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Life cycle assessment of kerbside waste material for an open-looped and closed-loop production– towards circular economy designs

Jingxuan Zhang [a], Muhammad Bhuiyan [a], Guomin Zhang [a,*], Malindu Sandanayake [b]

[a] *School of Engineering, RMIT University, Melbourne, VIC3000, Australia*
[b] *Institute of Sustainable Industries and Liveable Cities, Victoria University, Melbourne, VIC3011, Australia*

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ABSTRACT

Urbanization growth has increased the generation of municipal solid waste (MSW) and has the potential for recycling and reuse. However, it is frequently limited to a linear lifecycle mode which end up in landfills. A novel attributional lifecycle inventory model for lifecycle assessment based on value retention process (VRP) model of circular economy was developed to quantify the lifecycle inventory and measure the environmental impacts of multiple lifecycle stages, from in-community separation to the end-of-use/life stage and subsequent lifecycles. This investigation focused on assessing the environmental impacts of two distinct in-community waste glass separation methods - separate kerbside glass recycling bin (SKGRB) and mixed kerbside recycling bin (MKRB) - in combination with two recycling approaches - open-loop (asphalt) and closed-loop (glass container). The goal of the study was to make a comparative evaluation of the environmental impacts of these methods. Results showed that the SKGRB method had better environmental performance (40–60% reduction compared to the MKRB method) for both materials. Closed-loop recycling of glass container production had higher environmental impacts due to higher energy consumption in production in one lifecycle, while the open-loop recycling method of asphalt had higher environmental impacts despite fewer circulations, due to higher production volume in 21 years. The results of the sensitivity/uncertainty analysis showed that environmental impacts decreased as the allocation coefficient decreased, reaching stability when the coefficient reached the waste materials percentage in the new product's mixed design.

1. Introduction

Urbanization has led to a surge in waste proliferation in modern communities, attributable to factors such as manufacturing processes, service industries, construction activities, and evolving human lifestyles (Saberian et al., 2021). This waste overflow poses significant environmental challenges, as a considerable portion of the approximately two billion tons of solid waste generated annually is inadequately managed (The World Bank, 2021). Municipal solid waste (MSW) is of particular concern, with an average generation rate of 0.74 kg per person per day (Kaza et al., 2018). Improper handling of MSW jeopardizes the sustainability of local communities, resulting in environmental issues like the release of toxic chemicals, emission of pollutants and odours, and contamination of water sources (Kaza et al., 2018). Moreover, mismanagement of waste can lead to persistent and irreversible environmental problems, while attempts to address waste management's environmental impacts can disrupt the foundations of sustainable societies (Olapiriyakul, 2017). In light of these challenges, it is crucial to adopt practical approaches that effectively manage waste overflow and promote sustainable development.

It is widely recognised that the economic growth of the future will necessitate being boosted by greater energy efficiency (Zhang et al., 2020). The circular economy has emerged as a systemic framework to address global challenges, including climate change, biodiversity loss, waste, and pollution (Arruda et al., 2021). Unlike traditional linear economic models characterized by the "take-make-consume-dispose" pattern, the circular economy advocates for keeping resources in circulation for extended periods through practices like resource sharing, leasing, reusing, repairing, refurbishing, and recycling (Kalmykova et al., 2018). Within the realm of the circular economy, essential concepts such as the 3R and 6R approaches, as well as the Value Retention Process (VRP) model, offer opportunities to categorize and address a multitude of activities associated with material recycling (Reike et al., 2018; Nasr et al., 2018). The 3R approach, encompassing the reduction,

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* Corresponding author.
E-mail address: kevin.zhang@rmit.edu.au (G. Zhang).

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reuse, and recycling of waste, commonly referred to as the 3Rs (Zhang et al. 2023), has garnered substantial attention from researchers (Memon, 2010; Chi and Long, 2011; Liu et al., 2017). It serves as a foundational framework for the classification and analysis of waste management activities across diverse sectors and stakeholders, including waste generators, service providers, governmental organizations, and communities (Memon, 2010). Evolving from the 3R approach, a more comprehensive 6R framework emerged, introducing elements like recovery, redesign, and remanufacturing into the waste management process (Hartini et al., 2021). This expansion represents a pivotal shift towards considering the entirety of a product's lifecycle. As the discourse around the circular economy gained momentum, the proliferation of various "Rs" with distinct definitions became a source of confusion. To address this issue, Reike et al. (2018) and Nasr et al. (2018) introduced the Value Retention Process (VRP) model, which provides a comprehensive definition of the processes and methods critical to achieving a circular economy. This model not only classifies but also sheds light on the multifaceted activities related to material recycling within the circular economy context (Reike et al., 2018; Nasr et al., 2018). Within the VRP model, ten "R-imperatives," each commencing with the letter "R," serve as a means to delineate imperative activities within the circular economy, encompassing actions ranging from "Re-fuse" (refraining from purchasing) to "Re-mine" (retrieving reusable items from landfill waste) (Nasr et al., 2018). To further enhance the practical assessment of waste management within the circular economy framework, Pires and Martinho (2019) introduced waste hierarchy frameworks. These frameworks prioritize recycling, reduction, and reuse of waste over disposal methods, allowing for the evaluation of different waste management operations in terms of their contributions to the circular economy. The approach distinguishes between circular economy operations such as reuse, up-cycling, and re-recycling, and non-circular economy operations like incineration without energy recovery and landfill (Pires and Martinho, 2019). Weighting factors are applied to these options to calculate their circular economy performance. By maximizing resource utilization, the circular economy effectively reduces dependence on virgin materials and curtails the generation of waste. To realize the circular economy's goals and ensure environmental sustainability in Municipal Solid Waste (MSW) management, it is imperative to establish a comprehensive waste management framework that encompasses recycling, reuse, and reproductive processes (Arruda et al., 2021).

On the lifecycle assessment side, although there have been numerous life cycle assessment (LCA) studies on municipal organic solid waste, research on recyclable materials from MSW primarily focuses on sorting, separation, and transport on a large scale (Dastjerdi et al., 2019; Guven et al., 2019; Ascher et al., 2019; Plastinina et al., 2019; Vossberg et al., 2014). However, these studies often lack sufficient information regarding the use of waste in the production phase to create new products. For instance, studies on glass container separation methods are often combined with other MSW studies, resulting in a lack of clearly proposed steps for glass container recycling (Vellini and Savioli, 2009; Gaines, 2012). Similarly, LCA studies on producing new products from waste, such as asphalt and concrete from kerbside glass, often fail to explicitly present the initial lifecycle stages, including collection and separation (Hossain et al., 2016; Hilton et al., 2019). Similar issues can be observed in plastic recycling studies (Aryan et al., 2019; Al-Salem et al., 2014). Furthermore, studies like Schrijvers et al. (2016) have put forth approaches for conducting lifecycle assessments of recycling, both within open-loop (recycling a product into a different product) and closed-loop (recycling a product into the same product) methods. However, the oversimplification of recycling activities into just these two categories may not adequately encompass the complexity of the process. It's important to acknowledge that the evaluation with a circular economy thinking should extend beyond a single lifecycle and account for multiple lifecycles of waste materials. This lack of comprehensive research makes it challenging to assess multiple life cycles of waste materials and achieve the circular economy's goals.

Kerbside wastes, encompassing materials like food waste, paper, glass, plastics, metals, and yard waste, play a crucial role in the MSW category in Australia (Waste Management and Resource Recovery Association of Australia, 2020). Managing these wastes has become a focal point for circular economy strategies. Currently, waste plastics, cardboard, and glass are disposed of together in recycling bins, necessitating a complex and time-consuming sorting process at recycling facilities. This co-mingling of materials not only complicates the recycling process but also leads to contamination, ultimately reducing the overall recycling rate. To enhance the recovery rate of glass, the introduction of a separate waste glass bin in the household waste collection system has been proposed. However, the environmental impacts and sustainability implications of these recycling methods remain uncertain and require further examination and analysis.

Life cycle assessment methodology and framework are typically used to assess the environmental impacts of a product or a process. LCA analyzes complex processes involving inputs and outputs of energy, pollutants, and materials (Saghafi and Teshnizi, 2011). This methodology provides basis for assessing the kerbside recycling of waste materials' environmental impacts. LCA in this study was developed in accordance with the international standards such as ISO 14044 (2006) and ISO 14040 (2006). The study employs the four step LCA methodology, consisting of goal and scope definition, inventory analysis, impact assessment, and interpretation to ensure comprehensive and accurate evaluation of environmental impacts associated with the production of asphalt and glass containers from waste glass. Literature shows there is a noticeable gap between research on the sustainability of municipal solid waste management (MSWM) and the production process involving waste materials. Insufficient attention has been given to waste separation and sorting practices in large-scale LCA studies of MSW management. Similarly, studies on reuse and reproduction often lack comprehensiveness. LCA studies that employ recycled materials for new product production frequently overlook crucial aspects of MSWM practices, such as separation methods and the energy consumption of the collection process. Also, it is difficult to address every activity that is associated with circular economy activities along a kerbside waste's lifecycle.

To ensure accurate assessment of the environmental impacts and labelling of materials as green, it is essential to consider the entire recycling process. Additionally, there is a lack of studies measuring the environmental impacts of reused materials in open-loop recycling and closed-loop recycling, since their recycling activities are complex. Thus, this study aims to address these research gaps by providing a comparative assessment for researchers and industries pursuing the circular economy's goals within the kerbside waste material loop. The study aims to create a unified environmental life cycle assessment system. This system will enable comparisons among various recycling methods, including open-loop and closed-loop recycling approaches, and multiple life cycles. To achieve this, the attributional lifecycle inventory model is integrated with the VRP model which contains an extensive list of activities related to the circular economy. This integration allows us to identify and address these activities across all lifecycles comprehensively. This comprehensive framework will assist in assessing the sustainability performance of the kerbside waste material loop process in terms of various recycling methods and multiple loops, offering valuable insights for practitioners and decision-makers.

This study is an extension of Zhang et al. (2022), with three key distinctions. Firstly, we introduce a novel attributional lifecycle inventory model, which incorporates the VRP model of the circular economy to address various material loop methods and multiple cycles. Unlike Zhang et al. (2022), which primarily focused on connecting sorting and collection processes with recycled material manufacturing, this paper significantly advances the field of model building. Secondly, this study demonstrates the model's capacity to compare diverse waste material loop methods across multiple lifecycles, exemplified by examination of glass container and asphalt scenario, in contrast to Zhang et al. (2022), which solely considered a single lifecycle and recycling method. Lastly, our study presents comprehensive lifecycle assessment results specifically for glass container scenarios comparing to asphalt scenario which presented in Zhang et al. (2022), adding depth to our research.

2. Model development

2.1. Value retention process model of the circular economy

Over the past decade, there is an increasing attention of the circular economy concept in the area of sustainable policy development, consultancy, and science (Reike et al. 2018). The drive of this trend is considered to be the urgency for closing the material loop. However, due to the method complexity of closing material loops, there are many confusions in this process. Reike et al. (2018); Nasr et al. (2018) defined all the processes and methods for achieving circular economy in a Value Retention Process model. This VRP model helps to identify all the activities related to circular economy in kerbside wastes' lifecycle. It builds on foundation to enable the development of economic and social aspects with the environmental aspect.

In the VRP model, there are nine "R″s used to define the circular economy imperative activities. R0 represents Re-fuse, which means refrain from buying. R1 represents Re-duce, which means use a product longer and use less products. R2 represents Re-sell, which means selling products as second hand maybe with cleaning and some maintenance before sale. R3 represents Re-pair, which means repairing the products may be done by customers or a third party. R4 represents Re-furbish, which means the product will go to the original manufacturer to replace elements and then continue using it. R5 means Re-manufacture, which means the product will return to the original manufacturer to decompose. R6 is Re-purpose, which means the product will go to other users for other purposes. R7 is Re-cycle, which means the product will be disposed separately, and this action involve waste collection. R8 is Recover energy. It means the product is used for energy production, such as food waste to electricity. R9 is Re-mine, which is grubbing landfill waste to find reusable items, and it is considered as a rare activity (Nasr et al., 2018). R-imperatives of circular economy is presented in Fig. 1.

2.2. Incorporating VRP model into the attributional LCI model of life cycle assessment of kerbside wastes

Two main LCA inventory models exist attributional or consequential LCA (Ekvall et al., 2016). The Shonan database guide (Sonnemann and Vigon, 2011) clarifies these terms that attributional approach is a system modelling method where inputs and outputs are grouped into functional units of a system of products and the unit processes of the system are associated and/or allocated according to normative rules. Attributional LCI approach is used to construct the system model of kerbside waste material loop process, since the goal is to monitor the input and output of the process which contribute to the environmental sustainability of the kerbside waste material loop. This approach was also adopted by similar studies by Schrijvers et al. (2016) where attributional LCI models were constructed using recycling rates but only considered the limited recycling concepts for general wastes. It was also difficult for materials with multiple lifecycles to achieve circular economy. The novel circular economy attributional LCI model in this study considered different recycling methods and multiple loops for kerbside waste material loop process. It integrates Value Retention Process (VRP) model which defines varies end-of-use/life activities as a base for the attributional LCI model. This paper explains the VRP model and data sources for inventory, and then the allocation method of the attributional LCI model is explained.

Integrating the VRP model into the kerbside wastes' lifecycle assessment comes from two aspects: 1) It helps to define the suitable circular economy activities for starting the next lifecycle; 2) With the defined activities, it facilitates their allocation within the lifecycle inventory (LCI) calculations to construct the circular economy attributional LCI model for kerbside material looping process. It should be

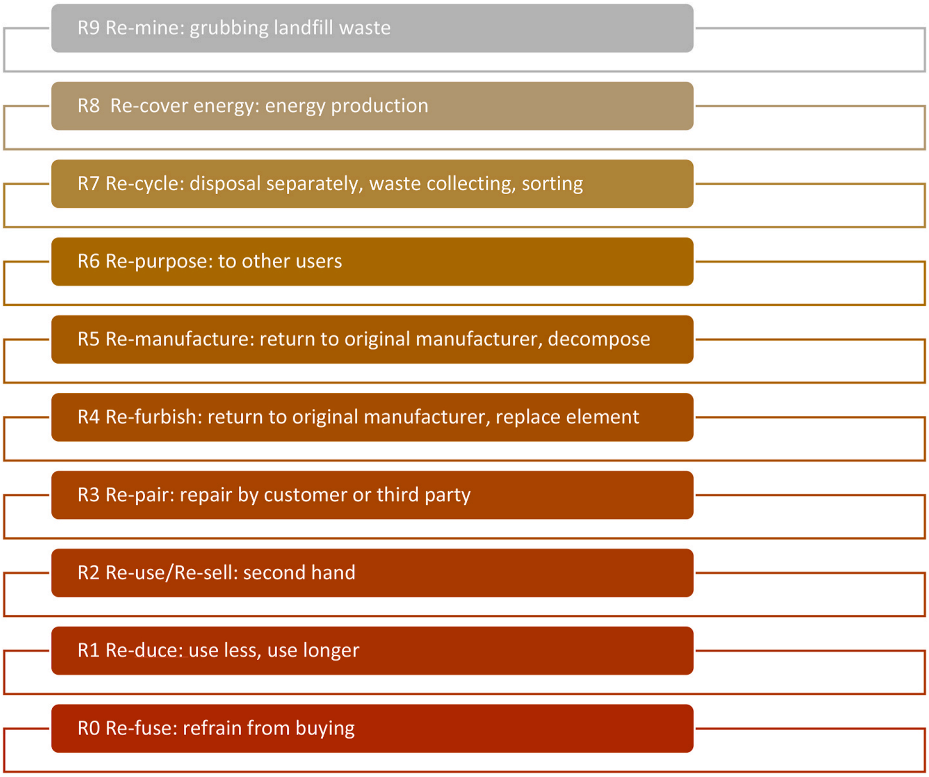

Fig. 1. R-imperatives of circular economy.

highlighted that Rs activities are not associated with new products' mix-design of wastes. They are only considered when there are activities to begin a new lifecycle and there are potential environmental impacts (when energy/resources/transportation is involved).

2.2.1. *Defining the circular economy activities in the kerbside wastes' lifecycles*

The first lifecycle of kerbside waste material is always R7 (recycling) since the R7 process involves separation, collection, disposal, and sorting of wastes. Depending on the produced product types in the first lifecycle, circular economy activity Rs is selected to start the second lifecycle. For example, using a kerbside glass cullet to produce asphalt (open-looped recycling)/glass containers (closed-loop recycling) in the first lifecycle are R7 (recycling) activities. However, in the 2nd lifecycle, the demolished asphalt can be R5 (remanufactured, returning to the original manufacturer) to produce reclaimed asphalt pavements (RAP), and used glass containers can be R7 (recycling) again as kerbside waste glass. The R5 and R7 are the circular economy activity Rs for starting the next lifecycle. Rs may start at any lifecycle stage. Table 1 describes the Rs in each lifecycle stage.

Table 1
Circular economy activities in each lifecycle stage.

Lifecycle stage	Circular Economy Activity (Rs)	Description	Resource and energy involvement
Collection	R7 (recycling)	Waste collection and disposal occur separately.	Energy consumption and environmental impacts of vehicles, machinery, and equipment.
Sorting	R7 (recycling)	R7 activities continue in the sorting stage as it also includes material sorting.	Energy consumption of vehicles, machinery, and equipment
Production	R8 (recover energy)	Wastes, such as food and yard wastes, can undergo R8 (recover energy) to produce electricity through direct incineration or biogas power generation. Marks the end of the first lifecycle for these wastes.	R8 activity is not associated with the calculation of energy/environmental impacts reduction in this model. It describes the transportation of materials and material treatment, which consume energy and resources during the process.
End-of-use/life	R0 (refuse) and R1 (reduce)	Not considered as they involve actions of reduction and absence of energy consumption.	Not considered. Reduction and absence of energy consumption.
	R2 (reuse/resell)	Perform an indirect functional change for other purposes.	Energy consumption for collection or transportation of materials.
	R3 (repair)	Replacement of deterioration by users or third parties.	Transportation and materials consumption for repair.
	R4 (refurbishment)	Non-standard and non-factory setting.	Consumes energy and resources.
	R5 (remanufacture)	Standard factory setting.	Consumes energy and resources.
	R6 (repurpose)	Applies to by-products, such as fly ash, can be repurposed for other users after the end-of-use/life stage.	Consumes energy and resources.
	R9 (re-mine)	Not considered as it describes urban or landfill mining, which is beyond the lifecycle boundaries.	Not considered.

The circular economy in lifecycle stages is shown in Fig. 2. Using the glass container case as an example (waste stream A), the collection stage and sorting stage, R7 activity is involved. Then in the production stage, the sorted glass cullet is used to produce new glass containers (product D) as closed-loop recycling or asphalt (product F) as open-looped recycling. In the end-of-use/life stage, glass containers can be R6 (re-purposed) or R2 (re-use/resell) to other consumers. These activities lead to a 2nd lifecycle starting at the consumer in-use stage. Glass containers can also be discarded in the kerbside waste bins and start the 2nd lifecycle with the collection stage for R7 (re-cycling) activity. Asphalt in the end-of-use/life stage can be R5 (re-manufactured) as RAP in the factory and start the 2nd lifecycle at the production stage to produce asphalt, then the asphalt will be R5 (re-manufactured) as RAP again in the 3rd lifecycle. Using kitchen waste as an example, R7 activity involves the collection and sorting stage and then the waste is considered in its end-of-life stage. The 2nd lifecycle is considered with R8 (recover energy) to produce electricity (product E). The by-product of electricity, such as fly ash, will be R6 (re-purposed) to start the 2nd lifecycle to produce concrete or asphalt. The concrete or asphalt in the 2nd lifecycle can be R5 (re-manufactured) to start the 3rd lifecycle.

2.2.2. *Circular economy attributional LCI model construction*

With collected data, allocation method of the circular economy attributional LCI model for kerbside waste material loop is presented. The allocation method is adopted from Chen et al. (2010) which targeted waste materials in concrete by using percentage of material's masses as allocation coefficient to define the main process (for the production of main products) and secondary process (for processing by-product or wastes). However, the method did not consider various stakeholders and multiple lifecycles in the process. Alterations have been conducted for the kerbside waste material loop process to suit for varies end-of-use/life material loop methods conducted by different stakeholders.

The allocation in the lifecycle assessment distributes the percentage of R-imperative activities in terms of material, energy, water, and transportation. It gives opportunities for easy quantification and analysis.

The general presentation of the inventory is as follows:

$$\vec{F}_{total} = \vec{F}_{collection} + \vec{F}_{Sorting} + \vec{F}_{production} + \vec{F}_{in-use} + \vec{F}_{end-of-use/life}$$

Equation 1

Where $\vec{F}_{total}$ refers to the total flow inventories of environmental burdens of all the lifecycle stages. $\vec{F}_{collection}$, $\vec{F}_{Sorting}$, $\vec{F}_{production}$, $\vec{F}_{in-use}$ and $\vec{F}_{end-of-use/life}$ refers to the flow inventories in each lifecycle stage. The basic logic in the inventory allocation is presented as follows:

$$\vec{F} = AC \times Rs \times Stakeholder_x \vec{F}_{primary} + AC \times Rs \times Stakeholder_x \vec{F}_{secondary}$$

Equation 2

where $\vec{F}_{primary}$ and $\vec{F}_{secondary}$ refer to the flow inventories of environmental burdens of kerbside waste material primary and secondary processes conducted by different stakeholders, and AC is the allocation coefficient that differs whether the circular economy R-imperatives (Rs) that is chosen.

As the transformation from the environmental inventory to the environmental impacts corresponds to a matrix A ($\bar{A}$) (Chen et al., 2010) that could be referred as a technology matrix. The impact can be presented in the following equation:

$$\vec{I} = \bar{A}\left(AC \times Rs \times Stakeholder_x \vec{F}_{primary} + AC \times Rs \times Stakeholder_x \vec{F}_{secondary}\right)$$

Equation 3

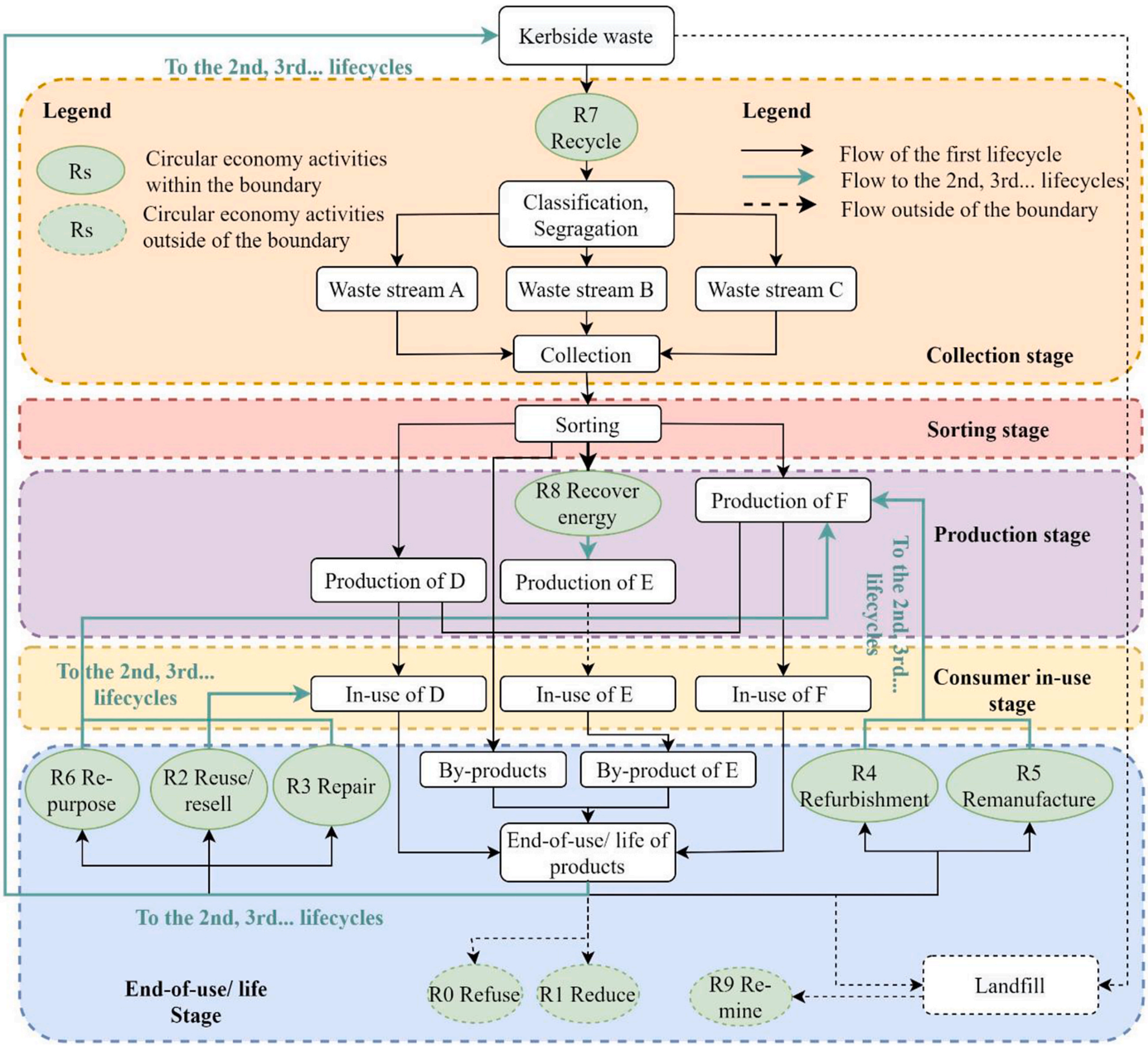

Fig. 2. Circular economy in the material flow and lifecycle stages of kerbside waste material loop process.

In all the lifecycle stages, the $\overrightarrow{F}$ is the flow of material, energy, water, and transportation of stakeholders involved in R-imperatives. The environmental impacts $\overrightarrow{I}_{lifecycle\ stage}$ can be calculated with Equation (4). In this equation, Rs is the VRP activity which is used to start the next lifecycle. A, B, and C represent each waste stream's allocation coefficient percentage. This equation translates as the environmental impacts of a lifecycle stage is the study of the environmental impacts of material, energy, water, and transportation inventory flow of every VRP activity stakeholder.

Use the glass container as an example. Two stakeholders are involved in the collection stage: the waste collection service provider (α_1) and waste transportation service provider (β_1) for R7 activity. If all the wastes in the kerbside waste bins are collected (A_1, $B_1 = 100\%$). The allocation coefficient of the glass container at the collection stage is 100% of the inventory flow $\overrightarrow{F}$ (material, energy, water, and transportation) for the waste collection service provider (α_1) and waste transportation service provider (β_1).

$$\overrightarrow{I}_{lifecycle\ stage} = \overrightarrow{A}\Bigg[A \times Rs \sum_{Stakeholder\ 1}^{Stakeholder\ \alpha}\left(\overrightarrow{F}_{material} + \overrightarrow{F}_{energy} + \overrightarrow{F}_{water} + \overrightarrow{F}_{transportation}\right) + B \times Rs \sum_{Stakeholder\ 1}^{Stakeholder\ \beta}\left(\overrightarrow{F}_{material} + \overrightarrow{F}_{energy} + \overrightarrow{F}_{water} + \overrightarrow{F}_{transportation}\right)$$

$$+ C \times Rs \sum_{Stakeholder\ 1}^{Stakeholder\ \gamma}\left(\overrightarrow{F}_{material} + \overrightarrow{F}_{energy} + \overrightarrow{F}_{water} + \overrightarrow{F}_{transportation}\right) + \ldots\Bigg] \qquad \text{Equation 4}$$

The same principle applies to the sorting stage. The sorting process also falls into R7 (Re-cycling) activity. Use the glass container as an example. Two stakeholders are involved in the sorting stage: the waste sorting service provider (α_2), and the waste transportation service provider (β_2) for R7 activity. In the sorting stage, the recycling rate of kerbside waste glass is A_2 and B_2. The allocation coefficient of the glass container at the sorting stage is 95% of the inventory flow $\overrightarrow{F}$ (material, energy, water, and transportation) for the waste sorting service provider (α_2) and waste transportation (β_2) for R7 activity.

In the production stage, R8, which represents energy recovery, can be involved in this stage. The R8 only happens for organic wastes such as kitchen waste. Use kitchen waste as an example. Stakeholders involved in the collection stage are the electricity production service provider (α_3), and the transportation service provider (β_3) for R8 activities. In the production stage, the energy recovery rate for production of electricity using kitchen waste is A_3 percent (allocation coefficient is A_3). Since energy recovery (R8) is the activity for kitchen waste to start a new lifecycle as electricity. This process involves a transformation of material chemical and physical characteristics. The allocation coefficient of kitchen waste to produce electricity at the production stage is A_3 (%) of the inventory flow $\overrightarrow{F}$ (material, energy, water, and transportation) for the waste collection service provider and transportation service provider (β_3) for R8 activity. The electricity generation by R8 recovery energy is the primary process in the production stage. If the by-product, such as fly ash, is generated as the secondary process. The allocation coefficient of fly ash at the production stage is B_3 for the inventory flow $\overrightarrow{F}$ (material, energy, water, and transportation) of the production service provider (γ_1). The fly ash is considered reached the end-of-use/life stage. The calculation for the next lifecycle of the secondary inventory flow of fly ash is presented in the end-of-use/life stage.

In the consumer in-use stage, there are no Rs involved. It is worth to mention, the percentage of waste materials in the mixed-design of products is not calculated with the allocation coefficient of the R-imperatives (Rs) since Rs and their allocation coefficient is used to describe the circular economy activities conducted to start the new lifecycle.

In the end-of-use/life stage, there are stakeholders involved in R2 (Reuse, Resell), R3 (Repair), R4 (Refurbishment), R5 (Remanufacture), and R6 (Repurpose). All the by-products generated in previous lifecycle stages are considered in this lifecycle stage. They will be either landfilled (not considered in the circular economy) or R6 (repurposed).

Use the waste glass cullet-produced asphalt as an example. Two stakeholders are involved in the end-of-life stage: the asphalt demolishing (α_4) and the transportation service provider (β_4) for R5 activity. In the end-of-life stage, the recycling rate of asphalt pavement is A_4. If all the asphalt is returned to the asphalt production service provider (R5 remanufacture) to produce RAP, then the allocation coefficient $A_4 = 100\%$, meaning there is no loss during demolishing and transportation. Thus, the activity for asphalt pavement starting the second lifecycle as RAP, the allocation coefficient is 100% of inventory flow $\overrightarrow{F}$ (material, energy, water, and transportation) for the asphalt demolishing (α_4) and transportation service provider (β_4) for R5 activity, since the product is returned to the asphalt production service provider. The second lifecycle for the RAP starts with the production stage. It is worth to mention that the second lifecycle only consider the weight of RAP, instead of the contained weight of waste glass cullet from the first lifecycle. For instance, first lifecycle produced *y* kg asphalt, which contains x kg of recycled glass cullet. The asphalt is 100% R5 remanufactured. Then the inventory flow of the second lifecycle considers *y* kg of RAP instead of *x* kg of recycled glass cullet.

Products such as glass containers are disposed of in kerbside waste bins in the end-of-life/use stage. This starts a new cycle which begins with the street collection and R7 (Re-cycle) activities. It means the environmental impacts calculation restarts the process with the street collection stage. Similar to asphalt production, it is worth to mention that the second lifecycle only considers the weight of new glass containers, instead of the contained weight of waste glass cullet from the first lifecycle.

Use fly ash as an example, the fly ash is the by-product of generating electricity in the production stage. It starts the secondary process at the end-of-use/life stage (The electricity generation by R8 recovery energy is the primary process in the production stage). If fly ash can be R6 (repurposed) as concrete. R6 means the products are sent to another user (R4 refurbishment and R5 remanufacture are returned to the original manufacturer). If all the fly ash is collected and sent to the concrete production service provider γ_1 (R6 repurposed) to produce concrete, then the allocation coefficient $C = 100\%$, which means there is no loss during collection and transportation. Thus, the activity for fly ash starting the second lifecycle as cementitious material, the allocation coefficient is 100% of inventory flow $\overrightarrow{F}$ (material, energy, water, and transportation) for the collection and transportation service provider (β_5) and concrete production service provider γ_1 for R6 activity. Since the fly ash is sent to the concrete production service provider γ_1, the second lifecycle for the cementitious material starts with the production stage. The third lifecycle for the cementitious material can be start with R5 activities to be returned to the concrete manufacturer to replace aggregates in concrete.

3. Life cycle assessment case study

To present the application of the improved model the recycling of kerbside waste glass mainly because; (1) kerbside glass is a common MSW that can be recycled in various ways multiple times, such as open-loop and closed-loop recycling; and (2) real-life separation of kerbside waste glass streams from mixed recycling steams conducted at local councils. A list of inventories for glass recycling practices can be collected. However, it is difficult to collect data on other kerbside wastes.

This case study shares the same case as Zhang et al. (2022). It was conducted at the Yarra City, Australia. Data were collected from 1400 households (trial area) over an 8-month period of kerbside waste glass container collection and recycling. Before this case study began, waste glass containers were discarded in a mixed recycling bin with cardboard, metal, and plastic. Throughout the case study, a separate recycling bin for waste glass was installed for glass containers only. A separate recycling bin for glass containers was added at the kerbside to guide people to transfer waste glass from the mixed bin to the separated glass bin. In each collection, the waste in the separated glass recycling bin varied from 3600 kg (in July) to 6430 kg (in December). Waste collected from separate glass recycling bins was transported to a Materials Recovery Facility (MRF) to conduct sorting, treatment, and processing. Rorted glass cullet was sent to an asphalt production factory for asphalt production, and then was used in road surface paving. Also, the pavement is reclaimed in the maintenance and at the end of service life. It would be removed and then eventually recycled as recycled asphalt pavement (RAP). Furthermore, the recycled glass cullet was used to produce new glass containers.

3.1. Goal and scope of the testing case

This study employs a life cycle assessment (LCA) methodology to evaluate and contrast the environmental impacts of closed-loop and open-loop recycling of waste glass cullet, encompassing various stages such as collection, sorting, processing, and utilization of the material in the production of asphalt and glass containers. It embraces two main areas: 1) MSW separation, collection, sorting, and processing; and 2) industries that consume wastes. Asphalt manufacturing and its use in construction and the manufacture of glass containers are chosen as examples in this paper.

3.1.1. Scenarios

In the test case, there are four main test scenarios: (1) SKGRB-A model: Asphalt production using waste from separate kerbside glass bins of recycling; (2) MKRB-A model: Asphalt production using wastes from a mixed kerbside bin of recycling; (3) SKGRB-G model: Glass container production using waste from separate kerbside glass bin of recycling; and (4) MKRB-G model: Glass container production using waste from mixed kerbside bin recycling.

3.1.2. Functional unit

Two functional units were utilized in the current study. Firstly, the chosen functional unit for analysis in this study is the production of 1-ton asphalt or glass containers derived from kerbside waste glass in the first life cycle. This unit enables a focused examination of results from the perspective of the industry utilizing waste materials. Secondly, the evaluation includes the weight of kerbside wastes collected in the first year under two different models, namely Separate Kerbside Glass Recycling Bin (SKGRB) and Mixing Kerbside Recycling Bin (MKRB), for the production of asphalt materials and pavements as well as glass containers over a 21-year period. It is important to note that the service life of an urban road is typically 20 years, with maintenance occurring every 5 years, while the lifecycle of glass containers is assumed to be 3 years. Multiple loops are expected within the asphalt and glass container scenarios. In the initial year, collected kerbside glass is utilized for asphalt and glass container production. In the second lifecycle, the asphalt is recycled as reclaimed asphalt pavements (RAP), while the glass containers become kerbside waste glass and are subsequently recycled to produce new glass containers. In the subsequent lifecycle, the newly recycled kerbside glass cullet is incorporated into the production of new asphalt. It is worth mentioning that the newly recycled kerbside glass cullet may not necessarily be collected from the trial area due to limitations on the weight that can be collected, but it undergoes the same collection and sorting process. This selected functional unit allows for the demonstration of the model's applicability in various loop methods and multiple circulation instances.

3.1.3. System boundary

The study considers a system boundary that encompasses all life cycle stages involved in the study, including street collection, sorting, production, in-use, and end-of-life/life-cycle stages, over a specific time period. Each stage contributes relevant data for analysis: Street collection involves data on energy consumption for transportation and the weight of the collected wastes. Sorting stage data includes energy consumption during the sorting process and the weight of the recycled materials. Production stage data encompasses energy consumption during production, including the weight of the produced product, virgin material extraction, and virgin material usage. In-use stage data covers transportation-related energy consumption for asphalt and glass containers, as well as energy consumption during asphalt paving. End of use/life (demolishing/excavation, discard) stage data includes energy consumption during excavation or demolition processes, transportation energy consumption, and the weight of the discarded products.

3.2. Inventory analysis

This study is a funded project in collaboration with the Yarra City Council. The data utilized for this research were predominantly sourced from various databases maintained by the city council, as well as from material recovery facilities and an asphalt production company. To gather and validate information pertaining to the trial area, we conducted twelve monthly interviews between December 2019 and December 2020 with an experienced manager from the Yarra City Council Recycling Centre. The Yarra City Council Recycling Centre also facilitated the provision of contacts for experienced managers at the material recovery facility and asphalt production company. In January 2020, we conducted one interview with the manager of the material recovery facility, and subsequently, three additional interviews were arranged with the experienced manager of the asphalt production company. The collected data was verified by member checking (Buchbinder, 2011) which we shared the findings and summary of the interview with the interviewees to validate that what they said was accurately represented. They can confirm or correct the interpretation of their responses. The inventory data extracted from Yarra City Council and material recovery facilities in the street collection and sorting stage are share by the asphalt scenario and glass scenario, which has been presented in Zhang et al. (2022). Carre et al. (2013) provide a case study of glass containers produced from recycled glass cullet which is newly collected in this study. This study utilized the Ecoinvent 2.2 database (Ecoinvent, 2007) within the SimaPro software for conducting the life cycle assessment. Figs. 3 and 4 show the integrated inventory data with the system boundaries of this study. The detailed inventory for asphalt scenario is presented in Zhang et al. (2022). The inventory for glass container scenarios is presented in the Table 2.

3.2.1. Street collection stage

The Yarra City Council, Australia who is responsible for the trial area waste collection, provided the relevant data concerning the separate glass recycling bins. Specifically, the annual collection weight of 108,095 kg was taken into account for this study. For the sake of ensuring comparability, it is assumed that the mixed kerbside recycling bins have an annual collection weight of 108,095 kg, which is equivalent to that of the separate glass recycling bins supplied by the local government of Yarra City Council in the trial area (Zhang et al., 2022).

The VRP model was based on the premise that all glass was collected without loss and that the allocation coefficient was 100% for the R7 activities (separation, collection) in the street collection stage. The annually collected waste was 108,095 kg and the housing blocks travel distance was 7 km, while the transportation distance for the materials to the next stage was 37.6 km.

3.2.2. Sorting stage

Information related to the sorting phase was acquired through consultations with a representative of the Materials Recovery Facility (MRF). In the course of waste recycling using glass cullet, distinct procedures are implemented by the SKGRB and MKRB methods. With the SKGRB approach, the waste is passed through a single glass sorting plant, while the MKRB model involves the use of both a MRF and a glass sorting facility for processing the glass cullet. This inventory analysis is documented in the publication by Zhang et al. (2022).

From the VRP (value retention process) model, the allocation coefficient for R7 activities in the sorting stage is 34% (in MRF) and 66% (in glass sorting facility) in MKRB model. For SKGRB model, the allocation coefficient for R7 is 95% (in glass sorting facility).

3.2.3. Asphalt production stage

The energy consumption per kilogram of recycled glass cullet was determined to be 0.0011 kWh of electricity and 0.00063 L of diesel, as reported in Zhang et al. (2022). This study also provided information on the energy consumption of RAP and aggregate production. It should be noted that this stage does not encompass any R-imperatives, as the material has not reached its end-of-life stage yet.

3.2.4. Asphalt in-use stage

This study accounted for the transportation of asphalt products and the usage phase during the laying process. The transportation distance was recorded as 19 km, as noted by Zhang et al. (2022). The environmental impact assessment for the asphalt paving procedure was drawn from the Ecoinvent 2.2 database, as incorporated into the SimaPro software. No R-imperatives were involved during the in-use stage of asphalt, as the material has not reached the end-of-life yet.

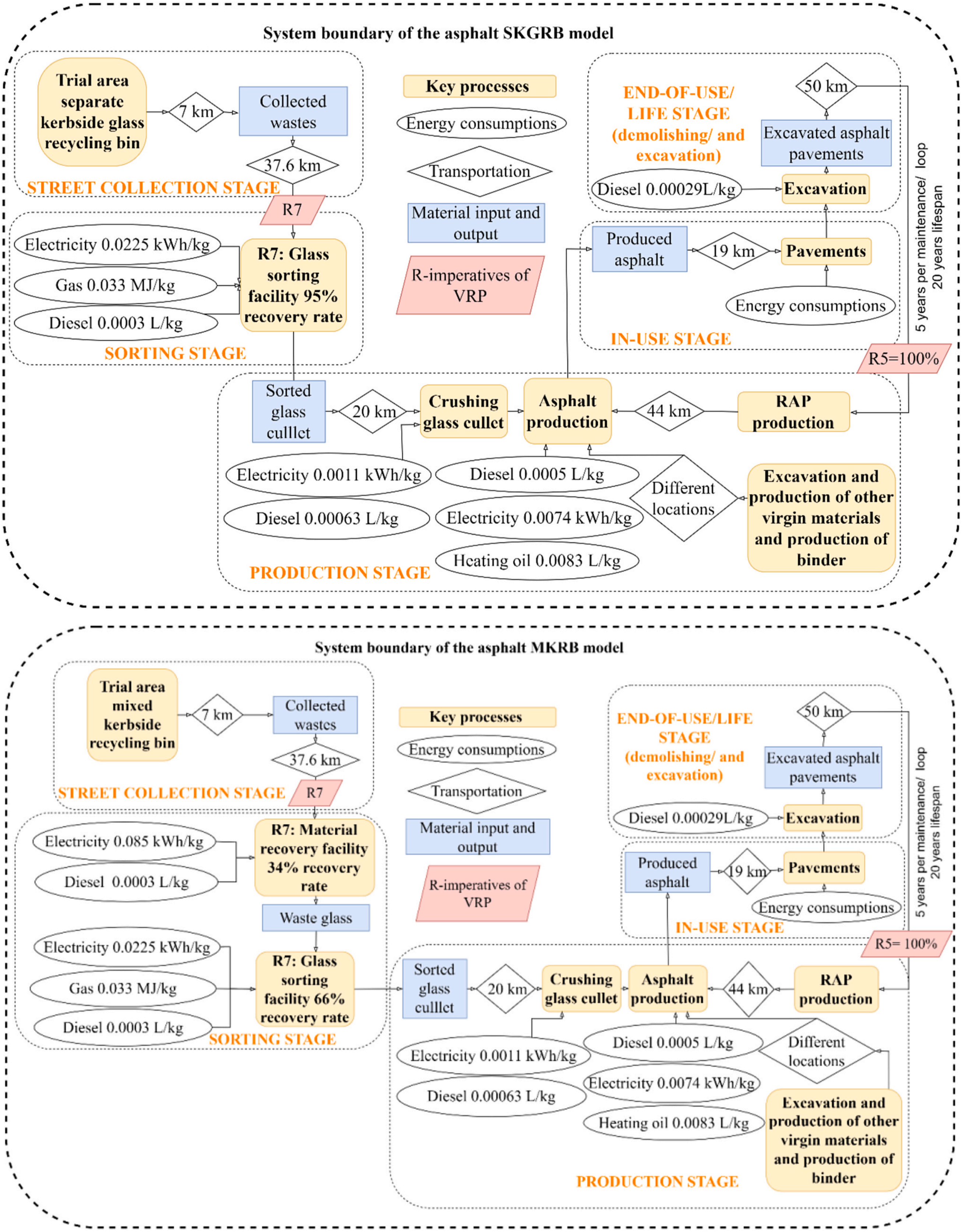

Fig. 3. Inventories and system boundaries for the SKGRB-A and MKRB-A models (Source: Zhang et al., 2022).

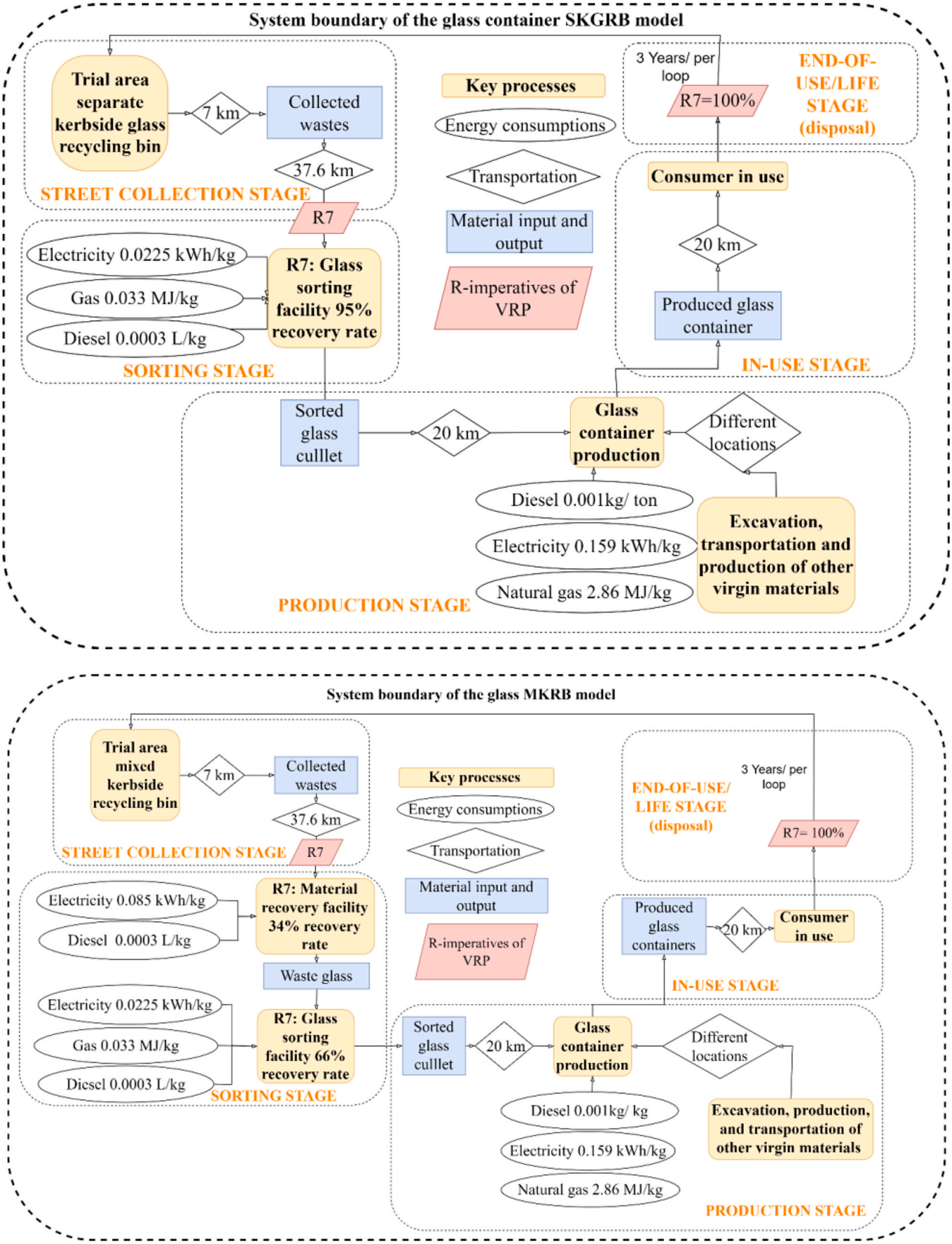

Fig. 4. Inventories and system boundaries for the SKGRB-G and MKRB-G models.

Table 2
Inventory data used for glass container scenarios.

Item	Amount	Source of data
Street collection stage		
Average waste weight in each collection	4158 kg	Interview with the City Council
Annually collection times	26	Interview with the City Council
Annually collected waste	108,095 kg	Calculation and assumption
Working hours per collection	7 h	Interview with the City council
Travel distance in the trial area	7 km	Interview with the City council
Transportation to the local MRF	37.6 km	Interview with the City council
Sorting stage		
Annual waste input in MRF	117000 ton	Interview with the local MRF
Diesel consumption per kg waste in MRF	0.0003 L/kg	Interview with the local MRF
Electricity consumption per kg waste in MRF	0.085 kWh/kg	Interview with the local MRF
Annual waste glass output in MRF	39780 ton	Interview with the local MRF
Annual waste glass input in a glass sorting facility	57200 ton	Interview with the local MRF
Waste glass recovery rate in MRF	34%	Interview with the local MRF
Diesel consumption for consumption per kg of waste glass in the glass sorting facility	0.0003 L/kg	Interview with the local MRF
Diesel consumption per kg of waste glass in the glass sorting facility	0.0225 kWh/kg	Interview with the local MRF
Natural gas consumption per kg of waste glass in the glass sorting facility	0.033 MJ/kg	Interview with the local MRF
Annual sorted glass cullet output	37752 ton	Interview with the local MRF
Glass cullet recovery rate for MKRB model	66%	Interview with the local MRF
Production stage		
Transportation of sorted glass cullet to the asphalt producer	20 km	Assumption
Production of soda ash		Ecoinvent 2.2 database in SimaPro
Production of Limestone		Ecoinvent 2.2 database in SimaPro
Production of Feldspar		Ecoinvent 2.2 database in SimaPro
Production of Silica sand		Ecoinvent 2.2 database in SimaPro
Total distances of transportation of materials (varies locations)	100 km	Assumption
Sorted glass cullet	64%	Carre et al. (2013)
Soda ash	6%	Carre et al. (2013)
Limestone	10%	Carre et al. (2013)
Feldspar	3%	Carre et al. (2013)
Silica sand	17%	Carre et al. (2013)
Electricity for producing glass containers	159 kWh/ton	Carre et al. (2013)
Natural gas oil for producing glass containers	2860 MJ/ton	Carre et al. (2013)
Diesel for producing glass containers	1 kg/ton	Carre et al. (2013)
In-use stage		
Transportation of glass containers	20 km	Assumption
End-of-use/life (disposal) stage		
User dispose of glass container	0	Assumption
Life span	3 years	Supermarket observation and assumption

Table 3
Asphalt and consumed waste weight inventory the first year collected kerbside wastes in 20 years.

SKGRB-A					
	First year	Year 5	Year 10	Year 15	Year 20
Asphalt produced with in every loop (ton)	1283.633	6418.14	32,090.70	160,453.50	0
Consumed waste glass in every loop (ton)	108.10[a]	540.47	2702.37	13,511.87	0
MKRB-A					
Asphalt produced with in every loop (ton)	303.20	1516.00	7580.00	37,900.00	0
Consumed waste in every loop (ton)	108.10[a]	540.46	2702.32	13,511.59	0

[a] Collected in the trial area.

3.2.5. *Asphalt end-of-use/life (D/E) stage*

This study accounted for the energy consumption involved in the excavation, demolition and transportation of asphalt pavement. The details of the energy consumption in the asphalt excavation and demolition process were presented in Zhang et al. (2022). It was estimated that the transportation distance from the location of the pavement to the production site of recycled asphalt product (RAP) was 50 km. The pavement design period for the urban road was established as 20 years, with maintenance performed every five years, as per the information provided by VicRoads (2018).

From the perspective of the VRP (value retention process) model, this is an activity of R5 remanufacture (describes returning to the original manufacturer, decompose). It is assumed that there is no loss during demolishing and transportation of asphalt pavements to the original RAP production site for maintenance after five years of service (VicRoads, 2018), which means that the allocation coefficient for R5 is 100%.

3.2.6. *Multiple lifecycles for asphalt scenarios*

The inventory analysis outlined for the functional unit of weight, specifically in regard to the initial year's collection of kerbside waste using SKGRB and MKRB models, with the ultimate goal of producing asphalt material and pavements that will last for 21 years. Given that the wearing course for the asphalt is expected to last for a period of five years, it is anticipated that the asphalt pavements will undergo four complete loops during this 21-year timeframe. The quantities of produced asphalt and waste consumed during each loop, or lifecycle, are duly provided in Table 3.

SKGRB-A model: In the first lifecycle, the first year collected waste glass produced asphalt (x_1) is 1,283,628 kg. Asphalt pavement is 100% remanufactured (allocation coefficient for R5 is 100%) to start a second lifecycle as RAP. The same idea applies for the future lifecycles of the asphalt.

MKRB-A model: The first year of collected waste glass produces 303,200 kg with MKRB-A model (x_2). For the MKRB model, Asphalt pavement is 100% remanufactured (allocation coefficient for R5 = 100%) to start a second lifecycle as RAP. The same idea applies for the future lifecycles of the asphalt. The multiple lifecycle process is presented in the Fig. 5.

3.2.7. *Glass container production stage*

A case study by Carre et al. (2013) presented the German example of using 69% of glass cullet to produce 1000 kg of glass containers which requires 689 kg glass cullet, 195 kg silica sand, 61 kg soda ash, 106 kg limestone, and 37 kg Feldspar. In glass production, the weight loss of materials is expected. The weight of the final output products is lower than the material input weight. Based on the interview with city council managers, the production of glass containers, in this case uses 64% of glass cullet, 6% of soda ash, 10% of limestone, 3% of feldspar, and 17% of silica sand. Ecoinvent 2.2 database in SimaPro was used for the production of each material. The transportation of materials was based on

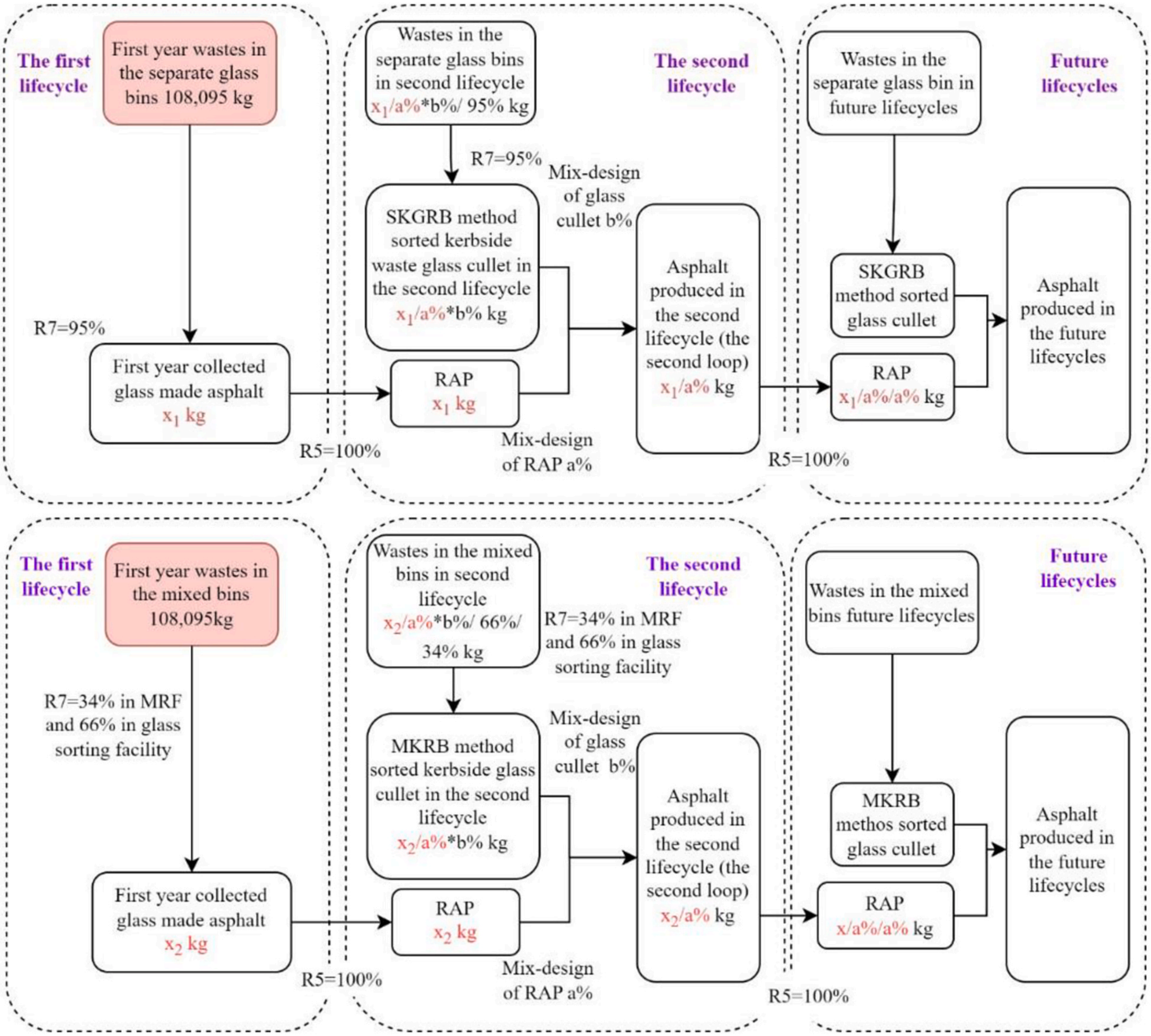

Fig. 5. Multiple lifecycle processes of SKGRB-A and MKRB-A.

assumptions.

3.2.8. *Glass container in-use stage*

Transporting the products is considered in the in-use stage and the distance was assumed as 20 km.

3.2.9. *Glass container end-of-use/life stage (disposal)*

Glass container disposal after use is considered as a “zero” energy consumption activity since it is manually done by consumers by dumping used glass containers in kerbside waste bins. According to observation in supermarket, the expired date of beverage such as Coca-Cola and Pepsi product is around 6–9 months. However, production and shipping of glass containers product can vary. It is assumed that the lifespan of kerbside glass is three years, from the kerbside glass has been disposed on the street to it’s been sorted, remanufactured, used, and disposed in the kerbside bins.

From the perspective of the VRP (value retention process) model, this is an activity of R7 (recycling). It is assumed that all the kerbside glass will go through the R7 activity after three years, which means that the allocation coefficient for R7 is 100% without any activities of R2 (re-

Table 4
Glass containers and consumed waste glass inventory for the first year collected kerbside wastes.

SKGRB-G								
in tons	Year 1	Year 3	Year 6	Year 9	Year 12	Year 15	Year 18	Year 21
Glass containers produced with in every loop	155.64	231.03	342.93	509.04	755.61	1121.60	1664.88	2471.31
Consumed waste glass in every loop	108.10[a]	155.64	231.03	342.93	509.04	755.61	1121.60	1664.88
MKRB-G								
Glass containers produced with in every loop	36.76	37.91	39.10	40.32	41.58	42.88	44.22	45.60
Consumed waste in every loop	108.10[a]	108.13	111.51	114.99	118.58	122.29	126.11	130.05

[a] Collected in the trial area.

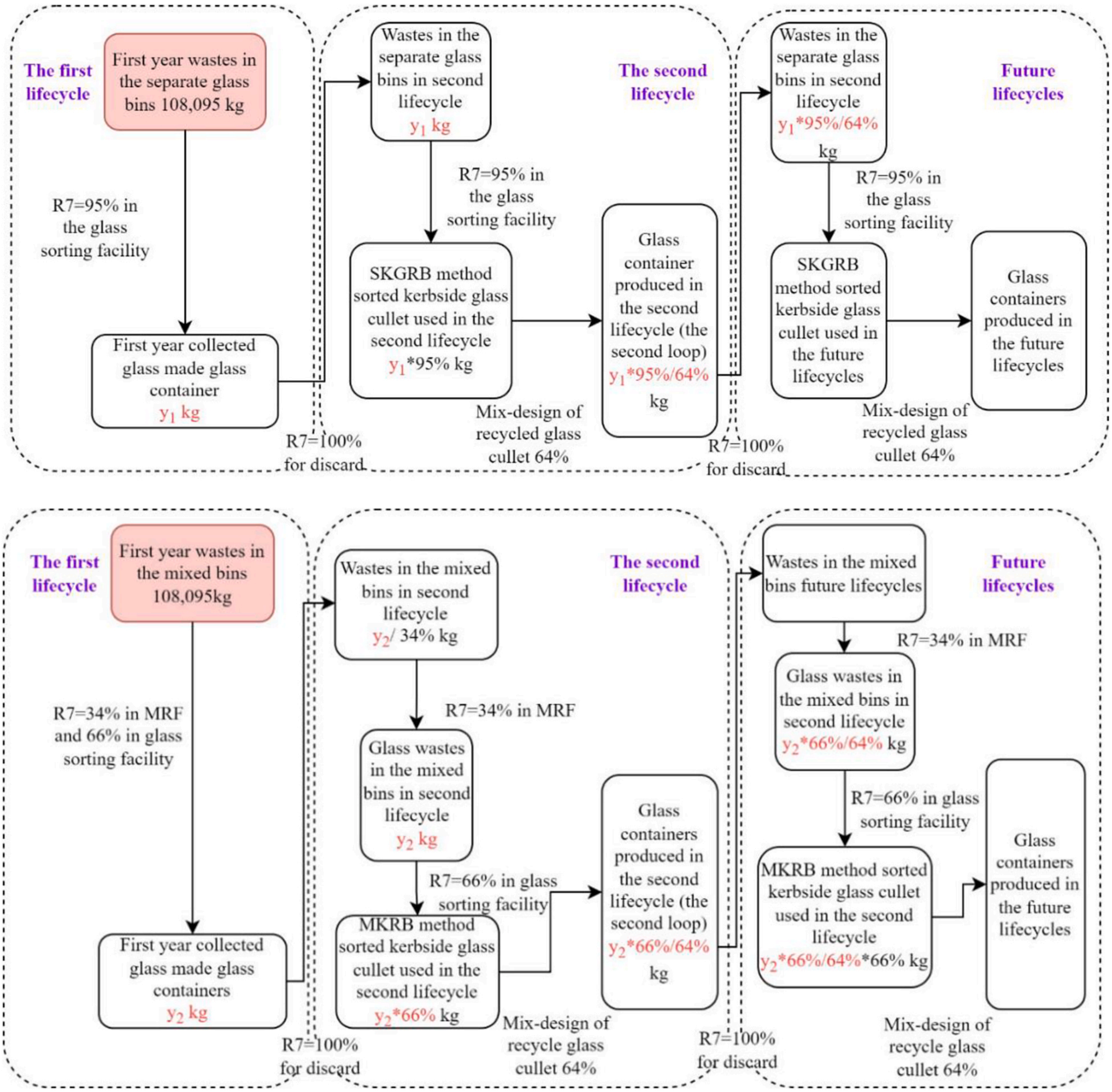

Fig. 6. Multiple lifecycle processes of SKGRB-G and MKRB-G.

use), R3 (re-pair), and R6 (re-purpose).

3.2.10. Multiple lifecycles for glass container scenarios

The following texts describe the inventory calculation for the functional unit of weight of the first year gathered wastes to produce glass containers in 21 years in SKGRB and MKRB models. Since the assumed life span for glass containers is three years. Thus, in 21 years, the glass container looped seven times. The weight of produced glass and consumed waste in each loop is presented in Table 4.

SKGRB-G: The functional unit weight of first-year collected waste-produced glass containers (y_1) is 155,640 kg with the SKGRB model. 155,640 kg glass containers are 100% recycled (allocation coefficient for R7 = 100%) in the end-of-use/life stage to start the second lifecycle in the street collection stage. It means no R2 (resell), R3 (repair) involved. Thus, the weight of the separate kerbside glass bin in the second lifecycle at year 3 is 155,640 kg. The same principle applies in the lifecycles afterward.

MKRB-G: For the MKRB model, the first year produced glass containers (y_2) is 36,763 kg. The recycled glass is 100% discarded (allocation coefficient for $R7_{\text{discard}} = 100\%$, no R2 resell, R3 repair) with other recyclable materials in the mixed bin. Thus, the weight of the glass in the mixed bin of the second lifecycle at year 3 is 36,763 kg. The same principle applies in the lifecycles afterward. The multiple lifecycle process is presented in the Fig. 6.

3.2.11. Assumptions and uncertainties

The study assumed similar weight of annually collected wastes for the MKRB model and SKGRB models. The allocation coefficient for R7 and R5 in the asphalt and glass container end-of-life stages were also assumed based on consumption. This meant, asphalt will be 100% recycled after the in-use stage (allocation coefficient R5 = 100%) regardless of the loss during demolishing and transportation, and it will be used 100% as RAP. For glass containers, it is assumed there is no R3 Repair, R2 Reuse/resell, and R6 re-purpose involved after the end-of-use/life stage. The glass container will be 100% R7 Recycled (allocation coefficient R7 = 100%). It was assumed in 21 years, there will be four times R5 for the first year of collected waste glass in the trial area under the asphalt scenario. In each R5, the RAP will be 100% recycled, and newly recycled kerbside glass cullet will be added to produce new asphalt. For example, the first R5 happens at year 5. The paved asphalt (produced with year 1 kerbside glass cullet) will be 100% R5 remanufactured with newly recycled kerbside glass cullet. The newly recycled kerbside glass cullet is not necessarily collected from the trial area due to the limited weight which can be collected, but it will go through the same R7 process. It was also assumed that there will be seven times of R7 for the first year of collected waste glass in the trial area under the asphalt scenario, in 21 years. In each R7, the glass containers will be 100% recycled, and newly recycled kerbside glass cullet will be added in the production process.

3.3. Impact assessment method

Life Cycle Assessment (LCA) for the analysis of environmental impacts is available from SimaPro software. This study employed the ReCiPe midpoint (H)/world recipe (H) approach, which is a widely used life cycle impact assessment method. It is based on the hierarchical approach, which allows for a more comprehensive analysis of impact categories. The method includes 18 midpoint impact categories, which encompass a range of environmental concerns. An updated version of ReCiPe 2016 was used in this study to present impacts on a global scale. The following environmental impact categories were selected: climate change, indicator is CO2 eq kg; terrestrial acidification, indicator is SO2

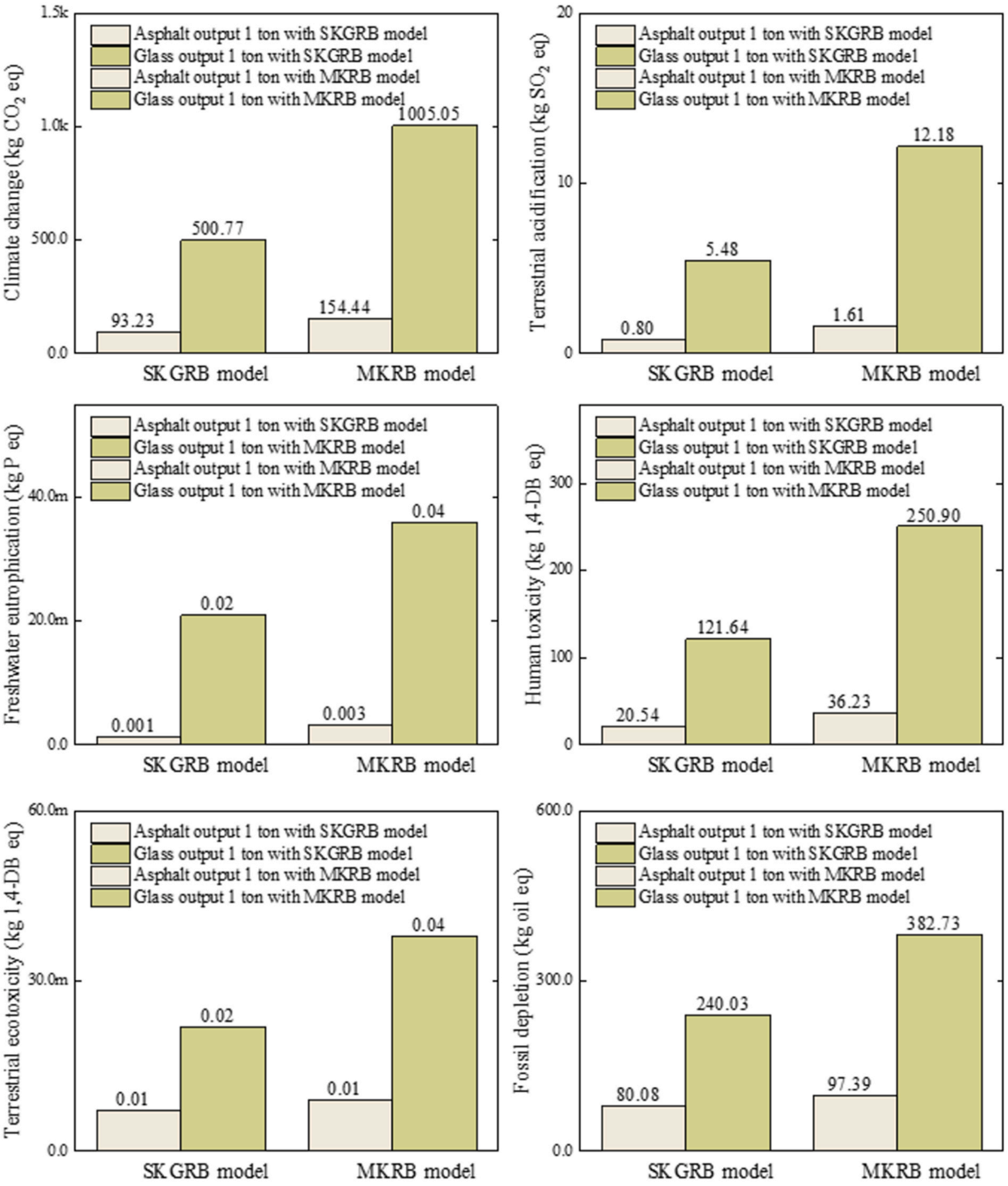

Fig. 7. Environmental impacts associated with producing 1-ton of asphalt (source: Zhang et al. 2022) and glass container using SKGRB and MKRB models.

eq kg; freshwater eutrophication, indicator is P eq kg; human toxicity, indicator is 1,4-DB eq kg; terrestrial ecotoxicity, indicator is 1,4-DB eq kg; fossil depletion, indicator is oil eq kg.

The choice of impact categories was based on their widespread use in the relevant literature. Moreover, this research aligns with the principles of sustainability development goals (SDGs) (Sachs et al., 2022) and reflects the commitment of the Australian government towards sustainable waste management and resource recovery. The SDGs provide a comprehensive framework for addressing global challenges and promoting sustainable development in various sectors, including waste

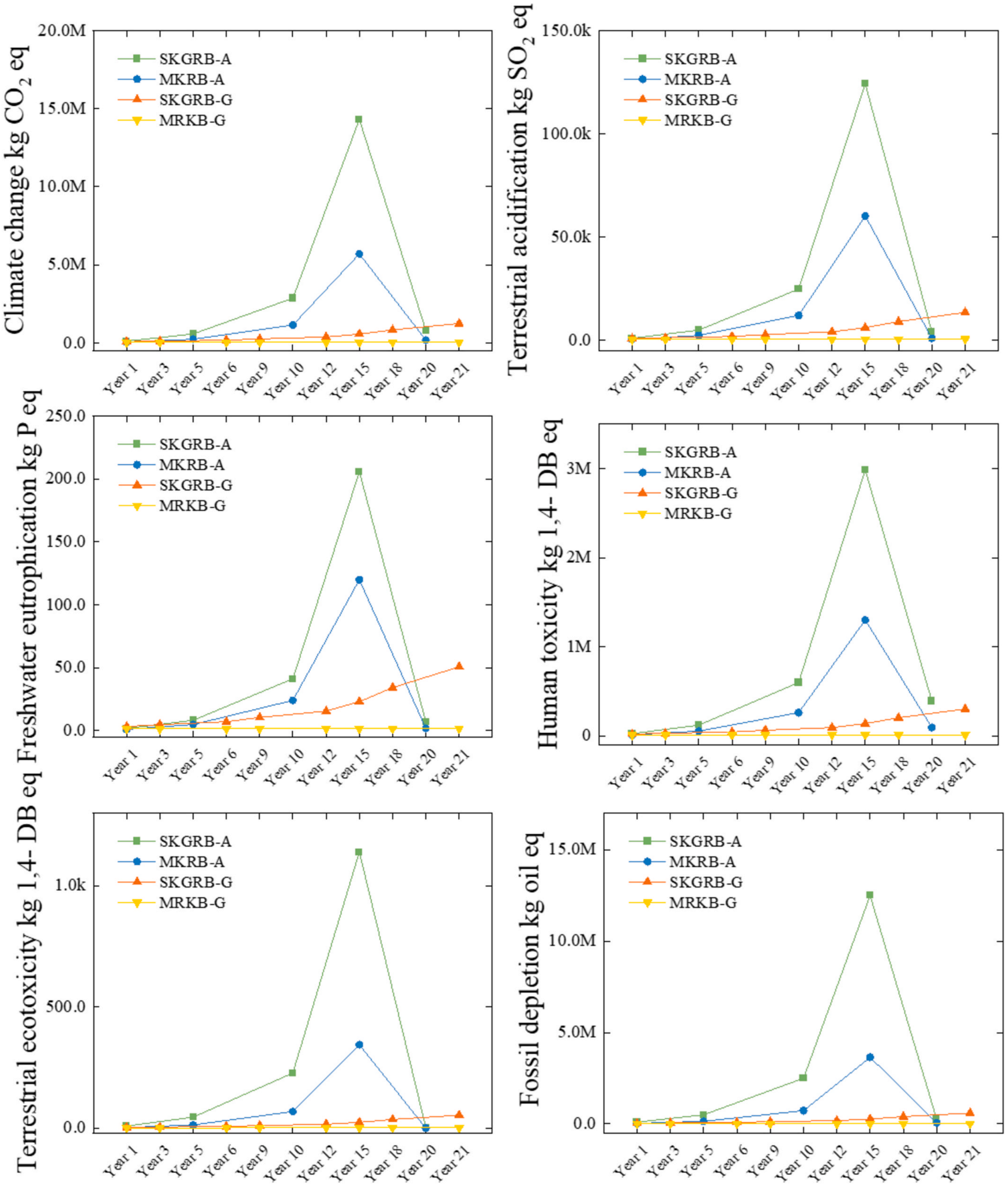

Fig. 8. Environmental impacts of SKGRB-A, MKRB-A and SKGRB- G, MRKB-G in 21 years.

management (Sachs et al., 2022). By incorporating relevant impact categories, this study contributes to the broader sustainability agenda and supports the attainment of specific SDGs related to waste reduction, resource efficiency, and environmental protection. Given the frequent application of the hierarchical (H) process in scientific models (Huijbregts et al., 2017), it was chosen as the analytical method for this study.

4. Results and interpretations

4.1. 1-ton production in the first lifecycle

Fig. 7 illustrates the comparison of 1-ton production during the first lifecycle of SKGRB and MKRB models in both asphalt and glass container scenarios. It presented the results of glass container scenarios for MKRB in comparison to the SKGRB model, using functional units of 1-ton production, and these results are furtherly compared with the Zhang et al. (2022).

When comparing the SKGRB and MKRB models in glass container scenarios, the implementation of a new separate bin method for producing one ton of glass containers results in an approximate 50% reduction in environmental impacts across almost all categories, compared to the previous mixed bin method. In the asphalt scenario, Zhang et al. (2022) observed that implementing the SKGRB model, as opposed to the MKRB model, led to a reduction of approximately 40% in climate change impact categories. For freshwater eutrophication, the SKGRB model demonstrated the potential for up to a 60% reduction in associated impacts. In various other environmental impact categories, the SKGRB model showed reductions ranging from approximately 20%–50%. This reduction in environmental impacts when implementing the SKGRB model can be attributed to a relatively higher energy consumption in the Material Recovery Facility (MRF) stage, with 0.085 kWh/kg, compared to the 0.0225 kWh/kg consumption in the glass sorting facility, particularly during the sorting stage. Waste processed through the MRF and the glass sorting facility in the MKRB model consumes more energy than that processed in the SKGRB model (which only processed through glass sorting facility), resulting in higher overall environmental impacts.

Fig. 7 also compares the environmental impacts of asphalt and glass container scenarios in both the SKGRB and MKRB models, revealing that the glass container scenario exhibits higher environmental impacts across all environmental impact categories. For instance, in the climate change category, CO2 emissions in the SKGRB model for the asphalt scenario are only around 20% of those in the glass scenario. This difference can be attributed to two key factors: 1) Variations in energy consumption during the production processes of asphalt and glass containers; 2) Differences in mix-design requirements. Glass container production requires significantly more energy due to the melting of waste glass cullet and additional materials like silica sand at furnace temperatures of approximately 1500–1600 °C, consuming 6100–7100 MJ of energy per ton of production (Schmitz et al., 2011). In contrast, asphalt production records an energy consumption of 2860 MJ per ton (Hammond and Jones, 2011). Therefore, the emissions associated with energy consumption are considerably higher for glass container production when producing 1-ton products. Further examining the mix-design aspect, waste glass cullet constitutes 64% of the 1-ton production for glass containers, while it accounts for only about 20% in asphalt mix-design. This difference necessitates a larger amount of waste glass cullet for producing 1-ton of glass containers. Specifically, in the SKGRB model, the glass container scenario requires 695 kg of waste input compared to 84 kg for the asphalt scenario. In the MKRB model, these numbers increase to 2941 kg and 357 kg for the glass and asphalt scenarios. The higher amount of waste glass cullet in the glass container scenario results in increased energy consumption during the collection and sorting processes, contributing to higher environmental impacts compared to asphalt during these stages.

4.2. Open-looped and closed-loop recycling of the first year collected wastes circulated in models for 21 years

Fig. 8 shows the comparison of the results of the weight of first year collected kerbside waste glass to produce asphalt/glass containers in 21 years of time. 20 years is the lifespan of an asphalt urban road. In these 21 years, the kerbside waste glass made glass container is assumed to be recycled 7 times. The asphalt wearing course has been maintained 4 times. From VRP perspective, for a closed-loop recycling, it has been R7 for 7 times, while for an open-loop recycling, it has been R5 for 4 times.

Fig. 8 presents the increased environmental impacts of every loop in 21 years for 4 scenarios of functional unit annually collected waste. SKGRB-A and MKRB-A loop every 5 years, and SKGRB-G and MKRB-G loop every 3 years. For SKGRB-A and MKRB-A which is chosen to represent the open-looped recycling, the loop stops at the year 20 for twenty year is regarded as the end-of-life for urban road in Victoria. The environmental impacts at the last loop at year 20 only considered the end-of-use/life stage, not further recycling activities due to the system boundary chose in this study. It does not mean that the demolished road cannot be R5 remanufactured. For SKGRB-G and MKRB-G, which is chosen to represent the closed-loop recycling, the loop continues after 21 years.

As it shows in the figure, SKGRB-A has the highest environmental impacts in all the categories due to the reason it has the largest amount of asphalt production in 21 years of 200, 245 tons in total and consumed 16,863 tons of wastes in the trial area. While MKRB- G which has the lowest environmental impacts in all the categories, only produces 328 tons of glass containers and consumes 940 tons of wastes in 21 years. In general, SKGRB-A and MKRB-A have higher environmental impacts comparing to SKGRB-G. However, it is worth to mention that with the functional unit of 1-ton production, the glass container method has higher environmental impacts comparing to the asphalt method. This is resulted by melting glass and other material requires large amount of energy. For example, the electricity used in glass container production is 0.159 kWh/kg while in asphalt production is 0.0074 kWh/kg.

4.3. Comparing the results of two functional units

Comparing the results of function unit 1-ton production in the first lifecycle and the first year collected kerbside waste glass to produce asphalt/glass containers in 21 years of time span, the implementation of early waste separation techniques significantly affects the environmental impacts of asphalt and glass container production derived from municipal waste glass. When considering a 1-ton functional unit of product, the separate glass bin method emerges as the most sustainable option for both closed-loop recycling (glass container production) and open-loop recycling (asphalt production), outperforming the traditional mixed bin method. With functional unit 1-ton production, through closed-loop recycling, a significant reduction of nearly 50% in environmental impacts can be achieved across most impact categories when switch the traditional mix bin method to the separate glass bin method. The open-loop recycling yields an environmental impacts reduction of approximately 40%, with some categories experiencing up to a 60% reduction when switch the traditional mix bin method to the separate glass bin method. The reason for the variation in environmental impacts reduction when switching the waste collection methods for the open-looped and closed-loop scenarios is due to differences in the production processes and mix-design of the glass container (closed-loop) and the asphalt (open-loop). These differences in production processes result in varying energy consumption during production stage. Additionally, the distinct mix-designs lead to different weight requirements for the glass, which in turn affects the energy needed for collection and sorting. Despite higher environmental impacts associated with asphalt production (open-looped) over a 21-year period due to the production of a larger quantity of asphalt, for a functional unit of one ton per lifecycle, waste material from glass container production (closed-loop) has greater environmental impacts when compared to that of asphalt production. It means that in 21 years, asphalt has higher environmental impacts but has lower environmental impacts in 1-ton production in the first lifecycle comparing to the glass container scenario. In 21 years, asphalt has higher environmental impacts because this scenario has higher total asphalt production with the first year collected waste material (Table 3) comparing to glass container scenario (Table 4). In 1-ton production in the first lifecycle, the asphalt scenario has lower environmental impacts due to the reason that asphalt production requires less energy comparing to glass container scenario in production stage.

4.4. Sensitivity/uncertainty analysis

Sensitivity/uncertainty analysis is performed to assess how

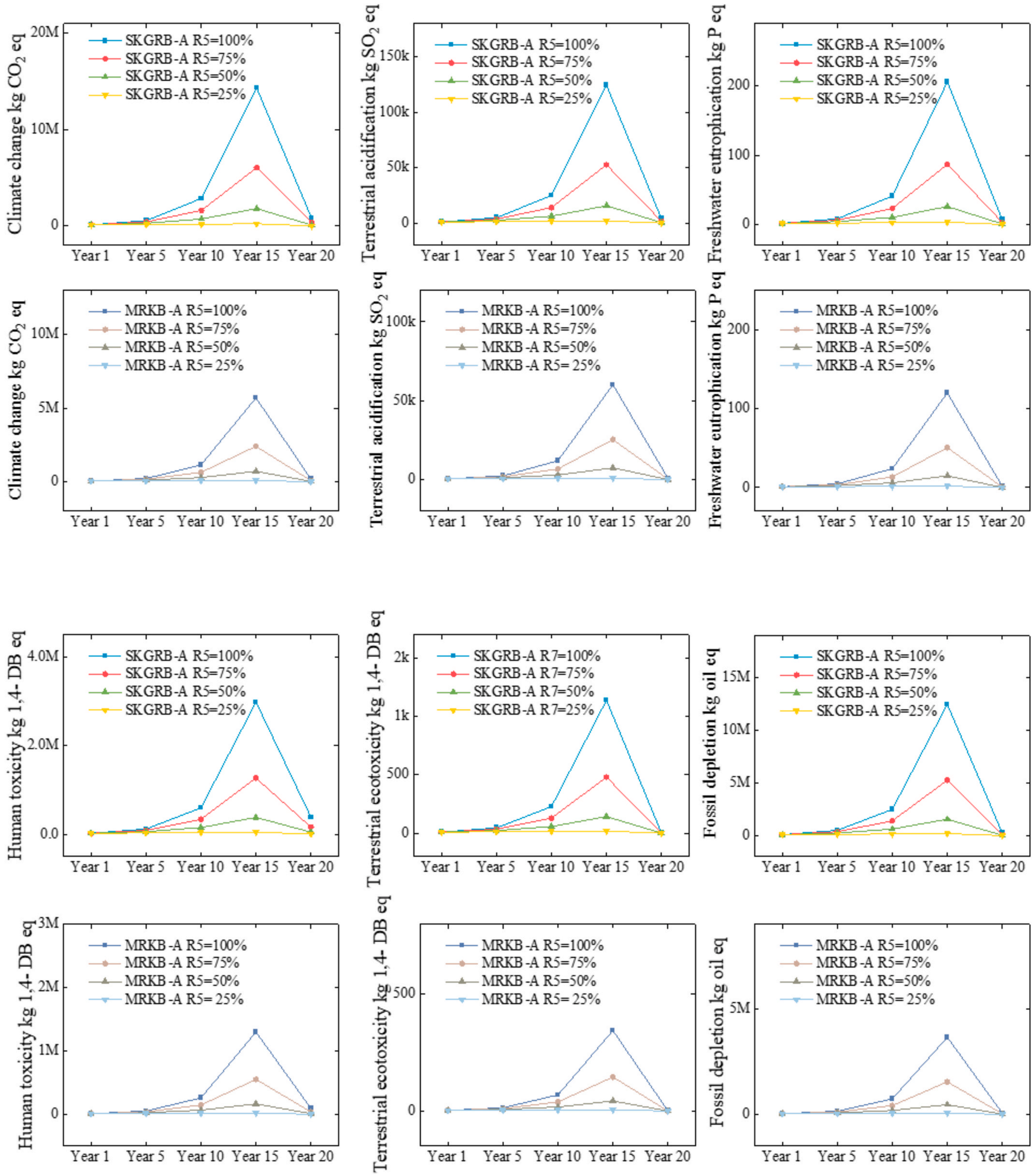

Fig. 9. Sensitivity/uncertainty analysis for asphalt scenarios.

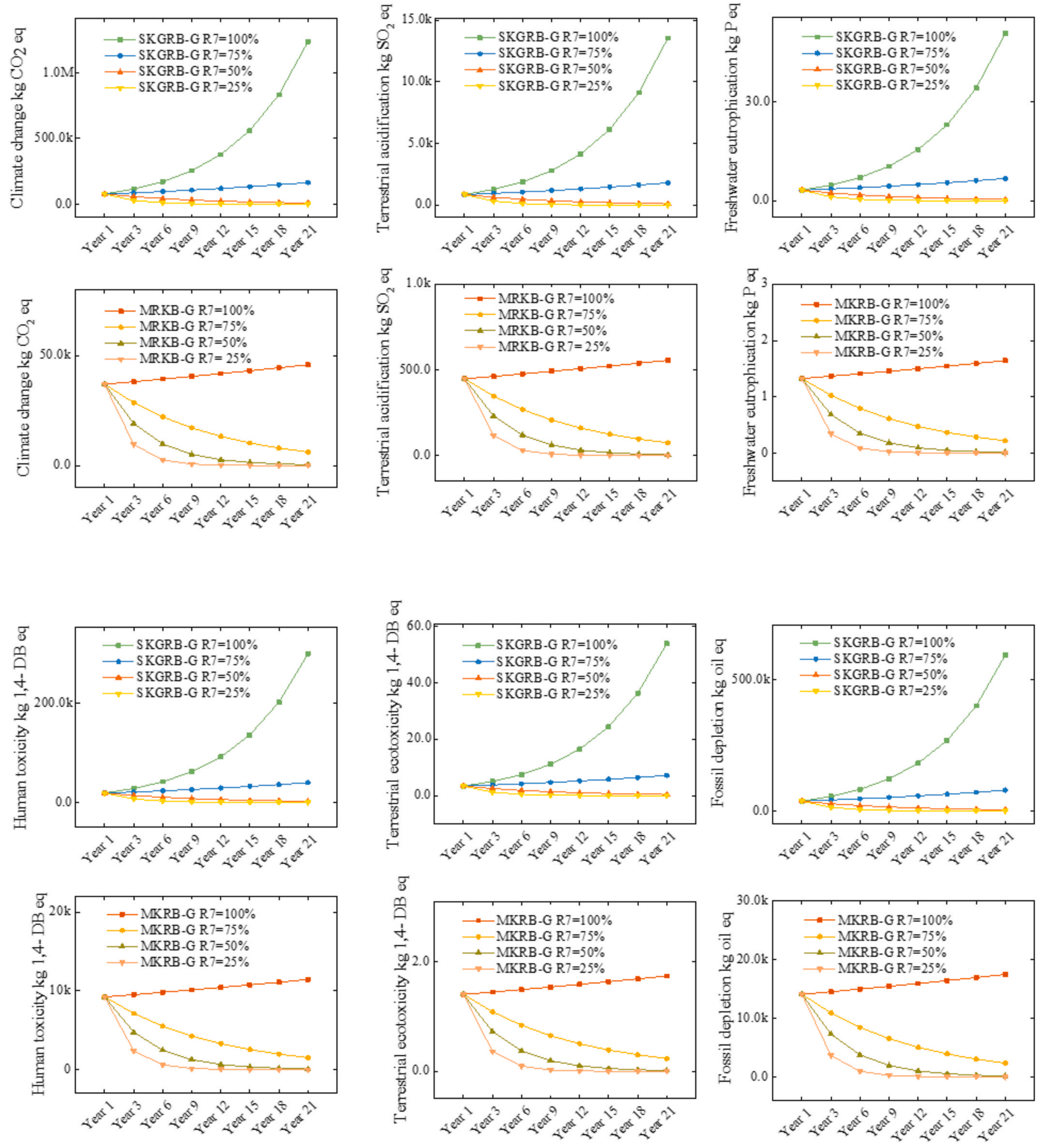

Fig. 10. Sensitivity/uncertainty analysis for glass container scenarios.

variations or changes in certain input parameters affect the outcomes or results of the model. It helps to 1) ensure the quality and reliability of models for applicability to other cases; 2) to explore various uncertainty scenarios effects on the model. The sensitivity/uncertainty analyses in this study were based on the key factor of R-imperatives which to start the second lifecycle. The allocation coefficient for R7 (glass container scenarios) and R5 (asphalt scenario) is assumed to be 100% for starting the next lifecycle. Since in the real life it is difficult for materials to be 100% R7 (recycled) and R5 (remanufactured), thus this study conducted sensitivity/uncertainty analysis of R7 and R5 = 75%, 50%, and 25% to monitor the change of environmental impacts for glass container and asphalt scenarios.

Fig. 9 shows the sensitivity/uncertainty analysis results of asphalt scenarios for SKGRB and MKRB model. As it shows in the figure, there is a rapid increase of environmental impacts when the allocation coefficient of R5 = 100%. As the allocation coefficient of R5 decreases, environmental impacts also decrease in every category. When the allocation coefficient of R5 = 25%, the increase of environmental impacts becomes steady. Both SKGRB and MKRB models follow this pattern. It is because of a% in the mixed design of asphalt is around 25%. For the comparison of SKGRB and MKRB. The increased environmental impacts for MKRB is around 60% less than the SKGRB due to the amount of produced asphalt is 60% less for MKRB model.

Fig. 10 shows the sensitivity/uncertainty analysis results of glass container scenarios for SKGRB and MKRB model. As it shows in the figure, there is a rapid increase of environmental impacts when the allocation coefficient of R7 = 100%. As the R7 decreases, environmental impacts also decrease in every category. When the allocation coefficient of R5 = 25%, the increase of environmental impacts becomes steady. Both SKGRB and MKRB model follow this pattern. It is because the a% in the mixed design of asphalt is around 25%. For the comparison of SKGRB and MKRB. The increased environmental impacts for MKRB is around 60% less than the SKGRB due to the amount of produced asphalt is 60% less for MKRB model.

5. Conclusions

The study introduces a novel life cycle inventory model that incorporates circular economy principles to evaluate the recycling processes of kerbside waste. The model effectively addresses crucial aspects, including the distinction between open-loop and closed-loop recycling methods, and facilitates comprehensive comparisons across multiple life cycles. These advancements in the model's design address significant gaps in the existing understanding and implementation of circular economy principles. Its significance lies in providing a scientifically grounded framework for life cycle assessment in the production of asphalt and glass containers, supporting waste management designs, studies, and environmental claims by producers.

Through a comprehensive evaluation, this study examines the environmental impacts associated with producing 1 ton of asphalt and glass containers using waste glass from separate kerbside glass recycling bins (SKGRB) and mixing bins of recycling (MKRB). Moreover, it aims to assess and compare the environmental consequences of the weight of kerbside waste collected over the course of 21 years for asphalt and pavement/glass container production using these two distinct recycling models.

The case study findings are as follows:

1. In a single lifecycle, for a functional unit of 1-ton production: The SKGRB method outperforms the MKRB method in terms of environmental performance, achieving a 40–60% reduction in both asphalt and glass container production. Glass container production has higher environmental impacts compared to the asphalt production method, primarily due to increased energy consumption during the production stage.
2. Comparing closed-loop recycling and open-loop recycling over a 21-year period: Despite its higher recycling rate and production, the SKGRB method results in higher environmental impacts. The open-loop recycling method (asphalt production) incurs higher environmental impacts, mainly due to the substantial volume of product manufactured, even though it involves fewer circulation cycles.
3. Furthermore, the sensitivity/uncertainty analysis reveals that as the allocation coefficient (R5 and R7) decreases, the environmental impacts also decrease. When the allocation coefficient aligns with the waste materials percentage in the mixed design of new products, the environmental impacts stabilize, indicating a notable change in the impact curves.

When recommending policies and practices, it is crucial to emphasize stakeholder identification and the selection of an appropriate functional unit for environmental assessment. One avenue to enhance the future sustainability of the kerbside waste material loop process is the integration of renewable energy into sorting and production processes. For the utilization of municipal solid waste materials in production, careful consideration must be given to early-stage recycling methods and processes. It is essential to recognize that different recycling methods and processes exert significant influences on the environment.

CRediT authorship contribution statement

Jingxuan Zhang: Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Muhammad Bhuiyan:** Conceptualization, Validation, Investigation, Resources, Writing – review & editing, Supervision, Project administration. **Guomin Zhang:** Conceptualization, Validation, Investigation, Resources, Writing – review & editing, Supervision, Project administration. **Malindu Sandanayake:** Validation, Investigation, Writing – review & editing, Project administration.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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