

Review

Environmental Sustainability of Industrial Waste-Based Cementitious Materials: A Review, Experimental Investigation and Life-Cycle Assessment

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Abstract: Wall plaster production induces significant environmental impacts during its entire life as it consumes a high amount of cement and natural resources. Therefore, in sustainable development, industrial wastes are partially replaced to produce cementitious material to reduce environmental impacts. This study aims to identify the optimal environmental benefits from the waste-based cementitious materials that are used to produce wall plaster. Thus, this study involved conducting a comprehensive review of the mechanical and sustainable performance of industrial waste-based cementitious materials focused on wall construction. Then, an experimental test was conducted to ensure the appropriate mix design to enable the required compressive strength. A comparative analysis of mortar showed that it contained 15% (by weight) of fly ash, blast furnace slag, bottom ash, recycled glass, ferronickel slag, expanded polystyrene and wood ash using life-cycle assessment. The results show that mortar containing fly ash has lower environmental impacts in almost all impact categories (i.e., human health, the ecosystem and natural resources). Endpoint damage assessment of mortar mixtures expresses resource extraction cost as the most affected impact criteria. The replacement of globally consumed cement with 15% fly ash can contribute to monetary savings of up to USD 87.74 billion. The assessment clarifies the advantage of incorporating waste products in cement mortar, which allows policymakers to interpret the analysis for decision making. This study also found that the production of industrial wastes for mortar mixes has a significant impact on the environment.



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Keywords: blast furnace slag; fly ash; recycled glass; life-cycle analysis; environmental impacts; compressive strength

1. Introduction

Construction industries are searching for a sustainable replacement for current construction materials in order to reduce the usage of raw materials and environmental impacts [1]. Concrete, timber, steel and masonry are the most common construction materials used and concrete is highly used in construction [2–6]. Natural sand, aggregates and cement are frequently used to produce mortar and concrete [7]. This significant amount of natural resource usage causes the depletion of natural resources, which induces negative impacts on the environment. Furthermore, the production of cement also generates greenhouse gas emissions (GHGE) and introduces volatile organic compounds to the environment. Population growth is increasing the demand for building and construction materials, including a high demand for cement production with a projected 50% increase in annual consumption by 2050 [8]. Consequently, this increases the demand for natural raw materials and leads to continued production of significant amounts of construction waste and GHGE. Therefore, the construction industries are facing challenges in meeting cement demand and reducing the negative impacts on the environment.

Converting construction and landfill waste into cementitious materials is a sustainable solution that can mitigate the negative impacts on the environment as well as reduce

the usage of natural raw materials in the construction process [9–11]. There are different types of industrial-related wastes that are presently used as partial or full substitutions for sand or cement in mortar or concrete (recycled glass [12–15], blast furnace slag [7], rubber waste [16–20], ferronickel slag [21], wood [22–26], expanded polystyrene (EPS) [27–29], bottom ash [30,31], fly ash [32–34], date palm [35] and rice husk ash (RHA) [36–39]). These research studies highlight that waste-based cementitious materials can be used and still achieve the required workability, strength, fire and energy performance requirements. However, the replacement level of sand or cement contents in the mortar varies from 1% to 80% and depends on the desired objectives. Despite these previous studies that have proved the advantages of waste-based cementitious materials over conventional mortar, few studies have focused on the environmental performance of waste-based mortar used for wall plaster.

Therefore, this study involved conducting a life-cycle assessment on the waste-based cementitious material in mortar used for wall plaster (Section 4). The aims of this study are to identify the optimal environmental benefits of using waste-based cementitious material while achieving minimum compressive strength (5.2 MPa) and workability [40,41]. To achieve these aims, this study utilized a comprehensive literature review and identified the industrial wastes that have been used to produce mortar (Section 3) and their replacement level to achieve minimum compressive strength and workability (Section 4).

2. Methods

This work investigates previous research to identify industrial wastes that have previously been used to produce cement mortar. Scopus and Web of Science (WoS) abstract and citation databases were used to identify the journal articles to be reviewed. The searches were limited to articles indexed from 2011-01-01 to 2021-12-31. The search strings used in this study are listed in Table 1. The results show that a great amount of research has been conducted on mortar produced with fly ash and blast furnace slag (Table 1). Based on the industrial waste availability in Australia and the target replacement level of over 10%, this study focused on the performance review (Section 3) and life-cycle assessment of the mortar produced with recycled glass, bottom ash, ferronickel slag, fly ash, blast furnace slag, wood and EPS wastes for wall plaster (Section 5).

Table 1. Search strings used in this investigation.

Search String	Sources	
	WoS	Scopus
"Mortar" AND "Recycled glass"	147	106
"Mortar" AND "Bottom ash"	261	251
"Mortar" AND "Rubber waste"	16	21
"Mortar" AND "Ferronickel slag"	46	32
"Mortar" AND "Wood waste"	37	28
"Mortar" AND "Fly ash"	3315	2934
"Mortar" AND "Blast furnace slag"	928	1098
"Mortar" AND "EPS" AND "Expanded polystyrene"	44	54
"Mortar" AND "Date palm"	45	35
"Mortar" AND "Rice Husk Ash" AND "RHA"	123	169

3. Review of the Performance of Waste-Based Cementitious Materials

The major aim of this review is to identify the workability, compressive strength and minimum and maximum level of replacement of waste in waste-based cementitious material. This section also presents an overview of waste-based cementitious materials in terms of physical and chemical properties and thermal performance. This offers the use

of industrial wastes in cementitious materials and their current state of development to increase their replacement level in cementitious material.

3.1. Fly Ash (FA)

Fly ash (FA) is a waste by-product produced from coal incineration [42]. FA contains a high amount of SiO_2 and it creates artificial pozzolan characters, which are amorphous in nature, solid or have a hollow spherical shape [43]. This pozzolanic activity enables FA to replace the binding material of mortar and concrete. The specific gravity of FA varies from 1.6–3.1, and this depends on the shape, chemical compositions and particle gradation [44]. Lower specific gravity increases the volume of FA replacement of cement in mortar compared with other industrial waste [44,45]. Further, due to its spherical particles, low bulk density and improved surface precision, FA enhances the flow properties of mortar [46].

Mirza et al. [47] and Shaikh et al. [48] state that an increased replacement level of cement with FA reduces the flow time and increases workability. The replacement of cement with fly ash up to 50%, 60% and 70% resulted in increased workability [49]. However, a study by Liang et al. [50] highlights that the flowability does not change much with different FA compositions (i.e., 135.2 mm, 135.5 mm and 135 mm for replacement levels of 30%, 50% and 60%, respectively).

Furthermore, the compressive strength of mortar reduces when increasing the cement replacement level with FA. Jiang's and Guan's [51] study highlighted that the compressive strength of mortar at 3 days was reduced by 67.3% and 77% when adding 50% and 70% of high-volume fly ash (HVFA), respectively. The compressive strength reductions at 28 days were 45.4% and 68.6% for 50% and 70% replacement of HVFA, respectively. This indicates that compressive strength reduction with the addition of FA decreased with increasing age [47]. Another study by Shi et al. [52] also noted that compressive strength reduces with increasing replacement percentage of HVFA at ages 7, 28 and 56. The compressive strength reductions at 28 days of curing were 40%, 54.3% and 74.3%, for 50%, 60% and 70% replacement of FA, respectively [49].

A study by Jiang et al. [51] states that the flexural strength of mortar also reduces with an increase in the replacement of cement with FA. Furthermore, the flexural strength and compressive strengths of mortars with different FA replacement levels increase over time and decrease with an increased percentage of FA [50]. Furthermore, a study by Avijit et al. [53] replaced the 10% sand with FA in conventional mortar. This study found that up to 10% replacement of sand with FA gives higher compressive strength than the conventional mortar. However, the replacement level of FA beyond 10% resulted in a reduction in compressive strength [53].

Another advantage of FA in wall plaster is that it reduces the thermal conductivity and improves thermal comfort, reducing the operational energy consumption [33,38]. The thermal conductivity of conventional mortar is reduced by 65% and 80% by replacing 60% and 100% cement, respectively, with FA [53,54]. The reduction in thermal conductivity could be attributed to the air in pores of mortar created due to the porous nature of fly ash [53]. Furthermore, FA has the ability to absorb CO_2 and it was found that 60% of cement replaced with FA in conventional mortar reduced CO_2 emissions by 60% [55]. Another study by Colangelo et al. [56] highlighted that the environmental impacts of recycled concrete with FA are less severe in terms of greenhouse gases when compared with conventional concrete.

3.2. Blast Furnace Slag (BFS)

Blast furnace slag (BFS) emerges from the blast furnaces used to make iron. The quality of the slag is assessed by the method of manufacturing and the characteristics of the products [55]. Blast furnace slag is granular, smooth and dark in colour [57]. The specific gravity, loose bulk density and compacted bulk density of BFS are 2.45, 1052 kg/m^3 and 1236 kg/m^3 , respectively [58,59]. Furthermore, Yuksel et al. [60] found that the fineness modulus and fineness of 75 μm granulated BFS are 2.37 and 6.14%, respectively. The flowability of conventional mortar is reduced when granulated BFS is added [61]. This is because

of the finer nature of granulated BFS, and it requires more water to wet the surface. A study by López et al. [62] found that the compressive strength of conventional mortar increased when adding granulated BFS. This was due to the irregular or angular shape of granulated BFS particles.

Khatib and Hibbert [63] highlighted that replacing 60% of cement in conventional mortar with ground granulated BFS enables similar compressive strength to that given by conventional mortar. However, increasing the ground granulated BFS to 80% did not allow it to reach the compressive strength of conventional mortar at 28 days [44]. Alaa et al. [64] found that at 7 days, the compressive strength of conventional mortar increased to 25% and 57%, respectively, when replacing 20% and 50% sand with ground granulated BFS. Further, at the age of 28 days, the compressive strength increased to 22% and 86% for replacement levels of 25% and 50%, respectively. The ground granulated BFS replacement level of 75% improves compressive strength by 69% and 93% at 7 and 28 days, respectively.

3.3. Bottom Ash (BA)

Bottom ash (BA) is a by-product formed from coal, biomass or solid waste burning. Unlike FA, BA (from coal and biomass) is made up of smaller particles and heavy metals deposited on the bottom of the furnace. The physical properties of BA vary with the fragments of the parent rock, degree of pulverization and burning temperature. BA particles are of a coarse, angular, rough texture and an irregular shape with interlocking characteristics [65], and their unit weights are between 1200 and 1620 kg/m³ [42]. Further, depending on the coal content, the specific gravity of BA varies from 1.2 to 2.47 and the fineness modulus has a range of 1.39–2.8 [65].

A study by Dash et al. [7] stated that partly substituted BA improved dimensional durability, and caused greater impermeability to chloride particle penetration and sulphate attack relative to conventional mortar/concrete. The influence of BA on mortar/concrete properties depends on its origin (coal, biomass, municipal waste, etc.), particle size and treatment process [7]. Usually, the flowability of the mortar reduces with the substitution of cement with BA. This reduction is caused by the more porous structure of BA. Higher porosity will result in higher water absorption, leading to an increase in the need for water to increase flowability [66]. Furthermore, Sajedeh et al. [66] state that workability is reduced while increasing BA percentage.

Hannan et al. [67] found that replacing 10% to 20% Portland cement with coal BA in conventional mortar gives similar compressive strength to that of conventional mortar at 28 days of curing. Further, at 60 days, the compressive strength was increased by about 15%–20%. Another study by Chai and Raungrut [68] highlighted that the compressive strength of conventional mortar at 90 days was increased by about 8–12% when replacing cement with 10%, 20% and 30% of grounded coal BA. An investigation was made regarding coal-BA-mixed mortars with a constant w/c ratio (0.55), where coal BA was replaced by 9%, 23%, 33% and 41% by weight of cement [68–70]. The results show that for all substitution levels, there was a 10% increment in compressive strength after 28 days of curing when the grinding period was 3 hours. Moreover, there were no improvements in compressive strength observed for the samples with more than 33% replacement with a grinding period of half an hour after 90 days of curing, and the readings were similar in all mixes [68–70].

Furthermore, the mortar composed of coal BA provides better thermal insulation characteristics than conventional mortar. A significant reduction in thermal conductivity was observed with the increase in the composition of coal BA [71]. Mortar with 100% replacement of coal BA showed a 68.61% reduction in thermal conductivity compared with the control [71]. This indicates that mortar with coal BA can be used to develop sustainable thermal insulation plaster for buildings.

3.4. Recycled Glass (RG)

In most nations, glass is one of the least recycled products; however, it can be recycled many times without altering its chemical composition [12,72]. Because of its similarity to

natural sand, waste glass which contains more than 70% SiO₂ can be successfully incorporated as a powder or aggregate (fine and coarse) into cemented composites [12]. Waste glass has the risk of creating an alkali–silica reaction if this mixture is dissolved in glass to form an alkali–silica reaction gel, which offers cracking and expansion possibilities. A 40% partial substitution of fine aggregate with fine glass waste is advantageous in improving mortar mechanical properties, and 100% substitution together with the normal coarse aggregate is also desirable [73–75].

The workability of conventional mortar increases when adding fine glass waste [76]. A study by Islam et al. [77] found that when adding 0–25% ground glass while maintaining a constant water-to-binder (glass + cement) ratio (i.e., 0.5), a slight increase in flow was observed with the increase in glass percentage. Furthermore, the recycled glass mortar produced had improved strength compared with conventional mortar [77]. Islam et al. [77] found that the concrete produced from waste glass mortar had higher compressive strength than conventional concrete at one year of curing. Similar results were obtained in the field investigation by Nassar and Soroushian [78].

A notable increment in compressive strength was observed in the paste that utilises waste glass crystal powder compared with Portland cement [79,80]. Aliabdo et al. [80] found that substituting 10% and 15% cement with glass powder enhanced compressive strength by 9% and 16%, respectively. An enhancement in compressive strength was noted when substituting 10% and 15% cement with glass powder. Substitution of cement with waste glass powder by 15% and 30% leads to an ultimate increase in strength and reduced porosity in cement [81].

Reductions in thermal conductivity and the sorptivity coefficient of the cement via the changes in the air hall that could be filled with water or moisture were observed with the presence of waste glass aggregate [82]. The reduced thermal conductivity and density of the cement in the presence of water glass can be attributed to its low thermal conductivity property and the density being more moderate [12]. The thermal conductivity coefficient of conventional mortar is predominantly reduced with the presence of glass particles [12]. Thus, adding glass waste powder to conventional mortar can be a sustainable solution for improving thermal performance.

3.5. Ferronickel Slag (FNS)

Ferronickel slag (FNS) is a by-product of smelting garnierite nickel mining and has been estimated to generate around 12t of FNS as a by-product in the processing of 1t ferronickel alloy. FNS comprises high-density particles which can increase the compressive strength of concrete while partly replacing the sand [21]. The source of the ore, the method of cooling and the smelting process to a high extent determine the chemical and physical properties of the FNS [83]. The density of FNS is 278 kg/m³, which is greater than the density of sand (i.e., 216 kg/m³). The fineness modulus of FNS is 4.07, and coarseness is also higher than that of sand (1.95). The shape of the FNS particles is angular and an increasing amount of angular size particles can change the workability [83]. The addition of FNS increases the flow of conventional mortar. However, it reduces with more than 50% replacement, which can be attributed to the increased angular size particles in the mixture [83]. Saha and Sarker [83] found that 50% replacement of FNS enables the highest flow rate. However, a study by Manal et al. [84] states that there is no effect on the flow time of all FNS slag replacements for cement.

Furthermore, the compressive strength of conventional mortar at the ages of 3, 7, 28 and 56 days of curing was increased with up to 50% fine aggregates replaced with FNS, and a further increase in replacement of FNS reduced the compressive strength [83,85]. This is attributed to the particle packing effect of well-graded aggregates. Saha and Sarker [83] found about a 50% increment in compressive strength at 28 days when adding 50% of FNS. Moreover, compressive strength gained from 100% replacement of FNS is still higher than that of conventional mortar [83]. Another study by Muhammad et al. [86] observed a reduction in early-age compressive strength with the addition of FNS as a cement substitute.

However, the study also found an increasing trend in compressive strength at the age of 90 days.

Moreover, the thermal conductivity decreases while the FNS replacement level increases. The reductions in the thermal conductivity of conventional mortar with FNS replacements of 50% and 100% were 30% and 50%, respectively [85]. Hence, the enhanced thermal properties of mortar, without losing compressive strength, can reduce the heating and cooling energy consumption of a building.

3.6. Expanded Polystyrene (EPS)

Expanded polystyrene (EPS) is a foam composite composed of expandable polystyrene beads and is a low-density, neutral, thermoplastic hydrocarbon that is commonly used in packaging and thermal insulation [27,87]. Polystyrene is a non-biodegradable, significant and severe danger to the climate, with global demand forecast to increase from 17.5 Mt in 2013 to 35 Mt by 2020 [27]. Disposing of EPS in landfills is undesirable, as it induces significant environmental emissions, obstructs rivers, causes flooding, increases aquatic life deaths and degrades aquatic ecosystems [27]. However, EPS particles have a major impact on concrete thermal efficiency [28]. Thus, EPS beads are also used to build composites produced from foamed cement pastes with thermal insulation, utilizing additives to avoid isolation and enhance adhesion [29]. Furthermore, EPS consists of an inorganic matrix and it is relatively lightweight and non-absorbent with a low density of 17 kg/m^3 [88]. EPS has a particle diameter from 0.2 mm to 3 mm with a 50-micron pore diameter [29,89].

The lower density of EPS results in the reduced workability of conventional mortars with an increment of dosage of EPS [90]. However, all mortars with partial replacement by EPS are categorized under stiff mortars (slump value $\leq 140\text{mm}$). The workability resulting from the replacement of virgin EPS is similar to that gained from recycled EPS [90]. High-resistance and compact mortar with reduced macro porosities can be produced by replacing recycled EPS partially because of its properties, such as good grain size distribution and rough surface, particularly when the EPS replacement is high [90,91].

Further, EPS addition improves the durability of mortar and this can be attributed to the capillary absorption coefficient of EPS mortars [29]. A study by Ana et al. [92] states that the compressive strength of conventional mortar decreases linearly with the increment of EPS replacement. However, when the same replacement is performed with recycled EPS, relative compressive strength tends to increase up to four times compared with that prepared with virgin EPS. This is because of the increased density, better grain distribution and rougher surface of recycled EPS compared with virgin EPS [90]. Moreover, the thermal conductivity of mortar with recycled EPS is less than that of conventional mortar. The thermal conductivity of conventional mortar decreased by 60% when 80% of the sand was replaced by EPS [92]. It is also noted that the thermal insulation property of mortar partially replaced with recycled EPS is less than that of virgin-EPS-based mortar [90]. However, it is significantly higher than that of conventional mortar.

3.7. Wood Waste

Wood ash (WA) is the debris from wood and wood materials (chips, sawdust, bark, etc.) combusted in coal-fired power plants, paper factories and biomass-burning plants [25]. Wood fly ash consists of particles of extremely porous surfaces that are irregular in form. The physical, chemical and microstructural properties of wood ash may influence pozzolanic and hydraulic reactivity significantly [25]. Furthermore, these properties are determined by wood types, combustion processes including temperature, certain fuels co-combusted with the wood, and the WA collection method.

Past studies showed that the chemical compounds found in wood and woody biomass ashes have large percentages of CaO in most forms of wood, such as in birch bark, pine bark and spruce bark [22,24,25]. The optimal amount of wood ash that can substitute cement is 15%, and it provides the required compressive strength for mortar that can be used as wall plaster [25]. Using wood ash in blended cement and concrete as a partial substitution of

cement content would be advantageous from both an environmental and an economic viewpoint [93–95]. This should offer a solution to the issue of waste management while reducing energy and carbon-intensive cement in the building. Currently, wood ashes are frequently used as soil supplements to improve the alkalinity of soil for agriculture applications, and as filler materials in the construction of flexible pavements for roads and highways [22,24,25].

Overall, these waste-based cementitious materials improve the strength, durability and environmental and thermal performance of wall plaster. However, the performance level varies with the replacement level of waste-based cementitious and replacement content, which is sand or cement in conventional mortar. Despite these benefits, the application of waste-based cementitious materials in contemporary construction is limited. This is because of a lack of knowledge about waste-based cementitious materials' strength and environmental performance. There are several studies that have proven the strength performance of waste-based cementitious materials. However, few studies are focused on the environmental impact of waste-based cementitious materials. Thus, this study focuses on the life-cycle performance of waste-based mortar used for wall plaster.

4. Mix Design and Compressive Strength

A study by Selvaranjan et al. [39] highlighted that a 1:3 cement-to-sand ratio is suitable for producing wall plaster. Thus, this study used a similar mix design to produce conventional mortar (Mo). The replacement level of industrial wastes in the mortar mix was selected considering a minimum compression strength (5.2 MPa), flowability and water-to-cement ratio (0.7 ± 0.2) [40,41]. Furthermore, to compare environmental sustainability, this study only considered adding 15% industrial wastes, which is the optimum replacement level of WA [25]. Previous studies highlighted that the replacement levels of 15% of FA [49,52], BFS [63,64], BA [67,68], RG [75,80], FNS [83,85], EPS [92] and WA [25,93] produce higher compressive strength than the minimum required strength of mortar for wall plaster. The mix design for mortar containing wastes (Table 2) was derived via maintaining the cement-to-sand and water-to-cement ratios between 0.34–0.41 and 0.6–0.7, respectively [40,41].

Table 2. Mix design of 1 kg mortars.

Mixes (g)								
Materials	Mo	M1	M2	M3	M4	M5	M6	M7
Cement	222	189	189	200	222	200	195	202
Sand	666	526	526	510	516	535	495	528
Water	112	135	135	140	112	115	160	120
FA		150						
BFS			150					
BA				150				
RG					150			
FNS						150		
EPS							150	
WA								150

Compressive Strength Tests

A Hobart concrete mixture was used to produce the mortar. Initially, the machine was running for 4 min with an angular velocity of 35–50 rpm to mix the dry materials. Once the mix reached homogeneity, water was added, and the machine continued to run at the same speed for another 6 min to achieve a homogenised mortar mixture. It was then poured

into a 100 mm × 200 mm cylindrical mould. Three cylindrical samples were cast for each mix design and tested after 7 days of curing in water. The test was conducted based on the ASTM C39 standard using an MTS testing machine. This compressive strength test aimed to ensure the minimum required compressive strength could be achieved from the proposed mix design (Table 2).

Figure 1 shows the average compressive strength of conventional and waste-based mortar at 7 days. This figure illustrates that mortar containing 15% (by weight) of FA, BA, RG, EPS and WA provides lower strength than conventional mortar. Furthermore, adding 15% of BFS and FNS increases the compressive strength of conventional mortar. However, all the waste-based mortar produces higher strength than the minimum required compressive strength for mortar.

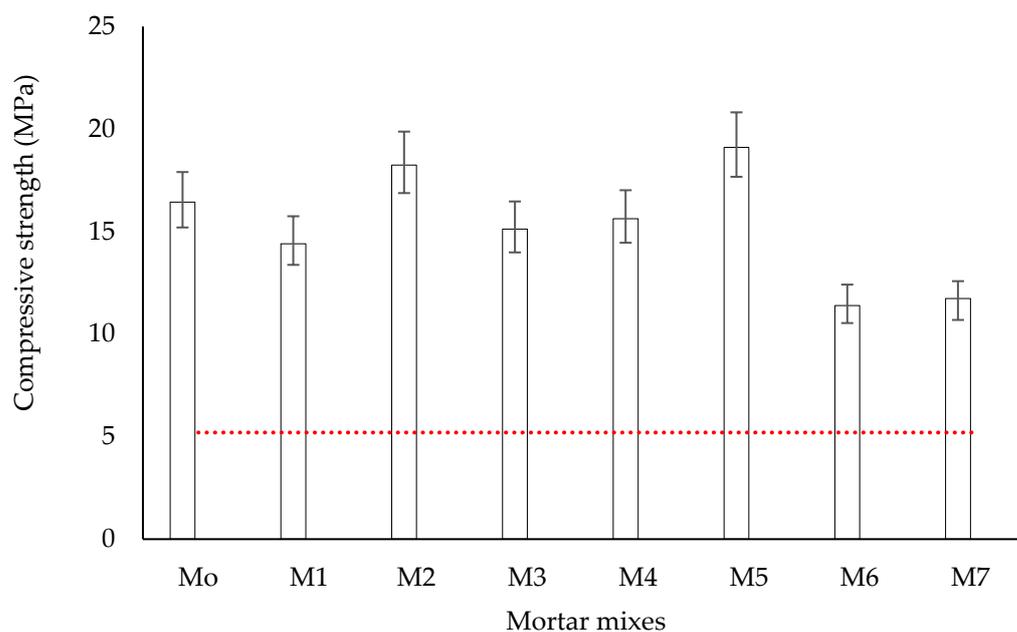


Figure 1. Compressive strength of conventional and waste-based mortar samples.

5. Environmental Impact Analysis

Life-cycle analysis (LCA) was conducted to evaluate the environmental sustainability of mortar containing industrial wastes (i.e., FA, BFS, BA, RG, FNS, EPS and WA) using LCA software SimaPro 8.2.0.0 [96]. This analysis aimed to identify the most appropriate wall plaster mortar with comparatively few environmental effects. The replacement level of industrial wastes in the mortar mix was selected considering a minimum compression strength (5.2 MPa), flowability and water-to-cement ratio (0.7 ± 0.2) [40,41]. Further, to compare environmental sustainability, this study only considered adding 15% industrial wastes, which is the optimum replacement level of WA [25]. The environmental impacts were compared by producing 1 kg of mortar as a functional unit with control and waste-based mortar mixes trialed (Table 2).

A harmonized life-cycle impact assessment, ReCiPe 2008, was developed by Goedkoop et al. [96], integrating midpoint and endpoint levels. The current study used the upgraded form of ReCiPe 2016 v1.1 initiated from ReCiPe 2008 [97]. The updated ReCiPe 2016 presents characterization factors at the global scale rather than at a specific country or continental scale. Relative uncertainties in midpoint and endpoint impact categories are reduced by working at the time horizon across cultural perspectives. This study articulates impact trajectories along the modelled framework, provides an overview of related emissions and quantifies sustainable indicators for decision making, categorizing them into three endpoint perspectives. Environmental interventions are expanded to calculate the impact of climate change and water use on human health, ecosystem damage and resource extraction.

The AS ISO 14040:2019 [98] and EN 15978 [99] specified LCA system boundary was followed in this study (Figure 2). A “cradle to gate” boundary with Recipe Midpoint (H)/World Recipe H method was used in this LCA. A similar method was used in the previous studies to assess environmental impacts [38,56,100,101]. Furthermore, this LCA process was limited to raw material processing to transportation of the mortar for wall plaster. The system boundary was accounted for in three stages: (1) material extraction, which includes extraction of raw materials and transport; (2) manufacturing stage (i.e., production of mortar mix); and (3) supply stage of the product, which does not include the treatment and disposal activities. The European Reference Life Cycle (ELCD) [102] and Australian National Life Cycle Inventory (AusLCI) [103] databases were translated into environmental impacts in this LCA model. More details on the data selection processes in the database can be found here [38].

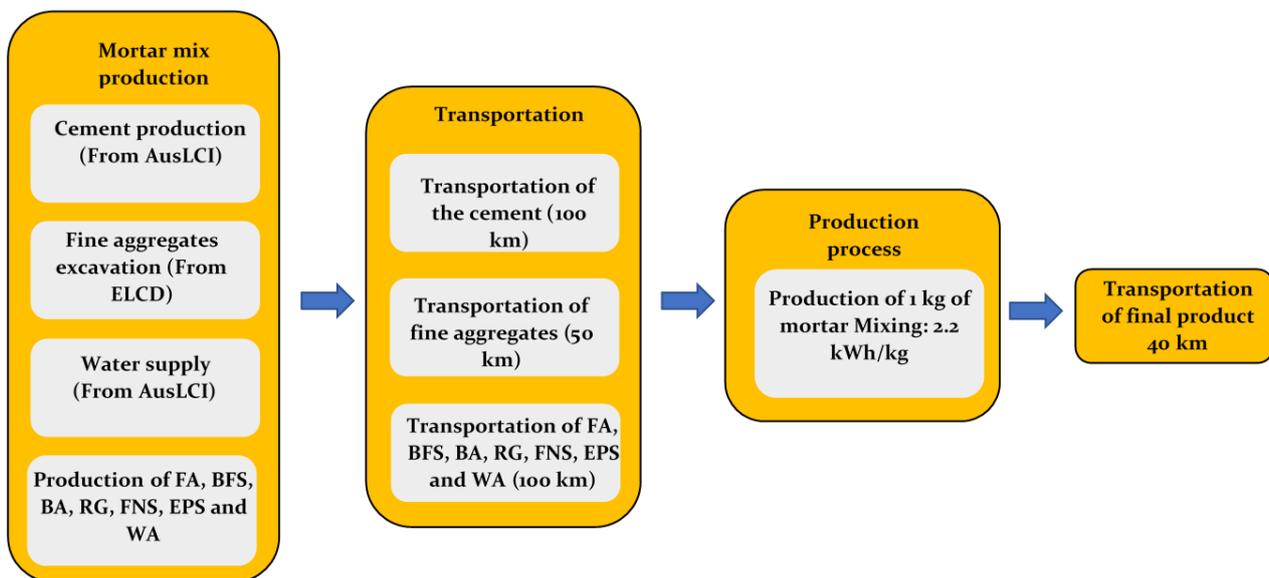


Figure 2. System boundary of LCA.

Eighteen midpoint impact indicators were generated in this LCA; these were climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation potential, particulate matter, terrestrial ecotoxicity, marine ecotoxicity, ionising radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, and fossil depletion. Moreover, the following assumptions and justifications were made in this LCA:

- This LCA did not assign the impact allocation. This was due to the inadequate available data, as it was difficult to obtain all the waste-based materials. Furthermore, the waste materials are produced as a by-product and not produced for the cementitious materials. Thus, this creates small impacts in environmental impact analysis. Similar approaches have been used by many studies [38,98,99,102–104].
- The transport distance of fine aggregates and both cement and waste-based materials to mortar manufacture was assumed to be 50 km and 100 km, respectively.
- The transport travel distance of mortar to the building construction site was assumed to be 40 km.
- The energy consumption of mortar mixing was 2.2 kWh/kg, which was calculated from the laboratory experiments with WA and RHA [38,93].

As stated by Selvaranjan et al. [39] and Dissanayake et al. [105], the energy consumption to produce waste products is zero. However, energy is required to convert these wastes into a suitable substitute for mortar mix. The ashes must be removed from the waste FA, BA and WA, and then they must be dried before being used in the mortar mix. This process

consumes energy. Granulation and grinding processes are involved in developing the binding properties of waste BFS and FNS [106]. The conversion of glass waste to suitable RG powder for mortar mix involves sorting, cleaning and grinding processes [107]. The EPS waste should be crushed using a mechanical crusher to produce the appropriate particle size for the mortar mix. The energy consumption required to produce suitable FA, BFS, BA, RG, FNS, EPS and WA for mortar mix was assumed to be 0.03 [39,105], 1 [108], 0.03 [39,105], 0.9 [107], 0.06 [109], 0.07 [105,110] and 0.03 [39,105] kWh/kg, respectively.

Midpoint and endpoint indicators were considered in this study along the impact trajectory [111]. Midpoint indicators are identical for relevant environmental flows as they are assigned directly to the impact categories. These two approaches are complementary to each other. However, the midpoint approach bears low uncertainty and has a higher association with the impact pathway; in contrast, the endpoint indicators reflect better provisions on sustainability relevance, but the uncertainty level is higher than that of the midpoint. Impact categories at the midpoint and endpoint levels were identified in this study for the selected design variables. Exhaustive Monte Carlo simulations were performed using SimaPro 9.2 software to show the possible variations in indicators. Relative uncertainties of these categories can assist in selecting a suitable design option for incorporating waste in the design mixture.

6. Results and Discussion

The eighteen midpoint impact indicators from LCA were categorised into three streams, which were human health, ecosystem quality and resources. The following sub-sections compare the environmental impacts induced by the production of 1 kg of waste-based cementitious materials.

6.1. Impacts on Human Health

The impact of various forms of pollution on human health is categorised as “human health” [112]. GHGE (i.e., climate change), ozone depletion, human toxicity, photochemical oxidant formation potential, particulate matter and ionising radiation are included in the “human health” outcome (Figures 3 and 4). The amount of GHGE released by the production of 1 kg of waste-based cementitious materials is shown in Figure 3a. This figure shows that the addition of 15% (by weight) FA (i.e., M1), BA (i.e., M3), FNS (i.e., M5), EPS (i.e., M6) and WA (i.e., M7) to conventional mortar reduces the amount of GHGE produced compared with conventional mortar (i.e., M0). Furthermore, the highest percentage of GHGE reduced by adding 15% was FA in the conventional mortar, which is around two times that of the GHGE reduced by BA, FNS, EPS and WA. Figures 3 and 4 show that mortar containing FA, BA, FNS, EPS and WA wastes reduced the negative human health impacts induced by GHGE, ozone depletion, human toxicity, photochemical oxidant formation potential, particulate matter and ionising radiation. Moreover, FA waste contributes to a significant reduction in negative human health impacts compared with other waste-based cementitious materials.

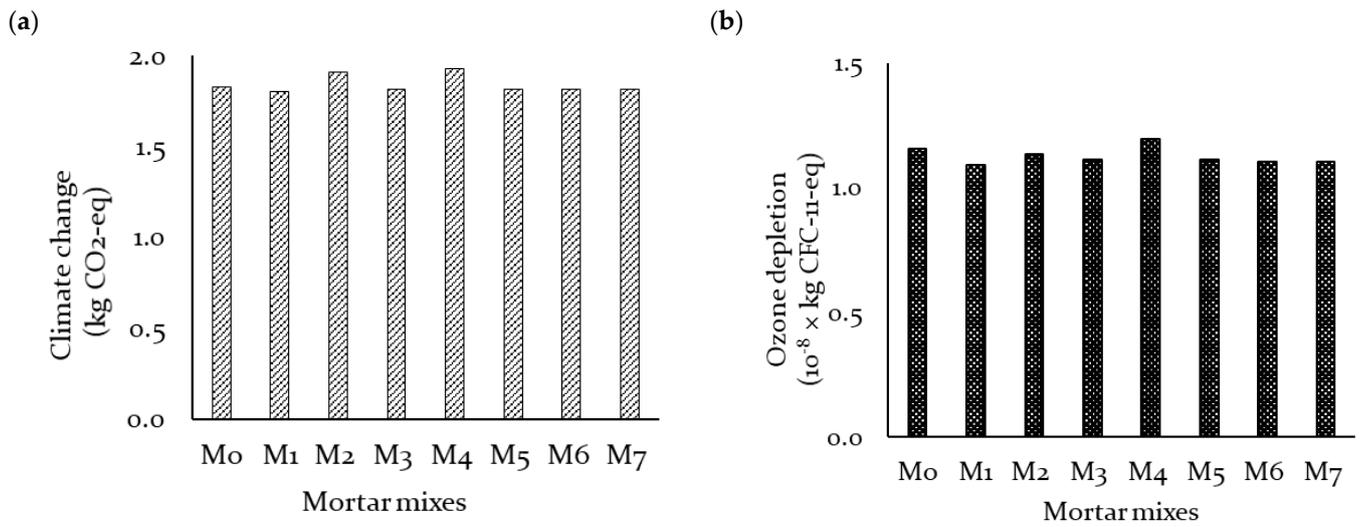


Figure 3. Impacts on human health from (a) GHGE and (b) ozone depletion.

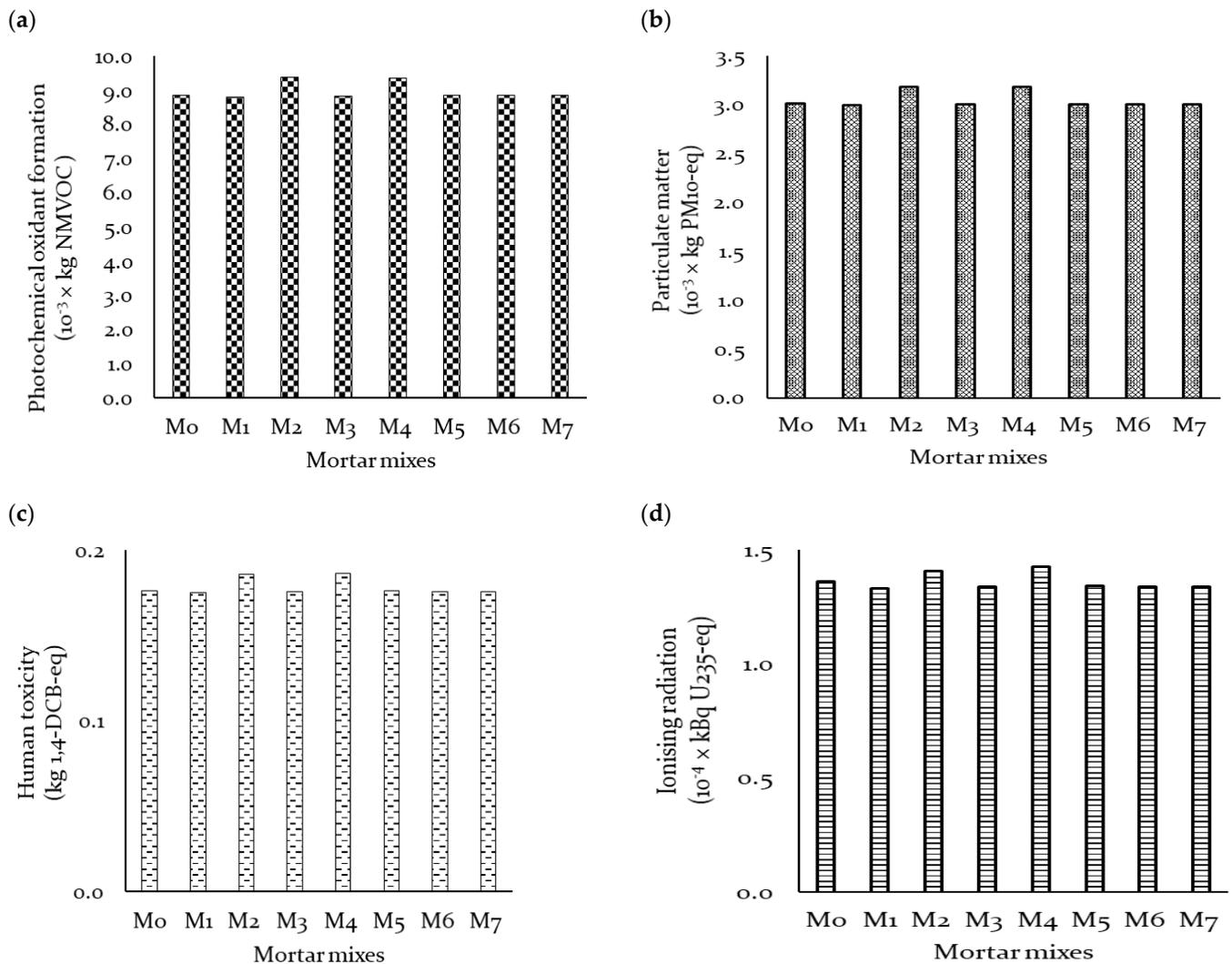


Figure 4. Impacts on human health of (a) photochemical oxidant formation; (b) particulate matter; (c) human toxicity; and (d) ionising radiation.

Figures 3 and 4 also show that adding 15% of BFS (i.e., M2) increases the negative human health impacts induced by GHGE, human toxicity, photochemical oxidant formation potential, particulate matter and ionising radiation compared with those of conventional mortar (i.e., M0). However, compared with conventional mortar, this mixture reduces the negative human health impacts created by ozone depletion. Furthermore, Figures 3 and 4 illustrate that mortar containing 15% of RG (M4) also has increased negative impacts on human health. This is due to the higher energy consumed to produce the BFS and RG compared with other wastes. This higher energy was consumed by the handling, grinding and recycling processes. Thus, reducing this energy consumption via energy-efficient handling, grinding and recycling processes can help to reduce these negative impacts. This also indicates that an effective way to reduce the human health impacts induced by the production of conventional mortar is directly using the appropriate industrial wastes to produce waste-based cementitious material.

6.2. Impacts on the Ecosystem Quality

The contamination that damages the ecosystem in terms of the number of species is expressed as “ecosystem quality” [112]. This category consists of terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation and natural land transformation. The impacts on the ecosystem quality induced by the production of 1 kg mortar are presented in Table 3. The highest ecosystem quality impacts in almost all impact categories were identified to be the mortars containing BFS and RG waste compared with conventional mortar and other wastes. This is because of the higher energy used to produce the BFS and RG wastes. The mortar containing FA produces the lowest ecosystem quality impacts in almost all impact categories compared with other mortar mixes. This indicates that using FA waste to produce mortar for wall plaster can significantly reduce the negative impacts on ecosystem quality.

Table 3. Impacts on ecosystem quality induced by production of 1 kg mortar.

Impact Category	Unit	Mortar Mixes							
		Mo	M1	M2	M3	M4	M5	M6	M7
Terrestrial acidification	$10^{-3} \times \text{kg SO}_2\text{-eq}$	9.49	9.45	10.05	9.47	10.04	9.49	9.48	9.48
Freshwater eutrophication	$10^{-6} \times \text{kg P-eq}$	6.26	6.00	6.30	6.07	6.50	6.09	6.05	6.05
Marine eutrophication	$10^{-4} \times \text{kg N-eq}$	2.92	2.90	3.09	2.91	3.09	2.92	2.91	2.91
Terrestrial ecotoxicity	$10^{-5} \times \text{kg 1,4-DB-eq}$	5.99	5.97	6.35	5.98	6.34	5.99	5.99	5.99
Freshwater ecotoxicity	$10^{-3} \times \text{kg 1,4-DB-eq}$	3.30	3.28	3.48	3.29	3.49	3.29	3.29	3.29
Marine ecotoxicity	$10^{-3} \times \text{kg 1,4-DB-eq}$	3.19	3.17	3.36	3.18	3.37	3.18	3.18	3.18
Agricultural land occupation	$10^{-3} \times \text{m}^2\text{a}$	3.63	3.32	3.42	3.41	3.70	3.42	3.37	3.37
Urban land occupation	$10^{-3} \times \text{m}^2\text{a}$	2.74	2.49	2.57	2.54	2.73	2.55	2.50	2.50
Natural land transformation	$10^{-5} \times \text{m}^2$	4.09	3.90	4.10	3.92	4.16	3.94	3.90	3.90

6.3. Impacts on Resources

The impacts associated with natural resources are categorised as “resource”, which accounts for water depletion, metal depletion and fossil fuel depletion [112]. Figure 5 shows the impact on these natural resources induced by the production of 1 kg mortar. Lower values of water, metal and fossil fuels were consumed when producing mortar with 15% (by weight) of FA, while the highest amounts of water, metal and fossil fuels were used to produce mortar containing 15% of BFS. The mortar containing RG waste also consumed similar amounts of natural resources to the mortar containing BFS. This was caused by the high energy requirements for the RG and BFS production processes.

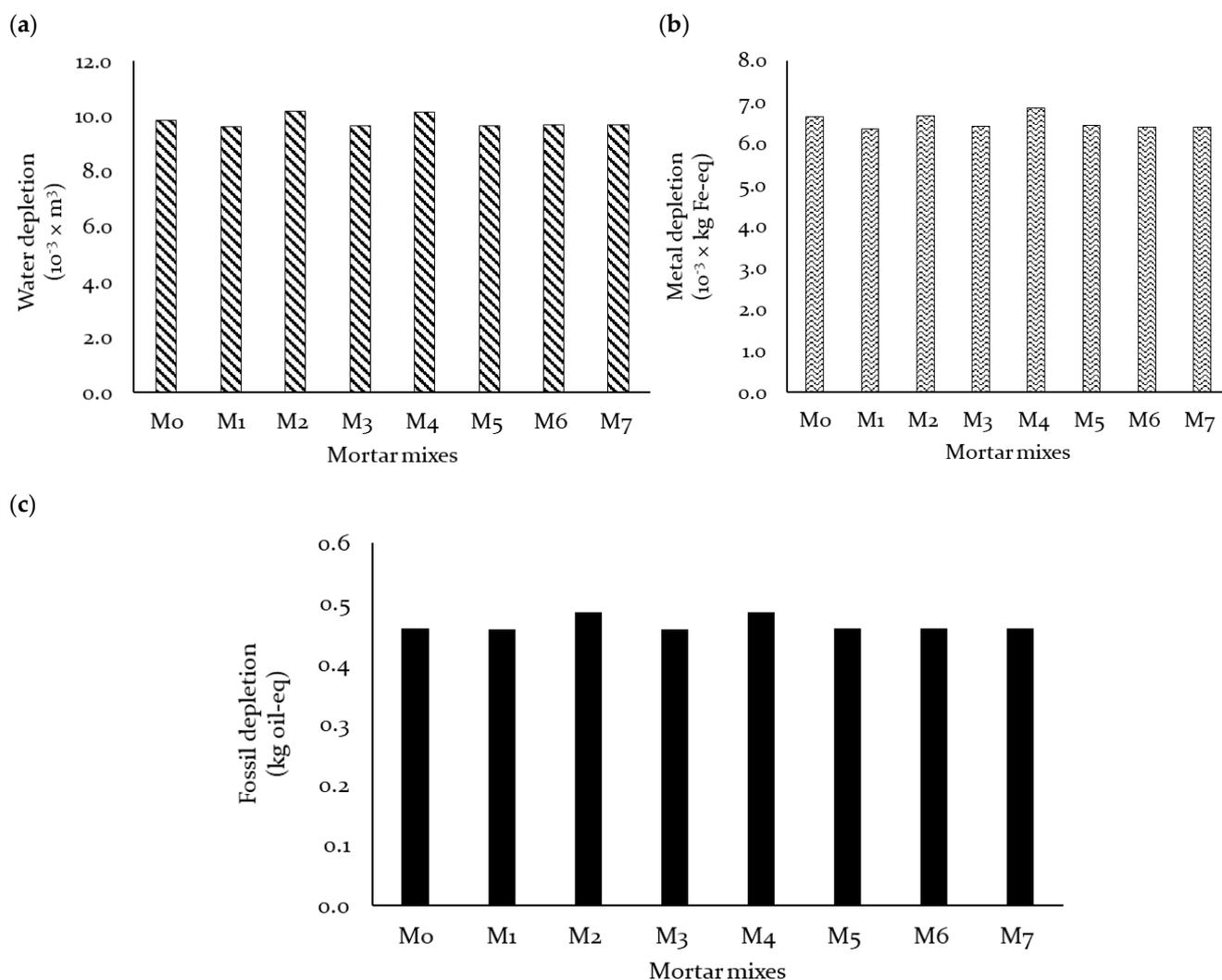


Figure 5. Impacts on resources of (a) water depletion; (b) metal depletion; and (c) fossil depletion.

Overall, the LCA study indicates that using industrial waste directly in the mortar mix reduces the negative impacts on the environment via reducing the impacts on human health, the ecosystem and natural resources. Furthermore, adding FA to the mortar mix enables higher environmental benefits than adding other wastes considered in this study. Additionally, the previous study highlights that adding 70% of FA [49] to conventional mortar enables the minimum required strength and workability for the wall plaster. This also reduces the thermal conductivity of mortar, and this improves the energy performance of plaster. This indicates that FA-based mortar can be used to develop green plaster for walls, as it reduces a significant amount of negative environmental impacts and improves thermal comfort. The LCA study also indicates that the energy required to produce the waste materials for a mortar mix has a significant role in terms of human health, ecosystem quality and natural resource impacts. Thus, the energy-intensive handling, recycling and grinding processes should be avoided in developing cost-effective sustainable green mortar for wall plaster.

Furthermore, the endpoint damage assessments of human health, ecosystem and resource scarcity from the production of waste-based mortar samples were quantified using ReCiPe [97,113]. Three conservative areas were expressed in terms of disability-adjusted life years (DALYs), loss of local species over time (species. year) and costs associated with mineral and fossil fuel extraction (USD) consecutively. DALYs indicate the number of years lost if a person becomes disabled due to illness or accident. Emissions and damage

assessment are complementary, and the relative uncertainties in assessing damage are higher than midpoint emission factors. However, identifying damage provides a clear view of emissions trajectory on sustainability measures.

Figure 6 shows a comparative analysis of damage assessment for the reference mortar mixture and other waste-based mortar. Interestingly, human health and the ecosystem are less impacted by damage assessment than resource scarcity is. Successive reductions of 27.34%, 16.3% and 10.78% DALYs are identified for using fly ash, EPS and wood waste in mortar, respectively. The obtained ecosystem results show that saving up to 40% of species lost per year is possible by incorporating waste materials. However, the recycling process of glass and slag does not lead to significant environmental benefits compared with the conventional mortar mixture.

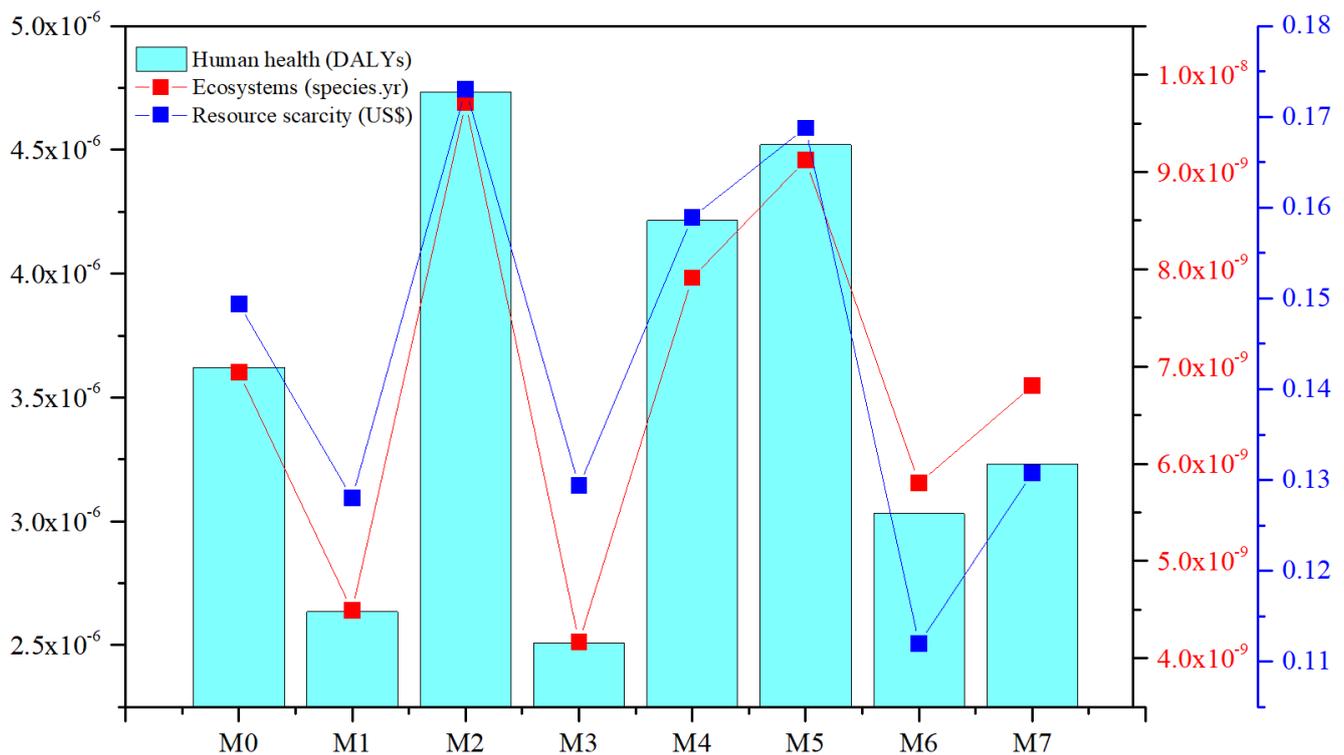


Figure 6. Potential damage assessments of conventional and waste-based mortar samples.

Figure 6 also expresses the extraction of resources such as minerals and fossils as resource scarcity (USD), which has been designated as the most influential factor. Resource extraction cost is supposed to be the minimum at the initial stage. However, the increased extraction rate leads to higher prices due to possible changes in production technology and shifting to a more expensive location. For example, alternative techniques are to be improved for oil recovery when sources of oil are depleted. Even alternate geographical areas for generating oil, such as arctic regions, are more expensive. A combination of increased cost and future extraction was applied in this study using the ReCiPe methodology to estimate the potential surplus cost for resource depletion.

Resource scarcity is the most affected criterion of mortar mixtures with different waste-based samples. In particular, decreases of 14.32% and 13.65% are feasible concerning the reference scenario for fly ash and bottom ash, respectively. Maximum savings in resource extraction are compromised by using EPS in mortar mixtures. However, the relevant cost of extraction increased by 13.80% for blast furnace slag due to the energy-intensive process of blast furnace slag recycling. A similar trend was observed for recycled glass in the mortar mixture. The results were identical for the abovementioned scenarios emphasizing waste recycling in the construction process regarding resource depletion.

6.4. Uncertainty Analysis on Design Mixture

Monte Carlo analysis was performed using the @RISK simulation tool on obtained data of LCA [114]. The analysis shows the possible variations and probable outcomes of CO₂ emissions for the different mixtures. The probabilistic approach of sensitivity analysis determines that the energy-intensive process of glass and slag recycling in concrete mixtures requires consideration before use. The lower mean and coefficient of variation (CV) of fly ash (M1), expanded polystyrene (M6) and wood waste (M7) indicate their suitability as sustainable solutions. The lowest CV value (10.01) of fly ash shows less variation in carbon around the mean. Even the confidence interval (CI) of the M1 mixture is determined to be lower; the upper bound of the carbon footprint is limited to between 1.41 and 2.02 kg CO₂ eq, as shown in Table 4.

Table 4. Sensitivity indices of carbon footprint incorporating industrial waste-based cementitious materials in design mixture.

Design Mixture	Mean	Median	Standard Deviation	Coefficient of Variation (CV)	Confidence Interval (CI)	
					2.5%	97.5%
Mo	1.83	1.79	0.25	13.66	1.55	2.21
M1	1.80	1.75	0.18	10.01	1.41	2.02
M2	1.91	1.89	0.21	10.99	1.56	2.39
M3	1.81	1.77	0.23	12.71	1.52	2.08
M4	1.93	1.91	0.27	13.98	1.58	2.45
M5	1.82	1.77	0.22	12.08	1.54	2.12
M6	1.81	1.78	0.19	10.49	1.44	2.07
M7	1.81	1.76	0.21	11.61	1.43	2.06

6.5. Endpoint Impact Assessment of Design Mix

Damage assessment of mortar mixtures quantifies sustainability in terms of human health, the ecosystem and the resource depletion cost. This assessment shows the advantage of incorporating waste products in cement mortar, which allows policymakers to interpret the analysis for decision making. Replacements of globally consumed cement (4.1 gigatons) with waste products significantly reduce resource extraction costs. Monetary savings of up to USD 87.74 billion are feasible by replacing cement with 15% fly ash worldwide.

7. Conclusions

Cement-based mortar is used as wall plaster to protect walls and to provide a smooth surface finish. Walls requiring plastering account for large portions of a building compared with other construction elements, and consume significant amounts of cement and natural resources (water and sand). This contributes to significant negative impacts on the environment. Thus, the development of a sustainable green mortar for wall plaster will reduce these negative impacts, provide better thermal comfort and reduce the operational energy and related costs. Previous studies highlighted that there is the potential to produce mortar with industrial wastes as an option to reduce negative environmental impacts. Thus, this study involved conducting a comparative environmental impact assessment of mortar containing 15% (by weight) of FA, BFS, BA, RG, FNS, EPS and WA using LCA software SimaPro 8.2.0.0. Furthermore, this study also conducted a comprehensive review of the strength, workability and thermal performance of waste-based mortars.

Based on the LCA analysis, this study found that mortar containing FA significantly reduces GHGE and other human health impacts. Overall, adding FA to conventional mortar reduces the negative environmental impacts in terms of human health, the ecosystem and natural resources. Furthermore, compared with other wastes, FA can be used to replace higher amounts (i.e., greater than 60%) of sand or cement in conventional mortar. This indicates that FA is a sustainable option for producing sustainable green mortar for wall plaster.

The highest environmental impact values were obtained for the mortars containing BFS and RG. This indicates that adding 15% (by weight) of BFS and RG to conventional mortar

does not make them environmentally suitable for the replacement of sand or cement. This was due to the high energy requirements to produce the BFS and RG for mortar mixes. This indicates that in developing cost-effective sustainable green mortar, the energy-intensive process that is involved in handling, recycling and grinding should be avoided.

The results from this study give fundamental insight into the environmental impacts of waste-based mortar for wall plaster. This can help decision makers and construction practitioners understand the sustainability of waste-based mortars. However, the results are only applicable to the mortar mixes, transport distances and energy consumption considered in this study. Furthermore, future research is needed to compare the variations in environmental impact with engineering properties to enable the optimum environmental benefits of waste-based mortar.

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