A feasibility study of using coffee cup waste as a building material - Life cycle assessment and multi-objective optimisation

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ABSTRACT

With the scarcity of land and rapid drive towards sustainable development, numerous research studies are conducted on diverting waste from landfills. However, majority of these studies are focused on either experimental investigation of material characteristics or environmental impacts. Due to heavy virgin material usage, building material manufacturing industries are increasingly interested in using waste materials to partially or completely replace virgin materials from building materials. The cost of production is still a governing factor in decision making process concerning sustainable green material procurement. Disposable coffee cups contain a plastic liner and annually 60,000 kilograms of coffee cup waste end up in Australian landfills. Therefore, the current study presents a LCA feasibility study focused on shredded coffee cup waste as sand replacement in concrete and wood chip replacement in particleboard manufacture. The results indicate that sand replacement in concrete can improve environmental impact savings as compared to particleboard manufacture. Sensitivity analysis demonstrated that percentage of sand replacement is highly sensitive to global warming potential (GWP) impact category and transport distance is highly sensitive to other environmental impacts. A multi-objective genetic optimisation is then conducted to obtain the cost-effective green mix designs for concrete samples. The results indicated that with 25% cost increase, emissions of CO_2, NO_x, CO and SO_2 can be reduced by 10%, 38%, 2.5% and 43% respectively. These research findings are valuable for stakeholders determined to adopt cost-effective green building materials in their construction projects.

Keywords: Building materials, sustainable, green, waste, multi-objective optimisation

1 Introduction

Responsible consumption and production is one of the major United Nations (UN) sustainability development goals (SDG) that aims to ensure sustainable consumption and production patterns [1, 2]. UN SDG consumption statistics reveal that global material footprint has increased a daunting 12.7 billion tons since 2010, which signifies the importance of converting waste to useful materials. Building and construction industry is considered as a significant consumer of natural resources and recent rapid developments have accelerated the usage to an alarming rate. Studies have emphasized that buildings at aggregate level produce one third of the worlds' greenhouse gas (GHG) emissions and one fifth of the resource consumption [3-6]. Construction materials usage for a building construction is a major contributor to this significant share. Extensive use of construction materials such as concrete, timber and steel in the building construction industry has led to significant raw material extraction, energy consumption for processing, manufacture and production methods. With heavy annual production rates reaching billions of tons, numerous research studies have concentrated on developing sustainable construction materials to reduce virgin resource usage [7-16]. Waste materials such as fly ash, different types of slag, glass and plastics have been researched extensively as virgin raw materials replacement.

With the drive towards circular economy concept, the industry is supporting ways to reuse more waste materials in manufacturing sustainable building materials [17-20]. Thus, even a small percentage of virgin material replacement is considered desirable and leads to sustainable benefits. Coffee is considered a major beverage and millions of people across the globe use take-away cups when consuming coffee. Every take-away coffee consumed results in about 80 grams of ground coffee waste and coffee cup waste which is a combination of plastic and paper. In Australia, plastic waste has the lowest recovery rate due to 19% being sent to landfill and coffee cup waste shares a significant component [21]. According to sustainability Victoria, Australians dispose 2.7 million coffee cups and 90% of them end up in landfills which is approximately 60,000 kilograms per annum [22]. Inability to recycle coffee cups through standard recycling processes due to the presence of plastic liner, which results in piles of landfill. Moreover, spent coffee ground in each coffee cup is weighed approximately 11 grams resulting in approximately 500,000 tonnes of wet, waste coffee grounds every year. While some of this waste is converted into composts, majority ends up in landfills through the general waste bins thus causing significant greenhouses gas emissions. Moreover, previous studies have signified the importance of exploring the balance between triple bottom approaches of sustainability (economic, environmental and social sustainability) to successfully achieve sustainable development goals (SDGs) [23, 24]. Therefore, reusing these waste products in building materials can lead to promoting circular economy concepts.

Promotion of such a novel material requires sustainable benchmarks in terms of economic and environmental benefits in addition to physical, mechanical and strength characteristics. However, majority of the previous studies have concentrated only on experimental studies to yardstick physical and mechanical characteristics, while broader sustainable benefits are either neglected or seldom considered. There is a contemporary requirement to develop systematic studies to compare the benefits and impediments at planning stages to optimise the sustainability benefits. The current study aims to conduct a comprehensive feasibility assessment of using various coffee related waste types as raw materials for three different building materials. i.e.., sand replacement in concrete and wood chip replacement in manufacture of particle boards. Using the multi-objective optimisation method, the study aims to inform a practical methodological framework to benchmark the promotion of sustainable materials within the building material industry.

2 Background and research significance

Life cycle assessment (LCA) is a worldwide recognised technique used to estimate and compare environmental impacts of a product or process for different life cycle stages [25-27]. Despite early significance of only environmental impact results, recent studies highlight the importance of considering economic and social aspects to consider triple bottom line approach of sustainability [10, 28]. Cement is considered as the most energy intensive material and therefore many previous studies have focused on replacing cement from concrete mixes [11, 29-31]. However, more cement is replaced, numerous studies have considered aggregate replacement from concrete due to its considerable high embodied energy consumption at the up-stream manufacturing stages after cement [32-36]. A recent study used coal bottom ash (CBA) as a sand replacement in concrete with the intention of improving the environmental sustainability of concrete [37]. The results indicated that due to the presence of pozzolanic characteristics, use of appropriate proportions of CBA can enhance workability, strength and durability. Several other studies have made attempts to partially replace virgin materials in concrete with potential waste materials [30, 38-40]. Nevertheless, these studies have mainly considered investigation of mechanical, physical and durability characteristics while seldom considering the cost and other project related limitations and constraints.

Many studies have made attempts to evaluate environmental incentives of replacing virgin materials in concrete with waste materials [11, 28, 41-43]. These studies have used waste materials to replace cement, fine aggregate and coarse aggregate in concrete and the results have highlighted significant environmental benefits and reduction in energy consumption. In addition to the landfill diversion and reduction of land usage, these savings are extremely advantageous in promoting green materials within the industry. However, majority of these studies have predominantly focused on greenhouse gas emissions on analysing upstream material embodied emissions. Several studies have estimated and compared environmental benefits of using waste to replace virgin materials in manufacture of particle boards. One study conducted in Brazil used agro-residual sugarcane bagasse as replacement for woodchips in particleboards production [44]. The LCA impact assessment results indicated that replacement only reduced wood consumption and did not significantly affect other environmental impacts. Another study compared LCA of wood waste generated from building construction activities [45]. Using cradle-to-gate system boundaries, the study included four scenarios of using wood waste for traditional particle boards production, cement-based particle board production, energy generation and landfilling. The results indicated that carbon emissions can be reduced by approximately 12% when using wood waste in traditional construction, and 9% for cement-based particleboard construction. Some studies have attempted to investigate cost and environmental impacts associated with partial replacement of materials in concrete [10, 28]. These studies have either not considered optimisation or multiple environmental impacts, thus limiting the scope the analysis.

Table 1 represents a summary of the reviewed studies on using waste materials for production of particleboards and concrete. The results indicate that majority of the studies have concentrated primarily on experimental research to determine mechanical, physical and other material related properties of building materials incorporating waste materials. However, transition of these materials into marketable products are often restricted due to cost escalations. Consequently, there is a contemporary requirement for a systematic methodology that can benchmark sustainability benefits to enhance the marketability of the product. Therefore, the current study attempts to present a systematic methodology to compare and analyse sustainability benefits of replacing virgin materials with used coffee-cups in the production of building materials.

3 Research Methodology

3.1 Life Cycle Assessment (LCA) Methodology

3.1.1 Goal, scope and system boundary

Several previous studies have conducted comprehensive LCA analyses of using different waste material compositions in concrete and compared several environmental impacts [46, 47]. However, the main goal of this study is to identify, compare and analyse environmental impacts related to production of concrete and particle boards using traditional virgin materials partially with used coffee-cups. Thus, the major focus of the study was to compare cost effective and environmentally friendly mix designs that can be marketed in the industry for different construction applications. The production is setup at laboratory scale to facilitate effective comparison and enable potential improvements. Effective LCA findings are strongly dependent on proper definition of functional units of the product and hence the study adopted following functional units to enable effective comparison of environmental impacts.

- Functional unit for Concrete – 1 m^3 of concrete
- Functional unit for particle board – 1 m^2 of particle board with 25 mm thickness

As shown in Figure 1, the system boundaries for the products involve a cradle-to-gate process including acquisition of raw materials, production of the main product and transportation of materials. Since the manufactured product will be experimentally compared with virgin product for performance and hence the maintenance and usage life cycle stages are assumed to be the same. It is also assumed that the final disposal of both the recycled and virgin products will be sent to landfill and therefore excluded from the system boundary.

Table 1 Summary of selected previous LCA studies on using waste materials in particle boards and material replacement in concrete

No	Application	Waste material	Scope	Reference
1	Particleboard	Rice husk	Investigation of processing parameters and binder content	[48]
2	Particleboard	Sugarcane residues	Life cycle assessment study of particleboards made from sugarcane bagasse residues and pine wood shavings	[49]
3	Particleboard	Wood waste	Environmental assessment and technical feasibility of using wood waste in cement bonded particle boards	[50]
4	Cement board	Pulverised fly ash, incinerated sewage sludge ash	Mechanical, durability and environment aspects of magnesium oxychloride cement boards production	[51]
5	Particleboard	Crop straw	LCA of straw particleboard and straw cement-bonded particleboard	[52]
6	Particleboard	Wood shavings	LCA of particleboards made from recycled wood and bio-resins	[53]
7	Particleboard	Wood waste	LCA of particleboards made from waste wood	[54]
8	Concrete	Recycled aggregate	LCA of concrete building blocks with recycled aggregate	[55]
9	Concrete	Polypropylene fibres	LCA of recycled polypropylene fibre in concrete footpaths	[56]
10	Concrete	Metalized plastic waste	LCA of metalized plastic waste from food packaging in geopolymer concrete	[57]
11	Concrete	Recycled aggregate	Carbon emission analysis of recycled aggregate by CML 2001 and ReCiPe method	[42]
12	Concrete	Alternate fine aggregate	A review study on using alternate fine aggregates in sustainable concrete production	[58]
13	Concrete	Sewage sludge ash (SSA)	GHG emissions and GWP impact assessment of replacing cement with SSA	[59]
14	Concrete	Coal bottom ash (CBA)	A review study on using coal bottom ash as a sand replacement material in concrete	[25]
15	Concrete	Waste fibre paper	LCA assessment study of cement replacement using waste fibre paper	[60]
16	Concrete	Glass waste	Evaluation of CO_2 footprint and utilization of natural raw materials	[61]
17	Aggregate	Aggregate	LCA assessment of production of virgin aggregate and recycled waste aggregate	[62]
18	Concrete	Glass powder and slag	LCA assessment of cement replacement using glass powder and alkali-activated slag	[63]
19	Concrete	Fly ash	LCA of high strength concrete for marine applications containing fly ash	[64]
20	Concrete	Fly ash	LCA of self-compacting concrete containing fly ash	[65]

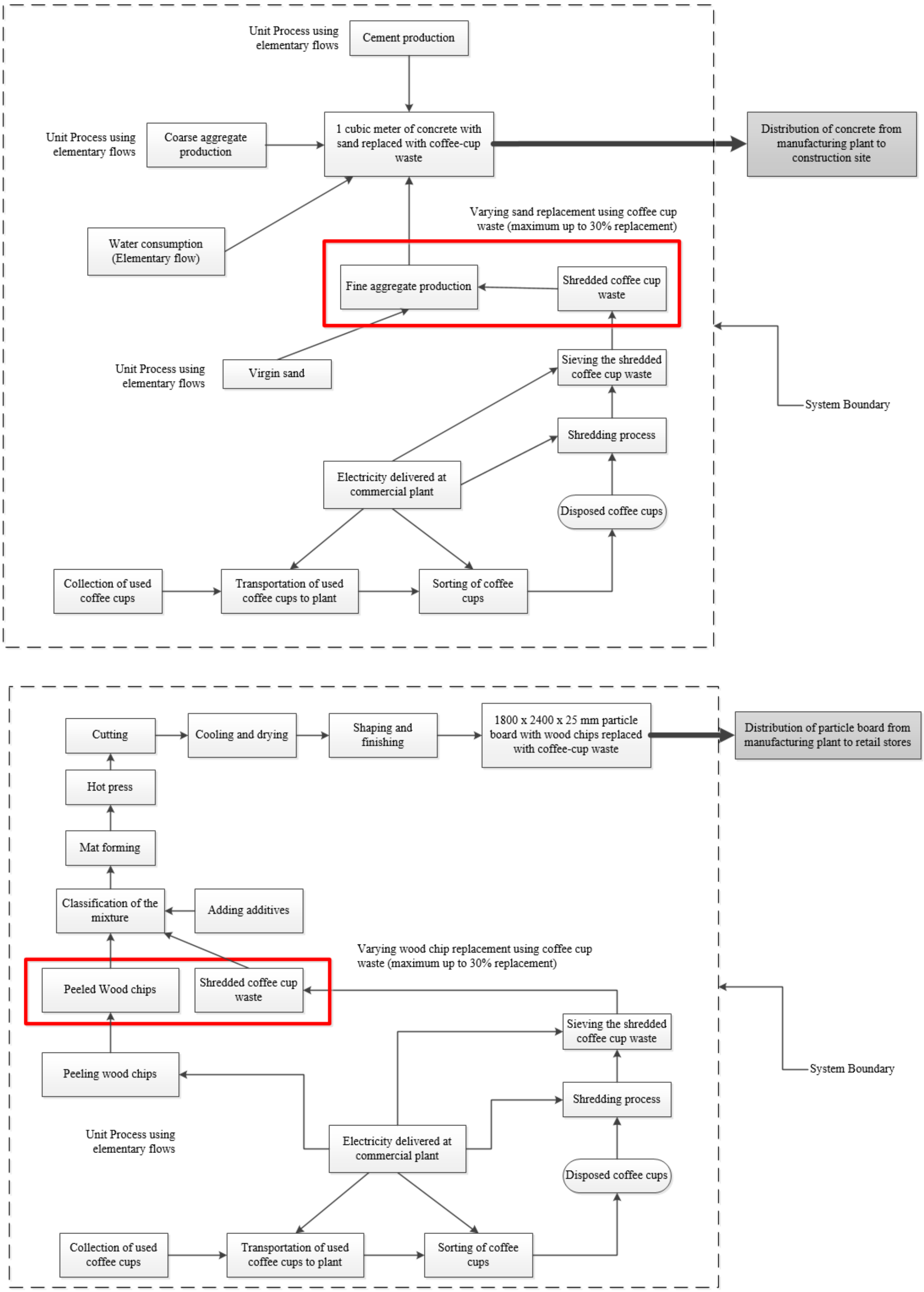


Figure 1 Major system boundaries for the two products

3.1.2 Life cycle inventory – mix design details for experimental study

Composite particleboard production with shredded coffee-cup waste used a flat-pressed production process which is similar to an industrial production process [49, 66]. The coffee-cups considered in this study were all paper-based with a plastic lining, typically polyethylene. It is possible that the processed cups were not all uniform and varied in composition based on the manufacture. The lids were disposed of and not utilised further in this study. The coffee cups were mechanically shredded to a size of 3-6 mm. The plastic liner was not removed from the coffee cups prior to shredding, and hence, the waste material is composed of both plastic and paper. Figure 2(b) illustrates the shredded coffee cup waste used as a wood chip replacement in particleboards. Wood chips are mixed thoroughly with shredded coffee cups for about 6 minutes in rotary drum to obtain a homogenous composite mixture. The mixture is then placed in an Aluminium caul plate to form a forming box and obtain a uniform mat for the particleboard. The initial mat forming includes a manual press to reduce the mat height. Subsequently hot pressing is performed with pressing temperature of around 185 ^{0}C to 195 ^{0}C, pressure of 5 N/mm^2 and pressing time of 6-7 minutes respectively. Following the hot press processes the boards are further cooled for cutting into desired shapes. Control particleboard sample with virgin material included 8% resin in addition to 92% wood chips in the mixture. All the particle board samples were tested according to the AS/NZS 4266.1.2017. The investigation for particleboards included the bonding strength (tensile test), density test and thickness swelling. The purpose of the tensile test was to determine the required force needed to separate the layers and to determine how well the wood and plastic bond together. The density test was conducted to determine the weight of the composite particleboard, essentially determining whether this prototype is of lighter weight when compared to traditional particleboard. The thickness swelling test is conducted to determine water-resistant capacity of the composite particleboard.

(2a) finely ground plastic from coffee cup waste (0.5mm) for sand replacement in concrete

(2b) shredded coffee cup waste (2-6 mm) for wood replacement in particleboards

Figure 2 samples of coffee cup waste used as plastic waste

The second material considered is an ordinary Portland cement concrete mix with fine aggregate substituted with finely ground recycled coffee cups. The coffee cups were sorted out by removing the lid, cleaning and drying them prior grinding them finely to obtain a powder form that could be used a sand replacement material. The obtained mixture is then passed through 0.6 mm sieve to obtain a uniform distribution sample. The mix designs used for the control sample included 355.9 kg, 733.6 kg, 1100.5 kg and 210 kg of cement, sand, coarse aggregate and water respectively per cubic meter. This concrete mix design is based on 25 MPa concrete. An additional 5 percent of concrete is considered during quantity calculation to incorporate material wastage during the casting process. 10 percent volume equivalent of sand is then replaced from the control mix using shredded coffee cup waste for the comparative assessment. The shredded coffee cup waste incorporated into the concrete mix is shown in Figure 2a. The cups were finely ground to an average size of 0.5 mm. This fine processing allowed separation of the plastic and paper components. The paperboard was discarded and only the plastic material was considered in this study.

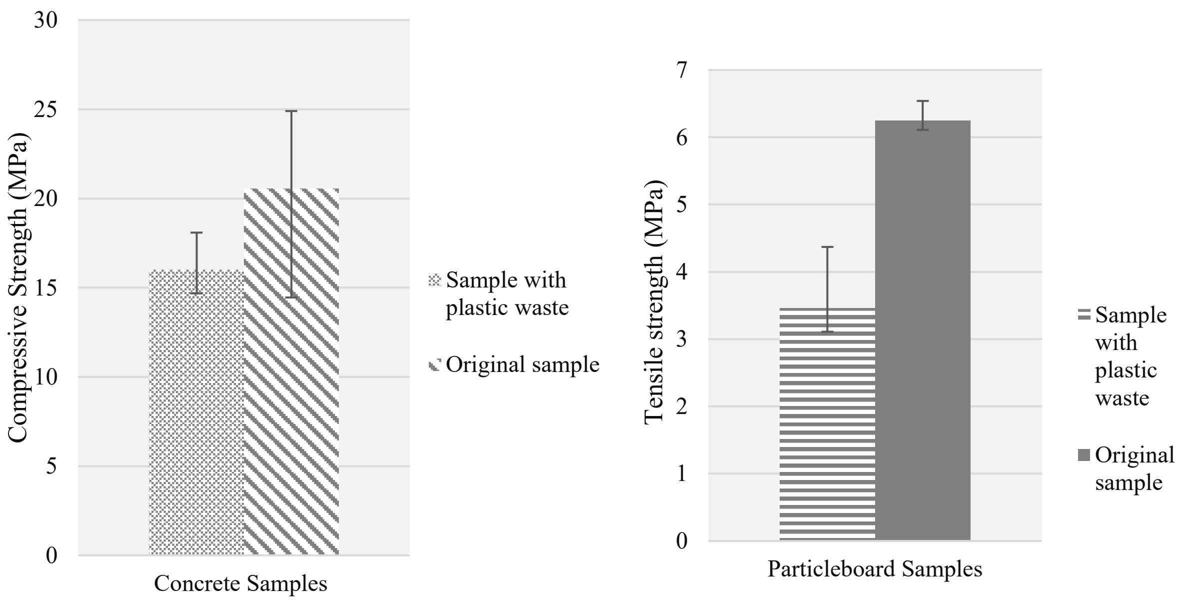
The waste material compositions and the corresponding transportation distances are illustrated in Table 2.

Table 2 Product types and design considerations in the current study

Product	Waste composition	Amount replacing virgin material replacement	Distance
Concrete	Sand replacement with finely ground sand particles	10%	20 km
Particleboard	Wood chip replacement with shredded coffee cup waste	30%	20 km

3.1.3 Experimental findings for concrete and particle board samples

Figure 3 represents the material properties and the resulting basic comparative experimental results of the two green products. Based on the results, none of the products (both concrete and particleboard with coffee cup waste) was able to achieve the designated strengths of the original control sample made from virgin materials. However, both samples were able to achieve 50% or more strength results as compared to strengths of control samples. Concrete samples with finely shredded coffee cup waste as a sand replacement material achieved 78% of comprehensive strength of the original control sample with virgin materials. Particleboard samples with shredded coffee cup waste achieved 57% of tensile strength of the original control sample with virgin materials. Therefore, assuming satisfactory strength results the study considered sample waste compositions for the LCA study.



(a) Comprehensive strength of concrete samples (b) Tensile strength of particleboard samples

Figure 3 Laboratory results of the samples used in this study

3.1.4 Life cycle impact assessment (LCIA)

ISO 14044 is the international standard that specifies the requirements for undertaking life cycle impact assessment (LCIA) of a product or process in LCA [67]. The objective of LCIA is to assess the environmental impacts of the inventory analysis to compare and understand the environmental significance. Based on the practical relevance and the global influence, six major impact categories, namely global warming potential (GWP100 in kgCO_2-eq), eutrophication potential (EP in kg-NO_x-eq), acidification potential (AP in kgSO_2-eq), photochemical oxidation formation potential (POFP in kg C_2H_4-eq) human toxicity potential – 100a (HTP in kg 1, 4-DCB-eq) and Terrestrial ecotoxicity - 500a (TAETP in kg 1, 4-DCB-eq), are considered in the study. These impact categories are chosen since CML baseline and ReCipe midpoint method are used for the LCIA and OpenLCA software using Ecoinvent database is utilised for impact assessment modelling. The major characterisation factors for the selected impact categories are shown in Table 3. These pollutant substances are considered as they constitute the major emissions associated with raw materials used in the current study. The normalisation factors for each impact category are also listed in Table 3.

Table 3 Characterisation and normalisation factors used in the current study

Pollutant name	Characterisation factors					
	Symbol	GWP	EP	AP	POFP	HTP
Carbon dioxide	CO_2	1		-	-	-
Methane	CH_4	21		-	-	-
Nitrogen oxides	NO_x	-	0.13	0.70	-	-
Ammonia	NH_3	-	0.35	1.88	-	-
Carbon monoxide	CO	-		-	0.03	-
Sulphur dioxide	SO_2	-		1.00	0.05	0.096
Particulate matter	PM_{10}	-		-	-	0.82
Non-methane volatile organic compounds	NMVOC	-		-	1.00	0.64

Impact category	Normalisation factors		
	Unit	Value	References
Global warming potential (GWP)	kgCO_2-eq	3.86E+13	[6, 28, 68]
Acidification potential (AP)	kgSO_2-eq	2.99E+11	[6, 28, 68]
Eutrophication potential (EP)	kg-NO_x-eq	1.29E+11	[6, 28, 68]
Photochemical oxidation formation potential (POFP)	kg C_2H_4-eq	4.55E+10	[6, 28, 68]
Human toxicity potential – (HTP 100a)	kg 1, 4-DCB-eq	4.98E+13	[6, 28, 68]
Terrestrial ecotoxicity potential – (TAETP 500a)	kg 1, 4-DCB-eq	4.98E+13	[6, 28, 68]

3.1.5 Cost calculation models used for material production

Since a cradle-to-gate system boundary was considered in LCA analysis, costs associated with end-product manufacture is considered in the cost analysis. Therefore, cost calculation can be divided into four major components of raw material procurement costs, equipment usage cost during manufacture, transportation of material and labour costs. These cost components are based on laboratory production of the materials.

3.1.6 Cost of procuring construction raw materials (C_m)

Cost of procuring material is often charged as per unit cost and can be estimated from the following equation. Where; $UC_{m,i}$ is the unit material cost for ith materials in AUD/unit material and $Q_{m,i}$ is the quantity of the ith raw material.

$$C_m = UC_{m,i} * Q_{m,i} \quad \textbf{(1)}$$

3.1.7 Cost of construction equipment (C_{eq}) and cost of transportation vehicles (C_t)

Cost of manufacturing equipment (C_{eq}) can be estimated by the following equation. C_h is the hiring cost or purchase cost of the equipment and FC is the fuel cost in AUD/unit of fuel consumption and Q is the fuel consumed. If the equipment is purchased only a fraction (t/T) of the purchase cost is used. This fraction is calculated by taking the ratio between actual usage of the equipment (or vehicle) for material manufacture in hours (t) and the life expectancy of the equipment (or vehicle) (T) in hours.

$$C_{eq}(or\ C_t) = \left(\frac{t}{T}\right) * C_h + FC * Q \quad \textbf{(2)}$$

3.1.8 Cost of labour (C_l)

Cost of labour (C_l) is usually charged as a daily rate or hourly rate and can be determined by the following equation. LR is labour rate in RMB/day or hour and t is the work duration in either days or hours.

$$C_{eq} = LR * t \quad \textbf{(3)}$$

3.1.9 Limitations and assumptions

Any LCA study is subjected to limitation and assumptions based on the scope and objectives of the study. The current study is subjected to following assumptions and limitations.

- The analysis is based only on laboratory scale production of materials and the mass-scale industry production could result in slight variations.
- The study assumes that concrete samples with up to a 50% maximum sand replacement with the assumption of using them in low stress applications in the construction industry.
- The optimal mix designs then need to be experimentally verified for desired mechanical characteristics before market use
- The study scope was only focused on analysing cost-effective and environmentally friendly construction materials. However, sustainable benefits with relevant to SDGs are not considered in the current study
- The study did not consider overall sustainability assessment and aspects such as product life span, durability and stability are not considered, which can be considered in future studies
- Wherever emission inventories were not available, emission factors were obtained from previously published literature.

- Procurement of waste material availability (coffee cup waste) could be affected with practical collection limitations and hence it is assumed that is available in abundance.
- Practical limitations of material manufacture is assumed to be negligible in the current analysis.
- Some other phenomena in concrete such as carbonation and carbon sequestration are considered negligible in the current analysis.
- Treatment and transport of any other residual materials are not considered in the study.
- Raw material prices for the current study are the retail prices and may differ from actual bulk procurement prices.

3.2 Multi-objective optimisation Methodology

Multi-objective optimisation (MOO) is a technique that can be used to optimise practical problems which have multiple conflicting objectives [69]. As compared to single objective optimisation, MOO is an evolutionary technique that can resolve existing optimising problems with multiple objectives. Out of the two distinct multi-objective techniques utilized, obtaining a Pareto-optimal solutions from the output subset is a preferred option to solve real-world scenarios [10]. Obtaining a set of optimal solutions has a major advantage as it provides the decision-maker with a set of possible optimal options with the desired results. Predominantly known as population approach, multi-objective genetic algorithm (MOGA) is an extension of the single objective genetic algorithm to optimise two objective functions with limited constraints and variables. In addition, one of the objectives of this study is to explore the preferred compositions of waste materials that would provide both environmental and economic benefits. Therefore, obtaining a range of optimised solutions is advantageous as it will provide multiple decision-making options for stakeholders who wish to benchmark different priorities. Moreover, MOGA is a well-known methodology that can optimise objective functions consisting both discrete and continuous variables [10]. Therefore, MOGA is selected in the current study to obtain the optimum composition with reduced costs and environmental impacts.

3.2.1 Objective functions

Based on the current scope and objectives, cradle-to-gate environmental impacts (E) and manufacturing cost of the product (MC) are defined as the two objective functions. If ‘δ’ denotes the product type that is considered in the optimisation problem, the following equations are defined as the objective functions.

Objective function 1: Minimise, $MC(\delta) = \sum \alpha_{i,\delta} (x_1 \rho C_{i,\delta} + x_2 pc_{i,\delta} + x_3 tc_{i,\delta})$ ---------------------------- (1)

Objective function 2: Minimise, $E(e, \delta) = \sum \alpha_{i,\delta} (y_1 MEE_{i,\delta} + y_2 EE_{i,\delta} + y_3 TE_{i,\delta})$ ---------------------- (2)

Where, α_i is the percentage of the i^{th} raw material from the total, $\rho C_{i,\delta}$ is the raw material procurement cost, $pc_{i,\delta}$ is the material production cost and $tc_{i,\delta}$ is the transportation cost to the manufacture plant of the i^{th} raw material. ‘x’ and ‘y’ are the priority factors assigned for each cost and emission component based on the project specific objectives. $MEE_{i,\delta}$, $EE_{i,\delta}$ and $TE_{i,\delta}$ are the material embodied emissions, equipment usage emissions and transportation emissions in kg-emissions/unit weight. The environmental variables in the objective function (2) are determined using the following equations.

$MEE_{i,\delta} = Q_j * eef_{j,} + eef_{\mu} * (Q_{T,j} - Q_j) + \sum Q_f * eef_f$ -- (3)

$Q_{T,j}$ and Q_j are the total original raw material quantity that is replaced and j^{th} quantity of virgin material used in the final mix design in kg respectively. Q_f is the quantity of the other raw material in kg, eef_j, eef_μ and eef_f are the embodied emission factors of the virgin raw material replaced, waste material and other raw materials considered in kg of emissions per kg of material quantity respectively.

$$EE_{i,\delta} = ef_k * t_1 * P \quad \text{--} (4)$$

ef_k is the emission factor for electric equipment in kg-emissions/kWh, t_1 is the duration of the electric equipment and P is the power of the electric equipment in kW.

$$TE_{i,\delta} = ef_m * t_2 * \rho_m \quad \text{--} (5)$$

Ef_m is emission factor for the m^{th} fossil fuel type used in kg-emissions/(litres-hour), "t_2" is the duration of travel for the transportation vehicle, ρ_m is the fuel average fuel consumption rate is litres/km-hour and d_2 is the two-way distance travelled by the vehicle in km.

3.2.2 Sensitivity analysis - design variables

The main objective of the study was to compare the environmental and economic savings of using waste materials in manufacture of building materials. In practical scenario, several variables influence the total environmental impacts, and hence having multiple optimum solutions will provide multiple decision-making options for stakeholders who wish to prioritize project specific and market specific sustainable benefits. Thus, the following variables are considered in the sensitivity assessment to investigate the effect on environmental impacts and total material production costs.

- Quantity of waste material - The composition of shredded coffee cup waste amount is a governing factor influencing environmental savings of the sustainable product. Therefore, the coffee cup waste amount incorporated in the mix design is considered a key design variable in the objective function.
- Transportation distance of raw materials – shredded coffee cup waste is not frequently available and often will have to be transported to production plants. Therefore, different transportation distance would significantly influence total environmental impacts. Thus, the transportation distance of the raw material is considered a design variable for the sensitivity analysis.

3.2.3 Constraints and design variables for multi-objective optimisation study

The mix design optimisation problem consists of both continuous and discrete variables based on the derived objective function. For example, the maximum amount of virgin sand or wood replaced from the reference product with shredded coffee cup waste is subjected to achieving the required strength characteristics. Therefore, definition of proper constraints is important to discontinue the optimisation algorithm beyond the desired limit.

- For multi-objective optimisation, combination of three other plastic waste, namely high-density polyethylene (HDPE) – (Q_2), Polyethylene terephthalate (Q_3), low density polyethylene (LDPE) – (Q_4), are used with shredded coffee cup waste (Q_1)
- The total sum of the coffee cup waste, plastic waste and virgin raw material is kept equal to the total virgin material quantity of the reference sample (i.e., $Q_1 + Q_2 + Q_3 + Q_4 + \text{Sand} = 733.6$)
- The maximum amount of virgin raw material replaced with coffee cup waste and other plastic waste is set as 30% and thus lower and upper constraints are set to $0 < Q_1 + Q_2 + Q_3 + Q_4 < 220.08$

- The other raw material compositions are not changed but retained the same as the reference mix design samples (virgin concrete sample)
- Transportation costs are calculated as a function of the distance travelled and the electricity costs is sourced from the electricity bills without considering any discounts

4 Findings and discussions

4.1 LCA results

The LCA impacts from Table 4 and Table 5 illustrate that sand replacement in concrete results in better environmental savings as compared to particleboard manufacture. Photochemical oxidation potential (POCP) is the impact category that provides the maximum savings with percentage reduction of 25.90%. In addition, other impact categories such as human toxicity (HTP), Acidification (AP) and Global warming (GWP) achieve more than 10% in life cycle environmental impact reductions as compared to a virgin concrete sample. These environmental impacts reductions are because of 10% virgin sand replacement by waste plastics obtained from coffee cup waste. Human toxicity and POFP impact demonstrate a significant reduction as compared to other impact categories. These results confirm that material replacement in concrete can achieve better environmental savings as compared to environmental savings with of 30% of wood chips replacement in particleboard production.

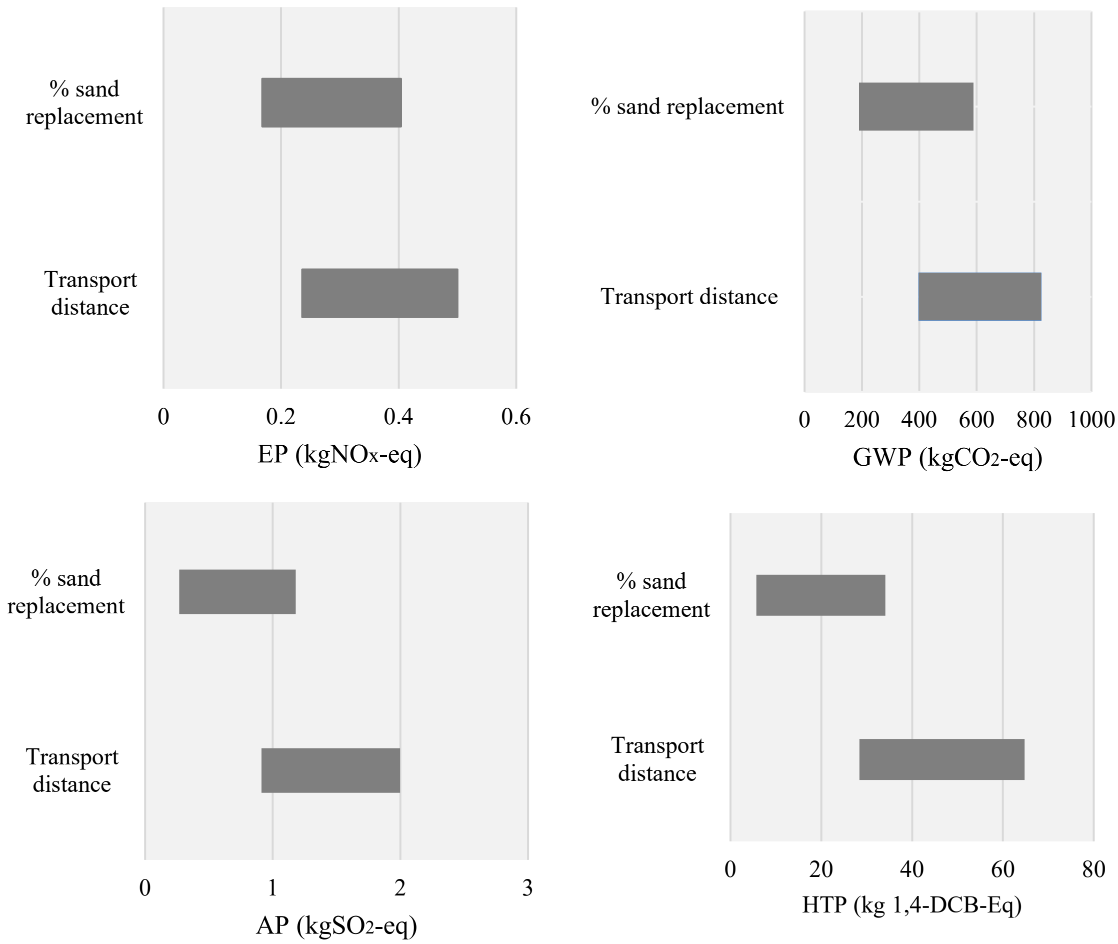
For the current LCA analysis, variations in quantity of plastic waste incorporated and the transportation distance between the waste processing plants, could affect the total output. Therefore, a sensitivity analysis as shown in Figure 4 is conducted to identify the importance of each variable on the net result. The results reveal that percentage of sand replacement is highly sensitive to GWP impact category and transport distance is highly sensitive to AP, EP, POFP and HTP.

Table 4 Life cycle impact results of 1m^3 concrete samples

Impact Category	Unit	Control	Plastic	savings
Acidification potential – generic (AP)	kg SO_2-eq	1.13E+00	9.50E-01	16.16%
Climate change - GWP 100a	kg CO_2-eq	4.46E+02	3.98E+02	10.74%
Eutrophication potential – generic (EP)	kg NO_x-eq	2.57E-01	2.36E-01	8.23%
Human toxicity - HTP 100a	kg 1,4-DCB-eq	3.50E+01	2.84E+01	18.89%
Photochemical oxidation - high NO_x POCP	kg ethylene-eq	4.29E-02	3.18E-02	25.90%
Terrestrial eco-toxicity - TAETP 500a	kg 1,4-DCB-eq	2.48E-01	2.41E-01	2.71%

Table 5 Life cycle impact results for the 1 m^2 particleboard manufacture

Impact Category	Unit	Normal	Plastic	savings
Acidification potential (AP) - generic	kg SO_2-eq	3.95E-02	3.89E-02	1.52%
Climate change - GWP 100a	kg CO_2-eq	8.19E+00	8.08E+00	1.36%
Eutrophication potential (EP) - generic	kg NO_x-eq	5.11E-02	5.02E-02	1.63%
Human toxicity - HTP 100a	kg 1,4-DCB-eq	1.52E+00	1.43E+00	5.35%
Photochemical oxidation (POCP) - high NO_x	kg ethylene-eq	1.61E-03	1.55E-03	3.82%
Terrestrial ecotoxicity - TAETP 500a	kg 1,4-DCB-eq	6.80E-03	6.37E-03	6.42%



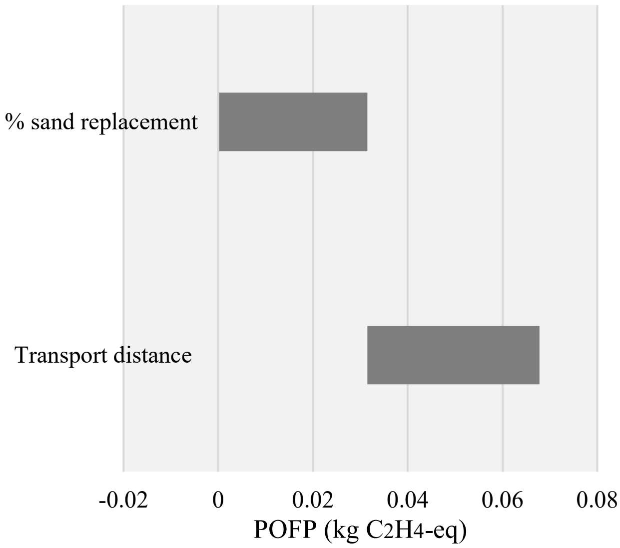


Figure 4 Impact variation due to sensitivity of variables of concrete samples

Based on the LCA results, emissions related to POFP, GWP, AP and HTP impact categories have more significance. Therefore, Carbon emissions (CO_2-eq), Nitrous oxide (NO_x), Carbon monoxide (CO) and Sulphur dioxide (SO_2) are considered as the environmental input for the multi-objective optimisation problem. These emissions are selected based on the major emission contributions to the resulting environmental impacts GWP, EP and POFP respectively.

4.2 Multi-objective optimisation results – Pareto front

The resulting non-dominated optimised solutions, often known as the Pareto front based on 100 iterative outputs, are illustrated in Figure 6. The environmental emissions and material production costs are represented for a functional unit of 1 m^3 of concrete. Obtained non-dominated optimised solutions can be categorised into three major regions based on the priorities, as highlighted in the first graph of Figure 6. Region 1 provides optimised solutions with low environmental emissions while region 3 provides cost-effective optimised mix designs. Region 2 provides the non-dominated optimised mixed designs considering both low cost and low environmental emissions for the concrete samples considered. Based on objectives and the project priorities the decision-making project stakeholders can select the most preferred mix design for the corresponding project. For instance, emission reduction priorities could be different for various regions across the globe and the acquired optimised solutions considering numerous environmental priorities would provide several decision-making options for selecting cost-effective sustainable mix designs.

The resulting most non-dominated optimised mix design for each pollutant type in each corresponding region is tabulated in Table 5. The values are rounded up to the nearest second decimal point and therefore, the total might be slightly changed. The results indicate that all the optimised mix designs in all regions are subjected to cost increase of at least 25% as compared to the reference sample. This is mainly due to the collection, sorting and converting of procured plastic waste to a useful raw material in the concrete mix design. The results also indicate that mix designs in region 2, can achieve around 26%, 73%, 5% and 81% for CO_2, NO_x, CO and SO_2 emission reductions respectively with 60-80% cost increase. In contrast, region 3 mix designs exhibit 10%, 38%, 2.5% and 43% for CO_2, NO_x, CO and SO_2 emission reductions respectively with around 25% cost increase. This reveals that if cost restrictions apply for green and sustainable selection, mix design from region 3 would be the most practical. However, if budget allows, mix designs from region 2 would provide better environmental savings. Mix designs from region 1 are not cost-effective with results indicating a minimum of 100% cost increase to achieve high environmental savings. This is highly an unlikely scenario when practical construction industry is considered because construction industry often operates with slim profit margins. Physical and mechanical characteristics of optimised mix designs obtained from the multi-objective optimisation are not experimentally verified in the current study. However, further studies can be focused on confirming the structural characteristics of the optimised mix prior to market usage.

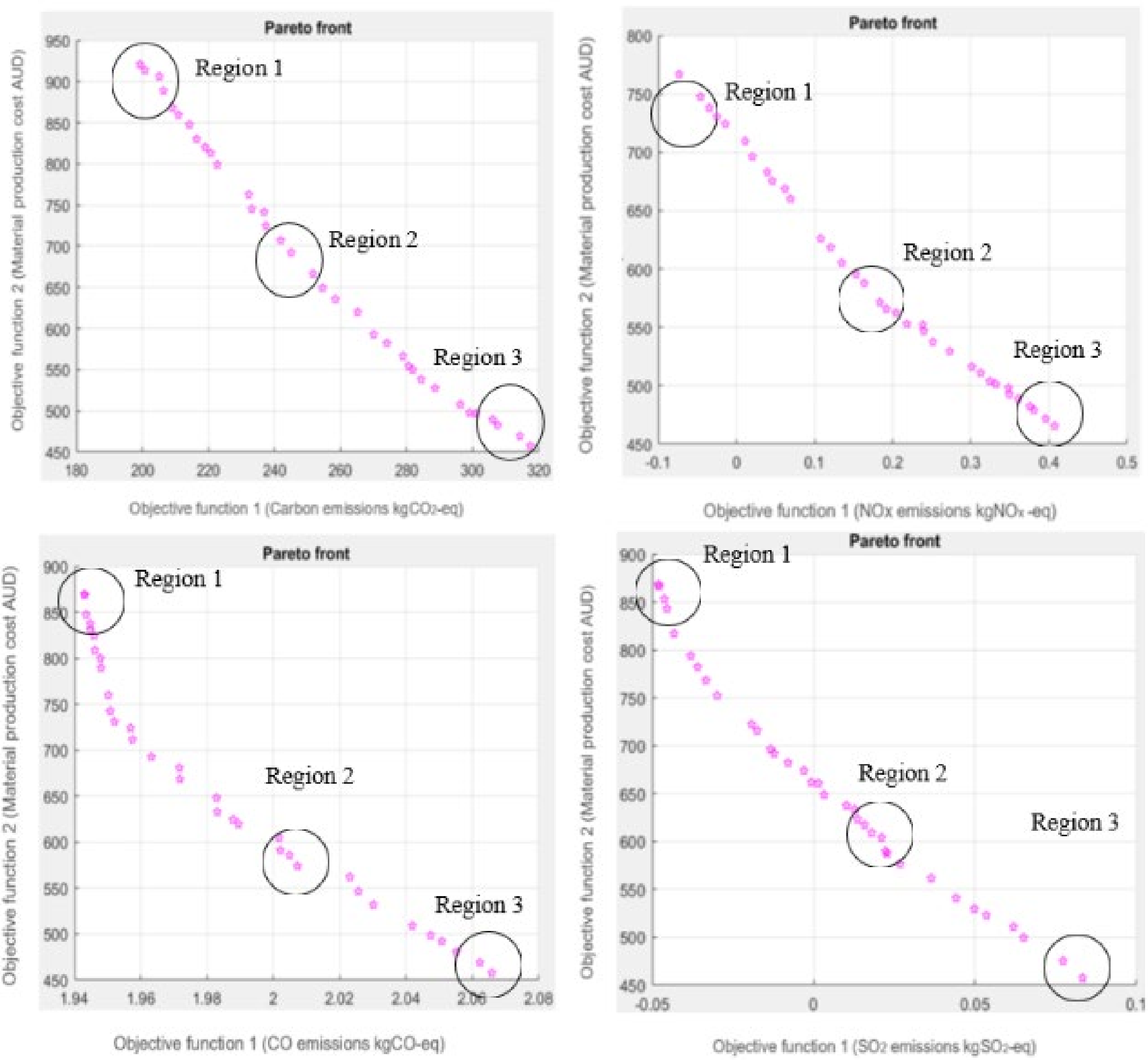


Figure 5 Pareto front for environmental emissions and material production costs

Table 6 Plastic waste quantities in the optimal mix designs for concrete samples

Region	Pollutant type	Plastic contents in optimal mix designs				Percentage	
		Q_1	Q_2	Q_3	Q_4	cost reduction	emission reduction
1	Carbon emissions	219.68	0.00	0.73	0.39	-158.76	42.77
	NO_x emissions	152.75	22.31	23.04	22.70	-116.70	100.75
	CO emissions	135.88	27.93	28.67	28.32	-137.65	8.51
	SO_2 emissions	71.05	23.53	1.90	123.65	-143.32	135.88
2	Carbon emissions	99.44	40.08	40.81	40.48	-85.15	26.79

	NO_x emissions	85.15	44.84	45.57	45.24	-59.50	72.92
	CO emissions	90.78	42.96	43.70	43.35	-60.55	5.21
	SO_2 emissions	57.22	21.55	1.98	140.04	-63.69	81.71
3	Carbon emissions	37.55	60.71	61.44	61.10	25.91	9.46
	NO_x emissions	10.65	69.68	70.41	70.07	-28.68	38.31
	CO emissions	87.57	44.04	44.77	44.43	-25.84	2.61
	SO_2 emissions	80.55	32.60	1.51	106.15	-25.87	43.71

5 Conclusions and future research

Plastic waste has the lowest waste recovery rate in Australia and the statistic reveal that annually 19% is sent to landfill. Coffee is a major beverage in the world and due to the plastic liner in disposable coffee cups, in Australia alone 2.7 million coffee cups per day end up in landfill as a plastic waste. The scope of the study was to conduct a LCA study to compare environmental benefits of using repurposed coffee cup waste as a sand replacement in concrete manufacture and wood chip replacement in particleboard manufacture. The life cycle assessment results revealed that 30% of partial sand replacement, when using coffee cup waste in concrete, can achieve 16.16%, 10.74%, 8.23%, 18.89% and 25.90% savings for AP, GWP, EP, HTP and POFP impact categories respectively. Particleboards production with wood chips replaced achieved only 1.52%, 1.36%, 1.63%, 5.35% and 3.82% for AP, GWP, EP, HTP and POFP impact categories respectively. Concrete samples were only considered for further assessment as the savings are significant in concrete samples as compared to particleboard manufacture.

Percentage of sand replaced and transportation distance are considered in the sensitivity assessment to investigate the influence of the variables on the output. Results revealed that percentage sand replacement is more sensitive to GWP impact potential while transportation distance is sensitive to other impact potentials. Multi-objective optimisation study is conducted to minimise environmental emissions and production cost as the main objective functions. Resulting Pareto front with 100 outputs, furnished three regions of non-dominated optimal solutions with mix designs. Comparative assessment of these results highlighted that with 25% cost increase, 10%, 38%, 2.5% and 43% of respective CO_2, NO_x, CO and SO_2 emission reductions can be achieved. The outcomes of the study are useful to understand potential cost and environmental benefits of using green and sustainable materials. The findings of the study clearly highlighted the importance of optimising cost and environmental savings when promoting sustainable and green materials. It will also encourage designers and contractors within the building and infrastructure construction industry to use green materials more frequently. The proposed solutions will provide long-term sustainable solutions by both diverting waste from landfills, reducing virgin material usages and reducing carbo emmisions. These environmental benefits indicate that incorporating recycled waste materials, such as coffee cups, in construction projects can contribute towards achieving SDG 12: Responsible Consumption and Production, and SDG 13: Climate Action. This study did not consider physical and mechanical characteristics of the two compared specimens apart from compressive strength of concrete samples and tensile strength for particleboards. Future studies can be focused on evaluating other properties of the sustainable materials. As the study considered a feasibility assessment, only replacement of virgin materials was considered in the analysis. However, further treatments and addition of activators may be required to achieve better physical and mechanical results. Moreover, the study only considered environmental and economic benefits in the sustainability assessment. The social sustainability assessment is not considered in the current study.

Future studies can also be focused on long-term economic and social benefits of replacing virgin materials with waste materials, and a comprehensive, quantitative assessment of SDG achievement.

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