LCA for experts (GaBi). https://sphera.com/life-cycle-assessment-lca-software/. Accessed 16 Apr 2023
36. Sphera (2023) Managed LCA content (GaBi Databases). https://sphera.com/life-cycle-assessment-lca-database/. Accessed 22 Mar 2023
37. Pickin J, Trinh J (2019) Data on exports of Australian wastes 2018–19. https://www.dcceew.gov.au/sites/default/files/documents/data-exports-australian-wastes-2018-19.pdf. Accessed 15 Jan 2023
38. Carre A, Crossin E, Clune S (2015) LCA of Kerbside Recycling in Victoria. https://assets.sustainability.vic.gov.au/susvic/Report-Lifecycle-assessment-LCA-of-kerbside-recycling-2015.pdf. Accessed 17 Feb 2023
39. Merrild H, Larsen AW, Christensen TH (2012) Assessing recycling versus incineration of key materials in municipal waste: the importance of efficient energy recovery and transport distances. Waste Manag 32:1009–1018. https://doi.org/10.1016/j.wasman.2011.12.025
40. Environment protection authority victoria australian greenhouse calculator: households and GHG emissions. https://apps.epa.vic.gov.au/AGC/r_emissions.html#/! Accessed 11 Feb 2023
41. Pickin J, Wardle C, O'Farrell K et al. National Waste Report 2022. The department of climate change, energy, the environment. https://www.dcceew.gov.au/environment/protection/waste/national-waste-reports/2022. Accessed 20 Mar 2023
42. Department of Climate Change, Energy, the Environment and Water (2022) New expert group to guide Australia's transition to a circular economy. https://minister.dcceew.gov.au/plibersek/media-releases/new-expert-group-guide-australias-transition-circular-economy. Accessed 25 Mar 2023
43. Department of climate change, energy, the environment and water (2022) Framework for understanding, measuring and communicating waste prevention. https://www.dcceew.gov.au/environment/protection/publications/measuring-waste-prevention. Accessed 16 Jan 2023
44. Department of agriculture, water and the environment (2020) 2018–19 Australian plastics recycling survey. https://www.dcceew.gov.au/environment/protection/waste/publications/australian-plastics-recycling-survey-report-2018-19. Accessed 02 Nov 2023