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Application of recycled crushed glass in road pavements and pipeline bedding: An integrated environmental evaluation using LCA

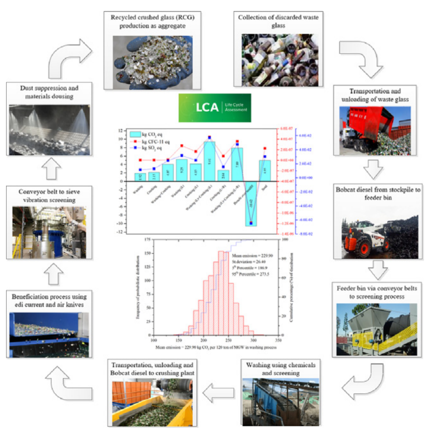
Quddus Tushar [a], Safoura Salehi [b], Joao Santos [c], Guomin Zhang [a], Muhammed A. Bhuiyan [a], Mehrdad Arashpour [b], Filippo Giustozzi [a,]*

[a] Civil and Infrastructure Engineering, RMIT University, GPO Box 2476, Melbourne, VIC 3001, Australia
[b] Department of Civil Engineering, Monash University, Melbourne, VIC 3800, Australia
[c] Department of Construction Management and Engineering, University of Twente, Enschede, the Netherlands

HIGHLIGHTS

- The environmental impacts to produce aggregates from the recovery of waste glass were evaluated.
- The processes of washing waste glass and crushing it were modelled using primary data from the plant.
- LCA shows environmental benefits from recycling waste glass compared to disposing it in landfills.
- Various applications were considered for the use of recycled glass aggregate in construction.
- Several scenarios analyses were conducted to identify variations due to energy sources.

GRAPHICAL ABSTRACT



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ABSTRACT

The study aims to conduct a comprehensive life cycle assessment (LCA) of mixed glass waste (MGW) recycling processes to quantify the environmental impacts of crushed glass as a partial substitute for virgin aggregate. Upstream washing, crushing, and sorting conducted at material recycling facilities (MRF) are the prime activities to assess whether reprocessed MGW in pavement construction is an alternate feasible solution. None of the previous studies explicitly account for the relative uncertainties and optimization of waste glass upstream processes from an environmental perspective. The study calculates environmental impacts using the LCA tool SimaPro considering design factors attributed to transportation, electricity consumption, use of chemicals, and water for reprocessing glass waste. Relative uncertainties of design variables and the national transition policy (2021 – 2030) from non-renewable to renewable energy sources have been validated by performing detailed Monte Carlo simulations. The correlation coefficients (r = 0.64, 0.58, and 0.49) of successive variables explain how the higher environmental gains of the glass recycling process are outweighed by diesel, energy consumption, and transportation distances. Compared to natural quarry sand, the recycled glass aggregate produced through crushing and recycling of its by-products reduces CO_2eq emissions by 16.2 % and 46.7 %, respectively. The need for a washing line at the plant, in addition to crushing, results in a higher environmental impact over natural sand by 90.1 % and emphasizes the benefits of collecting waste glass through a separate bin, hence avoiding contamination. The result indicates that the benefit of lowering emissions varies significantly when considering waste glass landfilling. Moreover, this study evaluates the potential impacts

* Corresponding author at: RMIT University, School of Engineering, 124 La Trobe St, VIC 3001, Australia.
E-mail address: filippo.giustozzi@rmit.edu.au (F. Giustozzi).

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on asphalt and reinforced concrete pavements (RCP) with 5 %, 10 %, 15 %, and 20 % replacement of natural sand with recycled glass aggregate. The LCA emphasizes the limitations of energy-intensive waste glass reprocessing. The obtained results and uncertainty analysis based on primary MRF data and recycled product applications provide meaningful suggestions for a more fit-for-purpose waste management and natural resource conservation.

1. Introduction

Traditional transport infrastructure significantly contributes to environmental degradation by depleting natural resources, consuming electricity and fuels, and generating emissions. The extraction of natural resources such as minerals and rock mining accounts for 7 % of global energy consumption. Energy-intensive resource extraction activities are divided into mainly crushing (32 %), transportation (24 %), ventilation (9 %), and excavation (8 %) (Holmberg et al., 2017). Population growth is the primary cause of booming construction activities and worldwide waste generation. Globally generated waste is projected to double by 2050 and triple by 2100 compared to 2016 (Ferdous et al., 2021; Tushar et al., 2019). Therefore, effective management and the potential for recycling waste are of utmost importance for a more sustainable development. The application of waste materials as an alternative source in construction activities should be assessed from a lifecycle and energy efficiency perspective.

A considerable amount of waste is dumped in landfills, causing significant environmental impacts such as soil and water contamination and air pollution (Abd El-Salam and Abu-Zuid, 2015). Globally produced solid waste is believed to account for 5 % of total carbon emissions and the incineration of waste further increases that estimate (Jia et al., 2018). Improvement of waste management practices can reduce CO_2 emissions by 15 % and save significant landfilling costs (Ferdous et al., 2021). The estimated cost per ton of dumping perishable waste in landfills ranges from $45 to $105 in urban areas and $42 to $102 in rural areas (Collins, 2009). However, landfilling waste is not a suitable option due to the scarcity of landfills, associated environmental impacts, and costs. Therefore, material recycling facilities (MRFs) have been developed to minimize these impacts, recycling and reusing waste products as alternative construction materials.

In Australia three primary sources of waste can be identified: municipal solid waste (MSW) from household activities, construction and demolition waste (C&DW), and commercial and industrial waste (C&IW). Approximately, 74 million tons of trash are generated annually in Australia, including masonry, organic matter, ash, hazardous waste, paper, plastic, glass, and metals, equivalent to 2.94 tons per capita (Joe Pickin et al., 2020). Nearly 46 kg of waste glass is generated per capita, and recycling rates remain between 54 % and 61 %. The trend of glass production continues to decline due to the sharing with the current plastic and aluminium cans markets. Nevertheless, glass jars and bottles have advantages over other recyclable products due to their endless 100 % recycling without compromising quality (Kovacec et al., 2011). However, waste sorting facilities tend to crush glass into smaller pieces contaminated with paper, cardboard, plastic, and others, which are difficult to recover. Therefore, the alternative use of recycled glass as aggregates in transportation infrastructure, such as road pavement layers has been prioritized in the Australian construction sector.

Several experimental studies have been conducted to evaluate the potential of waste glass aggregate in various construction forms. As an alternative to silica fume powder, recycled glass powder from waste improves concrete's loading capacity and ductility (Tayeh et al., 2021). Experimental studies reveal that using waste glass aggregates as a substitute for sand aggregates by 0–15 % reduces concrete's tensile and compressive strength (Taher et al., 2021). Recycled waste glass was blended with sodium hydroxide as an alkali-activated material, replacing up to 17 % binder ordinary Portland cement (OPC) (Samarakoon et al., 2021). However, the environmental impacts are yet to be addressed when using recycled glass in pavement construction aside from glass aggregates' mechanical and chemical performance. Therefore, the impacts of crushed glass processing and associated advantages over landfills have been verified in this study.

Further, from an environmental standpoint the use of recycled waste glass as a substitute for aggregates in road infrastructure has become questionable due to excessive energy consumption and carbon footprint during the recycling process in comparison with the extraction of natural quarry aggregate. Some scepticism has risen indicating that using recycled glass to replace aggregates causes more energy consumption and CO_2 emissions than sending it to landfills (Blengini et al., 2012; Didier Bodin et al., 2022). The inclusion of recycled materials in asphalt mixtures would require an up-to-date database of reprocessed products to properly identify the associated environmental emissions (Tushar et al., 2022b). Attributional life cycle assessment of the processes taking place at the material recycling facility (MRF) is one of the options to quantify the environmental impacts associated with the use of recycled glass aggregates for road pavement infrastructure. However, the literature on this domain remains scarce.

Deep decarbonization is an impressive trajectory of Australia's policy-making to limit global warming temperatures below 1.5 °C by a possible transition towards renewable energy sources as per the Paris Agreement (Pye and Bataille, 2016). The current transition towards renewable-based energy sources is projected to generate 64 % of electricity in the national grid by 2030 and 94 % by 2050 (Goddard and Farrelly, 2018). Detailed modelling of these scenarios was prepared in collaboration with CSIRO, the Brattle Group, and ClimateWorks Australia (Vorrath, 2021). Variations in potential energy sources are suggested to be conducted when analysing industrial applications. The study analyses the effects of the deep decarbonization strategy along with the impact pathway for industrial manufacturing processes, it also emphasizes the probable energy storage capacity in the future. The relative uncertainties of alternative energy production sources can be used as a driving force for shifting towards renewables.

Waste glass management at disposable sites is a severe environmental issue due to these wastes' non-perishable and non-combustible nature and the running shortage of landfill sites (Hayat, 2023; Muthuraman and Ramaswamy, 2019). Generated waste glass from household, construction, and demolition sites has the great potential to recycle as aggregates rather than disposed of in landfills. Additionally, alternative sources of aggregates are required to justify from a sustainability perspective, as local quarries are expected to run out shortly. Therefore, this study uses the primary data from recycling facilities to quantify, compare, and measure the relative environmental impacts of two consecutive processes of recycled glass aggregate production; washing and crushing. The consequential approach of LCA will assist in identifying the sustainability of RCG as aggregates substitute for various pavement applications (Giustozzi et al., 2012). Sensitivity indices of the recycling process assist in prioritizing the design parameter and optimizing waste management systems' efficiency to encourage the usage of recycled products instead of virgin materials.

2. Objectives and methods

This study conducted a comprehensive LCA of a glass recycling facility to estimate the environmental impact of recycled glass-derived products and determine more appropriate waste management options, as shown in Fig. 1. The environmental impacts and uncertainties of recycled crushed glass manufacturing were assessed by considering two processes commonly

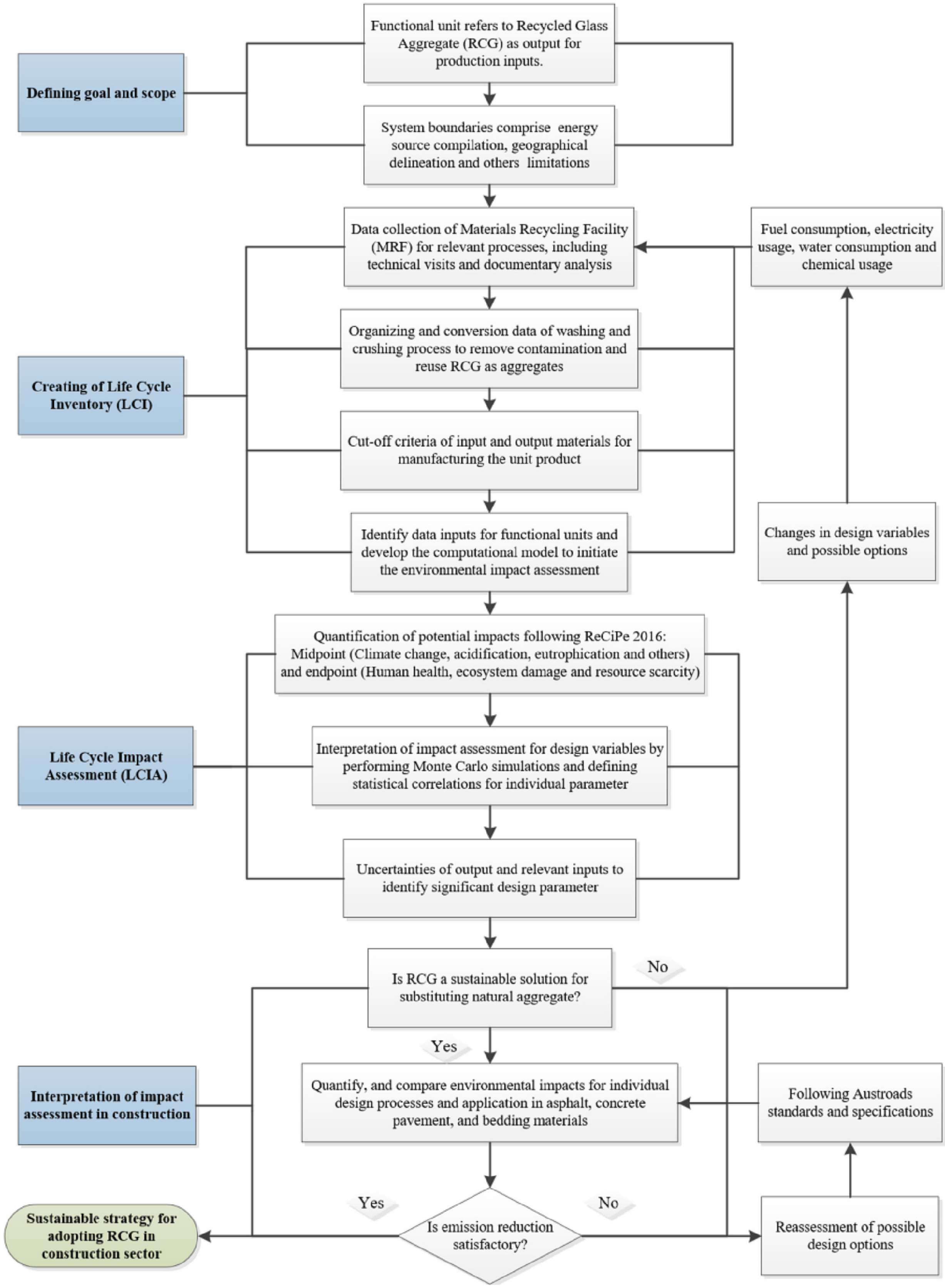


Fig. 1. Methodological framework for conducting LCA on recycling processes at materials recycling facilities.

taking place at the recycling facility during the handling of waste glass, washing and crushing. The LCA study was implemented following four sequential steps: defining the goal, creating a life cycle inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpreting the results. The conceptual phases of LCA are presented in this study according to the standard ISO14040 (Arvanitoyannis, 2008; Nizamuddin et al., 2021).

First, the scope of performing a LCA study on recycled glass aggregates is to evaluate the manufacturing system boundaries and product's functional unit. These provide the basis for comparing and analysing recycled crushed glass as an alternative to virgin quarry aggregate.

Secondly, LCI was developed considering the processes carried out at the recycling facilities to generate recycled glass aggregates. The necessary operations, such as collecting, washing, and crushing, are compiled to assess the product's environmental burdens at the 'gate'.

Thirdly, LCI was followed to evaluate the process impacts. The outcomes of the life cycle impact assessment (LCIA) were further processed to evaluate the weight of some uncertainties on the variation of the potential energy source. Monte Carlo simulations determine thousands of possible outcomes by sampling input design variables (Fichthorn and Weinberg, 1991; Tushar et al., 2022a).

Finally, the obtained LCA results for the production of recycled crushed glass (RCG) as a substitute for virgin aggregate (quarry sand) were applied to the practical construction scenarios of asphalt and concrete pavements, as well as filling material (piping). The overall outcome of this assessment will facilitate the adoption of more environmentally friendly strategies when selecting recycled materials for construction applications in road infrastructures.

2.1. Goal and scope definition

This stage defines the general objective, data sources, system boundaries, and functional unit of the LCA study. The study aims to assess the environmental impacts of recycled glass aggregates compared to the conventional sand aggregates used in infrastructure projects. Life cycle inventory identifies the recycling processes' significant inputs and outputs by balancing mass and energy (McDougall et al., 2008; Tushar et al., 2021b). This study considered a detailed life cycle inventory (LCI) of the RCG process, comprising inputs of material quantity, transportation distance, electricity consumption, use of chemicals, and outputs such as air, soil and waterborne emissions at each life cycle stage.

2.1.1. Functional unit

The functional unit is a crucial element of LCA, which provides a reference for comparing different products or systems that deliver the same function (Kim et al., 2017; Polo-Mendoza et al., 2022). The functional unit of the LCA performed in this study is 1-ton recycled glass aggregate (RGA) produced from waste glass in Australia. A relative comparison of 1-ton of sand produced from quarry extraction and RGA - through two recycling processes (washing and crushing) - was evaluated from a sustainability perspective. Moreover, the design of asphalt and concrete mixtures for a 1-km stretch of road was considered in this study by incorporating RGA in different proportions as per the individual mix design.

2.1.2. System boundaries

Specifications in LCA system boundaries require several dimensions, such as technical data compilation, energy sources, geographical delineation, time horizon, input and output relationships, and associated life cycles of other products (Li et al., 2014; Tillman et al., 1994). An iterative process is preferred to determine the initial system boundary for conducting LCA. However, further refinements were included in this study to incorporate variations in energy sources as a function in the system boundary by performing a sensitivity analysis of the parameters involved.

The system boundary for identifying the impacts of RGA included the processes occurring during two different activities at the recycling facility, i.e. washing and crushing, as shown in Figs. 2 and 3. The processes taken into consideration also include transportation/hauling and diesel consumption, electricity, chemicals, and water usage to produce glass aggregate. The extraction of other raw materials, such as sand, gravel, binders (cement and bitumen), hydrated lime, and their manufacturing, mixing, transportation, and placement, were also considered for pavement construction operations as shown in Fig. 4.

2.1.3. Allocation issues

The research significance was enhanced by looking also into the capacity of glass recycling to reduce landfills and the perceived environmental advantages of recycling over landfills. In fact, recyclable waste materials such as aluminium, glass, and other metals have low calorific values and are considered inefficient for energy recovery either in gasification pyrolysis or incineration (Demetrious and Crossin, 2019). This study calculates the environmental impacts associated with the recycling of waste glass, hence avoiding its dumping into landfills.

Usually, collected waste glass at MRFs is contaminated with food residues, foils, container tops, paper, wood, and labels. Similarly, glass from construction and demolition sites can contain metal, ceramics, plaster, rubber, plastic, bitumen, paint, cloth, and other organic matter. The collection of waste glass via a separate bin scheme can provide a product that is mostly free from debris such as cardboard, paper, plastic, fabrics etc. However, within the many sources of glass present in a waste container, laminated and reinforced glass, fluorescent and cathode-ray tubes, and light bulbs are considered hazardous and recommended not to be used for recycling purposes (Kaya, 2016).

Less contaminated glass is used successfully as a substitute for aggregates through the crushing process, where dust suppression and material dousing systems eliminate (or drastically reduce) the contaminants. However, contaminated mixed glass waste must be washed before crushing to ensure the removal of odours, soils, and organic substances such as sugar and oil. Soluble salts are removed through the washing process; otherwise, these mixed salts may deteriorate the pavement quality or cause efflorescence. The by-products of a glass recycling facility are usually plastic in various forms, plaster, and paper, which cannot be reprocessed and are commonly landfilled. Additionally, 5 % of by-products consist of high-density bricks and tiles that can be used further as coarse aggregates in fillings and embankments.

2.2. Life cycle inventory

Life Cycle Inventory (LCI) is the compilation of detailed inputs such as materials, fuel, and energy resources and their relevant output emissions to water, soil and air at each life cycle stage. Details about the modelling of the various stages and processes relevant for the system considered in this case study are provided in the following sections. Additionally, more details about the manufacturing process are provided in the following section. AusLCI is the national database covering Australia's primary materials, chemicals, electricity, fuel, and waste disposal system (Grant, 2016). The usage of the AusLCI database is more appropriate than others for this case study due to its operation management from industrial facilities. The consecutive steps of collection, transportation, and production of glass aggregates are modelled and evaluated using SimaPro 9.2 software. SimaPro is widely used and one of the most accepted tools for conducting LCA (Consultants P, 2008). The software comprehensively analyses successive procedures for the manufacturing and usage of RGA and compares those with alternative construction materials for achieving more sustainable construction operations.

2.2.1. The manufacturing process of recycling waste glass

A significant proportion of recycled glass is collected from drink bottles and food jars, including amber, clear and green glass, which can be used as glass cullets. However, glass obtained from kitchenware, light globes, windows, laboratory glassware and drinking glasses is not suitable for use as glass cullets for re-manufacturing bottles due to their different properties compared to jars and bottles. Therefore, much of the generated waste glass ends up in landfills, and recovery is still not widespread. The use of waste glass as aggregates in pavement construction is one of the suitable options for relieving landfilling space. The collected waste glass is transported to the MRF for relevant processes of washing and crushing. The average fuel consumption of a rigid truck is 28.6 L for 100 km, as per the Australian Bureau of Statistics (Statistics ABo, 2020). The fuel consumption of trucks was considered in this study to identify the relative impacts of transportation.

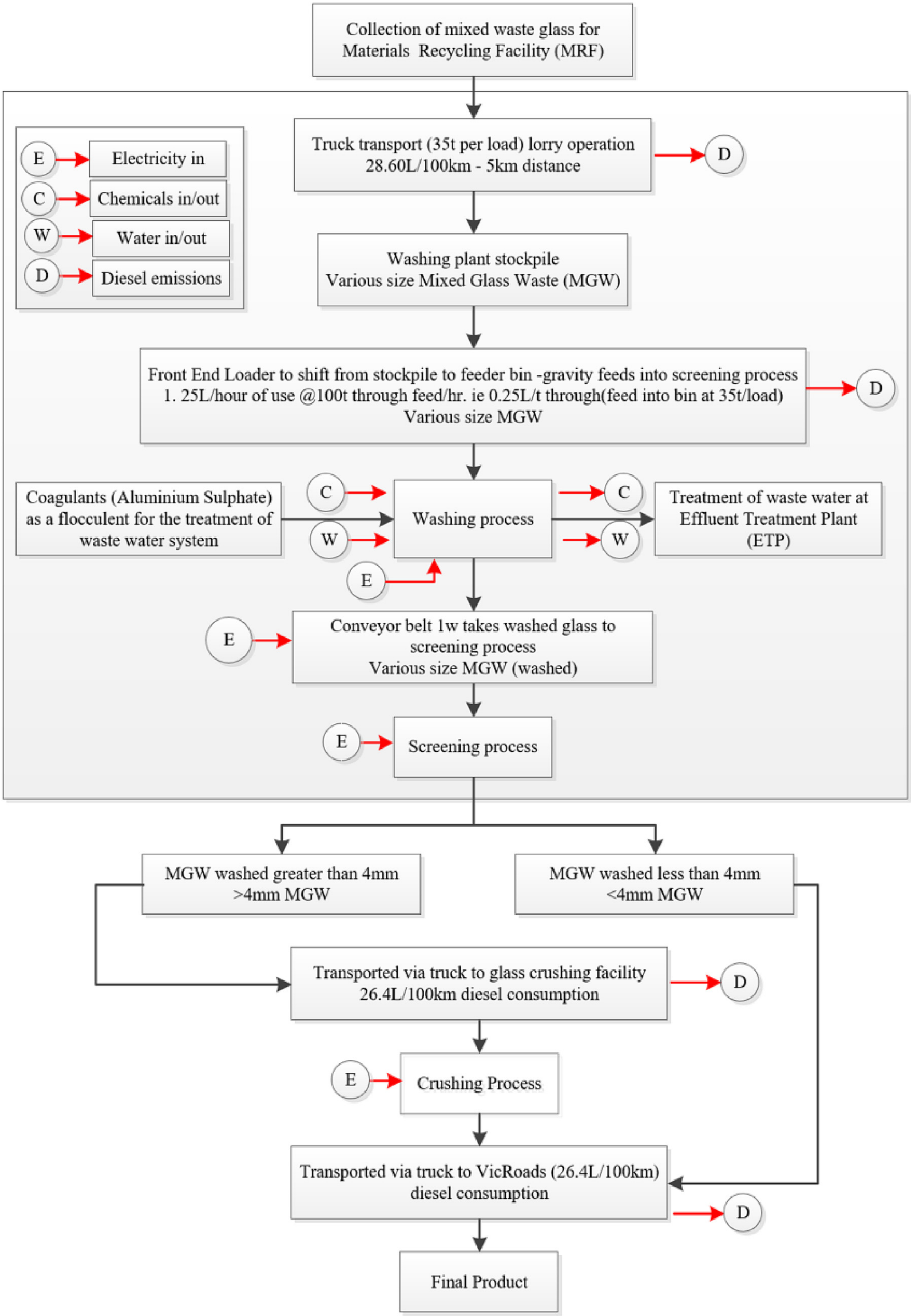


Fig. 2. System boundary of the washing plant for recycled crushed glass (RCG).

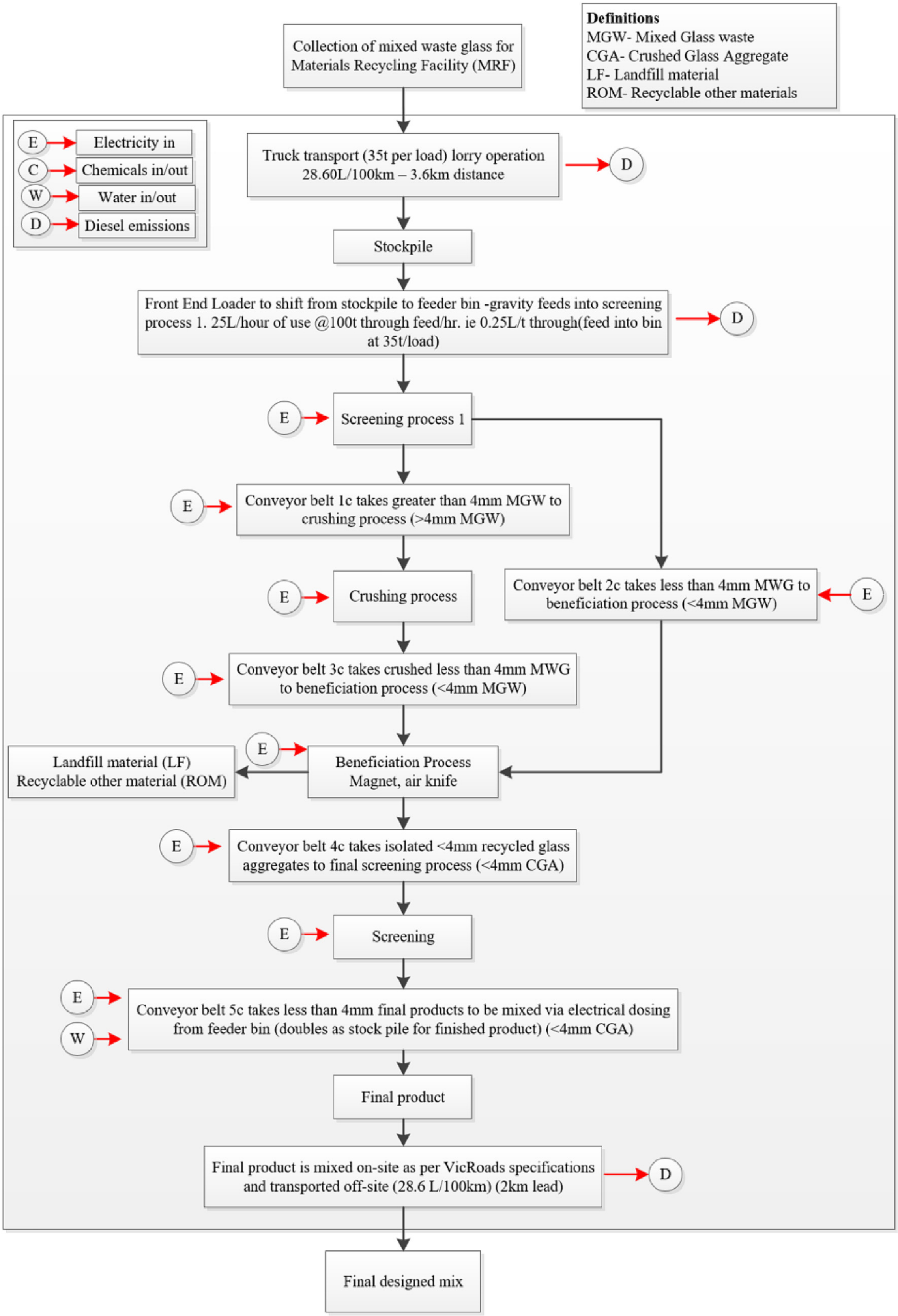


Fig. 3. System boundary of the crushing plant for recycled crushed glass.

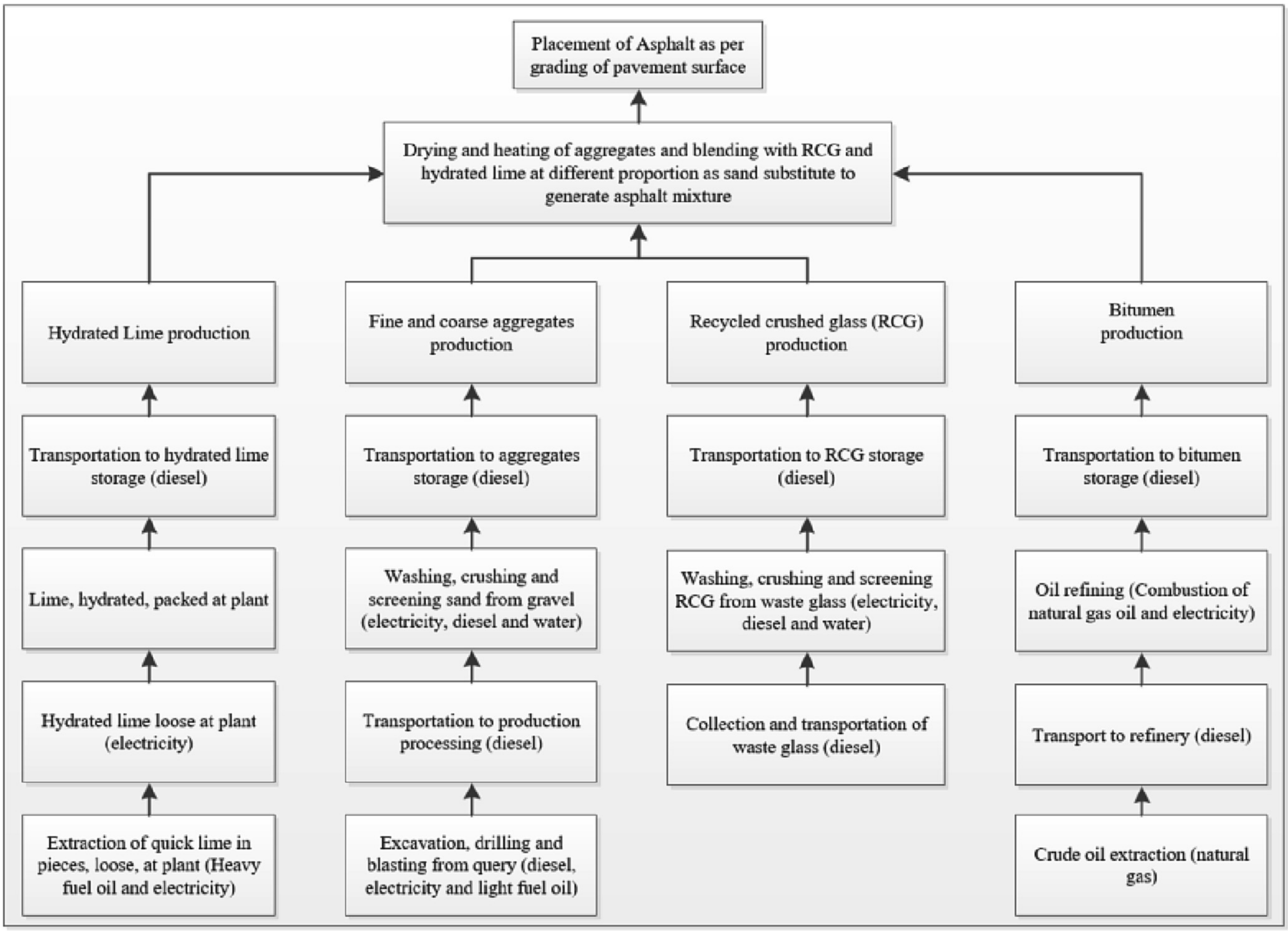


Fig. 4. System boundary of asphalt pavement construction as per Australasian Life Cycle Inventory (AusLCI)(Grant, 2016).

2.2.1.1. Recycling of mixed glass waste. Initially, mixed glass waste is transported to the recycling site to wash out impurities. Two categories of contaminants are present in mixed glass waste (MGW): contaminants that can be recycled after washing – recyclable other materials (ROM) – and contaminants that cannot be recycled after washing and require dumping in landfills (LF). The waste glass washing process is intended to remove impurities that can deteriorate the properties of glass. The presence of organic substances such as residual sugars, glues, and paper on the glass surface is the primary cause of this issue. Additionally, these contaminants deteriorate over time, hence leaving a void or a weak point in the concrete or asphalt mixture. The bonding properties of glass are affected by its contamination; the presence of contaminants should thus be limited to a specific threshold not to hinder the desired physical and chemical characteristics for usage in transport infrastructure projects.

2.2.1.1.1. Washing plant. The washing process of glass waste comprises some simple steps, as shown in Fig. 2. Transported glass is stockpiled at the MRF, where the sizes of stored glass vary from coarse (150 mm) to dust (0.75 mm). A front-end loader is used to transport glass to the washing and sorting plant. Conveyor belts carry the material from a gravity-fed silo to the next steps of the sorting process. Diesel fuel and electricity consumption are considered for front-end loaders and conveyors.

Then, the glass undertakes a screening process on the conveyor belt system to remove impurities/large particles from other waste. The screened glass is washed using a high-pressure spraying system and immersed in a chemical mixture controlled by an electric motor system. Aluminium sulphate (Alum) is used as a liquid flocculant for treating wastewater generated by the washing process (Asharuddin et al., 2019). Alum combines small impurities into a form of floc that settles at the bottom of the water tank and is filtered from time to time. Alum is widely used for the treatment of wastewater. The dose of alum varies from 50 mg to 15 mg per litre, depending on the water quality. The pH of water is regularly checked and, in the case of a low value (i.e. less than 6), baking soda (sodium bicarbonate) or soda ash is added to the mix. A continuous supply of 500 mL alum per 10,000 L of water is required to disperse the alum. A slow mechanical stirring is also carried out. It is desirable to mix the blend for several hours and leave it for 6–8 h to settle down.

The waste glass particles are passed through a series of sieves after decontamination. In the sieve analysis, the gradual agitation sorts out the

Table 1
Life cycle inventory of the washing plant for generating recycled glass aggregate.

Sequential steps	Washing plant processes	Resources	Consumption (fuel, electricity, and others)
1	Transport of 120 t mixed glass waste (MGW) to the washing plant	Diesel	4.90 L
2	Front end loader transport mixed glass waste (MGW) to conveyor belt	Diesel	25 L
3	Electricity usage by washing plant	Power	160 kW/h
4	Water consumption for the washing process	Water	6000 L
5	Chemical addition as coagulant during washing	$Al_2(SO_4)_3$(Aluminium Sulphate)	500 mL per 10,000 L of water

Table 2
Life cycle inventory of the crushing plant for generating recycled glass aggregates.

Sequential steps	Crushing plant processes	Resource	Consumption (fuel, energy and others)
1	Transport of 100 t mixed glass waste (MGW) to crushing plant and stockpiling	Diesel	4.57 L
2	Front end loader transport mixed glass waste (MGW) to conveyor belt	Diesel	25 L
3	Electricity usage by crushing plant	Power	150 kW/h
4	Dual suppression system	Water	14 L
5	Material dousing process	Water	100 L

particles in specific sizes as per the screen size. Appropriately sieved glass particles are used directly in a road subbase mix and mixed on-site with other components following the road subbase mix design specifications. The larger particles are transported to the crushing plant. The electricity consumption from the operation of the washing plant is carefully observed and noted for the consequent analysis. Fig. 2 shows the washing plant's consecutive processes and system's boundaries, which include electricity, diesel consumption, chemicals, and water usage at different phases of the materials recycling facility. The life cycle inventory (LCI) of generating recycled glass aggregate is extrapolated to obtain the environmental impacts associated with the washing plant's activities, as shown in Table 1. Collected waste glass is contaminated with paper, cardboard, plastic, fabrics, rubber, cloth, paint, bricks, wood, and other organic matter. The contaminated glass is to be washed before crushing to remove organic traces, soil, sugar, labels, and other disposable materials. Generally, 120 t of waste glass generate around 20 t of debris for landfills during the washing process at the recycling facility.

2.2.1.1.2. Crushing plant. Glass sorting, crushing, and other recycling processes are similar to the washing process, where the washed glass is now transported to the crushing site using a truck, as shown in Table 2 and Fig. 3. The transported material usually undergoes a washing phase when the load is considered particularly dusty or dry, but the overall process can also be streamlined to only considered crushing if the glass is free of impurities. The truck deposits the mixed glass waste as a stockpile for timely processing. Washed recycled glass sizes larger than 4 mm are stored in the stock and then transported to the gravity-fed "feeder" stage to begin with the crushing process. After sorting the glass through an industrial-size screen selection process at the first stage, the MGW is split into two groups based on a diameter of 4 mm. Both groups are transported via a conveyor belt. After screening glass waste, particles greater than 4 mm in diameter are shifted to the crushing process. To separate materials from foreign contaminants, materials less than 4 mm in diameter are sent through a separate conveyor to the beneficiation process, including magnets, eddy-currents, and air knives. In this beneficiation process, the recyclable materials are separated and sent to various stocks to recover and reuse. Any other material that contaminates the glass - but is not recyclable - is disposed of in landfills. The maximum size of the materials received by the crushing plant eventually turn into aggregates less than 4 mm. Recycled glass aggregates are uniform in size and nature after removing all impurities from waste glass. Approximately 90 % of recycled glass aggregate is generated from 100 ton of collected waste glass during the crushing process. Around 5 % of deleterious and non-recoverable materials such as container tops, wood, foil, and other materials go to landfills, while the remaining 5 % is made of bricks, plasters, and ceramic that are recovered and used as aggregates.

2.2.2. Applications of recycled glass in infrastructure construction

This study considers a suitable proportion of recycled crushed glass (RCG) as a partial substitute for fine aggregates in pavement applications. A series of laboratory tests, including particle size distribution, triaxial loading, Los Angeles Abrasion, unconfined compressive strength, California Bearing Ratio (CBR), and others, have been conducted to identify the suitable RCG proportion without compromising the engineering performance of the pavement sub-base (Ali et al., 2011; Senanayake et al., 2022). A reduction of up to 23.6 % and 27.9 % in concrete compressive strength and splitting tensile strength, respectively, was observed by replacing fine aggregate with RCG up to 50 % (Ali and Al-Tersawy, 2012; Sharifi et al., 2013). These experimental results suggest a decrease in strength with increased proportions of RCG in asphalt and concrete mixtures. However, a feasible range between 15 % to 30 % RCG by mass has been recommended to comply with the standards of different road authorities.

In the state of Victoria (Australia), the Department of Transport (DoT) - Victoria summarizes the permissible allocations of recycled materials in infrastructure applications (Austroads, 2022). Technical notes of DoT refer to a specific proportion of RCG to be allowed in pavement construction operations. However, RCG specification varies across the territories and states in Australia. Commonly, research on RCG recommends limiting the proportion to 20 % as a substitute for crushed fine aggregates or naturally occurring sand. The RGC portion should pass through a 4.75 mm sieve and possess an equivalent sand value of at least 80 %. It is also recommended that granular filler materials be free from clay and organic substances, and with a pH between 6 and 8. Among the applications of RCG in infrastructure projects, this study investigates the use of RCG in pavements (asphalt and concrete) and as a filling material for piping.

2.2.2.1. Recycled glass as a partial aggregate substitute in the wearing course of asphalt pavements. The wearing course is the top layer of an asphalt pavement that is in direct contact with traffic. Higher bitumen content and suitable quality aggregates are recommended for this layer compared to other asphalt sublayers since it is in direct contact with the vehicles' wheels. The principal function of the wearing course is to provide the functional capabilities of a road pavement including creating a skid-resistant friction surface. The structural design of flexible pavements is affected by three prime factors: (i) volumes of traffic, axle loads, axle configurations, and road design speed, (ii) uniformity and strength of subgrade, and (iii) bearing capacity of pavement materials. Commonly, the thickness of a wearing course varies between 30 and 50 mm as per the different design practices.

The system boundaries for the construction of the asphalt pavement in this study are shown in Fig. 4, while Table 3 presents the inventory and quantity of materials required to construct a 1-km asphalt pavement lane with a width of 3.5 m.

2.2.2.2. Recycled glass as a partial aggregate substitute in the base course of asphalt pavements. The asphalt base course acts as a connector between pavement layers; it distributes traffic loads from the upper layer to the

Table 3
Materials data to construct the asphalt pavement section object of this study.

Design components of the asphalt pavement	1-km long asphalt pavement section with a width of 3.5 m			
	Asphalt wearing course thickness			Base course thickness
	30 mm	40 mm	50 mm	75 mm
Bitumen (ton)	14.15	18.87	23.58	32.15
Gravel (ton)	216.36	288.48	360.60	543.76
Sand (ton)	24.31	32.41	40.52	61.09
Lime (ton)	2.43	3.24	4.05	6.10
RCG as a substitute of sand (ton)				
5 % RCG	1.22	1.62	2.02	3.05
10 % RCG	2.43	3.24	4.05	6.10
15 % RCG	3.64	4.86	6.08	9.16
20 % RCG	4.86	6.48	8.10	12.21

subsequent lower subbase and subgrade course. The thickness of this course is adequately designed to provide structural support and reduce the bearing capacity on the subbase and subgrade. A minimum thickness of 75 mm is commonly used for the base course depending on the condition of the subgrade. The base course is made of a coarser aggregate than the wearing course and includes lower bitumen content.

2.2.2.3. Recycled glass as a partial aggregate substitute in pipelines bedding/fillings. The most common method of pipe installation is by means of a trench. A typical pipeline cross-section comprises several zones, including the bedding, haunch support, side support, overlay, and backfill, as shown in Fig. 5. The choice of embedment materials is essential for the distribution of loads through the pipe's crown, to the backfill material along the sides, and then to the pipe bedding and foundation. The selection of the backfill envelop material is the first step in designing a pipe system with the desired strength. The bedding must be composed of a non-cohesive and non-composable material. The granular properties of bedding materials are to be compliant with AS/NZ-3725:2007 (WS-006 JTC, 2007). Side fill material is placed adjacent to the pipe culverts' centre.

This study considers the design of a pipeline alignment as per the sewerage code (WSAO2) and water supply code (WSAO3) of Australia. Granular backfill up to 150 mm is recommended to be compacted by a mechanical compactor; the relative compaction value is at least 95 % of the standard proctor density for filler with optimum moisture. The thickness of the cohesive backfill is limited to not exceeding 200 mm in the horizontal layers. Each layer is suggested to be tamped and well compacted before proceeding to the next layer. Recycled crushed glass (RCG) is uniformly distributed with a minimum thickness of 150 mm over the entire piping length.

2.2.2.4. Recycled glass as a partial aggregate substitute in concrete pavements. Most concrete used in pavement construction is graded with a minimum compressive strength of 20 MPa (i.e., N20 concrete) as per the Australian Standard Specifications AS13791 (Everist, 2015). A higher compressive strength is required for heavy traffic in some situations; i.e. N25 concrete is proposed considering the vehicles' mass and axle loads. A minimum thickness of 75 mm is always preferable for driveways and terraces. However, the designed thickness varies between 100 mm and 150 mm depending on the vehicles' gross mass which varies between 3 and 10 ton.

Mesh or steel reinforcement can also be used. The primary function of steel reinforcement is to hold concrete firmly and prevent developing of cracks. The right degree of controlling cracking depends on the required steel reinforcement, slab thickness, and joints. The minimum reinforcement used in concrete slabs for different conditions is described in AS3600 on "Crack control for shrinkage and temperature effects" (Mark Patrick, 2000). A total distributed rebar weight of 42–65 pounds per 100 square feet (2.10–3.20 kg/m^2) generally provides satisfactory results, as reflected by the service condition of concrete pavements. Typically, the steel bars used in the concrete pavements have a diameter range from #4 (12.7 mm) to #7 (22.2 mm). Bar size is selected by the percentage of steel and permitted maximum to minimum space. The mean crack size is observed to decrease with an increased proportion of R_b. The larger the joint area is, the greater the restriction of concrete movement imposed by the steel; hence, more minor cracks are developed. A higher reinforcement area is achievable using a smaller steel bar for the designed steel. The reinforcement area to concrete volume ratio is denoted as R_b; the ratio (R_b) considers the nominal bar size, slab thickness, and width, as shown in Eq. 1.

$$R_b = \frac{n\pi\varphi}{DW} \tag{1}$$

where n is the number of bars, φ is the bar diameter, D is the slab thickness in mm, and W is the width of the slab in mm. The minimum ratio of R_b (1.2 m^2/m^3) is recommended for warm weather conditions, whereas during cold weather conditions, the recommended value is 1.6 m^2/m^3. The longitudinal steel spacing should not be greater than 230 mm or less than 100 mm.

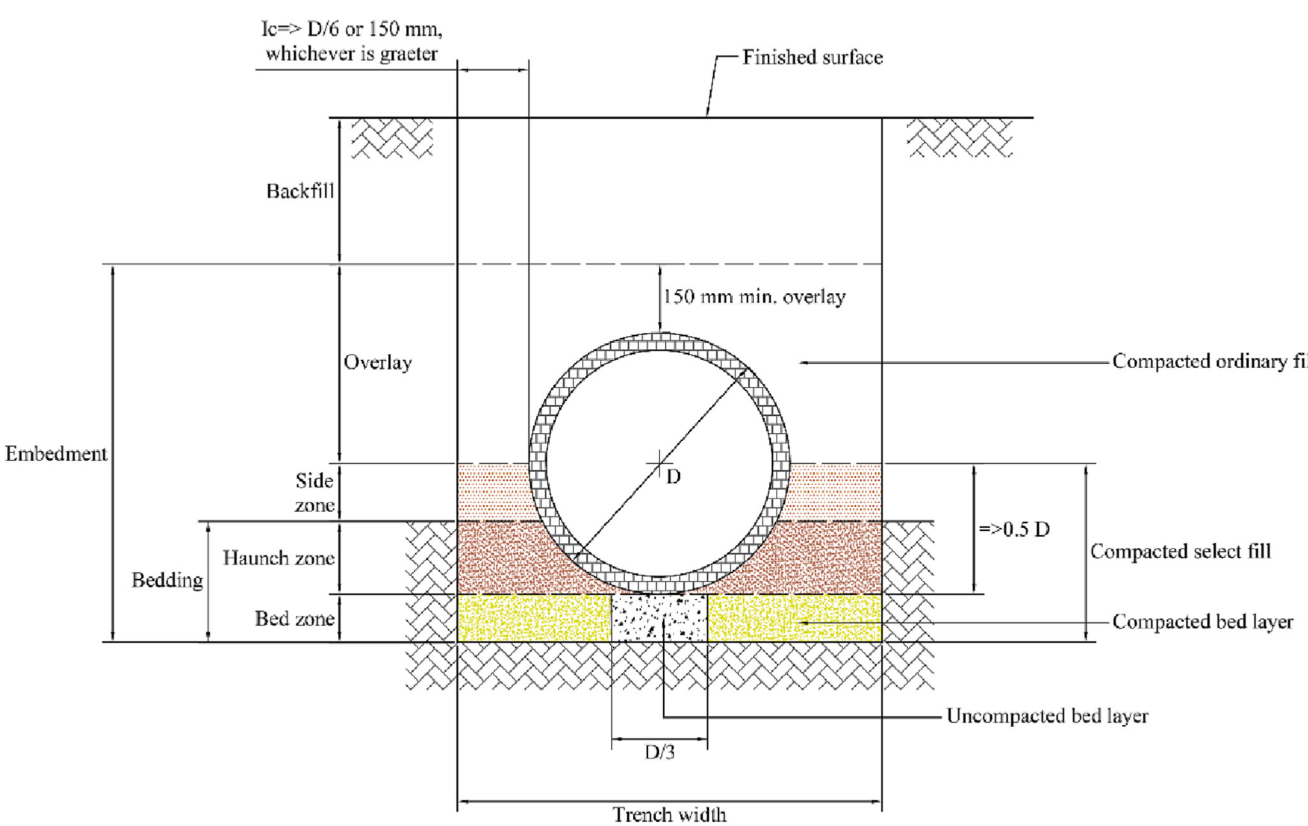


Fig. 5. Typical pipeline cross-section with backfilling materials.

Table 4
Environmental impact scores of washing mixed glass waste (MGW).

Impact categories and their unit	Transportation (washing plant)	Front end loader	Electricity usage	Water consumption	Chemical (coagulant)	Total impact	Per ton impact
Climate change (kg CO_2 eq)	16.57	84.53	122.48	5.72	0.63	229.90	1.92
Ozone depletion (kg CFC-11 eq)	1.92E-09	9.82E-09	4.27E-07	2.95E-08	1.88E-08	4.87E-07	4.06E-09
Terrestrial acidification (kg SO_2 eq)	0.11	0.58	0.65	0.03	0.01	1.38	0.01
Freshwater eutrophication (kg P eq)	4.66E-06	2.38E-05	1.47E-04	7.74E-05	1.20E-05	2.65E-04	2.21E-06
Marine eutrophication (kg N eq)	6.93E-03	3.54E-02	1.43E-02	6.82E-04	8.82E-05	5.74E-02	4.78E-04
Human toxicity (kg 1,4-DB eq)	9.54	48.65	1.17	0.32	0.07	59.74	0.50
Abiotic depletion (kg Sb eq)	3.70E-07	1.89E-06	2.91E-06	5.92E-06	1.45E-06	1.25E-05	1.05E-07
Abiotic depletion (fossil fuels) in MJ	244.75	1248.71	1437.93	63.65	7.58	3002.62	25.02

Alkali Silica Reaction (ASR) is commonly known as concrete cancer and causes micro-cracks in concrete when using RCG as a substitute for fine sand (Yang et al., 2018). This disruptive reaction occurs in several steps. First, alkali hydroxides (i.e., NaOH and KOH) react with volatile silica minerals of glass aggregates in the presence of moisture. Second, it generates one type of expansive alkali gel capable of absorbing excessive water. Third, this expansive gel fills the entire voids within the concrete. Finally, the expansion of concrete pores exerts significant internal stresses that can results in severe cracking.

This study has considered RCG a partial substitute for aggregates in concrete pavements. The workability of concrete is not affected by the use of RCG; however, voids content and density are decreased at a certain level. A reduction of concrete compressive strength (5 %–27 %) was observed by incorporating RCG as a substitute (5 %–30 %) of fine sand (Sagoe-Crentsil et al., 2001). Laboratory tests and ready-mix concrete design showed that incorporating 20 % of RCG as a substitute for sand performs satisfactorily (Austroads, 2022).

2.3. Life cycle impact assessment (LCIA)

LCA estimates the environmental burden of a product's entire life cycle. The product's life cycle is associated with the extraction of raw materials and relevant emissions in consequent processing and usage, which vary significantly for each process (Hauschild and Huijbregts, 2015). Life cycle impact assessment (LCIA) translates resources extractions and emissions into specific impact scores by using characterization factors.

2.3.1. Midpoint and endpoint environmental impacts assessment of glass aggregate

Characterization factors can be derived from two ways: midpoint and endpoint. Midpoint characterization factors are located somewhere along the cause-impact pathway, whereas characterization factors at endpoint reflect potential damages at several areas of protection. ReCiPe 2016 is a LCIA methodology that combines and harmonizes the midpoint and endpoint characterization factors (Huijbregts et al., 2017), and was chosen in this study for conducting the LCIA associated with extracting virgin sand and recycling crushed glass aggregates through different processes.

Resource depletion has been characterized as abiotic depletion considering the depletion of Earth's natural resources as per the CML-IA baseline (Renouf et al., 2016). Depletion is usually divided into two categories as abiotic and biotic resources. However, this study does not include biotics for relevant land usage damage. Abiotic Resource Depletion (ADP) is calculated by the depletion of non-fossil resources (kg Sb-eq) and the loss of fossil fuels' net-calorific value (MJ) following LCI.

The impact model has been developed by maintaining consistency between the midpoint and endpoint within an equal time horizon across cultural perspectives, as shown in Eq. (2). Endpoint characterization factors (*CFe*) respond to three conservative areas: human health (HH), ecosystem damage (ED), and resource scarcity (RS). These two strategies complement each other, where midpoint impact categories have a higher association with environmental flows and bear lower uncertainty. On the other hand, endpoint categories carry more uncertainty; however, they provide an overall relevance of environmental impacts from a broader perspective.

$$CFe_{x,c,a} = CFm_{x,c} \times F_{M \rightarrow E,c,a} \tag{2}$$

where c signifies the cultural perspective, a represents the protection area (e.g., human health, ecosystem damage, and resource availability), x stands for the stressor of concern, and $F_{M \rightarrow E,c,a}$ is the conversion factor from the midpoint to the endpoint for cultural perspective c and protection area a. The current study compares eight significant midpoint and three endpoint impact categories of RCG processing. RCG processing includes the impacts of washing, crushing, landfilling of by-products, and benefits over landfills compared to the extraction of natural sand from a quarry.

Table 5
Overall environmental impact scores of washing and crushing mixed glass waste (MGW).

Impact categories and their unit	Impact per ton RCG		Landfill of by-products from washing and crushing operations		Recycling of by-product from crushing	Natural Sand	Benefit over landfill of waste glass
	Washing	Crushing	Washing	Crushing			
Climate change (kg CO_2 eq)	1.92	2.15	5.25	4.15	2.64	4.95	−10.62
Ozone depletion (kg CFC-11 eq)	4.06E-09	4.12E-09	2.76E-07	1.67E-07	8.14E-08	2.26E-07	−1.19E-06
Terrestrial acidification (kg SO_2 eq)	0.011	0.013	0.032	0.025	0.016	0.030	−0.06
Freshwater eutrophication (kg P eq)	2.21E-06	1.68E-06	4.13E-05	2.51E-05	4.01E-06	8.6E-05	−1.68E-04
Marine eutrophication (kg N eq)	4.78E-04	5.53E-04	1.31E-03	1.05E-03	7.09E-04	1.08E-03	−2.65E-03
Human toxicity (kg 1,4-DB eq)	0.50	0.59	0.97	0.87	0.65	0.24	−0.97
Abiotic depletion (kg Sb eq)	1.05E-07	2.45E-06	1.38E-05	1.06E-05	5.40E-06	9.23E-06	−5.75E-05
Abiotic depletion (fossil fuels) MJ	25.02	34.67	74.93	64.62	43.53	61.89	−159.91

*Note: Impact per ton of RCG is evaluated by separating the impacts due to the washing and crushing processes and includes transportation, electricity, water consumption, and use of specific chemicals. Landfill of by-products from washing and crushing operations additionally includes the impacts of sending non-recyclable materials such as plastic, paper, paint, cloth, and other organic matter, generated by the washing and crushing process to landfills; the environmental impacts associated to this activity are generated through landfill operation, covering, compaction, and degrading of deposited materials. Recycling of by-products from crushing includes the previous impacts to produce 1 ton of RCG (crushing), the landfilling of any waste material generated during the process but also accounts for the recycling of concrete, brick, clay tiles, masonry, and crushed rock as construction aggregate. The benefit over landfill of waste glass considers the recycling of waste glass as RCG and compares it against the dumping of waste glass (no recycling or further reprocessing).

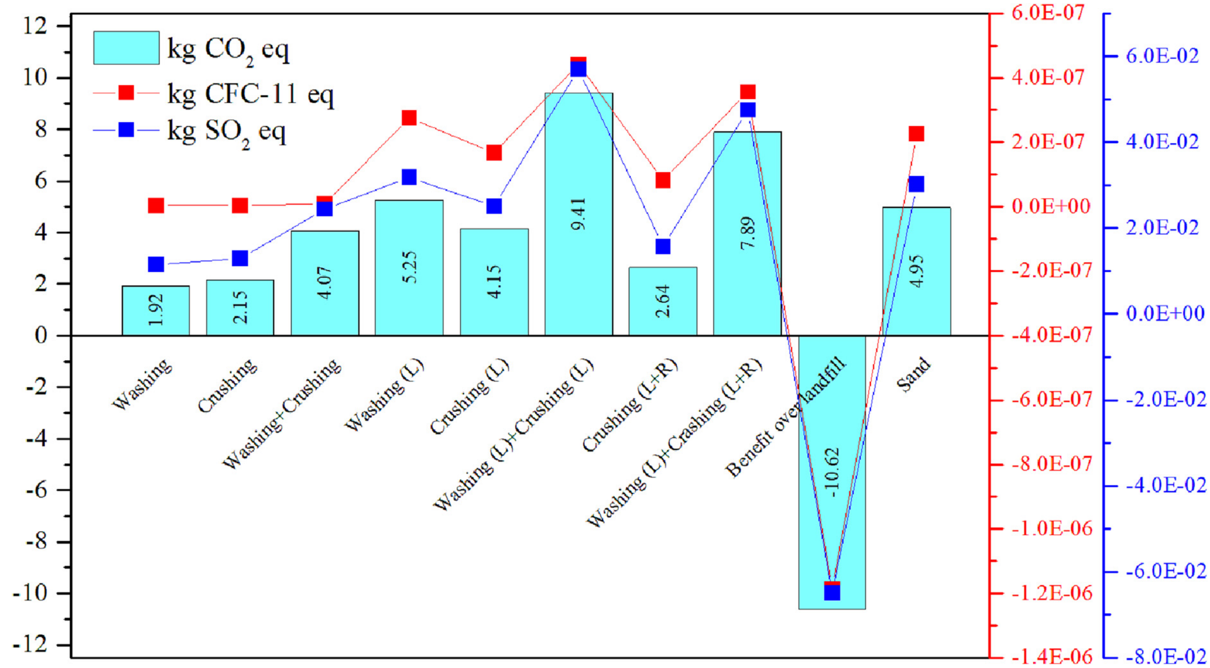


Fig. 6. Comparison of midpoint environmental impact scores of waste glass recycling process, where L is the landfill waste of the processed by-products, R is the recycling of processed by-products, and L + R indicates the specific residual portion of material that still goes to landfill after recycling.

2.3.2. The global environmental impacts assessment of glass aggregate

Relevant characterization factors of ReCiPe 2016 version 1.1 are updated globally rather than at any specific country or continent scale (Huijbregts et al., 2016). The framework of this LCA study provides an overview of the modelled impact paths - i.e., information regarding sustainable decision-making – which were assessed by grouping them into three values of global indicators. These three damage categories are related to: human health potential, representing the years lost or a person incapacitated by illness or accident; loss of local species integrated over the analysis periods (species. year) as damage to the ecosystem; and the additional costs in dollars ($) associated with the future extraction of fossil fuels and mineral resources. These damages are identified based on so-called characterization factors that indicate the above mentioned impacts per kg of raw material or released emissions on a worldwide scale.

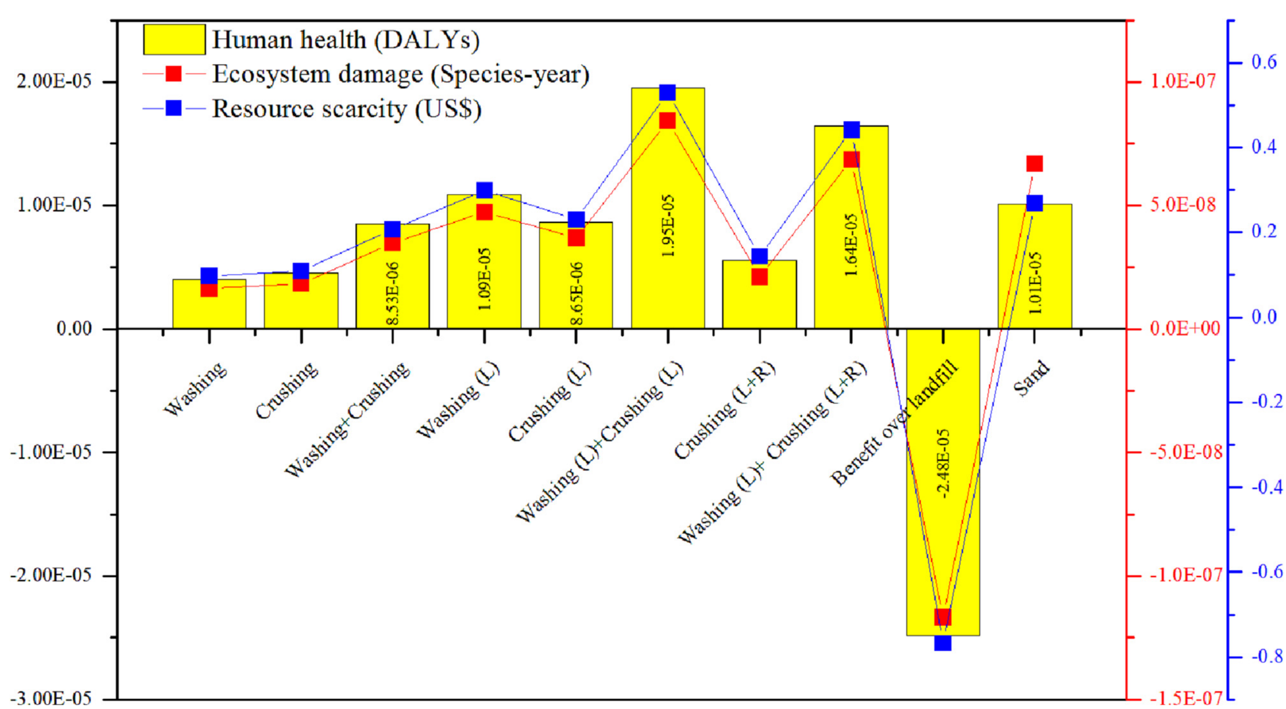


Fig. 7. Comparison of endpoint environmental impact scores of waste glass recycling process, where L is the landfill waste of the process, R is the recycling of processed by-products, and L + R indicates the specific residual portion that still goes to the landfill after recycling.

2.3.3. Uncertainty analysis of glass aggregate production

Several uncertainties influence the impact assessment of glass aggregate; therefore, the sensitivity analysis of design variables assists in checking the validity of collected recycling facility data and the outcome of possible variations. Monte Carlo simulation identifies possible effects by substituting a set of design variables; the probabilistic distribution of selected factors determines the inherent uncertainty of an individual variable (Tushar et al., 2021a). Simulation accuracy is obtained by performing thousands of iterative calculations on a range of random variables. Each design variable has a different probabilistic distribution, a realistic approach to

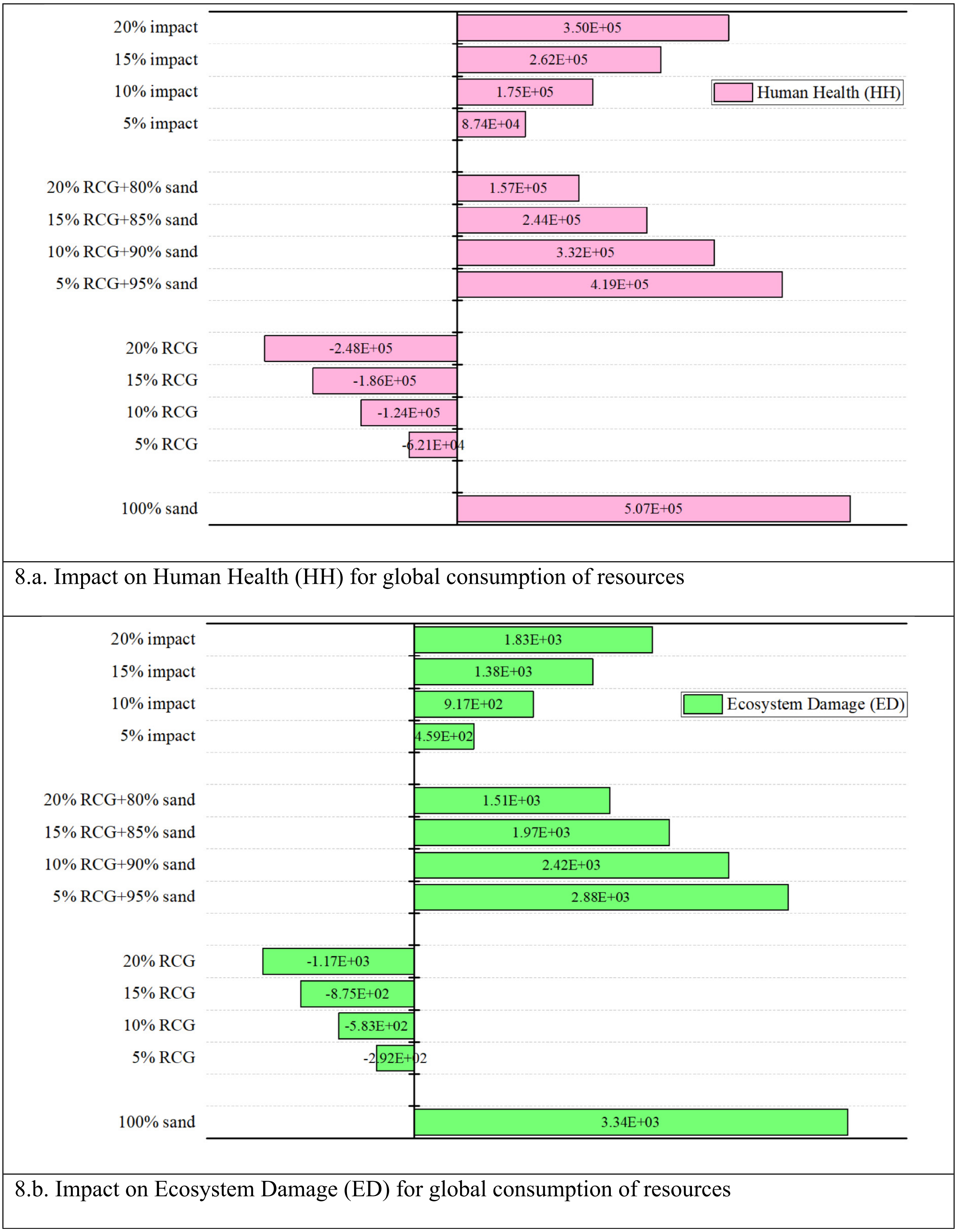


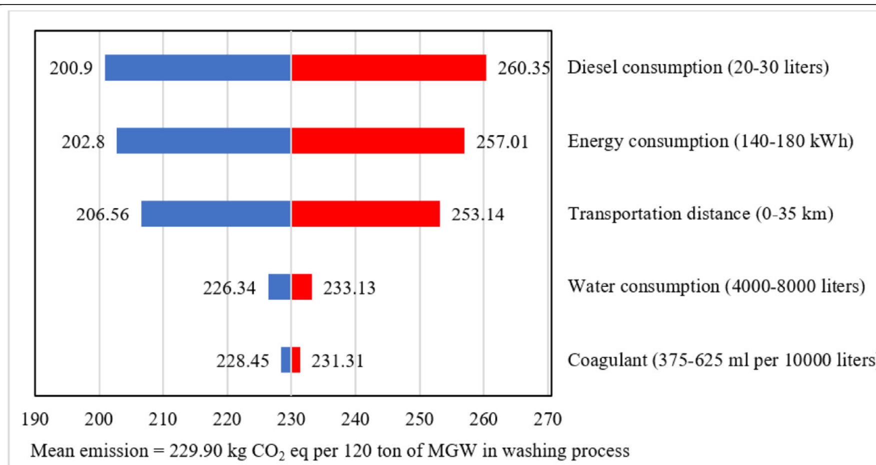
Fig. 8. Global damage assessment of the recycled crushed glass (RCG) process.

Table 6
Correlation coefficients of the design variables in the washing process.

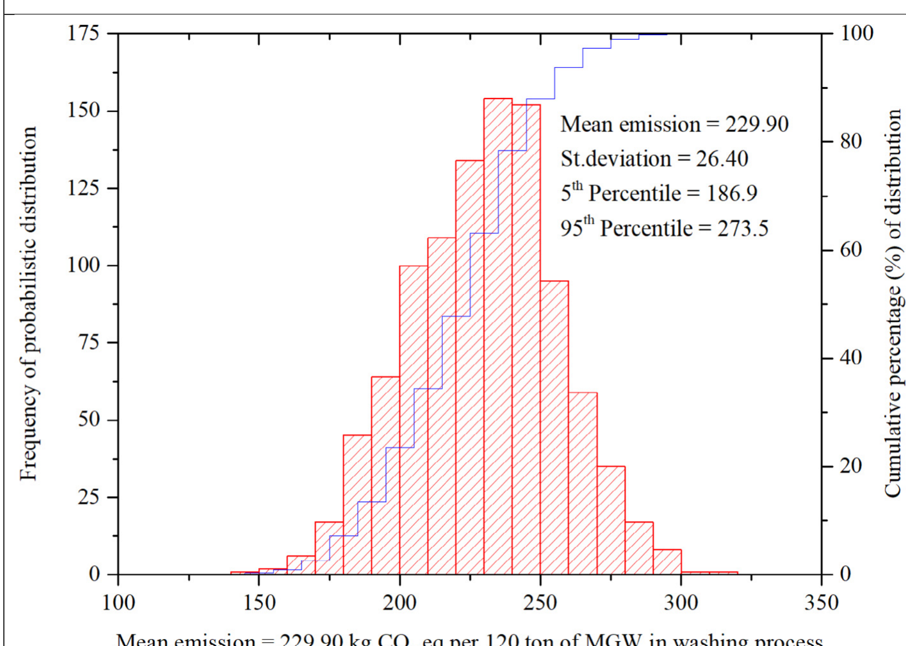
Input variables for carbon emission model (design factors)	Input variations (kg)		Simulation results of design variables			
	Mean (μ)	Standard deviation (σ)	Pearson correlation	Rank correlation	Lower limit* (kg)	Upper limit* (kg)
Transportation distance (0–35 km)	16.56	13.08	0.49	0.47	206.56	253.14
Diesel consumption (20 – 30*L*)	84.52	16.90	0.64	0.62	200.90	260.35
Energy consumption (140–180 kWh)	122.48	15.31	0.58	0.56	202.80	257.01
Water consumption (4000–8000 L)	5.72	1.90	0.073	0.070	226.34	233.13
Coagulant alum (375–625 mL per 10,000 L)	0.62	0.15	0.022	0.016	228.45	231.31

* Note: The probabilistic normal distribution identifies correlations, statistical inputs, and confidence interval CI (lower limit 5th percentile to upper limit 95th percentile) of selected design parameters.

relative uncertainties in a sensitivity analysis. This study identifies the range of possible consequences based on some design factors associated with the glass aggregate manufacturing process and with the energy sector's transition scenarios to renewable-based sources by the end of 2030 and 2050. The *@RISK* simulation shows the relative uncertainties of the carbon footprint due to the design parameters. The computational mathematical



9.a. Impacts of inputs design variables (washing process) on the climate change score



9.b. Probabilistic distribution of the climate change score (washing process)

Fig. 9. Probabilistic outcomes of the input and output variables of the design factors.

algorithm runs through the LCA tool *Simapro* outcomes for thousands of times to create a reasonable probabilistic distribution for the defined variables; this follows Eq. (3).

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad (3)$$

where: σ is the standard deviation and μ is the mean of the normal distribution.

3. Results and discussion

This study applies the ReCiPe methodology to categorize the impacts associated with extracting quarry sand and recycled crushed glass (RCG) aggregates through different processes. The ReCiPe methodology combines two approaches of impact assessment (IA): the midpoint of CML-IA and the endpoint of Eco-indicator 99 (Rashedi and Khanam, 2020). Each impact category does not bear equal importance and weight. Therefore, the current study compares eight significant midpoint and three endpoint impact categories of RCG processing. RCG processing includes the impacts associated with the washing, crushing, landfilling of by-products, and benefits over landfills compared to the extracted sand from a quarry.

3.1. Midpoint environmental impacts of recycled crushed glass (RCG)

The study identified midpoint environmental impacts associated with the production of 1 ton of recycled glass aggregates within the washing and crushing system boundaries highlighted in previous sections. Approximately 4.95 kg of CO_2-eq is emitted to extract 1 ton of sand from a quarry, whereas the process of washing and crushing waste glass emits 1.92 and 2.15 kg CO_2 eq, respectively, as shown in Tables 4 and 5. However, adding the impact associated with landfilling of the resulting waste material generated during washing and crushing operations of glass increases emissions significantly. The estimated abiotic depletion for extracted quarry sand is 9.23×10^{-06} kg Sb eq and 61.89 MJ of minerals and net-caloric value, respectively. In contrast, producing 1 ton recycled crushed glass contributes to (−) 5.75×10^{-05} kg Sb eq and (−) 159.91 MJ savings of abiotic depletion from resource extraction, as shown in Table 5. The LCA results indicate that the combination of washing and crushing process generated approximately 9.4 kg of CO_2-eq, which is relatively higher than virgin sand production by approximately 90 %. This figure provides an overview of landfill impacts and shows possible increases in GHG emissions from composting and degradation activities of waste generated from this combined process. Similar trends of cumulative emissions of kg CFC-11-eq and kg SO_2-eq are also observed to increase by 96 % and 90 % compared to natural sand, as shown in Fig. 6. In this figure negative impact categories indicate the net savings of recycling of 1 ton waste glass compared to landfill. Therefore, the analysis shows how applying both washing and crushing processes to produce recycled glass aggregates for pavements construction is not an environmentally satisfactory solution. However, it emphasizes that collecting glass through separate bins, hence reducing contamination with other undesirable materials, is a better provision for obtaining comparatively clear glass that may not need to undergo washing.

The recycling of by-products (i.e. fragments of bricks, etc) from the crushing process (approximately 5 %) as coarse aggregate for construction operations reduces the total environmental impacts by approx. 46 %. The challenge is to decrease the overall environmental footprint by only crushing the waste glass thus eliminating the landfill material, mostly generated through the washing process. Limiting the recycling operations to only cater for crushing by collecting cleaner glass from dedicated bins will enhance the sustainability of the use of recycled glass aggregates in infrastructure projects.

Subprocesses of washing and crushing reveal that the relevant attributes of diesel, energy consumption, and transportation distances are more significant than other recycling-related factors. Electricity consumption is the prime factor and involves 53.27 % of the entire washing process. The impact of transportation distance and diesel consumption by the front-end loader seemed higher than water and chemical usage, 7.20 % and 36.76 %, respectively. However, variations in GHG emissions linked with processing activities are critical and should be properly considered rather than relying on a specific point-based analysis. For this reason, in terms of electricity usage, the sources of energy production, such as fossil and renewable, are further analysed by performing an uncertainty analysis.

The values of other impact indicators, such as acidification, freshwater and marine eutrophication, metal and fossil depletion from crushing, and indirect benefits from landfills, are much lower than those of natural sand. However, human toxicity kg 1,4 dichlorobenzene (1,4-dB) eq increased during recycling of waste glass, but it has been offset significantly by considering the adverse impact of landfills of the waste glass (see last column in Table 5). For example, the corresponding impact on eutrophication potential (for both freshwater and marine) through the crushing process is 95.34 % and 34.35 % lower than that of natural sand.

3.2. Endpoint environmental impacts of recycled crushed glass (RCG)

Midpoint and endpoint approaches are complementary to each other. Endpoint categories are obtained from the midpoint assessment, where midpoint categories have lower uncertainty and have a substantial relationship to environmental damage. Endpoint shows the relevance of environmental flows to human health (HH), ecosystem damage (ED), and resource scarcity (RS) of midpoint damages. HH refers to the loss of a person disabled due to a disease or accident and it is expressed as DALYs (disability-adjusted life years). ED represents the number of lost species over time as species-year, and RS indicates the additional cost associated with the future extraction of mineral and fossil resources as US$.

Comparative results of endpoint impact assessment are shown in Fig. 7. The figure shows that RS is the most impacted area of protection among the three categories from all perspectives. The extraction of minerals and other resources is reduced significantly by recycling waste glass. The conjugate approach of washing and crushing of waste glass has a higher impact over the quarrying of natural sand by 92.8 %, 25.90 %, and 97.03 %, for HH, ED, and RS, respectively. A lower HH impact over natural sand is observed for crushing (14.62 %) and recycling of by-products alternatives (45.23 %). Similarly, the production of glass aggregates through the

Table 7
Effects of the variation of energy sources (fossil and renewables) on the carbon footprint for producing 100 t of recycled glass in a washing plant, where 20 % V indicates the percentage variation of energy sources.

Input variables to generate (160 kWh ± 20%V) for fossil fuels-contributed emissions (kg CO_2 eq)				Output
Summary statistics	Coal	Natural gas	Oil	
Mean (μ)	188.46	88.66	144.63	140.59
Standard deviation (σ)	37.68	17.73	28.91	16.90
5th percentile	126.2	59.5	96.8	111.7
95th percentile	250.3	117.7	192.2	169.1
Sensitivity Indices				
Regression Coeff. (β)	0.74	0.35	0.58	
Variance contribution	57.4 %	11.6 %	31 %	100 %
Input variables to generate (160 kWh ± 20%V) for renewables contributed emissions (kg CO_2 eq)				Output
Summary statistics	Hydropower	Wind	Solar	
Mean (μ)	1.02	0.14	0.11	0.42
Standard deviation (σ)	0.204	0.028	0.024	0.069
5th percentile	0.684	0.0971	0.0804	0.3131
95th percentile	1.358	0.1920	0.1593	0.5411
Sensitivity Indices				
Regression Coeff. (β)	0.98	0.14	0.12	
Variance contribution	96.7 %	2.0 %	1.3 %	100 %

crushing process has less influence in other categories of ED (44.9 %–68.3 %) and RS (14.1 %–46.8 %). The higher environmental benefits are attributed to a) the avoidance of waste glass going to landfills, b) sorting less polluted waste glass, and c) only processing waste glass through crushing.

3.3. The global environmental impacts of recycled crushed glass (RCG)

The last attempt at impact assessment is to convert these characterization factors into three sustainability perspectives, as shown in Fig. 8. Sand is the second most-consumed resource in the world after water and an

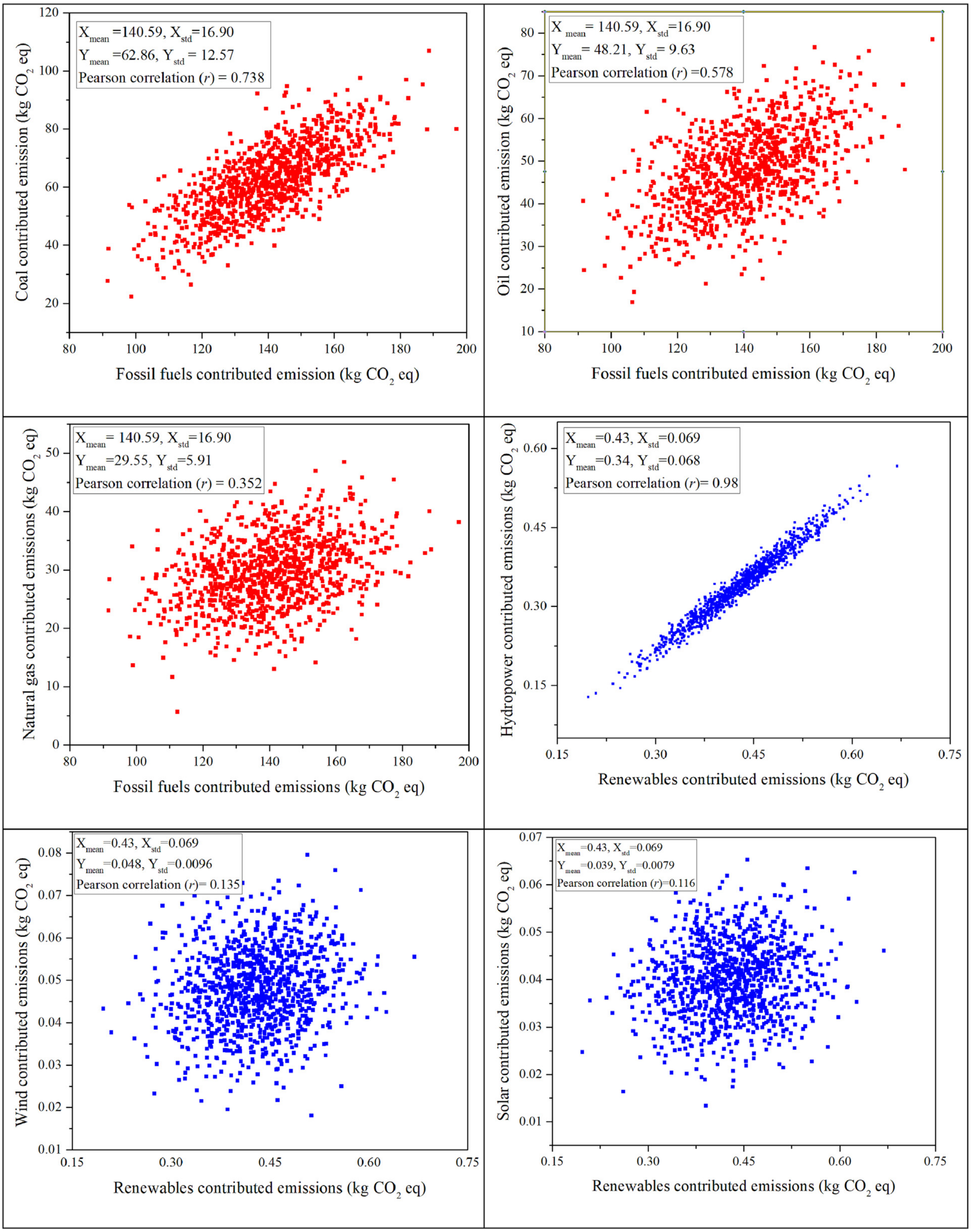


Fig. 10. Sensitivity indices and correlation coefficient (*r*) of fossil and renewable energy sources.

Table 8
Forecast impact assessment of the washing process electricity consumption (160 kWh) as per the transition of the national grid mix towards renewable sources.

Electricity generation		Percentage contribution of fossil fuels and renewable sources		
		Year 2022	Year 2030	Year 2050
Fossil fuels contribution		76 %	36 %	6 %
Non-fossil (renewables) contribution		24 %	64 %	94 %
Impact category	Unit	Year 2022	Year 2030	Year 2050
Climate change	kg CO_2 eq	122.480	58.202	9.995
Ozone depletion	kg CFC-11 eq	4.27E-07	2.06E-07	4.11E-08
Terrestrial acidification	kg SO_2 eq	0.650	0.308	0.052
Freshwater eutrophication	kg P eq	1.47E-04	7.11E-05	1.41E-05
Marine eutrophication	kg N eq	1.43E-02	6.81E-03	1.17E-03
Human toxicity	kg 1,4-DB eq	1.170	0.570	0.121
Abiotic depletion	kg Sb eq	2.91E-06	2.23E-06	1.71E-06
Abiotic depletion (fossil fuels)	MJ	1437.934	682.699	116.294

indispensable ingredient for construction projects involving roads, bridges, buildings, and land regeneration projects, as well as for windows, screens, smartphones, silicon chips, and others (Meredith, 2021). One of the greatest challenges of the 21st century is to meet the shortage of commodities such as sand and meet up demand with recycled materials. Fig. 8 shows that if globally consumed 40–50 billion tons of sand per year is substituted by 20 % of recycled glass aggregate on construction sites, approximately US$ 10.4 billion savings ($= 1.343 \times 10^{10}$–3.07×10^9) of resource extraction can be achieved. It also indicates that the potential human disability will affect less than approximately 0.35 million people annually ($= 50 \times 10^9 \times 1.013 \times 10^{-5}$-$(10 \times 10^9 \times (-)\ 2.48 \times 10^{-5} + 40 \times 10^9 \times 1.013 \times 10^{-5})$) due to emissions as per endpoint impact of Fig. 7. The net ecosystem damage (ED) shows the savings of 1830 species lost per year ($= 3.34 \times 10^3$–1.51×10^3) by adopting recycled crushed glass in construction. The endpoint contribution of impact categories with different proportions (5 %, 10 %, 15 %, and 20 %) of glass aggregates shows that recycling waste glass reduces the overall environmental impact significantly compared to virgin sand. Approximate resource extraction cost (2.6–10 billion US$), human disability (0.08–0.35 million), and species lost (459–1830) are possibly avoided by recycling waste glass as fine aggregate.

3.4. Uncertainty analysis of the recycling process

Monte Carlo simulation offers many advantages over single-point deterministic analysis. In a deterministic approach, combining input values to express the possible impacts of different scenarios is quite challenging. Therefore, this study performed an exhaustive uncertainty analysis to identify the effect of certain design parameters on the impact assessment by introducing different possible scenarios.

Based on the LCA results, electricity consumption is the most influential factor in the washing process for GHG emissions, as shown in Table 4. However, the possible variations of the process inputs via Monte Carlo simulation show that diesel consumption has greater correlation ($r = 0.64$) with the environmental footprint than electricity consumption ($r = 0.58$), as shown in Table 6. Three possible contributing factors (diesel consumption, energy consumption, and transportation distance) have been identified as principal elements towards the increasing of emissions. The magnitude of the correlation coefficients (r) is between 0.49 and 0.64, indicating a positive, meaningful, moderate linear relationship with CO_2 eq emissions. Higher Pearson correlation coefficient explains a linear trend of emission pattern over the Spearman rank-ordered coefficient.

Possible scenarios for various input variables were developed to conduct sensitivity analyses and compare the outcome with the baseline scenario, as shown in Fig. 9. The result reveals that the environmental impact is affected by a ± 19 % increase or decrease due to variations in the input parameters. The probabilistic distribution shows that the range of confidence interval (CI) values lie between 186.9 and 273.5 kg CO_2 eq. Variations in diesel consumption from 25 to 30 l increase CO_2 eq emissions by 13.25 %, whereas in the case of electricity and transportation, it is 11.8 % and 10.1 %, respectively. Further, no considerable emissions are induced by water consumption and use of chemicals at the washing plant during the washing process.

3.5. Effects of the national transition policy and impacts on industrial production

Australia's commitment to the Paris pact in 2016 was emphasized in this study to perceive the possible implications of the energy policy. The national transition towards renewable energy sources has a visible impact on reducing CO_2 emissions. The trajectory of mixed electricity generation in the years 2030 and 2050 is projected and calibrated with a reference grid of 2022. Possible sources of electricity supplies are assessed to identify the potentiality of fossil fuels and renewables from an emissions perspective. Variations in each energy source (± 20 %) for the washing process are compared with the baseline scenario, as shown in Table 7.

Coal ($\beta = 0.74$) is the prime emission contributor in the mixed grid system. The results indicate that fossil fuel natural gas ($\beta = 0.35$), renewable photovoltaic solar panels ($\beta = 0.12$), and wind ($\beta = 0.14$) are less affected by these variations. The sensitivity indices suggest that replacing primary fossil-based energy sources with solar panels and wind energy is a better

Table 9
Life cycle impacts assessment of asphalt pavements incorporating RCG.

Impact categories and their unit	1 km long asphalt pavement with a width of 3.5 m							
	Wearing course			Base course	Replacement of 20 % sand with RCG			
	30 mm	40 mm	50 mm	75 mm	30 mm	40 mm	50 mm	75 mm
Climate change (kg CO_2 eq)	19,200.23	25,602.07	31,998.56	46,463.51	19,124.51	25,501.17	31,872.32	46,273.14
Ozone depletion (kg CFC-11 eq)	2.08E-04	2.77E-04	3.46E-04	5.20E-04	2.01E-04	2.68E-04	3.34E-04	5.03E-04
Terrestrial acidification (kg SO_2 eq)	88.30	117.75	147.16	212.74	87.84	117.13	146.39	211.58
Freshwater eutrophication (kg P eq)	7.09E-02	9.46E-02	1.18E-01	1.74E-01	6.97E-02	9.29E-02	1.16E-01	1.71E-01
Marine eutrophication (kg N eq)	4.06	5.41	6.76	9.84	4.04	5.39	6.73	9.80
Human toxicity (kg 1,4-dB eq)	29,100.6	38,807.7	48,494.3	66,791.3	29,094.8	38,799.8	48,484.4	66,776.5
Abiotic depletion (kg Sb eq)	6.43E-03	8.58E-03	1.07E-02	1.61E-02	6.29E-03	8.22E-03	1.00E-02	1.47E-02
Abiotic depletion (fossil fuels) in MJ	814,741	1,087,378	1,360,015	2,038,437	814,284	1,086,160	1,357,731	2,033,868

provision to significantly decrease the carbon footprint of the recycling process. Nevertheless, the higher positive coefficient (r) for coal and hydropower indicate that additional efforts are required to implement the national strategy, as shown in Fig. 10.

The trajectory of deep decarbonization affects the reduction of CO_2 emissions by 52.48 % and 91.84 % at the end years 2030 and 2050, respectively, as shown in Table 8. Other impact categories are also observed in descending trends for relative electricity consumption. Generally, the possible transition towards renewable sources decreases metal and fossil depletion by 27.32 % and 91.91 %, respectively, with significant savings in resource extraction. However, the RCG washing process analysis shows that diesel consumption and transportation distances are other sensitive factors in the overall carbon footprint evaluation.

3.6. Environmental impacts of recycled glass aggregates in pavements

Table 9 presents the impact assessment results for the asphalt pavement thickness variations in wearing and base courses. The analysis shows that the asphalt mixture's bitumen content (5 %) is a dominant factor in CO_2-eq emissions, approximately 40.5 %, as shown in Fig. 11. The carbon footprint is significantly affected if the bitumen content changes slightly for different thicknesses. For example, raw materials such as gravel, sand, and hydrated lime represent 25.2 % of the total CO_2-eq emissions. The remaining 34.3 % of the impact is associated with asphalt mixing, storage, transportation, and placement (MSTP). A substantial proportion of emissions arises from MSTP, which recommends proper storage of the raw material to minimize the aggregate moisture content and reduce energy

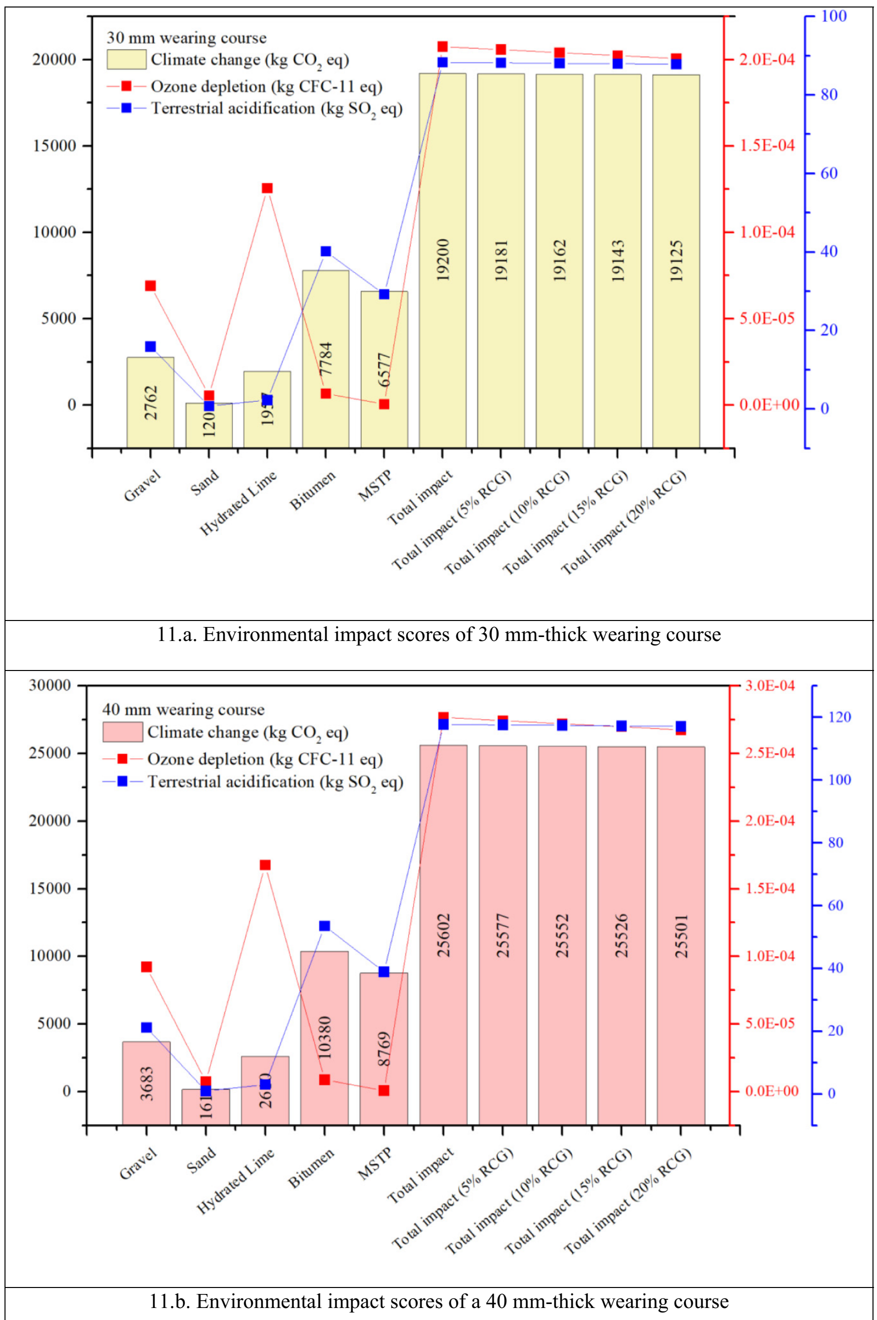
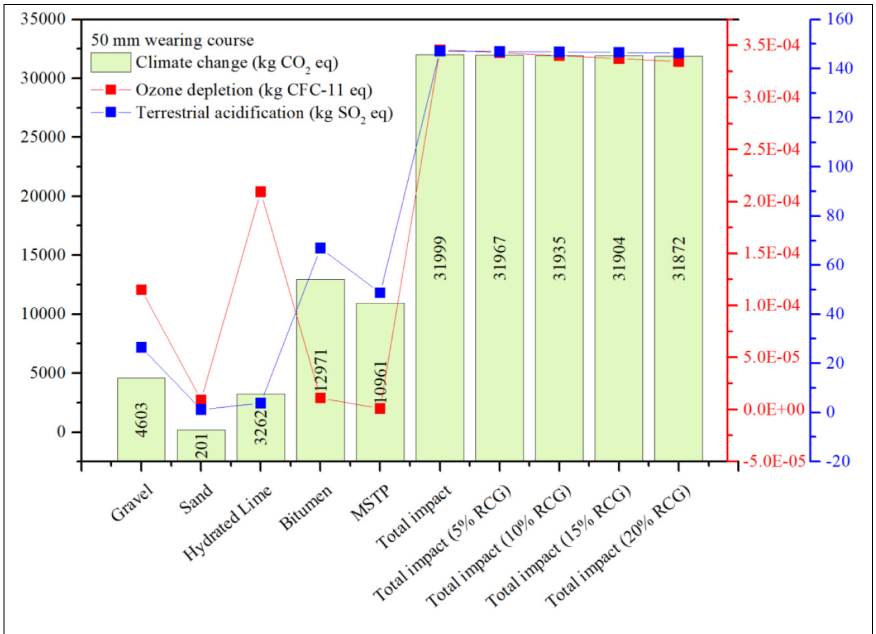


Fig. 11. Environmental impact scores of the wearing course of an asphalt pavement incorporating various RCG contents, where RCG indicates recycled crushed glass, and MSTP represents mixing, storage, transportation and placement of the asphalt mix.



11.c. Environmental impact scores of a 50 mm-thick wearing course

Fig. 11 (*continued*).

consumption during mixing. Similar types of reduction strategies are also observed in reducing CFC-11-eq and SO_2-eq, which are 3.37 % and 0.5 %, respectively. Generally, greater thicknesses of the wearing course (40 mm, 50 mm) and base layer (75 mm) increase the climate change indicator from 33.3 % to 142 % and the ozone depletion potential from 33.17 % to 150 %. This result reflects that the use of virgin and recycled contents increases for greater pavement thickness. However, it is thought-provoking to note that even a maximum replacement (i.e. 20 %) of natural sand with recycled glass aggregates contributes to a slight reduction in CO_2 eq emissions, which is only 0.4 %.

3.7. Environmental impacts of RCG in concrete pavements

A minimum thickness of 100 mm of concrete pavement is considered for a vehicle's gross mass of less than 3 t. However, a minimum thickness of 150 mm is recommended in Australia for vehicles' gross mass variations between 3 and 10 t (Standards, 2009). Statutory limits of heavy vehicles' axle load, tyres, and wheels are design factors to be detailed when calculating traffic loads. Raw material extraction (quarry sand, gravel, and reinforcing steel), concrete mixing, transportation, and placement (MTP) represent 18 %–20.1 % and 18.10 %–18.58 % of the total concrete pavement carbon footprint, respectively, as shown in Fig. 12. The remaining 61.8 %–63.4 % of CO_2-eq emissions is due to the manufacturing of cement. Different proportions of recycled crushed glass (5 %, 10 %, 15 %, and 20 %) reduce the emissions by a marginal amount of 0.12–0.51 %. Hence, the substitution of quarry sand with recycled glass aggregate does not suggest a significant drop in emissions. The analysis rather recommends replacing cement with other cementitious materials as a more suitable strategy to decrease the impact of concrete pavements.

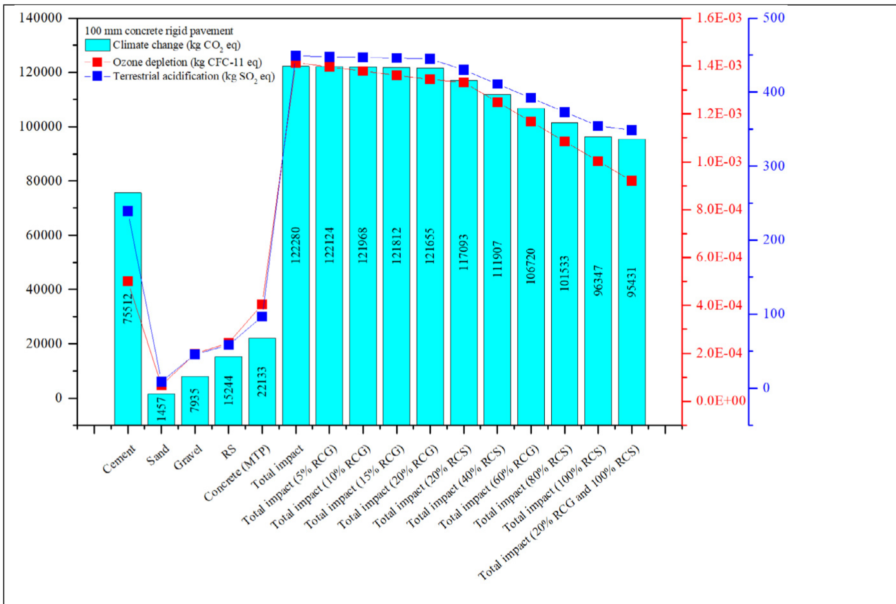
The quantity and properties of reinforcing steel (RS) are essential to compute the environmental impacts. RS manufacturing is the second-largest factor in the total CO_2 emissions of concrete pavements. However, RS is entirely recyclable, and greater contents of recycled steel in concrete can thus reduce the total emissions. Thus, similar to recycled crushed glass (RCG), recycled steel (RCS) is used in concrete pavement instead of using manufactured new steel to identify the variation in impacts. For example, using recycled steel at specific ratios – i.e. 20 % to 40 %, 60 %, 80 %, and 100 % - reduces the climate change impact from 4.24 % to 21.1 %, as shown in Table 10 and Fig. 12. By shifting the reinforcement for crack control from moderate (SL 92) to minor (SL 52), the RS's impact can be reduced by approximately 22.2 %. The complete removal of RS is another strategy to minimize the potential impacts of concrete pavements. However, eliminating RS from concrete pavement requires necessary modifications to pavement design, which may result in a shorter life span and more emissions due to increased thickness.

3.8. Environmental impacts of RCG in backfilling as filling materials

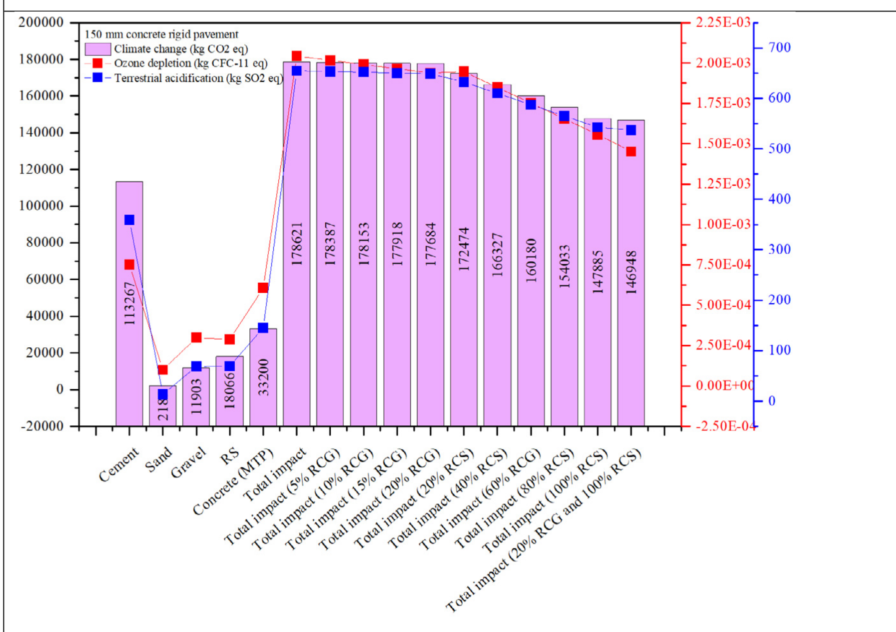
Projected emissions for backfilling materials with sand and different proportions of RCG are shown in Table 11. Approximately 4162 kg CO_2-eq is emitted when a 150 mm thick backfill with sand is constructed, while a complete substitute of sand (100 %) by RCG represents a net negative value of 8924 kg CO_2-eq. A 100 % replacement of sand is allowed by RCG as per the specification of subsurface drainage and filling materials. The possible reduction of emissions for different replacements of 20 %, 50 %, and 100 % shows the importance of RCG as a fine aggregate for granular backfilling. The estimated impact of producing one-ton RCG by avoiding landfill is around (−)10.62 kg CO_2 – eq, as shown in Table *5*, whereas 4.95 kg CO_2 – eq is emitted to extract one-ton sand from the quarry. For example, 20 % RCG replacement corresponds to a reduction of 62.88 % in carbon emissions rather than using sand as a backfill material. Similar types of reduction trends were observed for acidification and terrestrial eutrophication, which are approximately 59 % and 63 %, respectively.

4. Conclusions

A significant amount of glass waste is generated around Australia from three possible sources: municipal solid waste (MSW), commercial and industrial waste (C&IW), and construction and demolition waste (C&DW). Generated waste is dumped in landfills, which is a substantial cause of environmental burden due to excessive waste and landfill scarcity. This study conducts a comprehensive life cycle assessment (LCA) of crushed glass aggregate production through materials recovery facility (MRF) washing and crushing processes. The LCA provides a platform to compare the impacts of manufacturing aggregates from waste glass and natural sources. Comparative analyses show the environmental effectiveness of recycled



12.a. Environmental impact scores of a 100 mm thick concrete pavement



12.b. Environmental impact scores of a 150 mm thick concrete pavement

Fig. 12. Environmental impact scores of continuously reinforced concrete pavements. RS stands for reinforcing steel, RCG (20 %) stands for 20 % of recycled crushed glass as a sand replacement, RCS (100 %) stands for 100 % recycled steel usage as reinforced concrete steel, and MTP stands for mixing, transportation, and placement of concrete.

crushed glass (RCG) aggregate as a substitute for virgin sand and its possible uses in road construction, such as asphalt and concrete pavements, and bedding materials. The results of this research can be used as guidelines to emphasize areas for improving sustainability in construction.

Recycled glass aggregate produced by the crushing process reduces carbon emissions by 46.67 % compared to natural sand obtained from a quarry. However, CO_2 emissions increased by 89.9 % compared to natural sand extraction if both the washing and crushing processes are applied to produce recycled aggregates. Therefore, proper separation of waste glass at the collection stage – hence avoiding contamination – can significantly influence the manufacturing methodology under an environmental perspective; the emission indicators suggest higher environmental gain can be achieved by collecting waste glass through separate bins. In this case, comparatively clearer glass can be collected which can then be processed through simple crushing only. Nevertheless, recycling waste glass in crushed glass aggregate produces a significant reduction of the environmental impacts compared to sending it to landfills; this was quantified to be approximately (−)10.62 kg CO_2-eq per ton of recycled crushed glass (RCG). The Endpoint assessment shows that resource scarcity is a prominent factor over human health and ecosystem damage in measuring the net environmental benefit of waste glass recycling. Economic savings of 10.4 billion US$ (resource extraction) are feasible if substituting the globally consumed 40–50 billion tons of natural sand with 20 % RCG.

The LCA shows that electricity consumption is the most influential factor contributing to environmental impacts. However, the possible variations in the input parameters via Monte Carlo simulations showed that diesel consumption ($r = 0.64$) had a greater effect than the other factors, such as electricity and transportation distance. The national deep

Table 10
Environmental impact scores of continuously reinforced concrete pavements (100 mm and 150 mm). RS stands for reinforcing steel, RCG (20 %) stands for 20 % of recycled crushed glass as a sand replacement, and RCS (100 %) stands for 100 % recycled steel usage as reinforced concrete steel.

Impact categories and their relevant unit	1 km long concrete pavement lane with a width of 3.5 m and thickness equal to 100 and150 mm							
	No recycled materials		20 % RCG		100 % RCS		20 % RCG and 100 % RCS	
	100 mm	150 mm	100 mm	150 mm	100 mm	150 mm	100 mm	150 mm
Climate change ($kg\ CO_2$ eq)	122,280	178,621	121,655	177,684	96,347	147,885	95,431	146,948
Ozone depletion (kg CFC-11 eq)	1.41E-03	2.04E-03	1.34E-03	1.94E-03	1.00E-03	1.56E-03	1.00E-03	1.45E-03
Terrestrial acidification ($kg\ SO_2$ eq)	448.77	654.78	444.95	649.05	354.35	542.87	354.35	537.15
Freshwater eutrophication (kg P eq)	5.84E-01	8.42E-01	5.74E-01	8.27E-01	4.76E-01	7.14E-01	4.76E-01	6.99E-01
Marine eutrophication (kg N eq)	15.10	22.16	14.94	21.92	12.49	19.06	12.49	18.83
Human toxicity (kg 1,4-DB eq)	18,579	26,110	18,522	26,025	12,007	18,321	12,007	18,236
Abiotic depletion (kg Sb eq)	8.09E-02	1.19E-01	7.99E-02	1.18E-01	7.02E-02	1.05E-01	6.92E-02	1.04E-01
Abiotic depletion (fossil fuels) in MJ	1,157,460	1,704,426	1,153,551	1,698,555	899,484	1,372,744	895,576	1,366,872

decarbonization strategy of electricity generation will provide reductions of 52.48 % and 91.84 % at the end of 2030 and 2050, respectively. Relative uncertainty indices of the input variables suggest that replacing fossil-based energy sources with renewables is the optimum solution. The regression coefficients of photovoltaic solar panels (β = 0.12), wind (β = 0.14) as the renewable source, and natural gas (β = 0.35) as the non-renewable source have been emphasized in this study as possible provisions for the Australian national transition policy to renewables.

This study has facilitated the Australasian Life Cycle Inventory (LCI) to compare asphalt and concrete pavements from the initial transformation (raw materials extraction) to placement at the road construction site. The pavement service life is excluded from the LCA scope, as it depends entirely on local traffic, climatic conditions, and maintenance interventions. Natural sand substitution with RCG at different proportions (5 %, 10 %, 15 %, and 20 %) will not generate considerable drops in environmental impacts due to the higher impacts associated with the binder materials, i.e. cement and bitumen. However, reducing the environmental effects substantially by a complete replacement (100 %) for bedding/backfilling materials for piping is feasible. Overall, the recycling of waste glass can generate significant environmental savings compared to landfill. Therefore, the understanding of its application in the proper construction application is essential to produce noticeable environmental benefits.

The analysis of the processes within the materials recycling facility (MRF) shows a further reduction of environmental impacts can be achieved by considering a more effective waste management system and the transition of grid-electricity to renewable sources. However, from the perspective of policy implementation, waste management in cities should be improved by collecting waste glass through separate bins. This will allow recycling plants to invest less energy for recycling waste glass due to lower levels of contaminations. Moreover, as an alternate source of natural aggregate, RCG is a suitable solution to meet the worldwide scarcity of construction materials. Green public procurement practices that rely on LCA data can open new end-markets for recycled products, hence promoting a sustainable management of resources and stimulating recycling.

CRediT authorship contribution statement

Quddus Tushar: Conceptualization, Methodology, Formal analysis, Software, Writing – original draft, Visualization. **Safoura Salehi:** Conceptualization, Formal analysis, Software, Writing – original draft. **Joao Santos:** Conceptualization, Methodology, Writing – review & editing. **Guomin Zhang:** Conceptualization, Writing – review & editing. **Muhammed A. Bhuiyan:** Conceptualization, Writing – review & editing. **Mehrdad Arashpour:** Conceptualization, Writing – review & editing. **Filippo Giustozzi:** Conceptualization, Methodology, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

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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Table 11
Environmental impact assessment scores of RCG proportions as backfilling materials.

Impact categories	150 mm thick backfill of drainage conduits for 1 km pavement lane with a width of 3.5 m				
	Unit	100 % Sand	20 % RCG	50 % RCG	100 % RCG
Climate change	$kg\ CO_2$ eq	4162.14	1544.90	−2380.95	−8924.05
Ozone depletion	kg CFC-11 eq	1.90E-04	−4.72E-05	−4.03E-04	−9.96E-04
Terrestrial acidification	$kg\ SO_2$ eq	25.31	9.34	−14.62	−54.56
Freshwater eutrophication	kg P eq	7.23E-02	2.96E-02	−3.44E-02	−1.41E-01
Marine eutrophication	kg N eq	0.91	0.28	−0.66	−2.22
Human toxicity	kg 1,4-DB eq	201.26	−2.34	−307.75	−816.75
Abiotic depletion	kg Sb eq	7.02E-03	−3.14E-03	−1.84E-02	−4.38E-02
Abiotic depletion (fossil fuels)	MJ	47,110	13,342	−37,309	−121,728

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