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Comparative environmental and socioeconomic assessment on mixed plastic waste management: A Singapore case study

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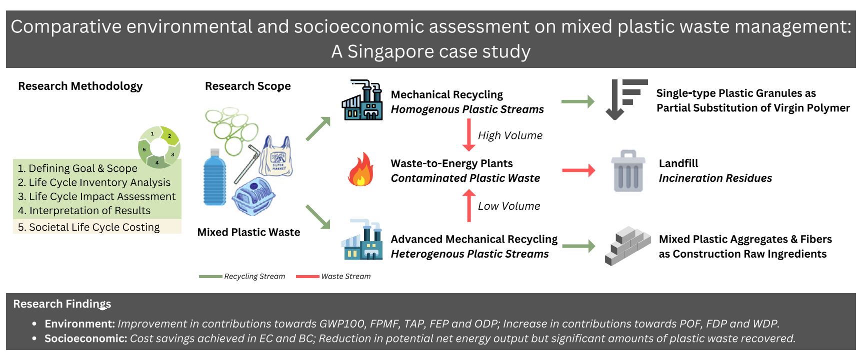
HIGHLIGHTS

- In Singapore, 868,600 tonnes of plastic waste were generated in 2020 and merely 4% of which were recycled.
- An advanced mechanical facility to process mixed plastic waste into alternative raw ingredients for construction materials.
- Prioritize efforts in maximizing mechanical recycling of mixed plastic waste alleviates the reliance on thermal energies.

GRAPHICAL ABSTRACT



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ABSTRACT

Proper end-of-life (EOL) management of mixed plastic waste remains a global challenge in both developed and developing countries as disposed plastic circulating within the ecosystem continues to increase at unprecedented rates. Presently, plastic EOL pathways are largely designed based on prevailing geographical conditions and environmental regulations across different regions. Till date, no work has been reported on the environmental and socioeconomic assessment on EOL pathway focusing on mechanical recycling of mixed plastic waste into raw ingredients for construction materials. This paper presents a life cycle assessment to characterize the environmental and socioeconomic impacts of four different plastic EOL pathways using Singapore as a case study. The present study describes how Singapore can redesign its current waste-to-resource taxonomy and reiterates the need to maximize mechanical recycling throughput of mixed plastic waste so to alleviate the reliance on thermal energies for waste valorisation and improve the overall performance of current plastic EOL pathway.

1. Introduction

1.1. Plastic waste management

Plastic, a term derived from a Latin word "*plasticus*" and a Greek term "*plastikos*" used in the early 17th century, is used to describe materials with an ability to be moulded into any shapes and sizes. In 2019, the volume of plastic produced globally was estimated around 368 million tonnes with the packaging and built environment sectors accounting for the largest market share of 39.6 % and 20.4 %, respectively (PlasticsEurope, 2020). The commonly used plastic includes polyethylene terephthalate (PET), high density polyethylene (HDPE), polyvinyl alcohol (PVC), low density polyethylene (LDPE), polypropylene (PP) and polystyrene (PS). Each plastic variant provides different strength-to-weight ratio, stiffness and toughness, corrosion resistance, thermal, and electrical insulation properties catering to a wide range of applications, such as food safety, healthcare sterility and buildings sustainability. Today, plastic has become an indispensable material that is integrated in every part of our lives. With

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the continued demand for plastic, the volume of plastic in circulation is projected at 417 million tons annually by 2030 (Schyns and Shaver, 2021).

The same material properties that make plastic ubiquitous and versatile have also presented major challenges at the end of its service life. The degradation rate of plastic waste ranged between 20 and 1200 years have resulted in closure of many open dumpling grounds and landfills at full capacities (Tejaswini et al., 2022). Active and closed landfills were found to be major sources of microplastic leaching into the environment (He et al., 2019; Su et al., 2019). With imminent needs to properly manage plastic at its end-of-life (EOL) phase, different EOL management pathways were developed to process plastic waste into primary, secondary, tertiary, and quaternary products (Davidson et al., 2021) as shown in Fig. 1. The primary products are derived from closed-loop recycling of single-type plastic waste, where recycled single-type plastic waste is recovered back into its original intended use. The secondary products are downcycled derivatives from open-loop recycling of mixed plastic waste, whereby recovered plastic waste is repurposed into recycled products for applications different from its original intended purpose (Ragaert et al., 2017). The tertiary products are recycled feedstock produced from chemical recycling processes, such as hydrocarbons from hydrocracking plants, monomers from solvolysis process, and biogas from pyrolysis systems (Vollmer et al., 2020). The quaternary products are thermal energies recovered from incineration of plastic waste in the waste to energy (WTE) plants (Singh et al., 2017).

The life cycle assessment (LCA) is a common approach to characterize environmental impacts of different plastic EOL pathways. Findings from these studies provide valuable understanding on the trade-offs between different plastic EOL pathways and helps to facilitate decision making process on proper management of plastic waste, based on pre-defined parameters, such as functional units (FU), system boundaries and geographical conditions.

Presently, several existing studies were reported on environmental impacts associated with various plastic waste EOL pathways specific to different post-consumer plastic products, such as plastic waste of electrical and electronic equipment (WEEE) (Ardolino et al., 2021), disposed PET bottle (Schmidt et al., 2020), plastic packaging waste (Ahamed et al., 2021) and post-industrial plastic waste (Huysman et al., 2017). Some focused on quantifying the environmental impacts of circular economies for plastic waste by accounting for stakeholders along the value chain (Karayılan et al., 2021; Schwarz et al., 2021), whereas majority of published studies reported environmental assessments on different plastic EOL pathways in specific geographical regions, such as Belgium (Ferreira et al., 2017), China (Chen et al., 2019), Denmark (Faraca et al., 2019), Hong Kong (Hossain et al., 2021), India (Aryan et al., 2019), Indonesia (Neo et al., 2021), Republic of Korea (M.-Y. Lee et al., 2021), Singapore (Khoo, 2019) and Spain (Sevigné-Itoiz et al., 2015).

From the review, mechanical recycling (MR) in material recovery facilities (MRF) was found to be the most preferred plastic EOL treatment as it attributes the least impact contributions to the environment in comparison to other technologies involving the use of thermal energies (Hou et al., 2018). However, it was also found that the wide composition variability of mixed plastic waste in postconsumer waste streams and presence of commingled waste (herein termed “mixed plastic waste”) have hindered the recovery efficiency of MR. Manual sorting of mixed plastic waste into homogenous plastic streams is costly, extremely labour-intensive and possesses significant health risks to operators from prolonged exposures (Moreira et al., 2019). Moreover, incentives for mechanically recycled hydrocarbon-based plastic products are often jeopardized by fluctuation of global oil prices, making it economically unattractive under existing policies (Larrain et al., 2021).

To overcome these challenges, chemical recycling has emerged in recent times as a promising EOL treatment for mixed plastic waste (J. Lee et al., 2021; Zeller et al., 2021), attributing to increased recovered energy derivatives and reduced solid wastes generated from the waste treatment processes. However, the plastic-to-fuel approach requires equivalently high degree of waste segregation to generate high-quality feedstocks during MR, in order to attain maximum yield from chemical recycling that attributes to lower environmental contributions arising from further downstream purification processes (Jeswani et al., 2021).

Apart from environmental assessment, life cycle costing (LCC) analysis is carried out to provide supplementary perspectives on economic and societal impacts. The LCC models are shown in Fig. 2. The conventional and environmental LCC (ELCC) models focus on economic feasibility with respect to the system boundaries of an LCA. For instance, Faraca et al. (2019) reported positive environmental savings and financial profitability arising

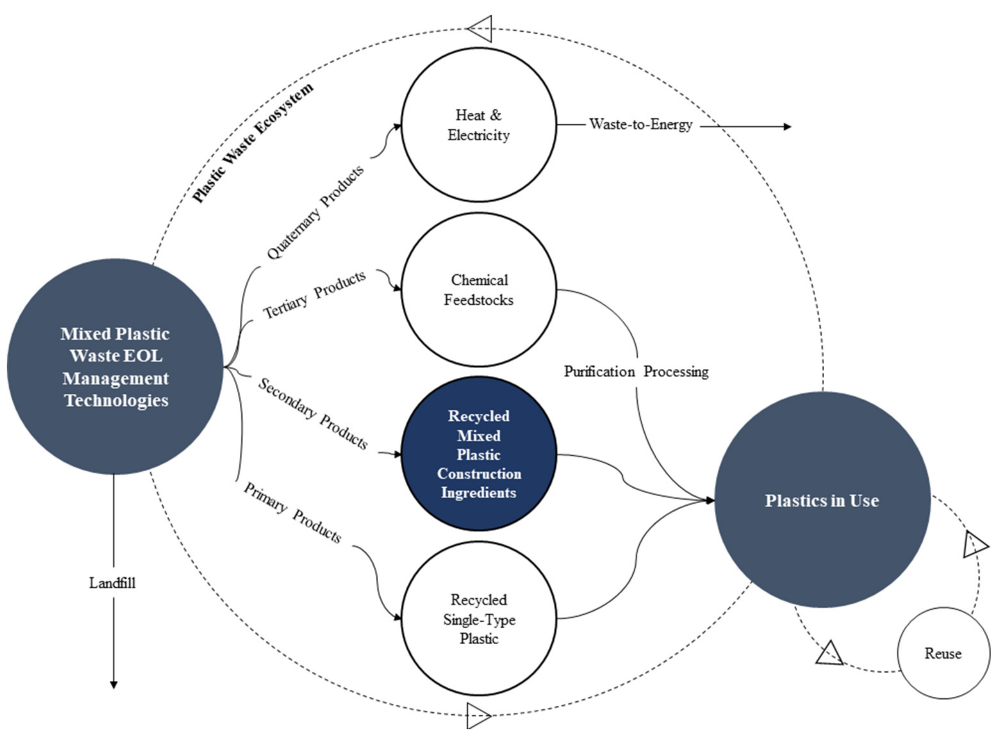

Fig. 1. Plastic EOL management pathways.

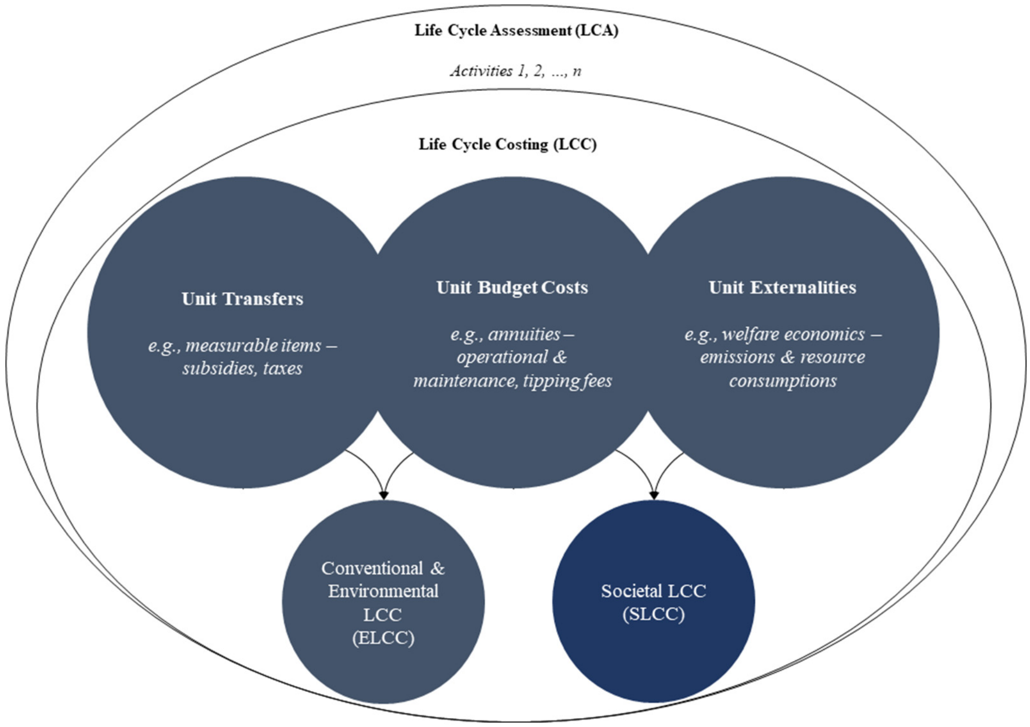

Fig. 2. LCC models.
(Modified from Martinez-Sanchez et al. (2015)).

from high quality recycled plastic in various modes of MR configuration through ELCC analysis. On the other hand, the societal LCC (SLCC) covers the social impacts, such as marginal abatement costs and welfare losses, in monetary valuations using accounting prices (otherwise termed “shadow prices”) which are price estimates for non-marketed goods, e.g., pollutants with respect to corresponding effects of an environmental emission. Further in-depth elaboration on application of LCC models can be found in studies carried out by Bernardo et al. (2016) and Martinez-Sanchez et al. (2015).

1.2. Research objectives

In Singapore, 868,600 t of plastic waste were generated in 2020 and merely 4 % of which were recycled with the remaining 96 % channelled into incinerators or WTE plants. One viable solution to improve the low recycling rate of mixed plastic waste is to repurpose them into heterogenous-based raw ingredients as alternatives to natural aggregate and virgin plastic fiber in construction materials. Numerous research works conducted on incorporation of plastic waste as raw ingredients in concrete and asphalt composites reported improvements in material toughness, thermal and corrosion resistance while reducing the overall density (lightweight) (Babafemi et al., 2018; Bahij et al., 2020; Gu and Ozbakkaloglu, 2016; Zulkernain et al., 2021).

Due to the lack of natural resources, Singapore relies heavily on foreign importation of natural aggregates to meet the demand arising from high levels of construction activities (Chew, 2010). UNEP (2014) reported about 517 million tonnes of natural sand have been imported into Singapore to support its developments over two decades. On the other hand, premiums for synthetic fiber have risen to exorbitant levels against the backdrop of extreme uncertainties in oil prices, making it economically unsustainable for construction businesses in the long haul. Hence, the utilization of recycled mixed plastic raw ingredients in construction materials can effectively double up as a sustainable plastic EOL pathway, with the construction industry absorbing large volumes of plastic waste and concurrently shifting the plastic waste management industry away from incineration and WTE plants.

With the launch of the Singapore's Green Plan 2030 to strengthen the country's commitments under the United Nation's 2030 Sustainable Development Agenda and Paris Agreement, one of the key targets is to reduce the daily amount of waste per capita channelled to the landfill by 30 % by 2030 (Ministry of Sustainability and the Environment, 2021). To the best of our knowledge, there are currently no recycling facilities operating in the country dedicated to recycling mixed plastic waste into heterogeneous-based raw ingredients for reuse in construction materials. Furthermore, there is no reported work on the environmental and socioeconomic assessment of EOL pathway for mechanically recycling mixed plastic waste into raw ingredients for construction materials in Singapore.

To bridge these gaps, this study proposes an advanced MR (aMR) facility to process mixed plastic waste into alternative raw ingredients for construction materials and presents a comparative environmental and socioeconomic assessment to characterize the impacts of different plastic EOL pathways in Singapore's context.

2. Research methodology

The LCA was conducted according to ISO 14040/44 frameworks comprising four key steps, namely (i) definition of goal and scope; (ii) life cycle inventory (LCI) analysis; (iii) life cycle impact assessment (LCIA); and (iv) interpretation of results (ISO, 2006a, 2006b). The simulations were performed using SimaPro 9.0 software loaded with Ecoinvent v3.7.1 database (Weidema et al., 2013).

The LCIA was conducted using the worldwide-based ReCiPe 2016 method (Huijbregts et al., 2017) developed by the National Institute for Public Health and the Environment (RIVM) and Radboud University Nijmegen, to characterize the environmental contributions of different plastic waste EOL pathways at midpoint level. Eight selected midpoint impact categories include global warming potential with 100-year time horizon (GWP100, kg CO_2-eq), fine particulate matter formation (FPMF, kg $PM_{2.5}$-eq), terrestrial acidification potential (TAP, kg SO_2-eq), photochemical ozone formation (POF, kg NO_X-eq), fossil depletion potential (FDP, kg oil-eq), freshwater eutrophication (FEP, kg P-eq), ozone depletion potential (ODP, CFC-11-eq) and water depletion potential (WDP, kg m^3-eq).

The externality costs (EC), which measures the marginal damage of emissions to the society is computed using Eq. (1). Eight selected pollutants accounted for under EC include CO_2, CO, CH_4, N_2O, NO_x, VOC, SO_2 and PM_{10}, with reference to Intergovernmental Panel on Climate Change (IPCC) guidelines. The budget costs (BC), which accounts for the social costs towards plastic waste producers and treatment facilities, is derived using Eq. (2). The tipping fees of key processes, namely WTE and SL are covered in this study.

$$EC = \sum_i W_i \cdot \sum_j \left(e_{i,j} \cdot AP_j\right) \tag{1}$$

$$BC = \sum_i W_i \cdot \sum_j \left(ubc_i \cdot NTF\right) \tag{2}$$

The EC represents the uncompensated environmental effects (marginal damage) measured in SGD. It is also interpreted as the degree of "willingness" of the society is willing to pay to avoid the emission of pollutants that affects the human health (Martinez-Sanchez et al., 2017). The EC is computed by the multiplication of waste input amount W_i for process i and the summation of the product between emission amount $e_{i,j}$ of pollutant j from process i and corresponding accounting price AP_j of pollutant j. On the other hand, the BC that covers capital costs, service charges, operational and maintenance expenses, expressed in SGD, is derived by the multiplication of waste input amount W_i for process i and the summation of the product between unit budget cost ubc_i arising from process i and net tax factor NTF. The NTF is used for conversion of factor prices (also known as market prices) into accounting prices.

2.1. Goal, scope, and functional unit

The goal of this LCA is to quantitatively compare the environmental and socioeconomic impacts of four different plastic EOL management pathways. The study aims to provide recommendations for policy makers and regulators involved in formulation of public policies and environmental regulations on sustainable plastic EOL management strategies in Singapore. The scope of this LCA study takes reference from the geographical boundaries of the country as a "whole system" covering key EOL treatment processes, namely transportation, MR, incineration at WTE plants and sanitary landfill (Khoo et al., 2012). The polymers considered in this study include PET, HDPE, LDPE, PP, PS, PVC, with all other polymeric variants classified as Others. The FU is defined based on the geographical region of Singapore corresponding to 868,000 t of mixed plastic waste generated in 2020 (National Environment Agency, 2021a). The plastic EOL management pathways covered in this LCA include the following:

- MR of sorted plastic waste followed by incineration of mixed plastic waste (RS)
- Incineration of mixed plastic waste (AS1)
- MR of sorted plastic waste coupled with pyrolysis of mixed plastic waste followed by incineration of mixed plastic waste (AS2)
- aMR of mixed plastic waste followed by incineration of mixed plastic waste (AS3).

2.2. Reference and alternative scenarios

The scenario RS (Fig. 3) represents the existing plastic EOL management pathway practiced in Singapore. The mixed recyclables manifested among mixed plastic waste disposed of in designated recycling bins are collected by appointed waste collectors across different geographical sectors. Public waste collectors (PWCs) collect mixed recyclables generated from domestic and trade activities in households, institutions, and establishments, whereas general waste collectors (GWCs) collect them from commercial and industrial premises.

Under the Singapore's National Recycling Programme, mixed recyclables collected by PWC are transported to MRF via dedicated refuse trucks, and subsequently segregated into various recyclable waste streams for glass, metal, paper, and plastic. The mixed plastic waste separated from other recyclables in the MRF is then sent to recycling facilities for further processing (National Environment Agency, 2021b). It is worthy to note that fractions of mixed plastic waste commingled with other municipal solid wastes disposed of in general waste bins are directly disposed at WTE plants. The GWCs, which are part of the waste management value chain, are typically designated municipal solid waste managers for various clusters of offices and industrial parks situated within different geographical regions of Singapore. Mixed plastic waste with low contamination levels collected by GWCs are usually sent directly to recycling facilities for processing.

Presently, majority of the mixed plastic waste transported to recycling facilities are mechanically recycled, where they are manually sorted into single-type polymers, giving rise to multiple homogenous streams of plastic waste. In some MRF, sorted plastic waste is mechanically compacted into standard bale size and secured with bale wires for exportation to recyclers in neighbouring countries around the Asia region (Kerdlap et al., 2020; Singapore Environment Council, 2018).

On the other hand, sorted plastic waste is downsized into fragmental sizes, washed and dried before passing through the extruder operating at predefined temperature profiles and processed into recycled plastic granules (National Environment Agency, 2019). The recycled plastic granules of individual polymer types can be used to replace virgin polymers for production of other polymeric-based materials. The contaminated plastic waste which are too difficult to be recovered, along with solid wastes generated from MR are incinerated at the WTE plants. Heat energy and electricity are harnessed for recirculation to reduce the energy requirements needed from the power grid. Subsequently, the incineration residues are conveyed to the Tuas Marine Transfer Station (TMTS) before being deposited at the Semakau landfill (SL), a 350 ha offshore landfill located down south of the Singapore mainland.

Analogous to scenario RS, the scenario AS1 represents the omission of recycling facilities from the existing plastic waste EOL management pathway where all collected mixed plastic waste are valorised at the WTE plants. Likewise, the incineration residues are transferred to TMTS and ultimately deposited at the SL. Given the extremely low plastic recycling rate in Singapore, scenario AS1 provides a comparative benchmark and useful insights on the current recycling efforts for EOL management of plastic waste in Singapore.

The scenario AS2 introduces a pyrolysis facility for recycling of high purity mixed plastic waste collected by GWCs to complement the plastic waste EOL management processes that predominantly focuses on treatment of sorted plastic waste. The pyrolysis process operates at elevated temperatures ranged between 400 °C to 600 °C in an inert atmospheric condition. Pyrolysis oil products are recovered from gaseous hydrocarbons and oily condensates formed during the degradation of mixed plastic waste, leaving behind residual solids from accompanying impurities in the feedstocks (Zeller et al., 2021). Further treatment of pyrolysis oil includes the conversion of pyrolysis oil into oil gas, fed into catalytic towers for purification, decolorization and deodorization, followed by condensation of purified oil gas into diesel.

Lastly, the scenario AS3 (Fig. 4) explores an aMR facility dedicated to mechanically convert mixed plastic waste into standardized forms of mixed plastic aggregate (MPA) and fiber (MPF) as alternative raw ingredients for reuse in construction materials. The aMR facility involves the integration of in-line NIR analyser and mixed plastic adjustment tank with existing plastic waste recycling processes namely, i.e., shredding, washing, drying, extruding, cooling, and pelletizing units.

The in-line NIR analyser, unlike conventional systems used in plastic sorting units, was loaded with a novel predictive model containing calibration libraries of different mixed plastic waste blends developed in-house to quantitively determine polymer composition of cleaned, mixed plastic fragments. Subsequently, the measured composition of mixed plastic fragments is mechanically adjusted to specific mixed plastic feedstock blend designed in-house for extrusion. The extrudate is then cooled, wiredrawn, and

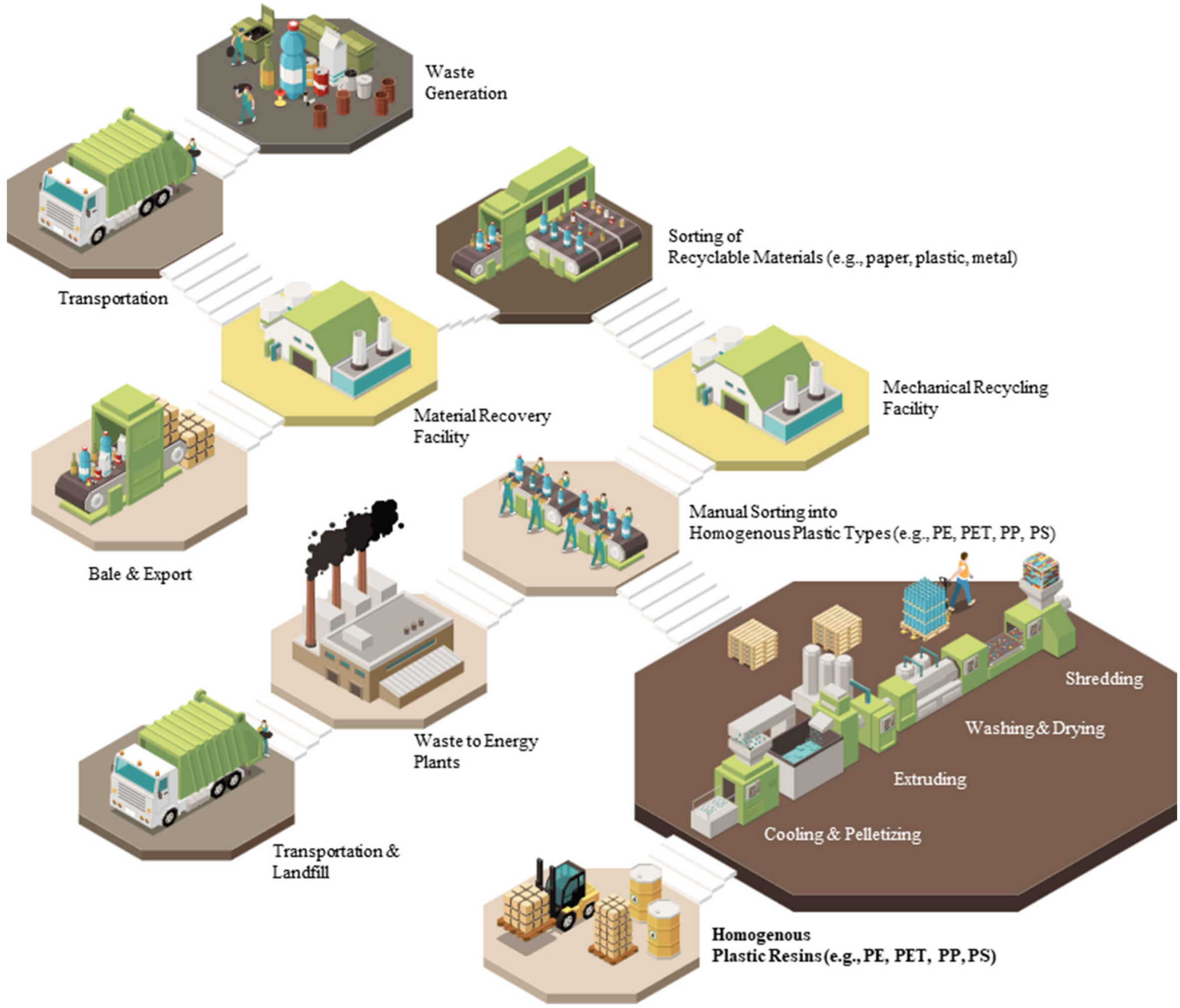

Fig. 3. Plastic waste recycling configuration for scenario RS.

pelletized into recycled MPA and MPF, respectively, for use in construction applications. The system boundaries for each scenario are illustrated in Fig. 5.

2.3. Life cycle inventory analysis

The input-output data of various processes within the system boundaries of reference and alternative scenarios were gathered in this section and summarized in Supplementary Data S1. The polymer composition dataset of mixed plastic waste streams was acquired from undisclosed statistics administered by local government agencies overseeing the plastic waste management infrastructures in Singapore.

Travel distances for transport vehicles namely, i.e., EURO VI refuse truck and sea barge, between plastic waste management infrastructures along the value chain were estimated based on literature reports together with Google Maps tools. The emissions for transport vehicles were referenced from Ecoinvent v3.7.1 database (Ecoinvent, 2021a, 2021b). In the absence of local datasets, the input-output data on MR of single-type plastic waste reported by Chen et al. (2019) was considered in this study. Likewise, the input-output data for unit operations within the aMR facility developed in-house supplemented with inventories from Ecoinvent database was incorporated in this study. The inventories for WTE plants were extracted from local plants data (National Environment Agency, 2021c) and official reports (National Environment Agency, 2020). The input-output data for pyrolysis of mixed plastic waste was adapted from Khoo (2019) and inventory for sanitary landfilling of incineration residues was obtained from Ecoinvent v3.7.1 database. The electric power supplied by Singapore's national power grid was generated using a mixed fuel blend comprising 95.30 % natural gas, 1.30 % coal, 0.20 % petroleum products such as, diesel and fuel oil, and 3.20 % of other energy derivatives, e.g., municipal waste, biomass and solar energies (Energy Market Authority, 2021). The input-output data of emission produced for every 1 MWh of electricity generated was adjusted using the model derived in previous study by Tan et al. (2010).

3. Results and discussions

3.1. Environmental assessment

3.1.1. LCIA results

The LCIA results of every process with respect to each scenario are shown in Fig. 6. As expected, WTE process was revealed to be the main contributor towards GWP100, FPMF and TAP for all scenarios. This observation is well-aligned with preceding reported studies when thermal energies are involved in plastic waste EOL pathways. Quantitatively, the proposed aMR facility in scenario AS3 achieved 52.24 %, 53.73 % and 49.59 % overall reduction in GWP100; 63.17 %, 64.56 % and 60.74 % overall reduction in FPMF; and 44.23 %, 45.71 % and 99.80 % overall reduction in TAP contributions when compared to scenario RS, AS1 and AS2, respectively. This is attributed to the reduced amount of plastic waste channelled into WTE plants as more mixed plastic waste were recovered from the aMR facility. It is also worthy to note that the drastic increase in TAP in AS2 was largely contributed by the pyrolysis process.

For POF, pyrolysis process in scenario AS2 was likewise found to contribute significantly. These increments reflected in scenario AS2 can be

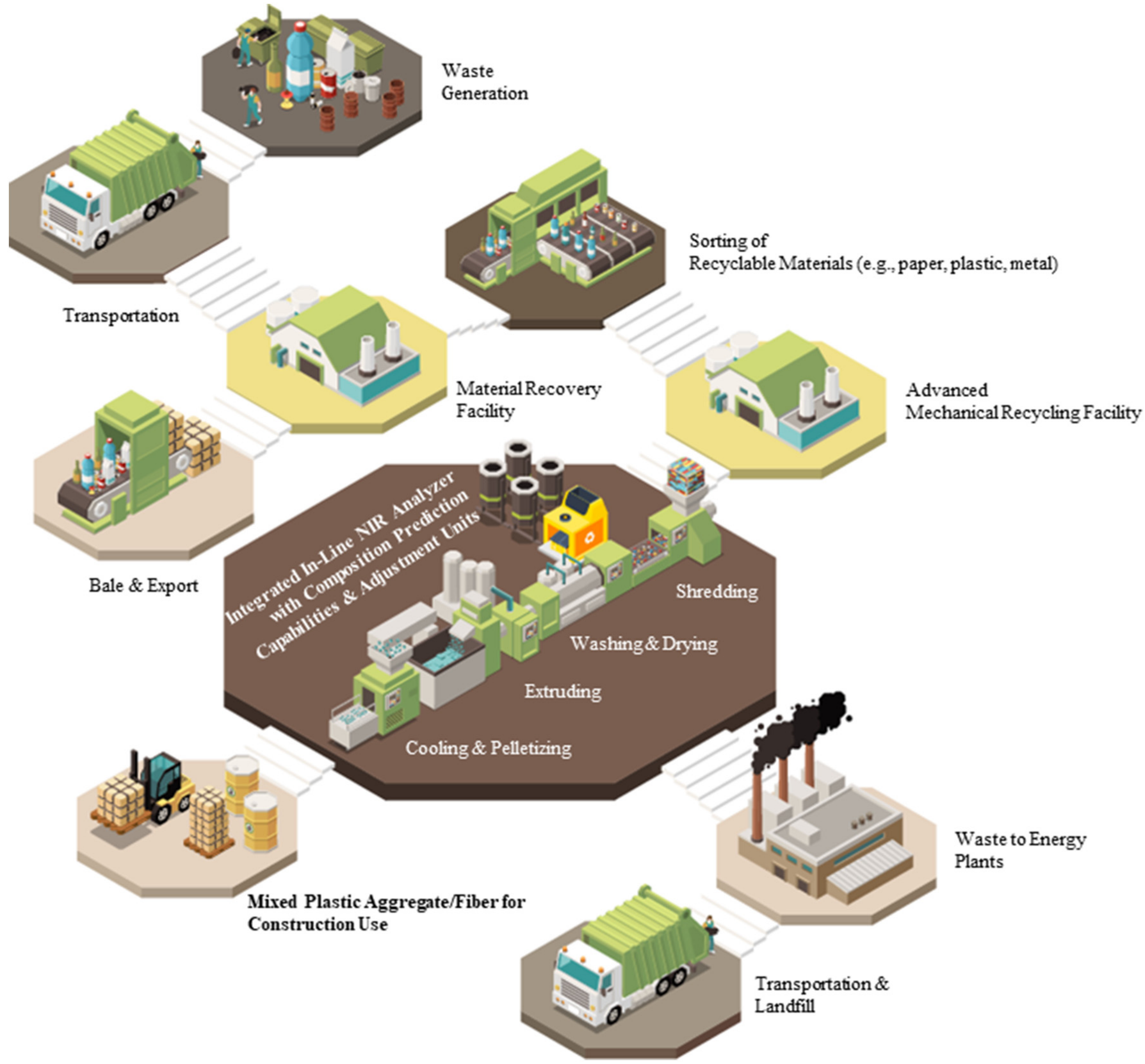

Fig. 4. Plastic waste recycling configuration for scenario AS3.

attributed to large volume of gaseous nitrogen and sulphur oxides generated from the pyrolysis process. Notwithstanding, suitable unit operations, e.g., scrubbing units, can be used to treat flue gas and by-products to improve the environmental contributions of pyrolysis process.

On the other hand, the contributions of aMR facility towards POF, FDP and WDP in scenario AS3 were comparatively higher than those of scenarios RS, AS1 and AS2 as higher electricity and water consumptions are needed for aMR processes, i.e., washing, drying, cooling, composition analysing, and mechanical adjustment of mixed plastic waste followed by extrusion of MPA and MPF. Given that the natural gas constitutes the major fraction of the fuel mix in Singapore, the use of limited alternative forms of cleaner and more efficient energy, e.g., solar power and hydrogen fuel, can be considered for restructuring of energy sources to improve the environmental impacts of the aMR facility. In addition, process integration of circulating water can also be improvised to lower the water requirements of the unit operations within the aMR facility.

Landfilling of incineration residues leads to significant FEP contributions. Hence, the substantial amount of mixed plastic waste recovered in the aMR facility produced less incineration residues landfilled in scenario AS3. This is represented by the 80.74 %, 81.49 % and 79.30 % overall reduction in FEP contributions when compared to scenarios RS, AS1 and AS2, respectively. Notably, the contribution of transportation, although almost negligible compared to all other processes, was also much lower in scenario AS3 due to lower transfer trips required between different facilities, e.g., truck transfer from WTE to TMTS and barge transfer from TMTS to SL, as bulk fractions of mixed plastic waste would be recovered in the aMR facility. The magnitude of overall contributions towards ODP was found to be relatively small across all scenarios. Nevertheless, scenario AS3 recorded 9.79 %, 7.55 % and 7.15 % lower than scenarios RS, AS1 and AS2, respectively.

3.1.2. Sensitivity analysis of input parameters

Sensitivity analysis was conducted whereby input parameters were perturbed one-at-a-time to identify sensitive parameters across different scenarios. The sensitivity ratio (SR), which is a ratio of relative changes between the derived results and the input parameter, is expressed in Eq. (3). For instance, a SR of 2 can be interpreted as a 20 % increase in derived results when the input parameter is increased by 10 %. For ease of interpretation, input parameters with SRs less than 0.2 can be considered negligible (least important), SRs between 0.2 and 2 can be classified as more significant (slightly important), and SRs greater than 2 can be denoted as impactful (very important). In this analysis, input parameters such as, electricity fuel mix, virgin plastic substitution ratio and all other parameters, were varied with ±10 % step change for SR quantification and only SRs with absolute value greater than 0.1 was analysed.

$$SR = \frac{\frac{\Delta\text{result}}{\text{initial result}}}{\frac{\Delta\text{parameter}}{\text{initial parameter}}} \tag{3}$$

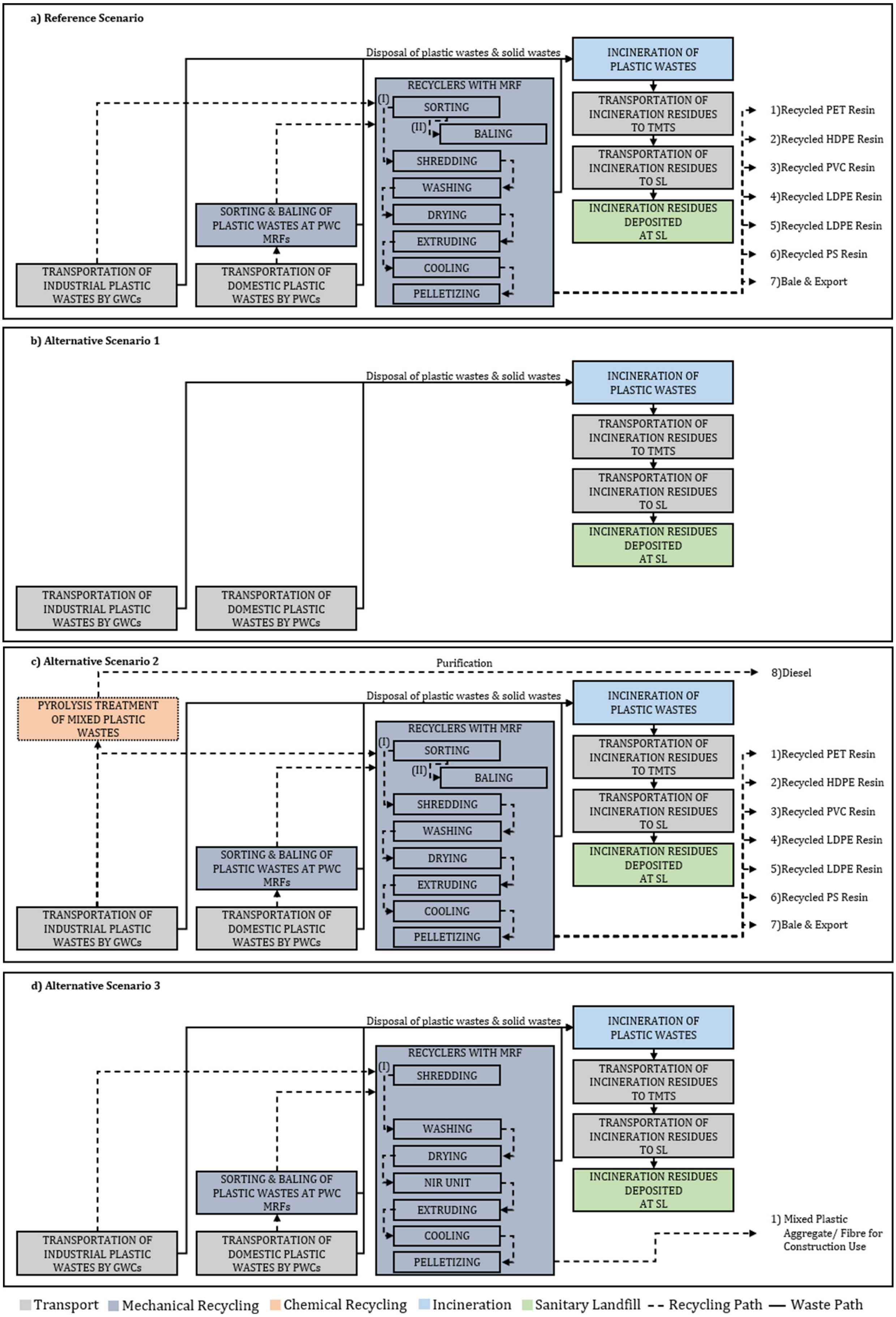

Fig. 5. System boundaries of plastic EOL pathways for scenarios (a) RS; (b) AS1; (c) AS2; and (d) AS3.

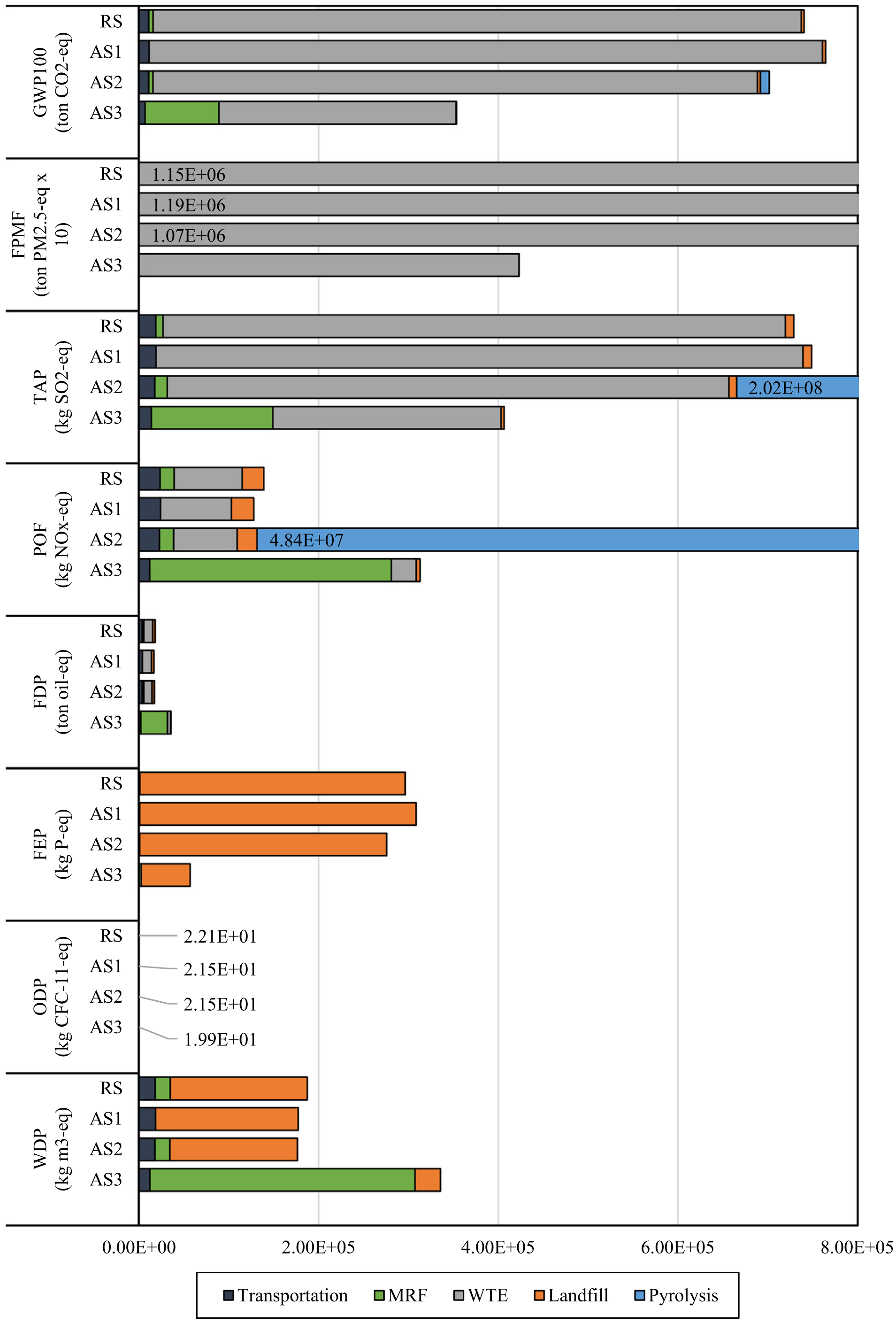

Fig. 6. LCIA results of scenarios RS, AS1, AS2 and AS3.

Four input parameters with SRs greater than 0.2 with reference to eight midpoint indicators namely, percentage of plastic waste channelled to WTE, percentage of plastic waste processed at MRF, percentage of plastic rejects at MRF and percentage virgin plastic substitution were retained for evaluation. The percentage of plastic waste channelled to WTE, and the percentage of plastic waste processed at MRF, which are closely related were considered since it is challenging to accurately account for all the mixed plastic waste at different stages of various plastic EOL management pathways. A higher percentage of mixed plastic waste processed at MRF could implies either an increment or reduction in percentage of plastic waste channelled to WTE, largely dependent on the technological capabilities of the MR process within the MRF. More advanced MRF, i.e., aMR in scenario AS3 would be able to process mixed plastic waste more efficiently compared to MR in scenario RS, as a result diverting a large amount of plastic waste away from WTE process. On the other hand, the percentage plastic rejects from MRF is also greatly influenced by the MR process due to its ability to process plastic waste in mixed forms, on top of fluctuating contamination levels of mixed plastic waste collected by different waste collectors. Similarly, the percentage of plastic rejects from MRF was perturbed due to the uncertainty in categorization of plastic rejects in different MRF. An increase in percentage plastic rejects from MRF would correspondingly increase the percentage of mixed plastic waste channelled to WTE. Finally, the percentage virgin plastic substitution was denoted to be an uncertain input parameter too due to potential variations in quality of recycled MPA and MPF.

Fig. 7 presents the SRs of LCIA results for ±10 % variations in input parameters for scenario RS, AS2 and AS3. Scenario AS1 was omitted from the sensitivity analysis as it does not provide much useful information given that all the mixed plastic waste generated are entirely channelled to the WTE process. From the results, the percentage increase in plastic waste channelled to WTE led to an increase in GWP100, FPMF and FEP across scenarios RS, AS2 and AS3. On the other hand, an increase in percentage of plastic waste processed at MRF resulted in an increment in FDP and WDP as more electricity and water are required to process larger amount of mixed plastic waste. As expected, the increase in percentage of plastic waste processed at MRF in scenario AS3 revealed an increase across the eight midpoint indicators as larger amount of recycled MPA and MPF would be produced from the aMR facility. On the flip slide, due to the enhanced capability to process mixed plastic waste in aMR, the percentage variation in plastic reject did not saw drastic increase in ODP and WDP for scenario AS3 as compared to those of scenarios RS and AS2. These observations from the sensitivity analysis are well aligned with the findings obtained in the LCIA results in preceding section. Finally, it was revealed that the percentage of virgin plastic substitution is a highly sensitivity input parameter as significant amount of virgin plastic is needed with large amount of recycled MPA and MPF produced from the aMR facility. This finding corresponds well with results of scenarios RS and AS2, since plastic EOL management pathways of both scenarios generally does not

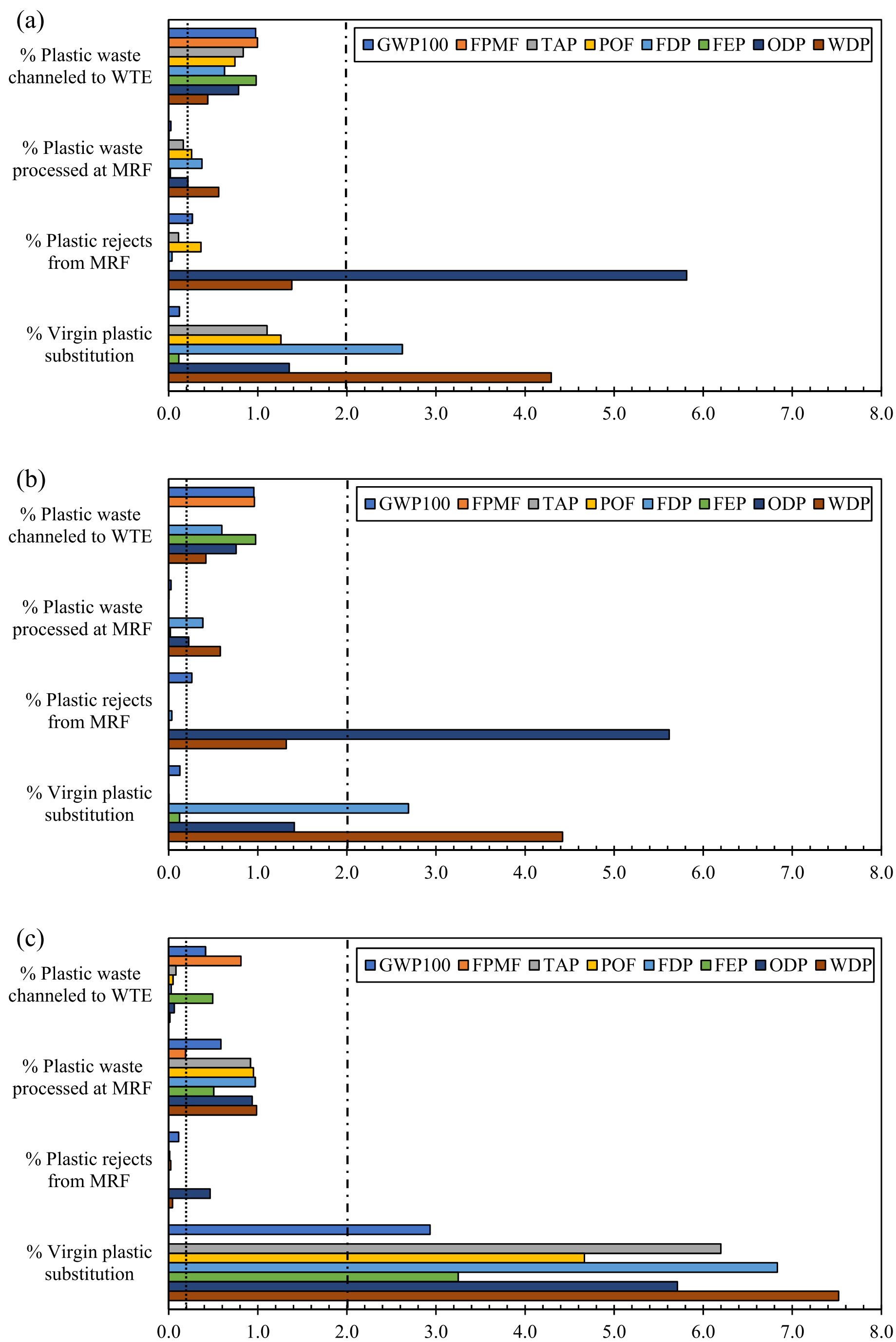

Fig. 7. Sensitivity ratios of LCIA results for ±10 % change in input parameters for scenarios: (a) RS, (b) AS2 and (c) AS3.

recovery large amount of sorted plastic resins and sensitivity of percentage virgin plastic substitution would be correspondingly lowered when compared to scenario AS3.

3.1.3. Sensitivity analysis of mixed plastic composition

For comparative evaluation, single score for scenarios RS, AS1, AS2 and AS3 were derived by normalization and weighing of environmental impact categories. The hierarchism perspective which underlies policy principles and scientific consensus with regards to timeframe and other potential impact mechanisms was adopted. The weighing allocation for endpoint impact categories, i.e., ecosystems, human health and resources are 40 %, 30 % and 30 %, respectively. The single scores for scenarios RS, AS1, AS2 and AS3 were computed to be 122 Pt, 127 Pt, 111 Pt and 45 Pt, respectively. A lower single score value represents better environmental performance and vice-versa. As expected, the scenarios AS1 and AS3 recorded the highest and lowest single score, respectively, with scenario AS2 obtaining a slightly lower single score in comparison with scenario RS.

The composition of mixed plastic is one of the key input parameters with the largest uncertainty due to the dynamic nature of mixed plastic waste streams and extreme difficulties to exactly quantify polymer fractions hindered by other commingled waste materials. Hence, a sensitivity analysis was carried out to quantify the effects of variations in mixed plastic composition on LCIA single score for various scenarios and the results are shown in Fig. 8. A ±10% step change for major plastic types, namely PE, PP, PET, and PS fractions with all other parameters fixed at baseline was input into to compute the single score of each scenario. Subsequently, sensitivity coefficients (SC) were derived for every perturbed parameter based on the ratio between the changes in output parameter value over the change in input parameter value as shown in Eq. (4).

$$SC = \frac{\Delta \text{result}}{\Delta \text{parameter}} \tag{4}$$

From the results, the SC for ±10 % variation of PE, PET and PP fractions in scenario AS3 ranges between 0.00323 and 0.00345, which are the lowest when compared with scenarios RS, AS1 and AS2. On the other hand, the SC for perturbation of PS fraction in scenario AS3 was found to be slightly higher than scenarios RS and AS1, though similar upward trends were observed across all scenarios. Understandably, the utilities consumption and emission inventories for MR of PS is lower than those of PE, PET and PP hence the sensitivity is considerably similar across all scenarios because of the relatively lower environmental impacts associated with MR of PS.

3.2. Socioeconomic assessment

From Fig. 9a, EC incurred for scenario AS3 was 30.95 % and 32.24 % lower compared to scenarios RS and AS1. Cost savings were achieved when mixed plastic waste is recovered in the aMR facility. This is attributed to the drastic reduction in pollutants generated as lower amount of mixed plastic waste were incinerated at the WTE plants. Correspondingly, the implementation of aMR facility for mixed plastic waste recovery in scenario AS3 was found to reduce 63.35 %, 64.72 % and 59.38 % of BC incurred as tipping fees for incineration of mixed plastic waste at WTE plants and

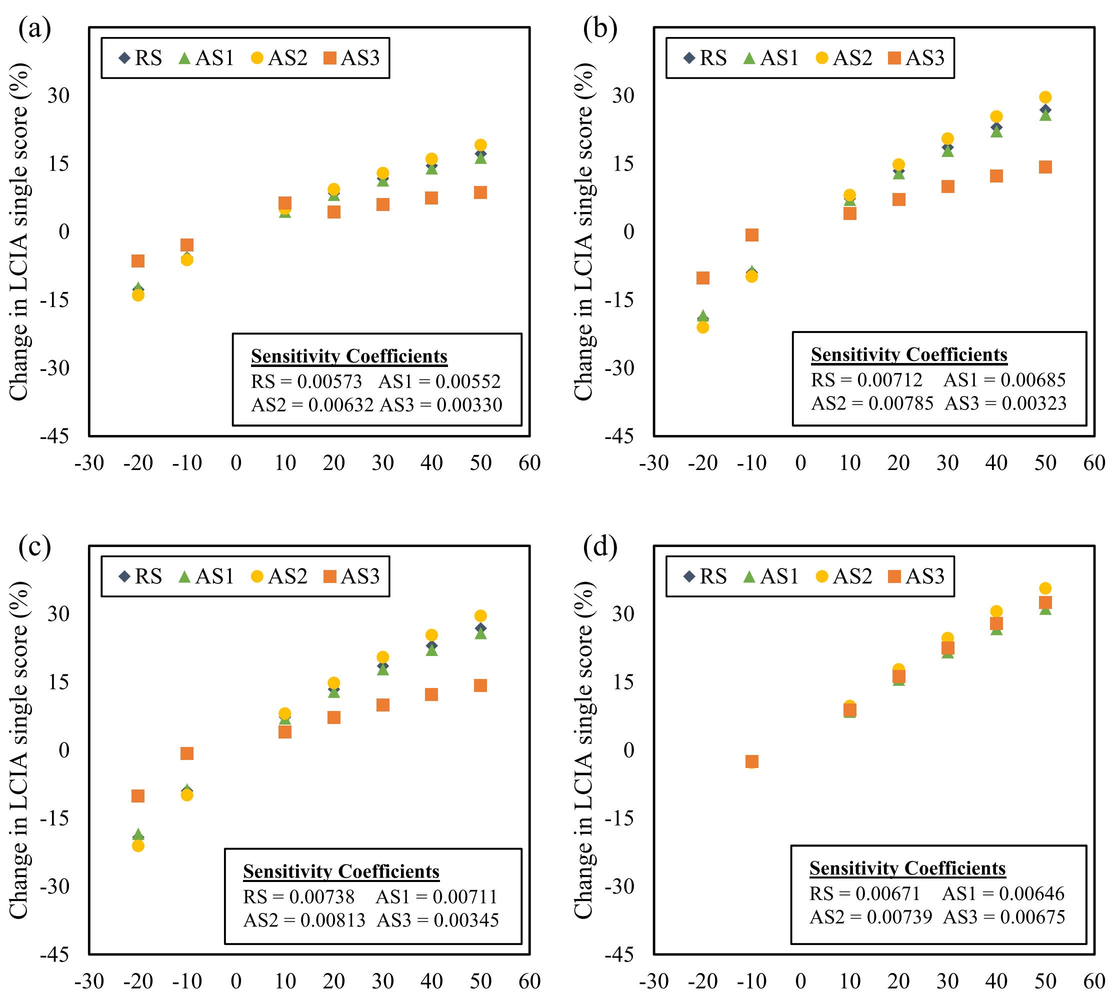

Fig. 8. Sensitivity analysis results of LCIA single score of scenarios RS, AS1, AS2 and AS3 for ±10 % step change in mixed plastic composition: (a) PE; (b) PP; (c) PET; and (d) PS.

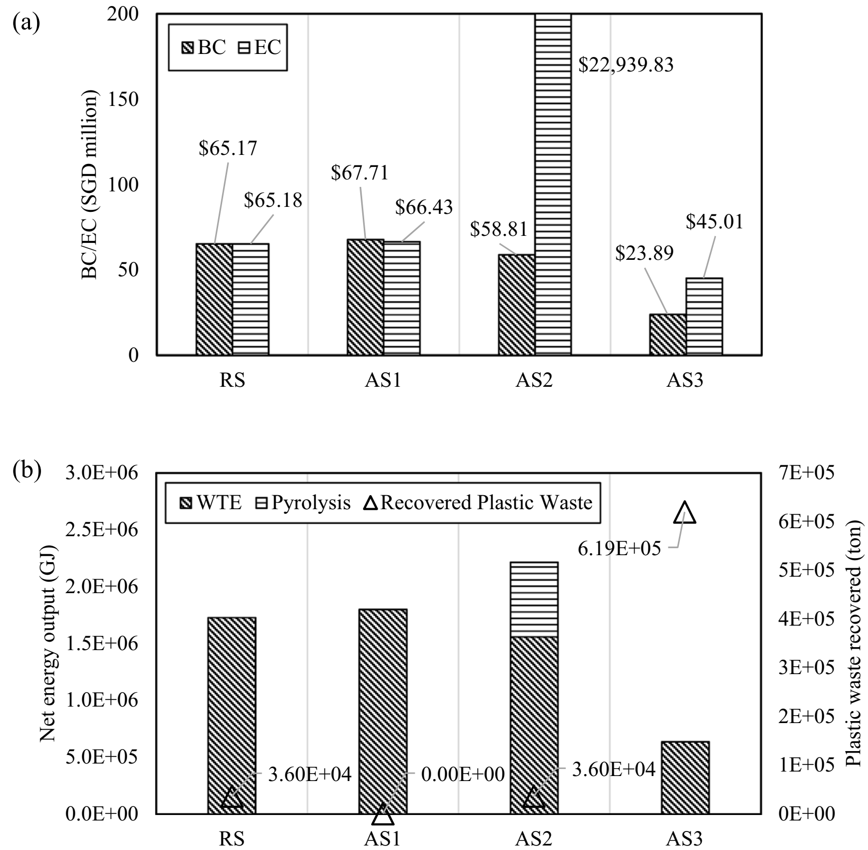

Fig. 9. Socioeconomic results of scenarios RS, AS1, AS2 and AS3: (a) BC/EC and (b) net energy output and volume of plastic waste recovered.

landfilling of incineration residues at SL were much avoided correspondingly in comparison with scenario RS, AS1 and AS2. The significantly high EC incurred in scenario AS2 corresponds well with the large amount of SO_2 generated from the pyrolysis process.

Fig. 9b shows the potential net energy output recoverable from WTE and pyrolysis processes and volume of plastic waste recovered in each scenario. The net energy output for scenarios RS and AS1 were found to be comparable. This can also be viewed as the current plastic recovery efforts are almost negligible given the heavy reliance on WTE plants as the main valorisation technology for mixed plastic waste in Singapore. It was observed that scenario AS2 recorded the highest net energy output with WTE and pyrolysis processes each contributing 70.40 % and 29.60 % respectively. Although scenario AS3 attained the lowest potential net energy output, it is worthy to recognize the substantial amount of MPA and MPF produced in the aMR facility could potentially outweigh the loss in energy generated for the construction industry in economic perspective.

4. Discussions

In this study, a comparative assessment between four different plastic EOL pathways was conducted in consideration of environmental and socioeconomical impacts. The LCA results confirmed the benefits of aMR over pyrolysis and incineration in WTE plants as an sustainable plastic EOL pathway, well aligned with findings reported by Faraca et al. (2019) and Hou et al. (2018). Moving away from traditional way of MR in sorting mixed plastic waste into homogenous streams of different plastic types, the proposed aMR facility in scenario AS3 enables the production of heterogenous-based mixed plastic products composed of a combination of different types of plastic catering to the needs of the construction industry. By allowing for more efficient recycling of mixed plastic waste mechanically, the plastic recycling rate can be increased, leading to a reduction in the amount of rejected mixed plastic waste sent to WTE plants in parallel with associated environmental and socioeconomic impacts.

This research work was conducted based on accessible information and available datasets of the current plastic EOL pathway practiced in Singapore. Interpretation of results gathered from the current work is subject to some limitations as several assumptions were imposed in terms of Singapore's context, such as composition of mixed plastic waste streams, which may differ significantly in developed and less developed countries that have varied waste profiles due to differing waste collection methods and infrastructures, characteristics of commingled wastes, e.g., agriculture by-products, and climate conditions. Hence, the composition and profile of plastic waste streams should be modified to prevailing waste management conditions and regulations depending on the system boundary. In terms of socioeconomic aspects, the BC may be quite different from other countries that are abundant in land space, e.g., India and China, for waste management infrastructures, i.e., open dumping ground and landfill, as a result having much lower cost for waste disposal compared to Singapore. In the same vein, it is worthy to note that the distance for transfers covered by conveying vehicles between waste management facilities are typically longer in larger countries than Singapore, which may also result in some disparities in the cost for waste treatment. Similarly, the accounting price of pollutants for computation of EC may vary drastically as the willingness of a society to pay to avoid the emission of pollutants that affects the human health is very much subjective to communities with differing cultures and governed under different environmental policies. In view of the foregoing, the costs associated with EC and BC should be correspondingly adjusted on a case-by-case basis.

With countries in the region such as China severely restricting the import of plastic waste since 2018, the pressure is escalating for governments and companies alike to sustainably manage recycled plastic waste. Traditional mechanical recycling is the most widespread and economical method used, but it requires careful waste sorting and cleansing before any actual recycling can be implemented. As such, mechanically recycled plastics obtained via this conventional method have limited usage in industries like food and beverage sector due to the possibility of extensive contamination. These limitations have inspired experts to explore other methods that can deal with diverse plastic streams for value-added applications.

Chemical recycling methods such as pyrolysis and gasification encompass different techniques with the common principle of breaking down plastic waste into basic building blocks using solvents or heat treatments. This makes them capable of handling mixed streams of plastic waste, with a view to produce feedstocks comparable to virgin plastics. More specifically, pyrolysis breaks down plastic waste using high temperatures into pyrolysis oil that can be refined into high-value feedstocks, e.g., diesel; and gasification which is a thermochemical process that converts plastic waste to energy, syngas, and recyclable ash. The potential deployment of such emerging technologies within the plastic waste value chain is currently being studied to identify the gaps and opportunities in the plastic recycling industry.

Singapore has committed to several ambitious climate targets as it takes on the stewardship towards net zero emission by 2050. Policy makers and governing authorities, i.e., National Environment Agency, play an important role to formulate viable waste management policies that contribute effectively to its decarbonisation efforts. Due to space constraints and the lack of natural resources, the current study revealed that adopting scenario AS3 as the national plastic EOL pathway could be one potential way to accelerate the green transition in both waste management and construction industries concurrently and achieve its national targets. To do so, cooperation between stakeholders from both industries and public authorities is necessary. First, existing PWC and GWC with suitable MR facilities should be adaptive towards technology adoption, i.e., installation of in-house developed in-line NIR analyser and mechanical adjustment units, to transit from status quo plant processes to heterogenous-based plastic waste recycling. On the other end, companies in the construction industry should be receptive towards the use of heterogenous-based mixed plastic products, i.e., MPA and MPF as alternative raw ingredients in construction materials for sustainable building and infrastructure developments. A good balance between recyclers, now as a producer, and construction companies now positioned as demand drivers would maximize the environmental and socioeconomic benefits revealed in this study. Finally, authorities could lead the change by reviewing prevailing code of practices and standard guidelines to adopt and incentivize the use of heterogenous-based mixed plastic products.

Although this LCA was conducted as a case study in Singapore, the life cycle inventories of waste management processes and costing models are vastly different in various countries. The detailed inputs for computation can be modified and improved further in re-assessments specific to different functional units and system boundaries. Notwithstanding, the key findings of this study remains valuable and serves as a thought-provoking statement to policymakers, researchers as well as stakeholders in the waste management and construction industries. This study will serve as a turning point in the development of sustainable plastic EOL pathway for many developed and less developed countries to move one step closer towards a green and clean environment.

5. Conclusions

This paper reports the development of an aMR facility in Singapore to process mixed plastic waste into alternative raw ingredients for construction materials as a potential plastic EOL pathway. A comparative environmental and socioeconomic assessment was carried out to characterize the impacts of different plastic EOL pathways. From the environmental assessment, the proposed plastic EOL pathway in scenario AS3 showed 52.24 %, 63.17 %, and 44.23 % reduction in contributions towards GWP100, FPMF and TAP, in comparison to scenario RS. It was also observed that scenario AS3 has significantly outperformed scenario AS2 in terms of TAP and POF contributions. However, scenario AS3 recorded comparatively higher contributions in POF, FDP and WDP than those of scenarios RS, AS1 and AS2 due to the higher amount of mixed plastic waste processed for production of MPA and MPF in the MRF. In terms of societal impacts, large volume of mixed plastic waste diverted away from WTE plants and SL in scenario AS3 achieved significantly high EC and BC savings as marginal damage towards the environment and human health arising from pollutive emissions as well as tipping fees for waste disposal were very much avoided. Consequentially, the potential net energy output was revealed to be lowered in parallel with the increase in mixed plastic waste recovered in aMR facility.

Overall, the present study showcases how Singapore can redesign its current waste-to-resource taxonomy and strengthen the robustness of its plastic EOL pathway. This study reiterates the need to prioritize efforts in maximizing MR throughput of mixed plastic waste so to alleviate the reliance on thermal energies for waste valorisation currently and improve the environmental and socioeconomic performance of current plastic EOL pathway.

CRediT authorship contribution statement

Kevin Jia Le Lee: Conceptualization, Methodology, Formal analysis, Writing – original draft, Investigation. **Sook Fun Wong:** Conceptualization, Writing – review & editing, Project administration, Funding acquisition.

Data availability

The data that has been used is confidential.

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.

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Appendix A. Supplementary data

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