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Evaluating Techno-Eco-Efficiency of Waste Clay Brick Powder in Geopolymer Binder

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Abstract: The global focus on geopolymer binder production has increased due to the adoption of waste materials and industrial byproducts. Given the gradual decline of the availability of fly ash and ground granular blast furnace slag (GGBFS) resulting from the decarbonization process in electricity and steel productions, waste clay brick powder (WCBP), could be a viable substitute of these pozzolanic by-products. This research is dedicated to thoroughly investigate the techno-eco-efficiency performance of WCBP when utilized as a geopolymer precursor. The favorable mechanical characteristics exhibited by fly ash-GGBFS-WCBP-based geopolymer binder emphasize the importance of assessing its sustainability alongside its technical viability. The study employed life cycle analysis (LCA), following ISO 14040-44 standards, and using the Simapro software, to evaluate the environmental implications of the use of WCBP-based geopolymer mixtures. Human toxicity emerged as the primary impact. Moreover, the analysis of life cycle costs highlighted key financial factors, with around 65-70% attributed to alkaline activators of the total cost. The production of alkaline activators was identified as a critical point for both environmental impact and economic considerations due to energy consumption. While WCBP-rich samples exhibit a 1.7-0.7% higher environmental impact compared to the control mix (CM), their high mechanical strength and cost-effectiveness make them technologically and economically efficient geopolymer mixes. In conclusion, the portfolio analysis for techno-eco-efficiency affirms that mixes containing 40%, 30%, and 20% WCBP are more efficient than those using 10% and 0% WCBP, respectively.

Keywords: waste clay brick powder; life cycle analysis; life cycle cost; techno-eco-efficiency

1. Introduction

The construction sector contributes significantly to the socioeconomic progress of a nation resulting from human and economic growth that requires housing conditions and civil infrastructure. The construction industries are heavily reliant on the use of cement, which is widely manufactured, and its production causes significant environmental impacts [1]. Cement is produced from the limestone calcination, which releases substantial amount of carbon dioxide, and the production process is energy-intensive [2]. Resource extraction such as limestone and the associated waste generation during production also impact the ecosystem. To address these challenges, the industry is exploring the use of alternative fuels in cement production and environmentally friendly cementitious materials.

Geopolymer presents a promising solution to address the environmental concerns associated with cement production [3]. Unlike conventional cement manufacturing, geopolymer does not rely on the carbon and energy intensive calcination process. Instead, geopolymer utilizes industrial by-products like fly ash or slag, which reduces the reliance on virgin materials for cement production and so mitigates the environmental impact by using recycled waste materials. Geopolymer production involves an alkaline activation process that reacts with these by-products to produce a binder similar to traditional cement [4]. This process requires less energy and may significantly reduce the carbon footprint associated with the manufacturing of cementitious binders.

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Alternatively, it diverts the industrial byproducts from the residue areas, which is avoiding land use changes.

A range of industrial by-products and mineral deposits, like Metakaolin, fly ash, GGBFS, ferronickel slag, and ultrafine slag, have been used as geopolymer precursors. Among these materials, fly ash is particularly noteworthy for its wider availability and its high silica (SiO_2) and alumina (Al_2O_3) content, exceeding 70% [5]. Fly ash is often combined with various industrial by-products, such as GGBFS, to improve both the fresh and hardened properties of the geopolymer binder. The combination of fly ash and GGBFS in geopolymer demonstrated excellent mechanical and durability properties [6]. GGBFS, characterized by its high calcium content, complements the very low calcium content of fly ash when used together as binary precursors. While curing at room temperature, GGBFS contributes to improved mechanical and microstructural properties due to its elevated calcium content and enhances binding properties when activated by an alkali [6]. By replacing silicon rich materials that has low calcium with a small proportion of GGBFS, the setting time can be reduced and mechanical properties in both the early and later stages of geopolymer development can be enhanced [6].

The production of fly ash, a by-product from coal combustion, has been gradually decreasing due to several factors. The shift towards decarbonization processes, such as natural gas and renewable energy, will gradually reduce the reliance on coal-fired power plants [7], which will result in the decrease in fly ash generation. Additionally, advancements in pollution control technologies in these plants have resulted in the reduction of fly ash generation. Furthermore, as a part of decarbonization process, the iron production process is switching from blast furnace to an electric arc furnace, which will result in the reduction of GGBFS [8]. As a result, it is crucial to discover a substitute material for these industrial byproducts with high pozzolanic properties to produce geopolymer binder. The solution lies in the waste that is generated within the construction industry.

Globally, approximately 25-30% of the solid waste generated is attributed to the construction industry, posing an escalating threat to the environment in recent times [9]. Australia's construction industry contributes to a substantial portion of the waste annually (i.e., 76 million tons). Despite a relatively higher recovery rate within the sector, about 24% of total construction waste remains unrecycled, leading to landfill disposal [10]. For every million dollars contributed to the economy, the construction sector produces about 87 tons of waste, which is could be eco-efficient [11]. The expenses allocated to waste services have surged since 2016, now exceeding $17 billion annually, with $2 billion attributed to the construction industry. This increase, amounting to a 35% rise from 2016-2017, underscores the concerning the annual growth of waste production [11].

The bulk of waste, around 80%, generated from construction and demolition waste includes concrete and brick waste [12]. Recycling these concrete and brick wastes in concrete production not only alleviates waste disposal issues but also decreases the construction industry's reliance on natural raw materials. Currently, researchers have made significant strides in utilizing recycled concrete aggregate and are initiating large-scale recycling efforts [13–15]. Regarding brick waste utilization, the usual practice involves crushing it and then utilizing it as fractional replacements for fine or coarse aggregates in concrete. Limited research has explored the utilization of this brick waste in the creation of the geopolymer binder [16]. To address this research void, the authors had previously examined the integration of waste clay brick into the geopolymer binder as a partial substitute for fly ash. However, it is crucial to assess the environmental sustainability and techno-eco-efficiency level, along with technical feasibility, to validate the geopolymer mix design employed in the prior study.

Salas et al. [17], Kastiukas et al. [18] and Kul et al. [19] demonstrated that geopolymer binders offer a more sustainable and environmentally friendly alternative to conventional cement, contributing to the reduction in greenhouse gas emissions by 27-64%. Life cycle assessment has been undertaken widely as a sustainability assessment tools for civil and construction engineers [20].

Only a few studies [21–23] have conducted LCA for geopolymer binders based on waste clay brick powder. Migunthanna et al. [21] performed a Life Cycle Assessment, comparing the environmental impact of conventional cement -based concrete and geopolymer concrete in rigid pavement construction, assessing CO_2 emissions and energy consumption across different stages of the LCA. The substitution of conventional concrete with geopolymer binders resulted in a nearly 50% reduction in total CO_2 emissions and a 72% decrease in energy consumption. This study used waste clay bricks, slag, and fly ash as precursors, with anhydrous sodium silicate as the activator, to produce one-part geopolymer concrete. Mir et al. [22] performed LCA using GaBi software and followed ISO 14040-44 guidelines to assess the environmental implications of the use of geopolymers made from red brick waste and red ceramic waste. The study had considered three optimized mixtures and curing methods for assessing environmental impacts including Global Warming Potential (GWP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP), Acidification Potential (AP), among others. In Phase I, using a binary composition, sodium silicate and electricity made significant contributions to environmental consequences. In Phase II, a ternary mixture, that slightly increased the use of sodium silicate but exhibited lower overall environmental effects compared to binary compositions. In Phase III, it resulted in similar environmental performance as Phase I, by producing higher GWP from additional curing. An environmental LCA conducted by Fořt et al. [23] found that the CO_2 was reduced by 112% due to the replacement of a standard cement paste with the geopolymer paste sample. Despite other factors being considered, the analysis specifically focused on the embodied energy, highlighting that the substantial impact observed was directly associated with the utilization of alkaline activators in the studied context. They found that the manufacturing of sodium silicate requires significant energy inputs, resulting in a larger environmental impact compared to conventional binders. For instance, producing one tonne of 48% Na_2SiO_3 consumes about 11.2 MJ of non-renewable energy, representing a substantial portion of energy utilized in geopolymer production.

However, the above-mentioned studies did not consider either life cycle costing or eco-efficiency portfolio analysis, particularly in the context of geopolymer concrete. These analyses are crucial in the engineering decision making process as environmentally friendly materials are not always eco-efficient or economically feasible. Dynan et al. [24] followed the ISO framework, encompassing several stages from goal and scope to creating an eco-efficiency portfolio, to assess geopolymer concrete as an eco-friendly alternative to traditional cement. While it proved effective in reducing emissions, particularly in terms of global warming potential, it encountered challenges in other environmental impact aspects. Nevertheless, this study did not consider techno-eco-efficiency portfolio analysis. Hence, there is inadequate research examining the techno-eco-efficiency performance of geopolymer binders to compare them against conventional ones, that evaluates the economic and environmental implications of engineering or technical strategies.

The research significance lies in its comprehensive approach. Initially, it studied a detailed LCA, specifically exploring the fly ash-GGBFS-WCBP binder to evaluate WCBP's environmental viability within the geopolymer mix. Additionally, the study investigated Life Cycle Costing (LCC) analysis for the geopolymer mortar mixes. The primary focus was on optimizing their cost-effectiveness. Through a meticulous hotspot analysis of these mixes, the research identified the specific areas characterized by the highest energy consumption. Lastly, the study utilized a techno-eco-efficient analysis to determine the eco-efficiency performance of the structurally sound fly ash-GGBFS-WCBP mixes as the techno-environmental benefits could be outweighed by the increased recycling costs.

2. Materials and Methods

To evaluate the suitability of WCBP as a substitute for fly ash in the production of fly ash-GGBFS based geopolymer binder, a LCA has been conducted following the guidelines outlined in ISO 14040 [25]. Four distinct mortar samples incorporating WCBP have been compared with the control mixture, comprising fly ash and GGBFS as source materials. The LCA scope employs a 'cradle to gate' methodology, covering processes starting from raw material extraction, through the production and handling the construction materials, to transporting them to the construction site area, and encompassing all manufacturing phases. The LCA was utilized to assess the environmental impacts and to conduct a life cycle cost analysis to evaluate the techno-eco efficiency of sample geopolymer mixtures. The LCA consists of four key steps: outlining goals and scope, performing an inventory analysis, calculating impact assessments, and analyzing the findings.

2.1. Goal and Scope

The objective of the LCA investigation is to evaluate and contrast the environmental effects of five different geopolymer mortar samples that have been manufactured. Each mortar samples contained varying proportions of WCBP, which serve as replacements for the fly ash component in fly ash-GGBFS based geopolymer mortar samples. GGBFS content was constant for each mix. 12M Sodium hydroxide and sodium silicate solution was used as alkaline activators to produce geopolymer mortar samples. Each variety of mortar mix underwent curing at room temperature. The LCA aims to generate normalized data tailored to Australian economic and environmental conditions, enabling the creation of an eco-efficiency portfolio that evaluates the eco-efficiency of each mortar samples. The system boundary encompasses all stages from the mining to material production, transporting those materials to the construction site and manufacturing geopolymer mortar, as shown in Figure 1. The manufacturing phase comprises energy usage related to processes like mixing, compacting, and curing. Figure 2 illustrates the complete manufacturing and curing process of geopolymer mortar mix.

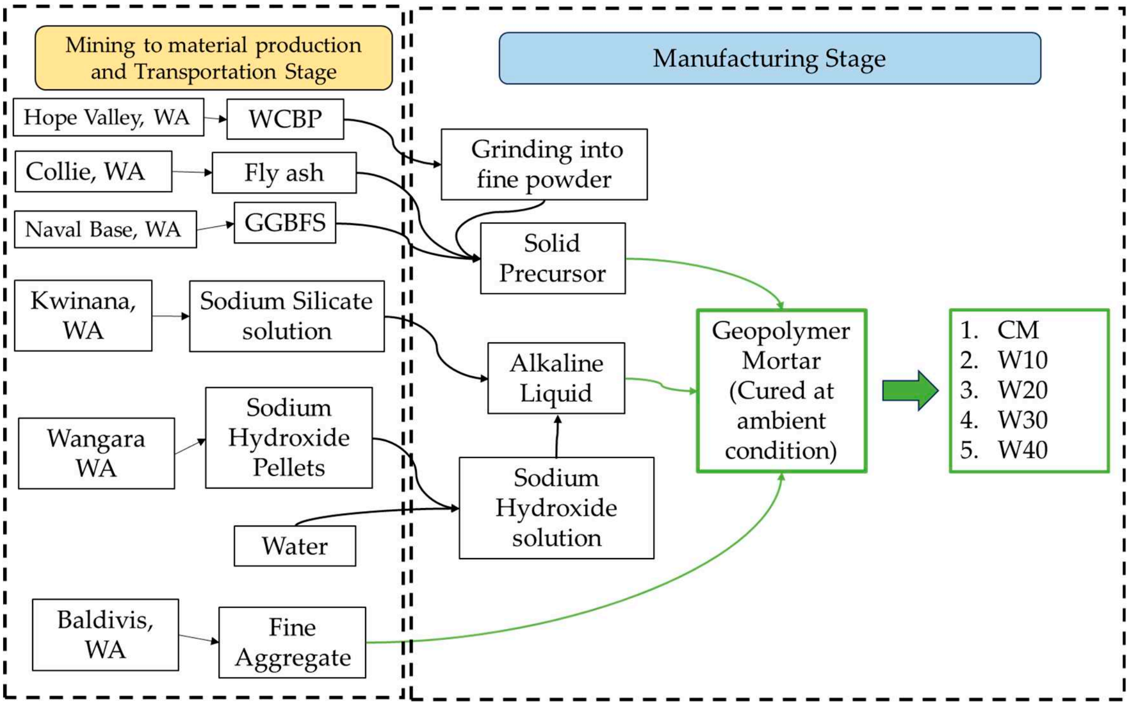

Figure 1. System boundary for conducting the LCA of 1 cubic meter geopolymer mortar.

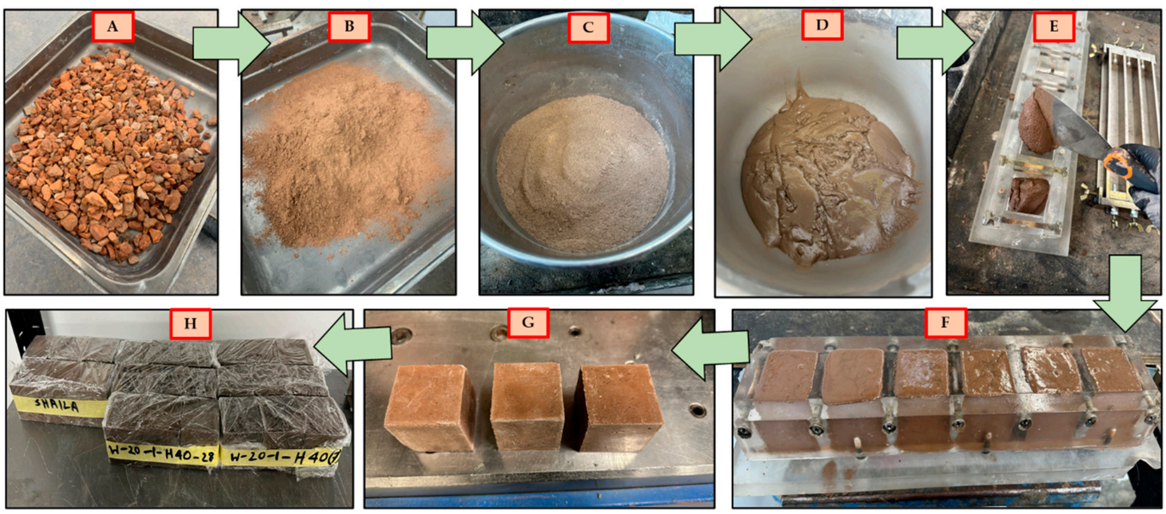

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Figure 2. Manufacturing and curing process of WCBP-based geopolymer mortar (W40) (A-Brick aggregate, B-WCBP, C-Dry mixing, D-Geopolymer mortar mix, E- pouring the mortar mix into mold, F – After finishing casting, G- 50mm cube mortar sample after demolding, H- Curing).

In this LCA investigation, a compressive strength of 1 MPa was selected as the functional unit to identify the geopolymer mixture that could deliver the greatest strength in an eco-efficient manner. The research used the Simapro LCA software that can compute environmental impacts for every cubic meter (m^3) of geopolymer mortar. As a result, the environmental impacts were initially assessed for a 1 m^3 mortar mix. Subsequently, these impacts were divided by the corresponding 28 days compressive strength. The selected unit for estimating emissions and economic factors in transportation stage was the t-km (tone - kilometer). This unit accounts for the effects of weight on material transport and processing, in addition to the transport distance. The reliable databases for t-km measurements are readily available in the SimaPro software, and t-km is the standard unit for impacts measurement in LCA software. A distinct profile was established for WCBP, considering the energy required for grinding the raw material into a suitable solid precursor. The system boundary encompasses all stages from the mining to raw material production, transporting those raw materials to the construction site and the manufacturing of geopolymer mortar (Figure 1). The manufacturing phase comprises energy usage related to processes like mixing, compacting, and curing.

2.2. Life cycle inventory (LCI) analysis

Developing an LCI is a necessary step prior to assessing the environmental consequences. The LCI is generated using data from the author's earlier research [26], which involved the assessment of the mechanical properties of the geopolymer mortar mixes. Table 1 presents the inventory analysis necessary for assessing the environmental impact of each mortar mix. This inventory includes raw materials such as fly ash, WCBP, GGBFS, sand, sodium silicate, sodium hydroxide, electricity used for manufacturing mortar samples, and transportation for the five different mortar mixes. It also specifies the source of material procurement. Curtin University is the site for manufacturing geopolymer mortars. The transportation distance for different construction materials was between Curtin and the origins of these materials. The amount of WCBP differs in every trial as the objective is to evaluate and contrast the mechanical properties of individual sample with varying proportions of WCBP.

Table 1. Life cycle inventory of geopolymer mortar samples.

Ingredients	Source Address	Distance (Km)
GGBFS	BGC CEMENT, Address 32 Beard St, Naval Base, WA, 6155, AUSTRALIA	33
Fly ash	Collie, WA	152
WCBP	192 Hope Valley Rd, Hope Valley, WA 6165	31
Sand	Baldivis sand quarry, WA	55
Sodium hydroxide pellets	Coogee Chemicals Pty Ltd, KWINANA BEACH WA 6167	36
Sodium silicate solution	11 Challenge Boulevard Wangara WA 6065 Australia	35

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Constituents	Mortar Mixes				
	CM	W10	W20	W30	W40
Fly ash (kg/m^3)	673	596	518	440	361
GGBFS (kg/m^3)	119	119	119	119	119
WCBP (kg/m^3)	0	80	160	240	321
Fine aggregate - sand (Kg/m^3)	1268	1271	1275	1279	1282
Sodium hydroxide pellets (Kg/m^3)	57	57	57	57	57
Sodium silicate solution (Kg/m^3)	238	238	238	238	238
Total kg/m^3	2355	2361	2367	2373	2378
Transportation (t-km)	187.35	148.66	121.98	106.99	100.79
Manufacturing (kWh)	10	10.03	10.06	10.08	10.11

2.3. Life cycle impact assessment (LCIA)

The data derived from the inventory analysis for each mortar mix was manually input into the SimaPro 9.2 LCA software. Subsequently, these input values were linked to the appropriate emission factor database. In most cases, the emission database from Western Australia were utilized for the inputs to accurately reflect the local environmental conditions. Distinct profiles were established for each unique geopolymer mortar mix, each accounting for its specific environmental impacts stemming from mining, transportation, and the construction stage. A novel database specific to WCBP was developed from the experimental work conducted by the authors at Curtin University for inclusion in this Simapro software. This database was based on the data on energy consumption during the process of crushing brick pellets (i.e., to 0.2 kilowatt-hours per kilogram of waste brick aggregate crushed). Since all these inputs cannot be calculated using an Australian Input Method, it was prompting the use of SimaPro 9.2 with methods the recommended by Bengtsson and Howard [27] and Renouf et al. [28] for this study. Four distinct impact evaluation techniques specified in Table 2 were employed to assess the valuation of fourteen environmental impacts.

Table 2. Impact category to evaluate environmental impact.

Impact Assessment Method	Impact category	Unit
Australian indicator set V2.01 / Australian per capita	Global warming	kg CO_2
	Eutrophication	kg PO_4^{3-} eq
	Land use	Ha a
	Water use	M^3 H_2O
ReCiPe Midpoint (E) V1.12 / Europe Recipe E	Ozone depletion	kg CFC-11 eq
	Terrestrial acidification	kg SO_2 eq
	Human toxicity	kg 1,4-DB eq
	Photochemical oxidant formation	kg NMVOC
	Terrestrial ecotoxicity	kg 1,4-DB eq
	Freshwater ecotoxicity	kg 1,4-DB eq
	Marine ecotoxicity	kg 1,4-DB eq
	Ionising radiation	kBq U235 eq
CML-IA baseline V3.03 / EU25	Abiotic depletion	kg Sb eq
TRACI 2.1 V1.03 / Canada 2005	Respiratory effects	kg PM2.5 eq

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Note: CO_2—carbon dioxide, PO_4^3 —phosphate, eq—equivalent, Ha. a—hectare years, CFC-chlorofluorocarbon, NMVOC—non-methane volatile organic compounds, U235—uranium 235, Sb—antimony, SO_2—Sulphur dioxide, PM—particulate matter.

2.4. Life cycle cost analysis

Utilizing the identical inventory evaluation, an economic assessment was conducted to ascertain the unit cost for five mortar mixtures. Consistency between economic and environmental evaluations was maintained by using the same functional unit as in the life cycle assessment, expressed in Australian dollars per megapascal of compressive strength (AUD/MPa).

The cost data in Table 3 represents the prices of raw materials for producing geopolymer mortars. These costs are based on prevailing market prices in the local market of Western Australia. WCBP was directly sourced from the regional supplier "Red Sand Supplies," situated at 192 Hope Valley Road, Hope Valley, Western Australia 6165, known for specializing in recycled materials.

Table 3. Prices of raw materials.

Raw materials	Cost (AUD) per ton material
FA	135
GGBFS	300
WCBP	55
Sand	31.3
SS	834
SH	800

The cost of transportation was approximated at AUD 0.09 per tonne-kilometre for road freight in accordance with the details provided by the Australian Government Department of Infrastructure and Regional Development [29]. The electricity cost during the manufacturing process was derived from publicly accessible information published on the Synergy website [30]. It was assumed that the electricity tariff corresponds to the Synergy business plan and is priced at 36.15 cents per unit (equivalent to 1 kWh) [30].

The total estimated life cycle cost for each of the mortar mixtures is presented in Table 4. This cost encompasses material costs, transportation expenses based on the t-km of materials in the LCI, and electricity costs for operating the mixing and compacting processes. It is worth noting that the labor costs were avoided as the author prepared these mixes as a part of their PhD project. The overall life cycle cost was subsequently divided by the corresponding compressive strength of the mixes to determine the cost in AUD per megapascal of compressive strength (AUD/MPa).

Table 4. Total cost of 1 m^3 geopolymer mortar sample.

Geopolymer mortar mix	Material price (AUD)	Life Cycle Cost (AUD)
CMA	408	426
W10A	403	417
W20A	397	409
W30A	392	402
W40A	386	396

2.5. Techno-Eco-Efficiency Framework

The portfolio analysis is involved in the development of environmental and economical portfolios of structurally and technically sound mixes. This techno-eco efficiency combines the effects of both the economic and the environmental values to ascertain eco efficiency portfolio positions of technically sound mortar mixes in this study. To standardize the environmental impact data acquired from the Simapro software, it is necessary to normalize these impacts by dividing them by the corresponding impact values for a particular region. The normalized values of the impacts were

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multiplied by the corresponding weights to transform all impacts to the same unit (i.e., 'inhabitant equivalents') in order to combine them and achieve a unified environmental score for each mortar mix [31]. This study utilizes the environmental impacts of Australia's gross domestic product (GDEI) (Bengtsson and Howard) [27] and corresponding weighting factors (WF) (Biswas) [31], as outlined in Table 5, to convert all impact values to a common unit i.e., per inhabitant equivalent.

Table 5. The gross domestic environmental impact and weighting factor for environmental impact.

Impact category	GDEI per Inh	WF
Global Warming	28,690	20%
Eutrophication	19	3%
Land use	26	21%
Water Use	930	6%
Ozone depletion	0.002	3%
Terrestrial acidification	123	7%
Human toxicity	3,216	8%
Photochemical oxidant formation	75	10%
Terrestrial ecotoxicity	88	4%
Freshwater ecotoxicity	172	3%
Marine ecotoxicity	12,117,106	3%
Ionising radiation	1,306	2%
Abiotic depletion	300	3%
Respiratory effects	45	8%

The normalized value (NEI_v) for each environmental impact of every geopolymer mortar mixture (g) is determined using Equation (1), where $EI_{v,g}$ is the environment impact values from the SimaPro software and $GDEI_{v.g}$ is the gross domestic environmental impact in terms of the amount of impact per Australian inhabitant per year.

$$NEI_{v,g} = EI_{v,g}/GDEI_{v.g} \quad (1)$$

The normalized values for all environmental indicators were combined by applying an Australian weighting factor that reflects the significance of each environmental impact under Australian conditions and is incorporated using Equation 2. Here, EI_g is the normalized environmental impact for each geopolymer mix and $WF_{v.g}$ is the weighting factor.

$$EI_g = NEI_{v,g} * WF_{v.g} \quad (2)$$

Much like the normalization process for environmental impacts, the overall life cycle costs associated with every mix were adjusted via the most recent Australian gross domestic product (Table 4). This adjustment allows the presentation of costs in terms of the number of inhabitants generating an equivalent GDP per year [32]. The normalized cost (NC_g) is articulated as the figure of Australian inhabitants generating an equivalent annual GDP (GDP_{cap}), as indicated by Equation 3 [33].

$$NC_g = LCC_{v,g}/GDP_{cap} \quad (3)$$

The author used a Shimadzu 300 kN Universal Testing Machine to conduct compressive strength tests on 28-day ambient cured geopolymer mortar samples (50mm * 50mm cubes) in accordance with ASTM C1437 [34]. The normalized environmental impact and cost were divided by the corresponding compressive strength values to derive the figures in relation to MPa.

The preliminary portfolio position environmental ($PP_{e,g}$) and economic ($PP_{c,g}$) impacts for the geopolymer mixes "g" were determined by comparing their normalized cost and environmental impact values against the average normalized values of cost and impact of geopolymer mixes using Equations 4 and 5 [33].

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$$PP_{e,g} = EI_g/(\frac{EI}{j}) \quad (4)$$

$$PP_{c,g} = NC_g/(\frac{NC}{j}) \quad (5)$$

The calculated portfolio positions were fine-tuned by applying the environmental-to-cost relevance factor ($R_{e,c}$) outlined in Equation 6. Its purpose was to ascertain whether cost or environmental impact holds more significance in determining the eco-efficiency of geopolymer mix. This determination involved comparing the average normalized environmental impacts against the average normalized costs.

$$R_{e,c} = \frac{\sum EI}{j}/(\frac{\sum NC}{j}) \quad (6)$$

Finally, the initial positions are enhanced by the relevance factor to attain a revised spot that strikes an equilibrium between environmental impacts and life cycle costs, as depicted in Equations 7 and 8 [33].

$$PP'_{e,g} = [\frac{(\sum PP_{e,g})}{j} + \{PP_{e,g} - \frac{(\sum PP_{e,g})}{j}\} * \sqrt{(R_{e,c})_g}]/[\frac{(\sum PP_{e,g})}{j}] \quad (7)$$

$$PP'_{c,g} = [\frac{(\sum PP_{c,g})}{j} + \{PP_{c,g} - \frac{(\sum PP_{c,g})}{j}\} * \sqrt{(R_{e,c})_g}]/[\frac{(\sum PP_{c,g})}{j}] \quad (8)$$

Here, $PP'_{e,g}$ represents the refined environmental portfolio locus of geopolymer mix "g", while $PP'_{c,g}$ denotes the amended cost portfolio position of the same mixture

Figure 3 illustrates a two-dimensional diagram depicting the normalized costs and environmental impacts for eco-efficiency analysis. This depiction is commonly referred to as the eco-efficiency portfolio. The horizontal axis represents normalized costs, while the vertical axis corresponds to environmental impacts. The scale ranges from the lowest numbers indicating the lowest impact and least cost to the highest numbers representing the highest impact and the highest cost values. The utmost eco-efficient option is identified by its space above the diagonal line, with the mix farthest from this diagonal line represent the most eco-efficient mix (Kicherer et al.) [33].

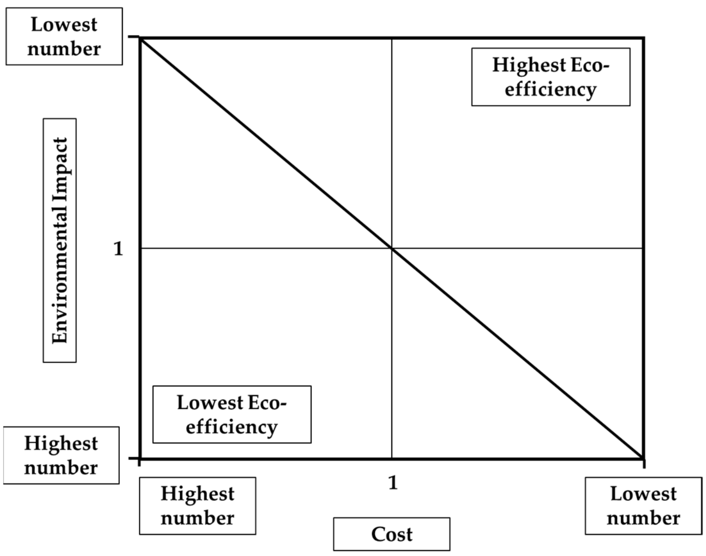

Figure 3. Eco-efficiency portfolio developed by Kicherer et al. [33.]

The study used emission factors derived from both local and foreign databases for construction materials, which could affect the accuracy of LCA results to some extent. To address these uncertainties, a Monte Carlo Simulation (MCS) was performed based on Clavreul's approach [35], to analyze uncertainties for each data point and forecast their influence on the LCA outputs for geopolymer mixes. The simulation process was performed for 1,000 iterations for a confidence level of 95% [36].

3. Results and Discussion

3.1. Environmental impact analysis of geopolymer mortar mix

Figure 4 illustrates the environmental impact analysis of five geopolymer mortar mixes in terms of per inhabitant equivalent. The environmental impact is most pronounced in geopolymer mixes featuring 40% WCBP, followed by those with 30%, 20%, and 10% WCBP, as well as the CM mix, in that order. To provide specific percentages, the W40 sample exhibited a 1.7% higher environmental impact compared to the CM mix, W30 showed a 1.17% increase, W20 displayed a 0.69% rise, and W10 demonstrated a 0.31% increment.

Human toxicity emerged as the primary environmental impact, making up almost 95% of the overall impact across all geopolymer mixes. Subsequently, global warming constituted the second significant impact, contributing only about 2% to the total impact. The heightened inclusion of WCBP in geopolymer synthesis resulted in increased levels of both human toxicity and global warming. Specifically, the W40 sample demonstrated a 1.56% higher impact on human toxicity than the CM mix, while W30 showed a 1.07% difference, W20 indicated a 0.64% distinction, and W10 presented a 0.28% variation. Additionally, concerning global warming impact, the W40 sample exceeded that of the CM mix by 6.44%, with W30 showing a 4.55% difference, W20 indicating a 2.84% distinction, and W10 presenting a 1.32% variation.

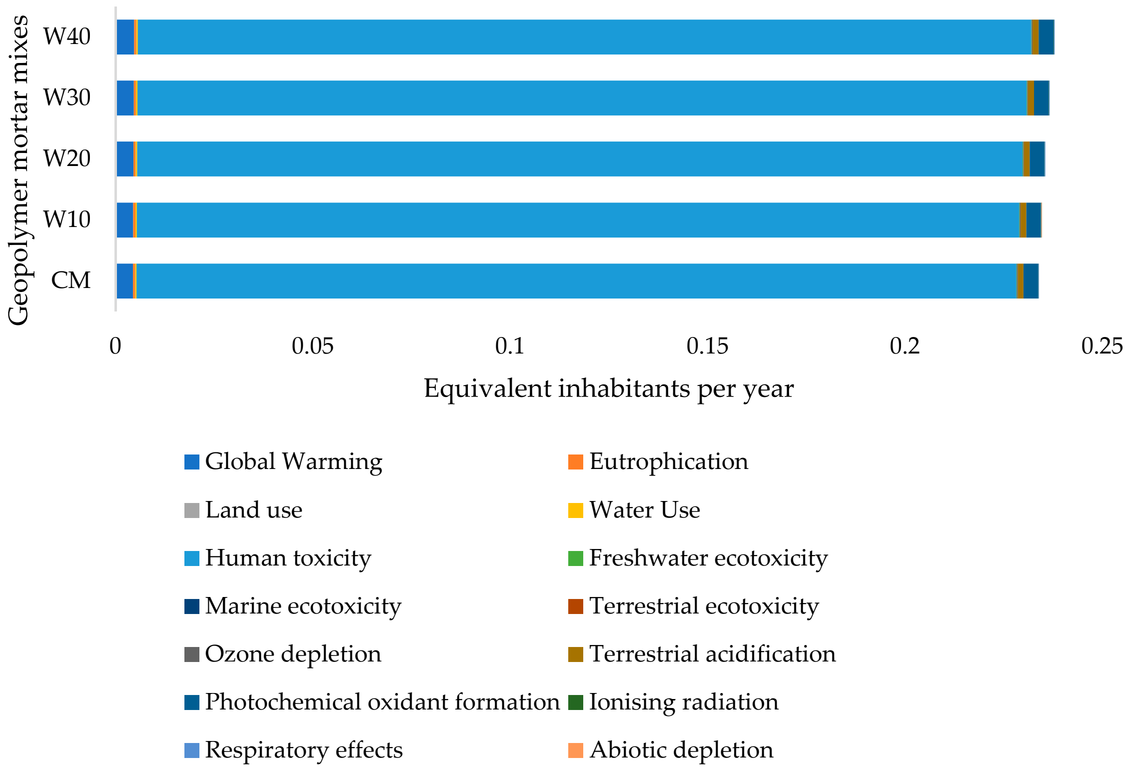

Figure 4. Environmental impacts per inhabitant equivalent of geopolymer mortar mixes.

Dynan et al. [24] also identified human toxicity as the dominant environmental impact category while performing LCA on geopolymer concrete using recycled glass aggregates. Li et al. [37] studied fly ash based geopolymer concrete and observed that opting for fly ash geopolymer concrete over conventional alternatives can lead to a reduction in carbon emissions. However, this shift may result in an increase in other environmental impacts, specifically energy depletion in their specific scenario.

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Nikravan et al. [38] stated that alkali-activated geopolymer mixtures contributed to significant reductions in carbon emissions, although there were higher values in other environmental impact categories such as "marine eco-toxicity" and "ozone layer depletion."

In summary, substituting the conventional binder with the eco-friendly option in "geopolymer binder," has the potential to lower carbon dioxide emissions. However, this shift may lead to a significant increase in other environmental impacts due to the use of alkaline activators or grinding.

3.2. Hot-spot analysis

Figure 5 presents the flow network diagram for energy consumption for the CM and W40, created by SimaPro software. This flow network helps identify the hotspots for each geopolymer mortar mix. In the case of the CM cured under ambient conditions, the mining to material stage was identified as the primary hotspot. This phase constituted 95.5% of the total energy consumption. Within this, 82.2% of the energy consumption was attributed to sodium silicate production at the batching plant, with an additional 9.04% stemming from sodium hydroxide production. In the case of the W40 mix, featuring a high WCBP content, 8.21% of the energy was consumed in grinding brick aggregate into WCBP. Subsequently, energy consumption was distributed with 76.8% from the production of sodium silicate and 8.9% from sodium hydroxide, both at the batching plant.

In summary, the noteworthy energy hotspot in both the CM and WCBP-rich mixes is the production of sodium silicate, followed by the production of sodium hydroxide. Furthermore, in WCBP-rich mixes, 5-8% of the energy is utilized in the preparation of WCBP.

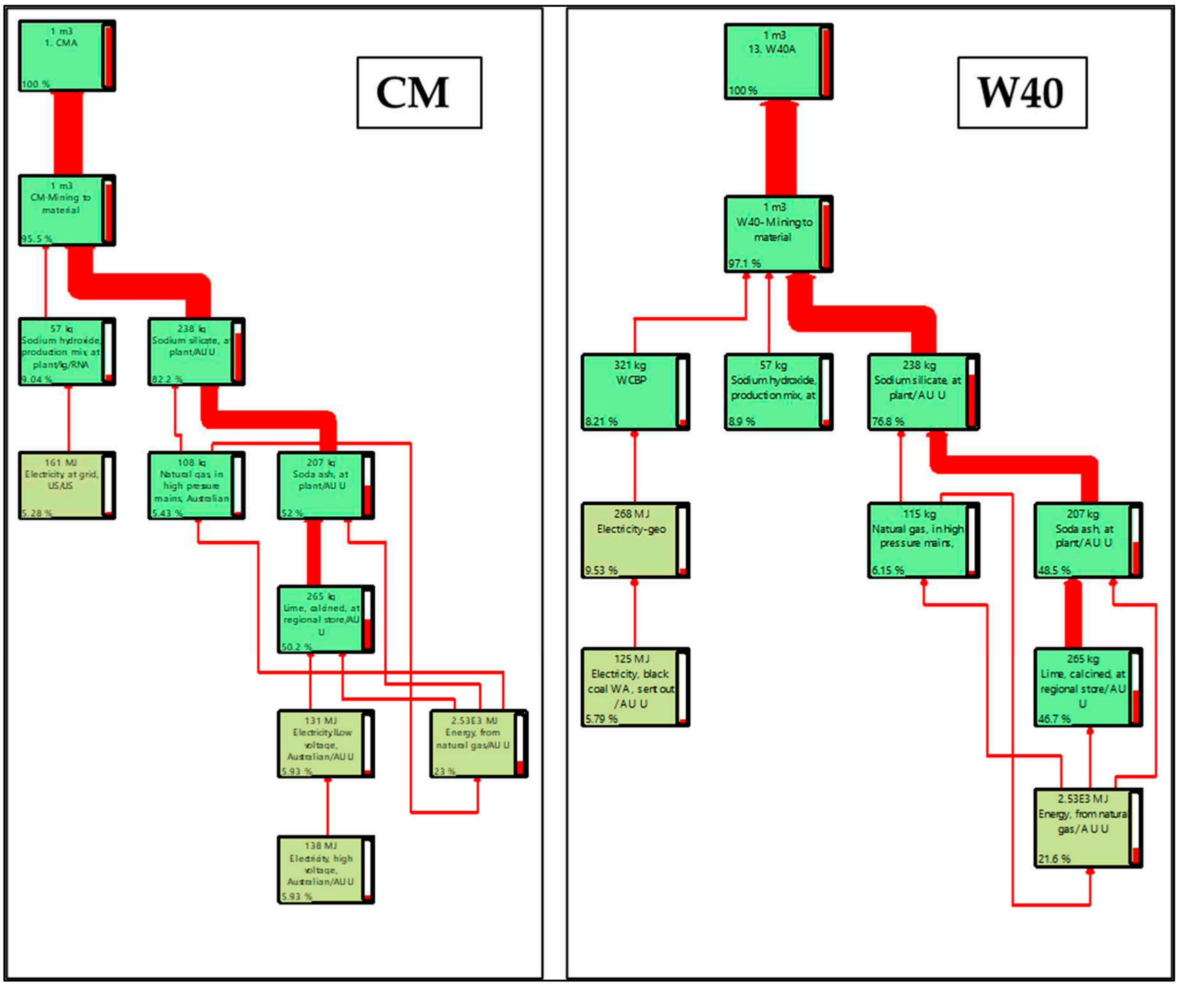

Figure 5. Hotspot analysis of geopolymer mortar mixes (CM and W40 – left to right).

3.3. Monte-carlo simulation

Figures 6 and 7 depict the Monte Carlo analysis (MCA) of the major impact, "Human toxicity," as identified through LCA analysis, specifically for CM and W40. Table 6 presents the mean values and coefficients of variation (CV) for dominant environmental impacts resulted from the geopolymer mixes. The CV ranges from 0.82% to 1.85% for the primary impact "Human toxicity," suggesting that there is relatively low uncertainty in the calculated values for these impacts.

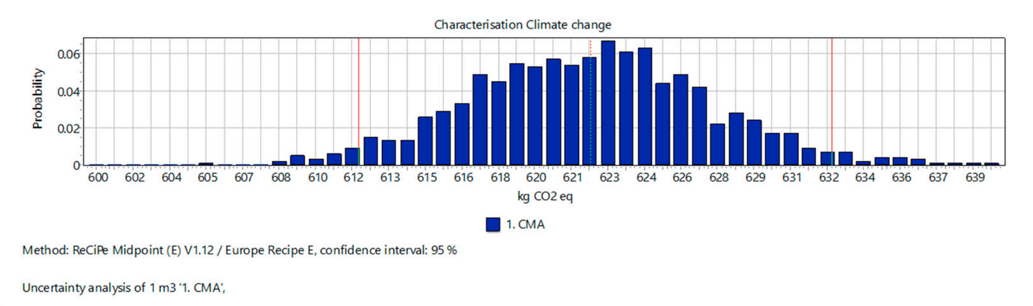

Figure 6. Monte Carlo simulation for human toxicity for CM.

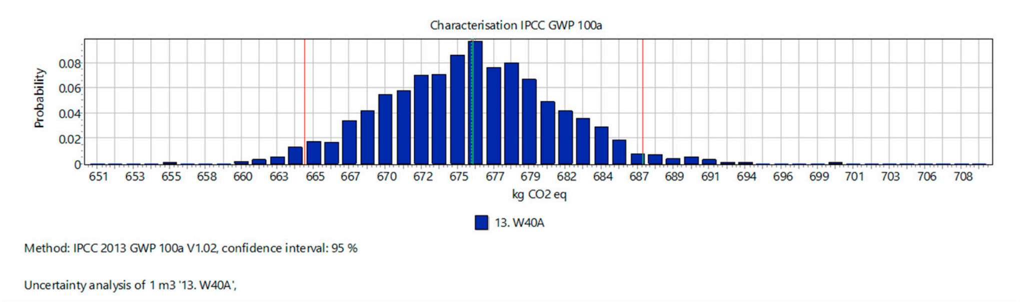

Figure 7. Monte Carlo simulation for human toxicity for W40 mix.

Table 6. Monte-Carlo simulation outcome of LCA for three major impact categories in ambient cured geopolymer mixes.

Geopolymer mix	Impact category	Unit	Mean	CV (%)
CM	IPCC GWP 100a	kg CO_2 eq	635.27	0.89
CM	Human toxicity	kg 1,4-DB eq	8951.7	1.85
W10	IPCC GWP 100a	kg CO_2 eq	643.52	0.82
W10	Human toxicity	kg 1,4-DB eq	8979.66	1.75
W20	IPCC GWP 100a	kg CO_2 eq	653.12	0.83
W20	Human toxicity	kg 1,4-DB eq	9010.23	1.69
W30	IPCC GWP 100a	kg CO_2 eq	664.2	0.84
W30	Human toxicity	kg 1,4-DB eq	9048.77	1.71
W40	IPCC GWP 100a	kg CO_2 eq	675.5	0.84
W40	Human toxicity	kg 1,4-DB eq	9091.85	1.67

3.4. LCC analysis

Figures 8 and 9 show the breakdown of LCC analysis for CM and W40 geopolymer mixes, respectively. In the study of the both CM and WCBP-rich sample, the cost analysis revealed that the costs of alkaline activator had the most significant influence, contributing to 95.9% and the 97.6% respectively of the total material expenses. This cost was further broken down to identify the cost hotspot. Sodium silicate constituting 48.56% for CM and 51.3% for W40 of the cost has been identified as the hotspot, followed by sodium hydroxide (19.38% for CM and 20.47% for W40). The slightly elevated cost of fly ash is accountable for the increased expenses in the CM sample compared to the WCBP-rich samples. To summarize, the expenditures associated with alkaline activators, specifically the prices of sodium silicate and sodium hydroxide, had the most significant impact on all geopolymer mixes.

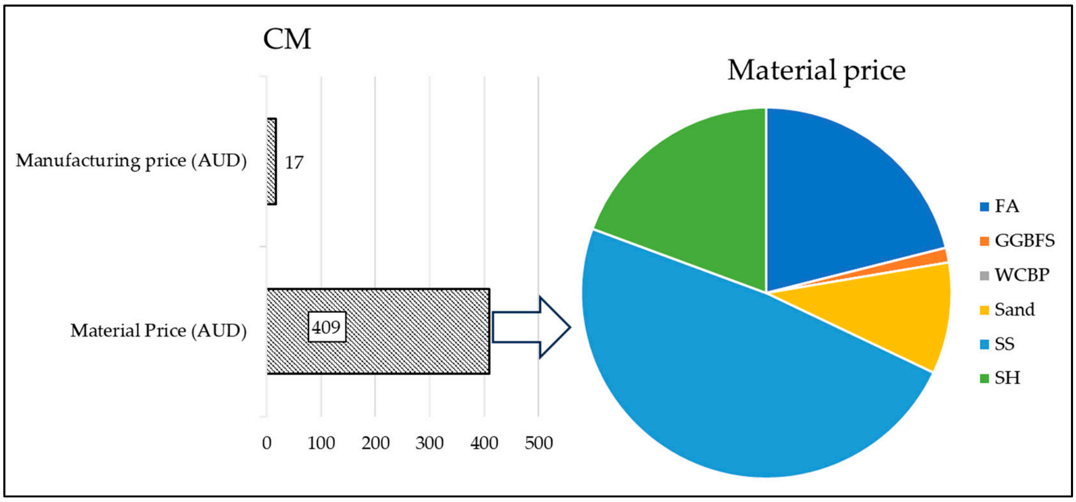

Figure 8. Breakdown of LCC analysis of CM geopolymer mix.

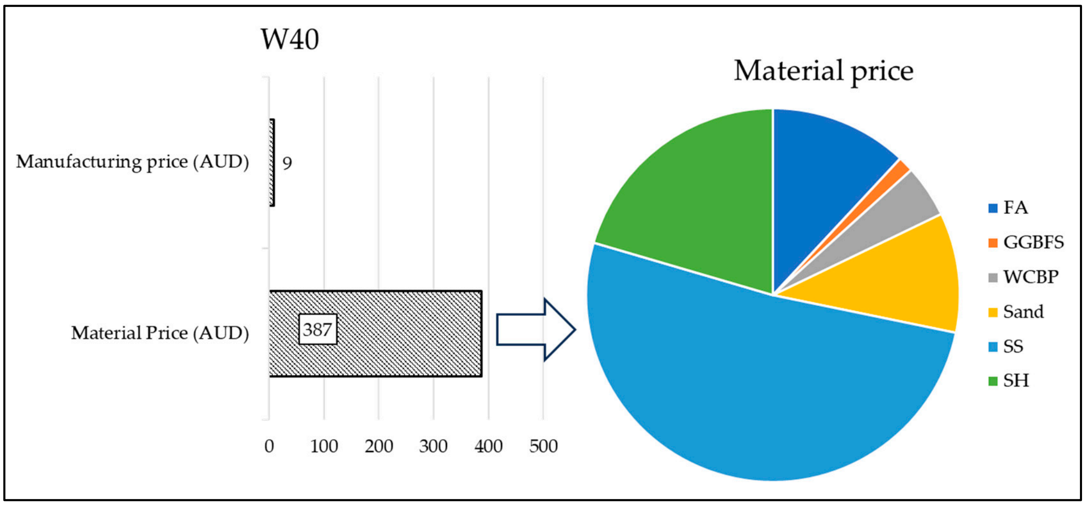

Figure 9. Breakdown of LCC analysis of W40 geopolymer mix.

3.5. Techno-eco-efficiency analysis

Table 7 presents the 28 days compressive strength results sourced from the author's previous study [26]. The compressive strength of each geopolymer mortar mix surpassed 40 MPa after a 28-day curing period, indicating their potential for use in structural applications. The geopolymer mortar mix incorporating 40% WCBP demonstrated the highest compressive strength among all the mixes. Following closely were the mixes containing 30%, 20%, 10% WCBP, and the control mix. This consistent trend strongly affirms the technical feasibility and effectiveness of employing WCBP as a solid precursor in the formulation of a geopolymer binder.

The analysis began by normalizing the characterized values of the environmental impact for each geopolymer mix using equations 1 and 2. These normalized values were then multiplied by the corresponding weights and then by corresponding compressive strength values presented in Table 7 in order to obtain all environmental impact values in terms of compressive strength (MPa). Similarly, the life cycle cost was also subjected to normalization, following a specific equation (equation 3). The resulting normalized cost figures were then divided by the respective compressive strength values

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from Table 7. This division aimed to ascertain the cost value per unit of compressive strength (MPa). The findings were then presented in Table 8, illustrating the normalized environmental impact value per MPa (EI/MPa) and the normalized life cycle cost value per MPa (Costs/MPa) for 1 meter cube of geopolymer mortar mixture. Notably, the study observed a trend where the Costs/MPa reduced as the proportion of WCBP in the geopolymer mix increased. This reduction was primarily attributed to the lower material price of WCBP. On the other hand, although WCBP rich samples has high environmental impact arising from the grinding process, the EI/MPa exhibited a decrease with a higher content of WCBP in the mix. This decrease was due to the high compressive strength of WCBP rich samples than the control one.

Table 7. Compressive strength of geopolymer mortar mix [26.]

Geopolymer mix	28 days compressive strength (MPa)
CM	72.38
W10	72.73
W20	78.86
W30	81.41
W40	91.87

Table 8. Techno-eco-efficiency outcome of 1 m^3 geopolymer mixes.

Geopolymer mix	EI/MPa	Costs ($)/MPa	PP'e,g	PP'c,g
CM	0.0032	5.89	1.0019	1.0031
W10	0.0032	5.74	1.0019	1.0024
W20	0.0029	5.19	0.9999	0.9999
W30	0.0029	4.95	0.9993	0.9988
W40	0.0025	4.32	0.9832	0.9881

The environmental to cost relevance factor, calculated as 0.000573 (which is less than 1), suggests that the financial cost outweighs the environmental impact in the analysis [32]. Following the calculation of initial portfolios (PPe,g and PPc,g) using equations 4 and 5, the refined portfolio positions (PP'e,g and PP'c,g) were determined using the environment to cost relevance factor through equations 7 and 8.

Subsequently, Figure 10 illustrates the techno-eco-efficiency portfolio for geopolymer mortar mixes. According to the portfolio analysis, W20, W30, and W40 geopolymer mixes exhibited techno-eco-efficiency, while CM and W10 samples are deemed not technologically and economically efficient. Despite the higher environmental impact observed in WCBP-rich samples outlined in section 3.1, the EI/MPa values declined with increasing WCBP percentage in geopolymer mortar mixes, owing to their elevated compressive strength. For instance, the W40 sample exhibits a total normalized environmental impact of 0.24 with a compressive strength of 91.87 MPa, while the CM has a total normalized environmental impact of 0.23 with a compressive strength of 72.38 MPa. Consequently, the EI/MPa value for CM is greater than that of the W40 sample.

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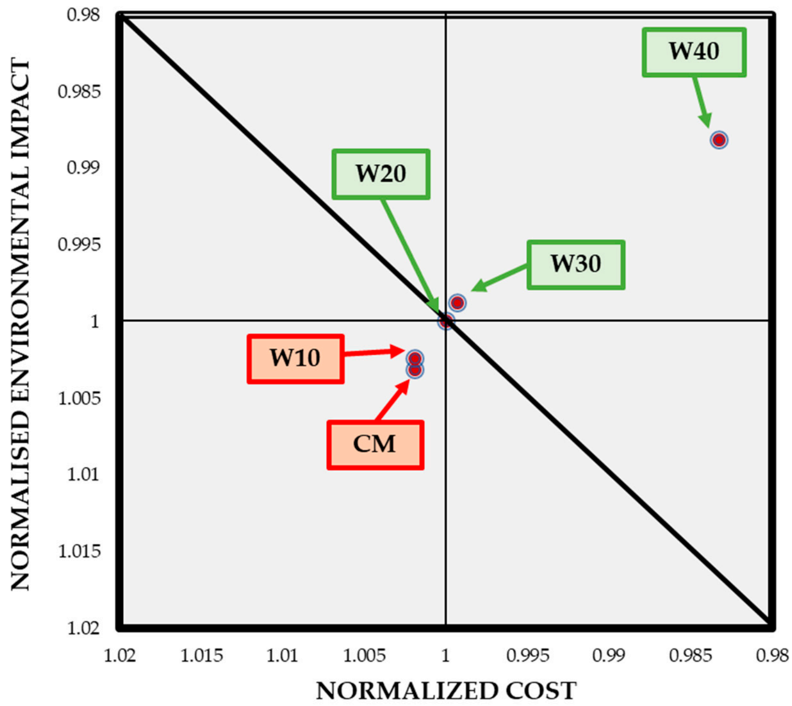

Figure 10. Techno eco-efficiency portfolio for geopolymer mixes.

The comparison between the W40 sample and the CM sample reveals a decrease in the EI/MPa value, dropping from 0.0032 to 0.0025. This indicates a favorable environmental impact per unit compressive strength for the W40 sample. Additionally, the WCBP-rich samples exhibit lower Costs (AUD)/MPa values due to their economical material pricing. Consequently, the PP'e,g and PP'c,g values surpass 1 for the CM and W10 samples, suggesting higher environmental and cost impacts. In contrast, the W20, W30, and W40 samples boast values below 1 for both indicators, establishing them as superior performers among the five mixes in terms of environmental impact and cost-effectiveness.

4. Conclusion

This study was undertaken to assess the techno-eco-efficiency of WCBP-based geopolymer mortar, particularly focusing on the substitution of fly ash with WCBP in ambient cured conditions. The environmental impact was higher for the WCBP rich sample (up to a maximum of 1.7% for W40) compared to the CM containing 0% WCBP. Among the fourteen impacts studied, human toxicity emerged as the dominant environmental impact, accounting for around 95% of the impact across all the mixes, followed by global warming at (2%). Similar outcomes have been demonstrated in prior studies on glass aggregate based geopolymer concrete [24].

Next, the primary area of concern was pinpointed, specifically the energy utilized in the production of alkaline activators at the batching plant, which emerged as a significant factor across all geopolymer mixes. Simultaneously, the activity of grinding brick aggregate into WCBP consistently stood out as a crucial hotspot in the geopolymer mortar mixes that incorporated WCBP. These findings emphasize the critical role of these processes in the overall energy consumption and environmental impact of geopolymer production. Prior research has demonstrated analogous findings for alkali-activated geopolymer mix [23].

In the case of LCC, the examination revealed that the greatest cost contributor for all geopolymer mortar samples was associated with alkaline activators, specifically sodium silicate and sodium hydroxide. These components stood out as the primary factors influencing the economic aspects of the geopolymer production process. Furthermore, in the case of WCBP-rich samples, the total cost was found to be lower than that of the CM. This cost reduction is attributed to the economical pricing of WCBP, signifying its potential as a cost-effective alternative in the formulation of geopolymer mortars.

Eventually, the geopolymer mixes enriched with WCBP—namely W40, W30, and W20—were recognized as technologically and economically efficient (techno-eco-efficient). This designation is attributed to their favorable combination of higher compressive strength and lower costs. On the contrary, both the CM and W10 mixes were not considered eco-efficient due to their lower compressive strength and higher associated costs. This conclusion underscores the importance of both mechanical performance and economic considerations in determining the overall efficiency of geopolymer mixes. Future studies should integrate solutions to treat the hotspots to further enhance the techno-eco-efficiency of geopolymer mixes.

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