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Decarbonizing concrete with biochar:Insights from life cycle sustainability assessment

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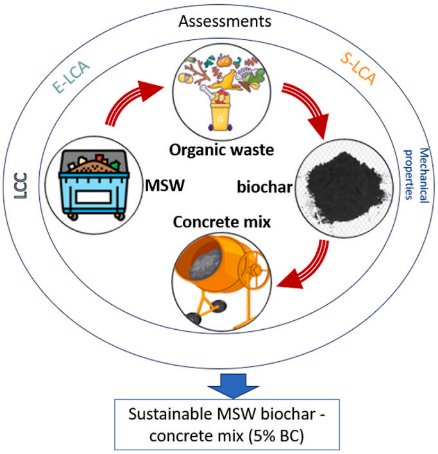
HIGHLIGHTS

- First integrated social, economic, and environmental assessment of biochar concrete.
- 5 wt% biochar replacement improves strength and reduces environmental and social impacts.
- Life-cycle costs of biochar concrete are comparable to conventional mixes.
- Biochar concrete at 5 wt% shows superior overall sustainability performance.
- Social impacts, especially health damage, dominate total sustainability outcomes.

GRAPHICAL ABSTRACT



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ABSTRACT

Currently, substituting cement with biochar in cementitious composites has drawn considerable attention within the scientific community. The use of biochar produced from municipal solid waste offers a promising approach to improve concrete performance while promoting a circular economy and a sustainable management approach. However, most of the studies on biochar-enhanced concrete focused on mechanical properties; life cycle sustainability assessments (social, economic, and environmental) of biochar in the life cycle have not been addressed. This paper presents an integrated life cycle sustainability assessment that combines economic, social, and environmental impacts to evaluate municipal solid waste biochar-enhanced concrete in comparison with conventional concrete. A multi-criterial decision-making framework employing the technique for order preference by similarity to ideal solution was used to identify the most sustainable mix design. The result shows that replacing 5 wt% of cement with MSW-derived biochar increases compressive strength from 43.3 MPa to 45.5 MPa and lowers the global warming potential by about 5 wt%, without significant cost variation. The multi-criteria decision analysis confirmed that a 5 wt% of the biochar mix concrete represent the optimal

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alternative, achieving the best balance among the economic, social, and environmental indicators. Social impact showed the largest improvement: health-related damage, expressed in terms of societal willingness to pay to avoid these effects, decreased from an estimated USD 6487 for conventional concrete to USD 3538 for biochar-enhanced concrete. When the three sustainability pillars were integrated, the social life cycle assessment accounted 99.9 wt% of the total sustainability gap, emphasizing the dominant role of social factors. Overall, biochar produced from municipal solid waste not only enhances concrete performance but also supports waste valorization and circular economy objectives. Future research should address the long-term durability and large-scale applicability of biochar derived from municipal solid waste based concrete systems.

Abbreviations

AHP	Analytic Hierarchy Process
BC	Biochar
CEM I	Ordinary Portland Cement
DALY	Disability-Adjusted Life Year
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life cycle inventory
LCSA	Life Cycle Sustainability Assessment
MCDM	Multi-Criteria Decision-Making
MSW	Municipal Solid Waste
NIS	Negative Ideal Solution
PIS	Positive Ideal Solution
S-LCA	Social Life Cycle Assessment
SCMs	Supplementary cementitious materials
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VLY	Value of Life Year
VSL	Value of Statistical Life
WTP	Willingness to Pay

1. Introduction

Cement is a key component of the worldwide construction industry and ranks as one of its most carbon intensive materials (Ee et al., 2025). The production consists of the mixing of raw materials, which are then heated in a kiln at >1400 °C to produce clinker and grounded with mineral compounds to obtain cement (Ee et al., 2025). The process produces around 2 million tonnes of CO_2 for every million tonnes of cement manufactured, resulting in a substantial amount of CO_2 emissions. The anticipated expansion of the sector is forecast to be 12-23 wt % from 2005 to 2050, and the environmental impact associated with cement production is also likely to rise (Ee et al., 2025). Cement is the predominant construction material, constituting 70 wt% of concrete consumption, underscoring its cost-effectiveness and practicality as a structural component. Due to its strength and versatility, the material is invaluable for the construction of buildings, bridges, dams, and transportation infrastructure (Rajendran et al., 2025; Ndahirwa et al., 2022). More than 35 billion tons of concrete (used for the buildings construction) are being produced annually, whose volumes significantly exceed those from other materials (Ndahirwa et al., 2022; Tkachenko et al., 2023). Nevertheless, traditional concrete is harmful to the environment as a result of energy-consuming Portland cement manufacturing process which involves high-temperature calcining of limestone that results in CO_2 emission. Furthermore, the extraction of natural aggregates distruct habitats and ecosystems. It is the reason scientists and industry professionals are researching alternative materials and technologies that can reduce concrete's environmental impact yet maintain or enhance its performance (Ramsden, 2020; Rajendran et al., 2025).

To decrease the CO_2 emission of concrete, the concrete industry initially explored alternative binders and supplementary cementitious materials(SCMs) resulting in “green concretes” (Habert et al., 2020). The utilization of waste based supplementary cementitious materials including Ground Granulated Blast Furnace Slag (GGBS), Fly ash (FA) and biochar has been a great focus for its mechanical enhancements and decrease in environmental load (D'Alessandro and Ubertini, 2024). The incorporation of waste derived SCMs like GGBS, FA and biochar are promising due to its mechanical improvements and reduction of environmental burden (D'Alessandro and Ubertini, 2024). Biochar, a carbon rich and chemically stable material obtained from the pyrolysis of biomass, is being considered for its capacity to store carbon as well as exhibit pozzolanic reactivity. Its low carbon-high silicon content can improve cement hydration, decrease cement consumption, and be conducive to prolonging service life of concrete (Rashid et al., 2024; Barbhuiya et al., 2024). Results of experimental investigations reveal that biochar has the potential to improve mechanical and durability performance of concrete. For instance, hazelnut shell biochar improved compressive strength and toughness (Ferro, 2016), while low dose of wood biochar enhanced both flexural and compressive strengths (Akhtar and Sarmah, 2018; Gupta et al., 2018). Biochar also impact on CO_2 sequestration and immobilization of hazardous elements in contaminated soils (Wang et al., 2019). However, its performance is highly related to the feedstock composition, particles size and pyrolysis condition (Jia et al., 2023).

New directions in sustainable building construction processes have emphasized the importance of addressing several sustainability dimensions through integral evaluation systems (Yi et al., 2025; Sánchez-Garrido et al., 2022; Theilig et al., 2024; Apostolopoulos et al., 2023; Fernando et al., 2023). Studies employing Life Cycle Assessment coupled with multi-criteria decision-making methods have demonstrated significant potential for optimizing construction material selection (Theilig et al., 2024). For example, combined LCA-MCDM methods have been used to assess cement production options where alternative binders such as ground granulated blast furnace slag could perform better in several impact categories (Akintayo et al., 2024). In addition to this, research on Building Information Modeling integrated with Life Cycle Sustainability Assessment has shown that combining environmental, economic, and social criteria enables more robust decision-making for sustainable concrete structures (Han and Rajabifard, 2024). These methodological advances stress the value of holistic assessment schemes that go beyond one-dimensional environmental assessments.

While various biochar produced from wood, rice husk and grasses have been studied extensively its replacement for production of concrete. However, most of the studies on biochar-enhanced concrete focused on mechanical properties, and its sustainability aspects and environmental benefits are still at early stage (Ee et al., 2025). For concrete production to be truly sustainable, decisions must consider People, Planet, and Profit together, not only the environmental aspect. This approach considers social and economic impacts as well, such as creating jobs, supporting communities, and reducing carbon emissions and waste. Life cycle assessments have demonstrated that biochar can reduce greenhouse gas emissions. Biochar concrete may also produce a benefit of USD 92–116 per m^3 in some research (Chen et al., 2022).

Recent work has further demonstrated that multi-criteria decision-making techniques such as AHP and TOPSIS, when combined with LCA, provide transparent and reproducible frameworks for evaluating construction materials across environmental, economic, and technical dimensions (Theilig et al., 2024). Yet these economic opportunities apply only to small-scale systems, with more substantial benefits anticipated from economies of size (Labianca et al., 2024). Nevertheless, the social dimension is still being neglected due to the lack of multinational standardized S-LCA approaches in buildings sector (Backes and Traverso, 2024). Despite biochar derived from municipal solid waste exhibits significant potential in the construction industry (Jia et al., 2023), particularly as a concrete additive, marking a novel advancement in sustainable building materials, life cycle sustainability assessments (social, economic, and environmental) of biochar enhanced concrete in the life cycle have not been addressed.

To address this critical research gap, this study investigates MSW biochar-cement composites using a comprehensive Life Cycle Sustainability Assessment (LCSA) paradigm. This study combines life cycle assessment to quantify environmental impacts, life cycle costing to evaluate costs over the full product life cycle, and social life cycle assessment to capture social implications, all within a multi-criteria decision-making framework. Such integrated approaches are increasingly recognized as necessary for understanding trade-offs between environmental, economic, and social dimensions, and for supporting sound material choices in the construction sector.

The contribution of this work can be summarized in three points. First, most previous studies focus on biochar produced from agricultural or forestry residues, whereas this study examines biochar derived from municipal solid waste as a partial replacement for cement. In doing so, it directly links concrete production with waste management challenges while improving the sustainability profile of the material. Second, instead of assessing biochar-modified concrete using isolated indicators, such as environmental impacts or mechanical performance alone, this work combines experimental compressive strength results with environmental, economic, and social assessments to provide a more complete evaluation. Third, the application of multi-criteria decision-making methods allows the identification of optimal mix designs, offering a practical way for stakeholders to balance technical performance with sustainability objectives.

Overall, the proposed framework reflects current best practice in sustainable construction by combining life cycle thinking with multi-criteria assessment. It addresses a clear methodological gap in existing research on sustainable concrete and provides evidence-based support for decision-making aimed at low-carbon construction and progress toward carbon neutrality.

2. Materials and methods

This research was conducted in four consecutive stages, as illustrated in Supplementary Material B, Figure S1. Phase 1 monitored the social life cycle impacts of the proposed mixed designs with a Social Life Cycle Assessment (S-LCA), considering indicators like health damage, fair wages, working hours and willingness-to-pay (WTP). Phase 2 The environmental impacts were evaluated by an LCA including goal and scope definition, life cycle inventory analysis (LCI), and key impact categories. Phase 3 estimated the economic costs through Life Cycle Costing (LCC), which included construction cost, operation & maintenance, and externalities. Eventually, Phase 4 involved the social, environmental, and economic dimensions of sustainability in a Life Cycle Sustainability Assessment (LCSA) methodology. Results from S-LCA, LCA and LCC were integrated through Multi-Criteria Decision Analysis (TOPSIS) to obtain a single sustainability index in order to select the most sustainable concrete mix.

2.1. Case study description and identification of alternatives – mix design for biochar-mix concrete production

As a case study, the 28th day compressive strength of which is 42.5 MPa; ordinary Portland cement (shortened as OPC,P.O.42.5) with high fineness was applied in this paper. The fine aggregate used was natural river sand (<4.75 mm) and the coarse aggregate (4.75–20 mm) had an apparent density of 2756 kg/m^3 and bulk density of 1526 kg/m^3. A water/binder ratio of 0.45 was used for all mixtures. The compositions of the two mix designs are shown in supplementary material B Table S1 (Jia et al., 2023). Biochar (BC) was produced from MSW by restricted pyrolysis. The dewatered MSW was removed manually after the screw press, including metals, plastics and building materials. The remaining organic matter was ground crushed and pyrolyzed at 600 °C to biochar and then ground and sieved to <48 μm in order to improve its reactivity (Jia et al., 2023). Concrete mixtures were designed to achieve a target compressive strength of 40 MPa. Municipal solid waste–derived biochar was used as a partial cement replacement by weight (wt.%) at substitution levels of 1, 2, 3, 4, 5, and 10 wt%, and additionally at higher replacement ratios of approximately 20–30 wt%. No superplasticizer was used, in order to maintain mix consistency and avoid variations in mechanical performance arising from chemical admixtures (Jia et al., 2023; Lin et al., 2023; Wang et al., 2025).

2.2. Environmental assessment

The environmental impact of the biochar–enhanced concrete was assessed using a Life Cycle Assessment (LCA) following ISO 14040 and 14044 guidelines (ISO, 2006a, 2006b). The LCA consisted of the standard four steps including (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation.

Objective and scope: The objective of the study was to conduct a cradle-to-gate LCA of concrete biochar production in order to compare its environmental sustainability against standard concrete. The functional unit considered 1 m^3 of concrete blend at the target compressive strength; hence all other input quantities were referred to this value. The system boundary was on a cradle-to-gate basis, including the stages of raw material extraction and fresh concrete production. The phases of use and end-of-life were not considered in this evaluation. A system boundary sketch is shown in Fig. 1.

2.3. Life cycle inventory

Input material and energy consumption were obtained from literature or industrial reports supplementary material B Table S2 (Worrell et al., 2013; Nair et al., 2024). Life cycle inventory of building materials was developed in the Brightway interface with Python (Mutel, 2017). Because the study only considered a specific product system – concrete – and no co-products were produced, allocation methods for the inventory or any environmental impacts were not necessary. Background data were mainly retrieved through the consultation of the Ecoinvent 3.10 database coupled with Brightway, but they were also complemented by literature values as in other studies presented in scientific literature. Moreover, Key life-cycle inventory assumptions for biochar production, including pyrolysis yield, energy demand, pre-treatment steps, transport distances, and waste management credits, are summarized in the Supplementary Material B Table S3.

2.4. Life cycle impact assessment

Environmental impacts were evaluated using the ReCiPe 2016 method, one of the most up-to-date and widely applied frameworks for life cycle impact assessment (Huijbregts et al., 2017) . The hierarchical (H) consensus model at the midpoint level was adopted, as it provides a balanced and scientifically recognized perspective suitable for cross-study comparisons.

Environmental impacts were assessed by the ReCiPe 2016, which is one of the most recent and commonly used impact assessment methods on a life cycle basis. The hierarchical (H) consensus model of response was utilized at the midpoint level and is a balanced perspective that has been validated scientifically for comparison across studies. Ten midpoint impact categories were analyzed: global warming, ozone depletion, terrestrial acidification, freshwater eutrophication, human carcinogenic toxicity, human non-carcinogenic toxicity, water

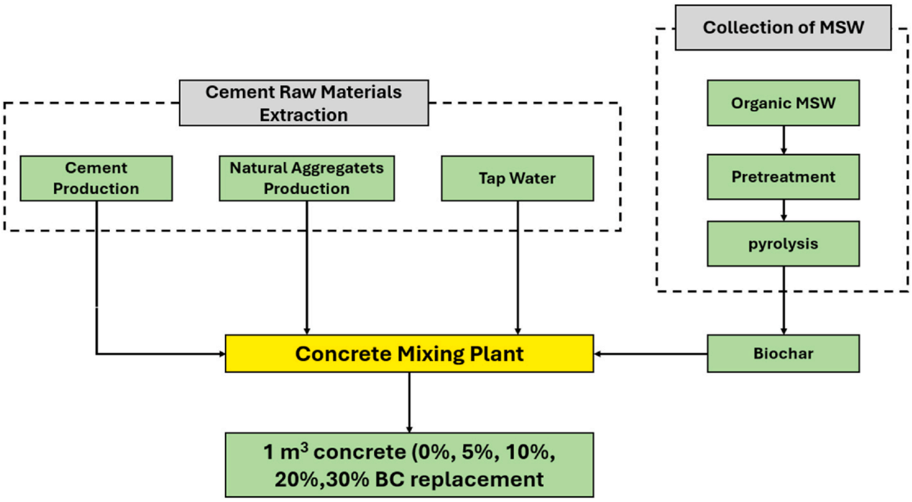

Fig. 1. System boundary of biochar concretes manufacture. On the left are traditional cement inputs, natural aggregates, and water from extraction processes. On the right, there is management of municipal solid waste (MSW), where organic MSW was pretreatment followed by pyrolysis and led to biochar. At the concrete mixing plant, all three inputs in which biochar is partially substituted for cement at different levels of substitution from 0 to 30 wt% in order to generate 1 m^3 of concrete.

consumption, particulate matter formation, and land use. The resulting impact profiles were benchmarked against values reported in peer-reviewed literature to identify the key contributors to environmental burdens and highlight potential pathways to enhance the sustainability performance of biochar–concrete production.

2.5. Social-life cycle assessment (S-LCA)

In this research, an input-output framework approach was used to assess the health risks of making concrete with different production technologies and added biochar application compared to a reference case to conventional concrete. Extending beyond the LCA framework, the model considers resource inputs and air pollutant emissions throughout life cycle in terms of their effects on human health. Outcomes were presented using disability adjusted life years (DALYs) for premature life loss and WTP for the economic loss associated with diseases caused by air pollutant emissions as shown in supplementary material A Fig. S2. Such an approach in accordance with ISO 14040, ISO 14044 and ISO 14008 allows holistic sustainability assessment with the include of health-related social-impacts within established environmental assessments.

The life cycle inventory analysis of concrete production, with and without biochar, identified the health damage arising from harmful emissions supplementary material B Table S4. These impacts were classified into four categories: circulatory system damage, global warming–related diseases, respiratory disorders, and carcinogenic effects, underscoring the significant health risks associated with concrete production.

2.6. Quantitative assessment

The willingness-to-pay (WTP) approach is used to estimate the economic burden of a disease by assessing how much people are willing to pay for improving health or preventing hazardous working conditions, and vice versa, how much compensation to be subjected to these risks Gao et al., 2015. Though common in studies of environmental science and occupational health, this approach is growing in its application to monetize health impacts in sustainability research (Sexton and Sexton, 2014). Health damage from air pollutant emissions was quantified by monetizing the disability-adjusted life years for which a willingness-to-pay (WTP) framework has been used to generate monetary estimates of the social costs associated with biochar and conventional concrete production as shown supplementary material B Table S9 (Jung et al., 2020)):

The formula for the weighted score calculation is:

The social damage indicator U_{ij} represents the disability-adjusted life years (DALYs) associated with damage category j caused by pollutant i, and is calculated as:

$$U_{ij} = E_{ij} \times F_i \times M_i \times DALY_j$$

where E_{ij} is the emission of pollutant i contributing to damage category j, F_i is the characterization factor, M_i is the exposure or fate modifier, and $DALY_j$ represents the disability-adjusted life years associated with damage category j.

This study adopts the U_{ij} values reported by (Tong et al., 2022), which are presented in Table 4 of the Supplementary Material B Table S9, and provides the life-cycle health damage assessment results for both conventional and biochar–concrete production. The latter results were used as the foundation for the S-LCA assessment in this work.

The average value of a statistical life (VSL) for the adult population in Denmark was estimated at USD 4.3 million (based on the difference between the average life expectancy and mean working age). In 2024, Denmark had an average life expectancy of 79.9 years, and an average working age was 42.6 years so remaining expected lifespan would be 37.3. Using these values, the Supplementary Material B Table S 11 details the calculation of the social willingness-to-pay (WTP) for health damages attributable to 1 kg of CO_2 emissions during the production of concrete with and without biochar addition.

The value of a statistical life (VSL) for the target region was taken as:

$$VSL_{\text{targ}} = 4.36 \times 10^6 \text{ USD}$$

The elasticity of income was assumed as:

$$e_I = 0.7$$

The value of a life year (VLY) was calculated from the VSL using an annuity approach:

$$VLY = \frac{VSL_{\text{targ}} \times r}{1 - (1+r)^{-n}}$$

where r is the discount rate (4 wt%) and n is the remaining life expectancy (37.3 years).

For carbon dioxide emissions, the VLY was therefore calculated as:

$$VLY_{CO_2} = \frac{4.36 \times 10^6 \times 0.04}{1 - (1 + 0.04)^{-37.3}}$$

For other pollutants, the same procedure was applied using mass-equivalence factors, by multiplying the pollutant-specific equivalence factor with the calculated VLY value.

The willingness to pay (WTP) for health damage was then calculated as:

$$WTP = U_{ij} \times VLY$$

where U_{ij} represents the disability-adjusted life years (DALYs) associated with damage category j caused by pollutant i.

2.7. Life cycle sustainability assessment (LCSA)

Life cycle sustainability assessment provides a holistic framework for evaluating the environmental, economic, and social performance of a product over its life cycle. It is based on three complementary methods: environmental life cycle assessment, life cycle costing, and social life cycle assessment. The conceptual foundation of this approach is defined in the (United Nations Environment Programme UNEP & Society of Environmental Toxicology and Chemistry SETAC, 2012), which establishes common scope conditions and evaluation principles. In this study, LCSA is applied to compare the sustainability performance of conventional concrete and biochar-modified concrete. Environmental impacts are quantified through LCA, economic performance through LCC, and social health impacts through S-LCA. To enable transparent integration, all three dimensions are converted into a common monetary unit. Environmental impacts are monetized using damage cost factors, social impacts are expressed in monetary terms based on disability-adjusted life years and willingness-to-pay approaches, and economic costs are directly reported in monetary units.

As a result, the three sustainability pillars are directly aggregated into a single sustainability index expressed in USD per functional unit. This cost-based integration avoids the need for additional normalization or weighting procedures and allows a consistent and transparent comparison between conventional concrete and biochar concrete based on their overall sustainability performance.

2.8. Multi-criteria decision-making (MCDM) process

AHP and TOPSIS are chosen together for analysis due to their distinctive fundamentals and extended usage of sustainability assessment. In the present context of multi-disciplinary issues such as environmental, economic, and social indicator criteria. AHP is a useful structured and transparent method for extracting weights from indicators in terms of their relative importance. TOPSIS operates by ranking alternatives based on their distance to an ideal solution, and results are intuitive and interpretable. Together, this combination offers a practical and well-established decision-support framework that is compatible with the structure of the monetized sustainability indicators used in this study, while avoiding excessive methodological complexity.

Identification of the criteria: The optimal concrete mixture was determined by integrating environmental, economic, and social criteria derived from experimental testing and the LCA results. Environmental performance was assessed using midpoint impact categories (climate change, resource use, and ecosystem quality). Economic performance was presented as the overall cost per m 3 of concrete, including energy used. Social performance was measured by the health damage WTP index.

Criteria weighting (AHP): The criteria were weighted using the analytic hierarchy process of Saaty's method. The methodology to be followed is decision hierarchy built in three different levels, pair wise comparison, and normalized decision matrix. Consistency of judgment. The relative importance of the environmental, economic, and social dimensions was determined using the Analytical Hierarchy Process (AHP). Pairwise comparisons were conducted following Saaty's scale, resulting in the comparison matrix reported in Table S7. The priority weights were derived from the principal eigenvector of the normalized matrix, yielding weights of 0.10 for environmental, 0.14 for economic, and 0.76 for social criteria. The internal consistency of the judgments was evaluated using the consistency index (CI) and consistency ratio (CR). The computed consistency index and consistency ratio were 0.03 and 0.05 as reported in supplementary material B Table S7, respectively, which were significantly less than the threshold of 0.10 as widely accepted in AHP. This implies that the pairwise comparisons are consistent and the corresponding weights can be used in the following TOPSIS analysis. For the sake of transparency and reproducibility, we report in Supplementary Material both the full pairwise comparison matrix, the resulting weights as well as all consistency metrics.

Ranking of alternatives: TOPSIS was employed to identify the most sustainable alternative. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was employed. This method ranks alternatives based on their relative distances from the positive ideal solution (PIS) and negative ideal solution (NIS). The details are provided in the Supplementary Material B Table S 16.

2.9. Sensitivity analysis

A sensitivity analysis was performed on the experimental weights (ωk) as well to maintain robustness. This is done such that the impact of changing weights on the ranking of alternatives can be analyzed, therefore offering some perception into stability of the decision.

3. Results and discussion

3.1. Mechanical strength

Biochar can function as a micro filler, enhancing the microstructure of concrete by filling pores and promoting the formation of additional C–S–H gel responsible for strength development. The average 28-day compressive strengths of concretes containing biochar replacement levels from 0 to 30 wt% were measured in megapascals (MPa) using cubic, measured using cubic specimens, are presented in Supplementary Material A, Fig. S3(Jia et al., 2023). Performance was significantly affected by both the biochar content and the cement type. At a 5 wt% biochar (BC) addition, the highest strength (45.5 MPa) was achieved, an increase of 3.9 wt%, 1.2 wt%, and 5.2 wt% compared to replacement levels of 1 wt%, 2 wt%, and 5 wt%, respectively(Jia et al., 2023).

The results indicate that by adding low dose of MSW-originated biochar (up to 5 wt %, the compressive strength of concrete can be improved. This enhancement may result from the filler effect of biochar particles that will fill micro-voids between cement grains, facilitating a denser microstructure and thereby, more C–S–H gel that promotes strength gain(Jia et al., 2023). The 5 wt % of the optimal concentration since it reinforced the matrix of concrete and improved water retention by not interfering with hydration reaction of cement. Similarly, when the biochar content was greater than 10 wt %, the effect reversed (Jia et al., 2023). The strength of the concrete was reduced to approximately 15 wt % at 10 wt %, 35 wt % at 20 wt %, and nearly 50 wt % at 30 wt %. This implies that an excessive biochar prevents cement hydration, contributes to the porosity, and decreases active binder amount which is responsible for keeping the material together. Overall, MSW derived biochar is a double-edged material: it can be highly beneficial at low replacement levels but detrimental at higher dose. Finding the right balance is therefore essential to capture its environmental benefit while maintaining satisfactory mechanical performance(Jia et al., 2023).

Beyond the replacement level, the compressive strength of biochar–cement composites is influenced by several factors, including the water-to-binder ratio, binder composition, admixture type, casting and curing regimes, and the physical characteristics of the biochar. Although the representative mix design used in this study satisfies standard performance requirements, further enhancement of mechanical properties remains possible through mix optimization. In general, the incorporation of biochar at dosages below 5 wt% has been reported to increase compressive strength, with improvements of up to 17 wt% observed in some studies, whereas higher replacement levels (>25 wt%) tend to reduce strength and should be avoided for structural applications (Jia et al., 2023). A notable exception is ultrafine powder biochar incorporated into 3D-printed cement paste that follows different rheological and microstructural mechanisms. These findings are consistent with earlier studies. For example, Gupta et al., 2018 observed that adding biochar increased 28-day compressive strength by 16 wt percent at 0.5 wt percent biochar and by 9 wt percent at 2 wt percent biochar, compared with the control concrete.

3.2. *Life cycle assessment(LCA)*

Life cycle assessment has shown that biochar addition can significantly lower the environmental impacts of concrete (Kennedy et al., 2025). Partial cement replacement decreases the global warming potential (GWP) in proportion to the substitution level. Fig. 2 illustrates this trend: compared with conventional cement concrete, biochar incorporation at 5 wt%, 10 wt%, 20 wt%, and 30 wt% achieved GWP reductions of 5 wt%, 17 wt%, 29 wt%, and 48 wt%, respectively. These findings demonstrate the double benefit of using biochar; carbon sequestration as well as reduced emissions intensity from concrete production (Patel et al., 2025).

Cement and gravel were identified as the dominant inputs in concrete mixtures. The choice of functional unit is critical in sustainability assessments (Gutiérrez et al., 2017); in this study, the impacts were evaluated per unit mass of concrete. Table 1 summarizes the principal environmental effects of conventional and biochar–concrete mixtures, which show minor differences in density per m^3. The table compares selected midpoint life cycle impact categories for conventional concrete and concrete incorporating 5 wt% MSW-derived biochar, expressed per functional unit and reported together with the relative uncertainty (±). In general, the findings suggest that adding biochar moderately reduces a broad set of climate- and resource-relevant impact categories but increases slightly others associated with further processing and energy application. The global warming potential improves from 0.17 kg CO_2 eq of the regular concrete to 0.15 kg CO_2 eq in biochar-amended concretes. This decrease is due to the partial replacement of cement, meaning less Greenhouse gases (GHGs) are produced by clinker calcination and fossil fuels burning. A comparable downward trend is observed for ozone depletion, which decreases from 1.93 × 10^{-8} to 1.44 × 10^{-8} kg CFC-11 eq., and terrestrial acidification, the drop of which remains marginal from 2.18 × 10^{-4} to 2.07 × 10^{-4} kg SO_2 eq. Land use also exhibits a slight decrease from 0.0084 to 0.00808 m^2·a crop eq. This reflects the lower demand for virgin raw materials associated with cement production. Freshwater eutrophication remains unchanged between the two mixes, indicating that nutrient-related emissions are not significantly affected by the substitution at the applied replacement level.

Table 1
Life cycle environmental impacts of biochar-added and conventional concrete mixes (functional unit: 1 m3), cradle-to-gate.

Impact category	Unit	Types of concrete	
		Biochar added to concrete (5 wt% BC)	Conventional concrete
Ozone depletion	kg CFC-11 eq	1.44E-08 ± 0.12	1.93E-08 ± 0.17
Global warming	kg CO_2 eq	0.15 ± 0.11	0.17 ± 0.13
Terrestrial acidification	kg SO2 eq	0.000207 ± 0.16	0.000218 ± 0.14
Fresh water, Eutrophication	kg N eq	2.62E-05 ± 0.24	2.62E-05 ± 0.23
Human carcinogenic toxicity	kg 1,4-DCB	0.001612 ± 0.10	0.001561 ± 0.12
Human non-carcinogenic toxicity	kg 1,4-DCB	0.04365 ± 0.14	0.040577 ± 0.18
Water consumption	m3	0.000565 ± 0.12	0.000544 ± 0.15
Particulate matter formation	kg PM2.5 eq	3.09E-05 ± 0.16	3.02E-05 ± 0.10
Land use	m2a crop eq	0.00808 ± 0.11	0.0084 ± 0.13

In contrast, several impact categories increase slightly in the biochar-added concrete. Human carcinogenic and non-carcinogenic toxicity show modest increases, as do particulate matter formation and water consumption. These increases are mainly attributed to additional processing steps in biochar production, including feedstock preparation and energy use during pyrolysis, which introduce extra emissions of combustion-related pollutants and increase auxiliary resource demand.

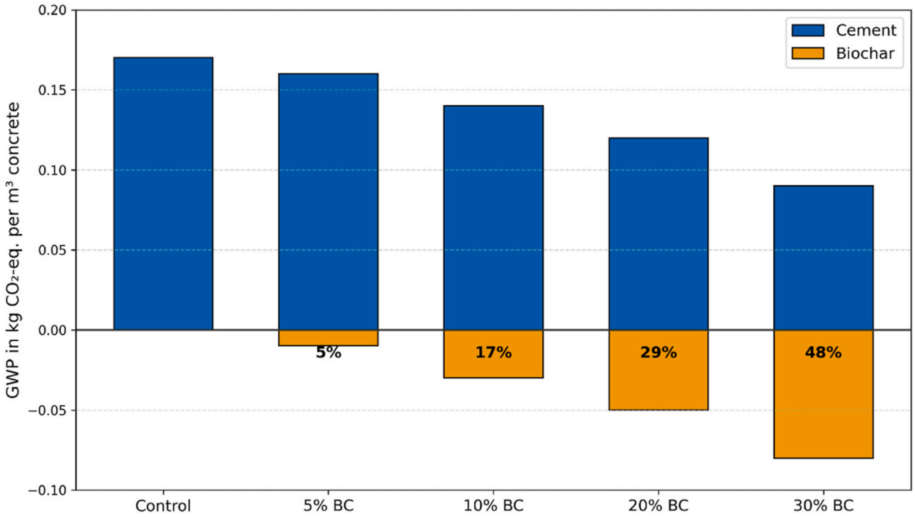

Fig. 2. impact of biochar on global warming potential of cement and MSW-derived biochar to the of concrete production expressed per functional unit of 1 m^3 of concrete, across different biochar replacement levels. Positive values represent CO_2-equivalent emissions from cement, while negative values indicate avoided emissions associated with biochar substitution. Percentage labels show the relative reduction in GWP compared with the control mix. Increasing biochar content progressively reduces net climate impacts, with the highest mitigation observed at higher replacement levels.

For most categories, the reported uncertainty ranges overlap such that the differences between the two systems are likely mild rather than large at 5 wt % replacement level. This indicates that substitution of biochar changes most the environmental profile of concrete, yielding - positive outcome in climate categories and building trade-offs in toxicity- and process-related impacts. Biochar has been implemented as an additive instead of a direct material substitution and based on experimental data, the addition of biochar can enhance the resulting properties of concrete and may have potential to lower the amount of material consumption for specific applications (Gutiérrez et al., 2017). However, it is worth noting that the LCI data for biochar are generally obtained from laboratory demonstrations, where production tends to be energy-intensive (Balea et al., 2019).

Contribution analysis reveals that cement contributes approximately 98 wt% to the overall global warming potential, which is mainly attributed to CO2 emissions from limestone calcination and combustion of fossil fuels. The specific environmental effects per category are reported in Table 1. Chen et al. (2022) reported similar findings, showing that high level of biochar substitution can reduce GWP in concrete, but at the expense of a noticeable decline in compressive strength. This indicates a fundamental trade-off: the introduction of waste-derived additives in cementitious systems to reduce cost and environmental impact may lead to its impairment in mechanical properties (Zhou et al., 2024). The comparison among LCA studies remains difficult owing to diversity of processes, material compositions, and applications. Interestingly, studies focused on the LCA of the MSW-based biochar, especially to be applied in construction field are still limited.

Moreover, using MSW-derived biochar as a partial replacement of cement (by weight) significantly affects both the mechanical performance and long-term durability of concrete, as shown in Supplementary Material A (Figure S4). At a 5 wt % cement, a slight increase in compressive strength was found and this may be associated with fine-powdered and porous biochar that can improve particle packing and matrix densification. On the other hand, when the replacement rate of cement increases to 30 wt % led to a significant decrease in the compressive strength of around 25 MPa as a result of dilution of the cementitious phase with water and diminished continuity of binder. Despite this weakening effect on high replacement ratios, the introduction of biochar significantly reduces global warming potential by mitigating cement-related emissions and the carbon storage benefit.

In general, this study suggests that 5 wt% biochar replacement achieved an optimal balance between mechanical strength and environmental sustainability, thereby enhancing structural integrity while minimizing the carbon footprint. Moreover, the results confirm that low-level biochar substitution can contribute to climate change mitigation and resource efficiency, while highlighting the importance of improving the energy intensity and emission performance of biochar production to avoid burden shifting to other environmental impact categories.

3.3. Life cycle costing

The cost analysis presented in Table 2 indicates that raw materials, especially cement and gravel, remain the dominant contributors to concrete production costs, in line with sector-wide exposure to energy price and CO_2 costs associated with limestone calcination. The economic feasibility of biochar enhanced concrete therefore depends strongly on the cost of biochar production, including type of feedstock availability, pyrolysis technology, energy demand, and production scale. While partial cement substitution can offset some material costs, higher replacement levels must be balanced against potential performance losses.

Table 2
Market prices per kg for each type of material and the price of each mixture for 1 m^3.

Material	Cost (USD/kg)	Reference	Concrete Mixtures	
			Conventional (USD/m^3)	Biochar-added concrete (USD/m^3)
Cement	0.06	(Yu et al., 2021); (CEMBUREAU, 2023)	25.98	24.68
Sand	0.0046	(Yu et al., 2021)	2.69	2.69
Gravel	0.0176	(Yu et al., 2021)	20.89	20.87
Water	0.007	(Yu et al., 2021)	1.37	1.37
Biochar	0.0234	(Maroušek et al., 2023)	0	5.77
Total cost			50.93	55.38

In the current study, the concrete mix containing 5 wt% biochar had a production cost of USD 55.38/m^3, compared with USD 50.93/m^3 for the control mix, corresponding to an increase of USD 4.45/m^3. This cost increase is mainly attributed to the energy demand for pyrolysis processes. When evaluated on a strength-normalized basis, the cost per unit strength was USD 1.176 per MPa for the control mix and USD 1.217 per MPa for the 5 wt% biochar mix, representing an increase of 3.5 wt%. This occurred despite a compressive strength improvement of 5.2 wt%, with average strengths of 45.5 MPa for the biochar mix and 43.3 MPa for the control mix, as shown in supplementary material A Fig. S5.

In general, these findings demonstrate that the efficiency and scalability of pyrolysis technology to large-scale is crucial in order to improve cost-effectiveness which would result in decrease energy demand and thus cost for production. While the mix design is secondary to biochar production economics, it is important for maximizing material inputs while preserving or enhancing mechanical performance and environmental benefits.

3.4. Social LCA result

The analysis quantified the human health damage associated with conventional and biochar–concrete production. Conventional concrete resulted in approximately USD 6487 in health-related damage per m^3, whereas biochar-mixed concrete resulted in USD 3538 per m^3, corresponding to a 45.5 wt% reduction in health impacts, as shown in Fig. 3. Fig. 3 further provides a detailed breakdown of monetized human health impacts for conventional and biochar-mix concrete using the willingness-to-pay (WTP) approach. Panel A presents the absolute WTP values for different health damage categories, while Panel B illustrates the relative percentage change associated with biochar substitution.

In absolute terms, respiratory health damage is the dominant contributor to total social cost in both systems. However, the biochar-mix concrete exhibits a pronounced reduction in respiratory damage compared with the conventional mix. This reduction drives most of the overall decrease in health-related impacts observed in the S-LCA results. Global warming–related diseases also show a smaller but consistent reduction, reflecting the lower greenhouse gas emissions associated with partial clinker replacement. By contrast, circulatory damage shows a slight increase for the biochar-mix concrete. This increase is linked to emissions associated with biochar production and handling, particularly energy use during pyrolysis and material processing. Although this effect is visible, its magnitude is small relative to the reductions achieved in respiratory impacts.

Panel B highlights these trends in relative terms. The biochar-mix concrete achieves a substantial reduction in respiratory health damage of approximately 65 wt%, while global warming–related health effects decrease by about 3 wt%. The extra circularity effects remain less than 20 percent and are not greater than the net social benefits. In summary, these findings reveal that the social sustainability edge of biochar-based concrete lies primarily in a decline in air-pollution-related health effects comprised mainly of respiratory impacts. This finding accounts for the more prominent role of S-LCA in the LCC analysis and confirms the relevance of health-based indicators in low-carbon construction

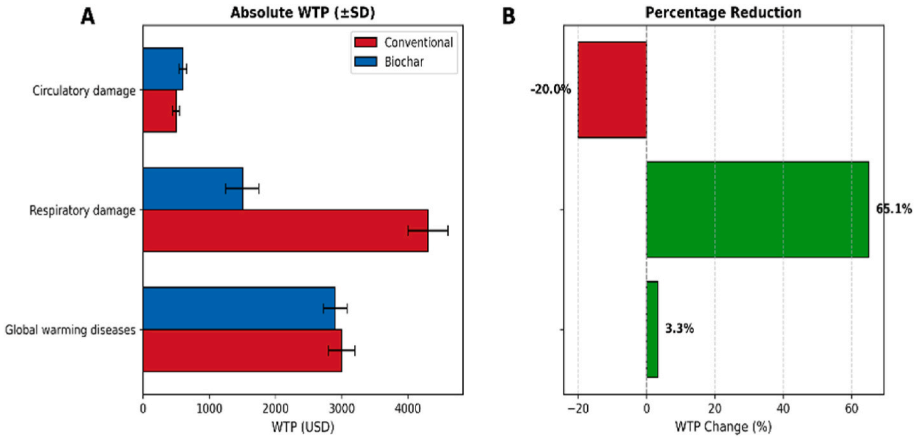

Fig. 3. Health and economic benefits of biochar-based concrete compared with conventional concrete expressed per functional unit of 1 m^3 of concrete. (A) Absolute willingness-to-pay (WTP) for avoiding circulatory damage, respiratory damage, and global warming–related diseases, showing reduced WTP for biochar. (B) Percentage reduction in WTP, indicating major decreases for respiratory damage (−20.0 wt%) and global warming diseases (−65.1 wt%), with a minor reduction in circulatory damage (−3.3 wt%).

material assessment.

Adding 5 wt% MSW-derived biochar improved the compressive strength of concrete from 43.3 MPa to 45.5 MPa and reduced health-related damage willingness-to-pay by 45.5 wt%, from USD 6487 to USD 3538. This indicates potential benefits for both technical performance and societal sustainability of low-carbon concrete systems as shown in Supplementary Material A, Fig. S6. The associated improvements in structural behavior as well as social impact simultaneously indicate a possibility for biochar to have a beneficial effect on technical performance and societal sustainability of low-carbon concrete systems.

Global warming impacts were significant, contributing 97.0 wt% to damage in conventional concrete and 92.7 wt% in the biochar scenario, largely due to CO_2 emissions from cement manufacturing processes, as shown in Fig. 3. These findings emphasize the need for circular economy strategies to decrease clinker demand and mitigate climate change and health impacts.

Diseases linked to air pollution were among the leading contributors to health damage, as detailed in Supplementary Material A, Fig. S7. Emissions of nitrogen oxides, particularly NO_2 and N_2O, were especially harmful, contributing 50.3.% and 40.6.% of the total health damage in conventional and biochar concretes, respectively. These pollutants are harmful to the respiratory and cardiovascular systems and can cause long-term harm to heart and lung function, chronic obstructive pulmonary disease, acute respiratory infections, among other conditions. Practices and policies aimed at mitigating the greenhouse gases from climate can increase or decrease climate impacts, but may also modify emissions of local air pollutants, pointing to possible interactions between climate goals and public health. In summary, the results have shown that concrete production significantly to NOx, CO2, and particulates. The identified synergies and trade-offs call for holistic mitigation strategies to mitigate both global climate impacts and local health, in support of a more politically acceptable way forward for sustainable concrete production.

3.5. Life cycle sustainability assessment (LCSA)

LCSA is a well-defined methodology to assess the environmental, economic, and social aspects of product systems. However, these methods have limited utility for stakeholders due to their separation and lack of compatibility. To overcome this problem, monetization provides a common denominator and quantifies complicated environmental and social impacts in economic terms, facilitating comparability as well as decision-making. LCSA were put into practice by integrating LCA, LCC and S-LCA results with monetary aspects of the environmental and social indicators lending to a single sustainability index.

LCA monetization: LCA was used to determine the environmental impacts between classification, characterization, and weighting. Although the pollutants and their impact categories are determined by this approach, the relative severity of different impacts is challenging to compare. To address this, sustainability indicators were monetarized by transforming environmental burden into WTP values. Conversion was calculated as:

$$\mathrm{WTP(j)} = \mathrm{WF(j)} \times \mathrm{EP(j)}$$

where WF(j) is the impact category weighting factor j, and EP(j) is emission i's contribution to category y j. Corresponding environmental impact factors were obtained from (Gao et al., 2025) and are presented in Supplementary Material. This monetization approach provides a direct economic interpretation of LCA results, summarizing weighting factors for environmental categories in supplementary material B Table S 7.

The monetized results presented in Supplementary Material B, Table S5, show that global warming is the dominant contributor to the environmental cost of concrete production. Conventional concrete generated 0.17 kg CO_2 per m^3, corresponding to an environmental cost of USD 2.85, whereas biochar–concrete produced 0.155 kg CO_2 per m^3, equivalent to USD 2.60, confirming its mitigation potential. Smaller but consistent reductions were also observed for acidification, decreasing from USD 4.74×10^{-3} to USD 4.50×10^{-3}, and for ozone layer depletion, decreasing from USD 1.89×10^{-6} to USD 5.44×10^{-4}. In contrast, eutrophication and water resource depletion exhibited negligible or mixed differences between the two mixtures. Overall, these results indicate that the environmental benefits of biochar–concrete are most pronounced in climate-related impact categories, while improvements in other environmental indicators remain limited.

The willingness-to-pay approach was applied to monetize the environmental and social impacts of concrete production per m^3, using the environmental impact monetization factors presented in supplementary material B Table S 8. This monetization–weighting approach, consistent with Environmental Priority Strategies, reflects society's willingness to pay to avoid environmental degradation by assigning monetary values to emissions, resource use, and associated damages (Li et al., 2018). Although there are notable benchmarks (social cost of carbon), considerable uncertainty remains as to whether such indicators adequately reflect the multiple attributes faced in developing countries where demographic, cultural, and economic influences lead one to infer that valuation tasks will be more strongly affected. This points to a long-standing trade-off: monetization increases comparability and policy relevance but also entails uncertainty in the results. In the aggregate, monetization enhances LCA by facilitating the combination of environmental, economic, and social dimensions into one common unit for expression. In the present research, life cycle sustainability assessment was developed by integrating environmental LCA, social LCA and life cycle costing to obtain a holistic sustainability indicator.

As shown in Supplementary Material B, Table S6, conventional concrete production resulted in environmental costs of USD 29.6, economic costs of USD 53.5, and social costs of USD 6487.1 per m^3, yielding a total life cycle sustainability cost of USD 6836.8. In comparison, biochar–concrete exhibited slightly lower environmental damage at USD 26.1 and higher economic costs at USD 58.2. Most importantly, its social impact was substantially lower at USD 3538.7, resulting in a total sustainability cost of USD 3858.4 per m^3. This corresponds to an overall reduction of approximately 44 wt% in total sustainability costs, driven primarily by a near-halving of health-related damages captured by the social life cycle assessment.

These results highlight social impacts as the dominant contributor to the life cycle sustainability profile of concrete production, with the majority of the difference between conventional and biochar-based systems attributable to health-related indicators. The use of monetized impact assessment makes the potential for reducing environmental and societal damage more explicit and illustrates how biochar substitution can provide meaningful pathways towards more sustainable construction practices.

In the comparison between conventional and biochar-concrete, the social life cycle assessment explained 99.9 wt% of the variation observed at the aggregated LCSA level, as shown in Fig. 3. This underlines the critical role of social factors in determining the overall sustainability performance of concrete production systems. Furthermore, as indicated in Fig. 4, compares the indexed life-cycle sustainability performance of conventional concrete and biochar-mix concrete, with the conventional case normalized to 100 for each indicator. This normalization allows a direct comparison across environmental, economic, social, and aggregated sustainability dimensions.

For the environmental indicator based on global warming potential, the biochar mix shows a modest reduction relative to the conventional reference, reflecting the lower clinker demand and associated CO_2 emissions. In contrast, the life-cycle cost indicator increases for the biochar mix, which is mainly driven by the additional energy demand and processing costs associated with biochar production. This confirms that the economic dimension remains a short-term trade-off under current biochar supply conditions.

The most pronounced difference is observed for the social life-cycle assessment. The biochar mix exhibits a substantial reduction in indexed social impact, primarily due to lower health-related damage expressed through the willingness-to-pay metric. This reduction dominates the overall sustainability outcome and explains the strong improvement in the composite LCSA score.

As a result, the aggregated LCSA composite index is lower for the biochar-mix concrete despite its higher cost, indicating a net sustainability benefit when social and environmental dimensions are considered alongside economics. The spread shown in the distributions reflects uncertainty propagation, while the consistent separation between the two cases indicates a robust improvement in overall sustainability performance for the biochar-based system. This finding reinforces the importance of health-related impacts within the S-LCA framework and demonstrates their decisive influence on life cycle sustainability outcomes.

Moreover, the social influences are stronger than both environmental and economic on sustainability profile of concrete. Reduced cement, gravel, and electricity consumption can cut emissions and health damage, but the sector's lest it challenges efforts to be net zero. Significant advances will therefore depend on technological routes, e.g., low-cost, low carbon and zero emission materials development and superior waste utilization in combination with workforce strategies like skill training and enhanced construction management. In tandem, these strategies have the potential to reduce health burdens, create greater industry resilience, and propel the transition to sustainable concrete manufacturing.

3.6. Ranking of the best concrete mixtures using multicriteria decision-making and ranking

Sustainability assessment of the developed concrete mixtures was performed using the Technique for Order of Preference by Similarity to Ideal Solution, with weighting factors derived from the Analytic Hierarchy Process. Among the three main sustainability dimensions, the social dimension was assigned the highest relative importance with a weight of 0.76, followed by the economic dimension at 0.14 and the environmental dimension at 0.10 as shown in Supplementary Material

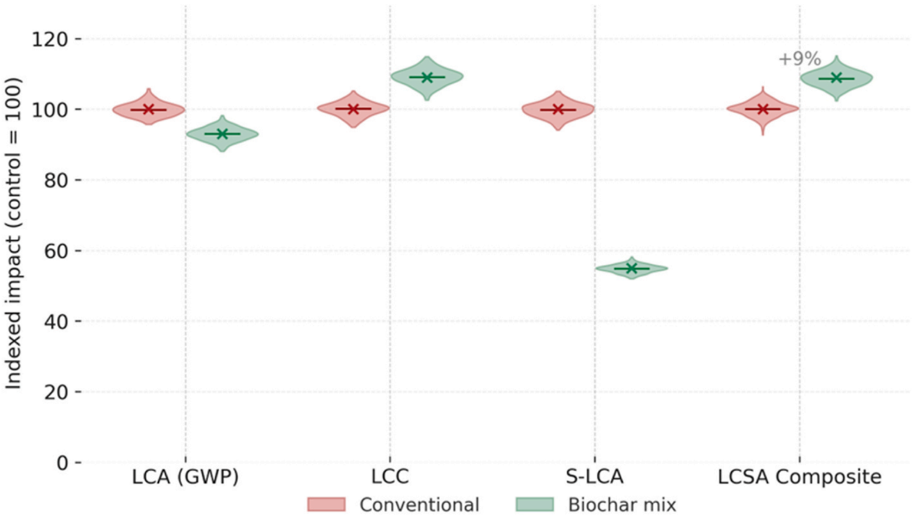

Fig. 4. Violin plots showing the indexed sustainability impacts of conventional concrete and biochar-mix concrete across life cycle assessment (LCA, global warming potential), life cycle costing (LCC), social life cycle assessment (S-LCA), and the aggregated life cycle sustainability assessment (LCSA) composite score expressed per functional unit of 1 m^3 of concrete. All impacts are normalized to the conventional concrete baseline (control = 100). The distributions represent uncertainty derived from Monte Carlo simulations, with markers indicating mean values. The biochar-mix concrete exhibits reduced environmental and social impacts and an overall improvement in the composite LCSA score, despite slightly higher economic costs.

B, Table S7. This weighting reflects the dominant role of social impacts in the overall sustainability evaluation. Global weights for the sub-criteria were obtained by multiplying the weight of each main criterion by its corresponding local weight, following consistency checks to ensure acceptable judgment coherence.

The ranking results indicate that biochar–concrete mixtures align most closely with the ideal sustainability solution, whereas conventional concrete performs least favourable, as shown in Supplementary Material A, Fig. S8. Specifically, biochar–concrete achieved a TOPSIS closeness coefficient of 0.780, compared with 0.220 for conventional concrete. This pronounced difference is primarily driven by the substantial reduction in health-related damage associated with biochar substitution, which strongly influences the social weighting within the model. These findings demonstrate that when sustainability assessments simultaneously account for social, environmental, and economic dimensions, biochar–concrete consistently emerges as the preferred alternative. To ensure transparency and reproducibility, the complete AHP pairwise comparison matrices, consistency ratios, and all intermediate TOPSIS calculation steps are provided in the Supplementary Material B (S7, S12-S16).

3.7. Comparison between conventional and biochar mix concrete production

The assessment of biochar as a partial cement replacement is largely driven by social and environmental considerations, including climate change mitigation, human health impacts, and resource efficiency associated with the production of both cement and biochar, as shown in Fig. 5. Moreover, Fig. 5shows that biochar-mix concrete performs better than conventional concrete in the environmental and social dimensions, with normalized scores of approximately 0.72 vs. 0.60 for environmental performance and 0.88 vs. 0.85 for social performance. These improvements are mainly driven by reduced climate impacts and lower monetized health damage. Conventional concrete remains economically favourable, with a higher economic score (0.70) than biochar-mix concrete (0.60), reflecting the additional cost of biochar. Overall, the numerical comparison indicates that the environmental and social gains of biochar substitution outweigh the moderate economic penalty in the integrated sustainability assessment.

Among the three sustainability criteria, social performance was assigned the highest weight at 76 wt%, followed by economic factors at 14 wt% and environmental indicators at 10 wt%. Similar findings have been reported by Mekky et al. (2024), who highlighted the importance of social and environmental criteria in the selection of sustainable construction options such as pavements and permeable bricks.

These trade-offs are also illustrated in the radar diagram shown in Fig. 6. Conventional concrete performs slightly better in the economic dimension due to its historical cost advantage, whereas biochar–concrete shows clear improvements in both environmental and social performance. These gains are largely attributed to the low carbon footprint, diminished health impact, and resource efficiency. Furthermore, the findings raise attention to an inherent conflict between mechanical performance and sustainability while biochar is applied as a partial substitute for cement. At lower replacement rates, the level of biochar could retain or slightly increase compressive strength because biochar has filler effects and good particle packing, rendering it suitable for some concrete structures. On the other hand, more than 20% of substitution is enough for causing a considerable loss in strength what could restrict its applications where structural elements are needed but not in non-structural ones (pavements, blocks or precast elements) to whom less demanding strength conditions are imposed. From a sustainability point of view, the highest biochar contents have more environmental and social benefits, mainly related to health impact and waste valorization. This indicates that the optimal biochar doses should be considered in accordance with the practical purposes, considering performance demands and sustainability goals. Future research needs to be directed towards the various durability aspects (durability mechanical performance in long term, freeze–thaw resistance, moisture transport) and coping with functionalized biochar results or mixes designs related to extend the application range toward a broader substitution ratio under similar immobility. Sensitivity analysis also confirmed biochar–concrete as the best alternative, which means that on a more comprehensive sustainability scorecard biochar replacement is to be prioritized for further sustainable concrete production.

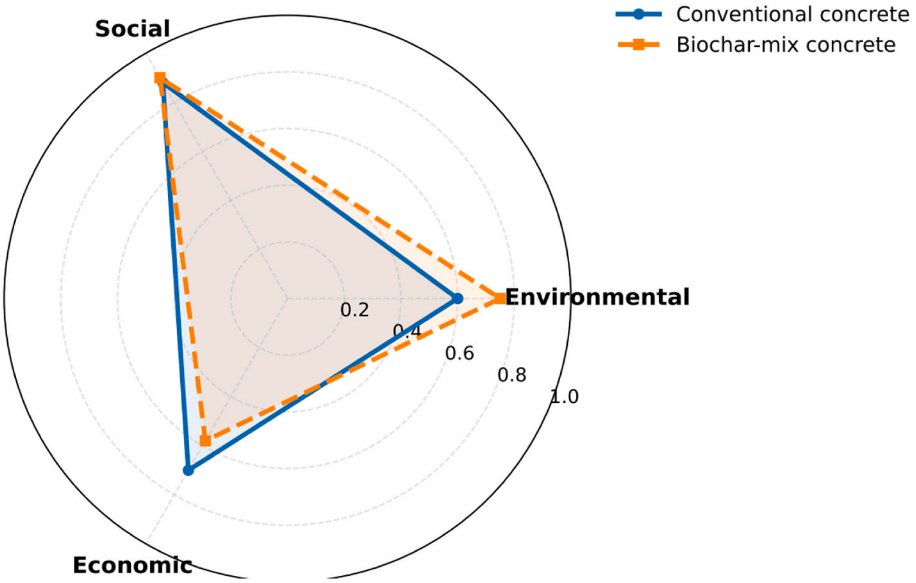

Fig. 5. Normalized radar plot comparing the sustainability performance of conventional concrete (solid blue line) and biochar-mix concrete (dashed orange line) across environmental, economic, and social dimensions expressed per functional unit of 1 m^3 of concrete. Scores are normalized between 0 and 1, where higher values indicate better performance. The biochar-mix concrete shows improved environmental and social performance, while conventional concrete retains a slight advantage in the economic dimension. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

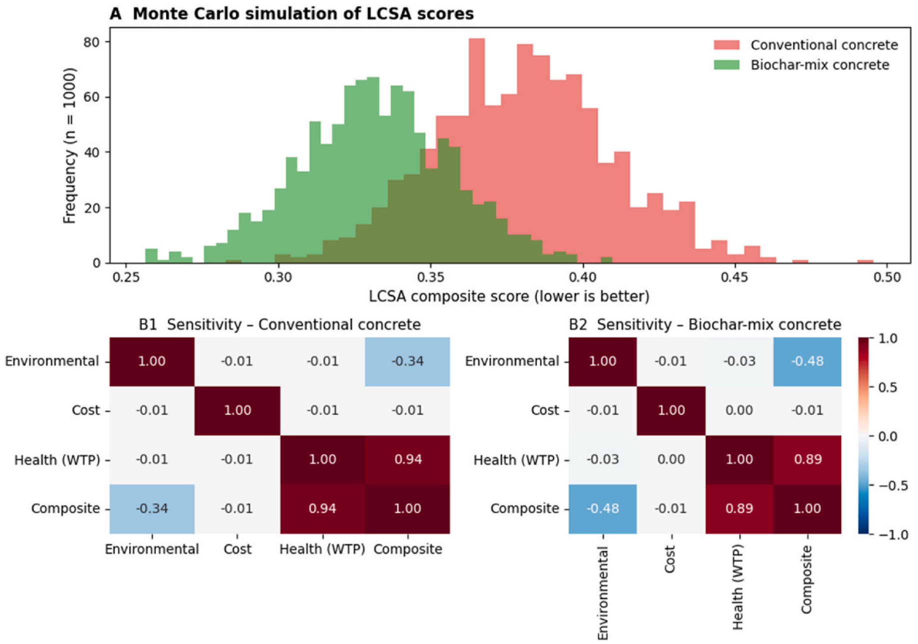

Fig. 6. Side-by-side comparison of the life cycle sustainability performance of conventional concrete and biochar-based concrete expressed per functional unit of 1 m^3 of concrete. (A) Monte Carlo simulation of LCSA composite scores shows that biochar-based concrete consistently attains lower scores than conventional concrete, indicating superior sustainability performance under uncertainty. (B) Sensitivity analysis of the LCSA components reveals that overall sustainability scores are strongly driven by willingness-to-pay (WTP) for health impacts in both systems (correlation coefficients of 0.94 for conventional concrete and 0.89 for biochar-based concrete). Environmental indicators exhibit a stronger negative influence in the biochar mix (−0.48) than in conventional concrete (−0.34), while economic factors play a minor role.

3.8. Uncertainty and sensitivity analysis

LCSA was also applied to compare conventional concrete and biochar–concrete by integrating social, economic, and environmental dimensions into a single composite score. To account for uncertainty, Monte Carlo simulations were performed to generate probabilistic score distributions, and a sensitivity analysis was conducted to identify the most influential parameters affecting sustainability performance, as shown in Fig. 6.

The Monte Carlo simulation results presented in Fig. 6a show a clear shift of the cumulative distribution towards lower composite sustainability costs for biochar–concrete compared with conventional concrete, accompanied by a broader but stable distribution. This indicates that biochar–concrete consistently achieves better sustainability performance and remains robust under uncertainty. The relatively smaller variance of the biochar–concrete distribution further confirms the consistency of its performance across different assumptions, supporting its potential as a sustainable substitute for conventional cementitious materials.

The sensitivity analysis shown in Fig. 6b demonstrates that health-related impacts, expressed through willingness-to-pay, are the dominant drivers of the sustainability profile, exhibiting strong correlations for both conventional concrete (0.94) and biochar–concrete (0.89). In addition, the biochar mixture shows a stronger sensitivity to environmental indicators, with a correlation coefficient of −0.48 compared with −0.34 for conventional concrete, indicating a greater influence of environmental performance on its overall sustainability score. In contrast, cost-related parameters have a relatively minor effect, suggesting that sustainability outcomes in this assessment are driven primarily by social and environmental considerations rather than by economic variability.

Overall, those results demonstrate that biochar–concrete not only mitigates emissions and health damages but also provides strong and stable sustainability performance under uncertainties. The results emphasize the value of combining probabilistic and sensitivity analysis to sustainability assessments so that decision making captures both performance, consistency, and relative influences from social and environmental drivers. Moreover, to the global Monte Carlo analysis, a targeted robustness check was performed to evaluate the sensitivity of the decision-support results to key assumptions. Selected biochar life-cycle inventory parameters (energy demand and production cost) were varied within ±10 wt%, and the AHP weights of the three sustainability dimensions were perturbed by ±5 wt% while maintaining their relative order. The resulting TOPSIS closeness coefficients and rankings were recalculated. In all tested cases, the ranking of biochar-mixed concrete as the preferred alternative remained unchanged, indicating that the decision outcome is stable and not driven by minor variations in inventory assumptions or weighting choices.

3.9. Future perspectives on the integration of biochar in construction materials

Cement and concrete are still one of the dominant industrial contributors to CO_2 emissions and resource use, making it a necessity for carbon-negative construction materials (Soomro et al., 2022, 2023). Despite technological advances, emissions from the sector are still rising as a result of increasing global demand for raw materials, and cement's energy intensity in particular. Here, biochar provides a tangible pathway to address emissions and circular resource use. Its use in concrete also has the tradeoff of partially mitigating carbon footprint while there is no need for virgin raw materials (Mokhtar and Nasooti, 2020). Apart from emissions, the industry is responsible for large-scale resource extraction that results in deforestation, soil erosion, and depletion of aggregates. Concrete, which also uses ~12 wt% cement by mass (Timmermans et al., 2004), requires the annual crushing of 10–11 billion tons worth of rock, gravel, and sand (de Brito and Saikia, 2013) ; an activity that ruins riverbeds; and landscape features. Water usage is equally important and about 1 trillion liters are needed each year to mix, cure, and clean. Construction activities also released 53 wt% more CO_2 in 2020 than they did in 1990, with cement alone responsible for 36 wt% of building sector emissions and roughly one-twelfth of all anthropogenic CO_2 (International Energy Agency, 2022; Min et al., 2022). These developments underscore the importance of advancing carbon-negative construction solutions in practice now.

Biochar is classed by the Intergovernmental Panel on Climate Change as a negative-emission technology owing to its potential to sequester carbon during biomass pyrolysis in low-oxygen environments. Biochar, unlike raw biomass, locks away carbon for 10–100 times longer and life-cycle assessment studies have reported net negative emissions between −2.0 and −3.3 kg CO_2 eq per kilogram of biochar produced from feedstocks (also depending on application). At global scale, biochar application could reduce between 3.4 and 6.4 Pg CO_2-eq per year with direct atmospheric removal making 49–59 wt% of that reduction (Zhang et al., 2022). The focus of this research is in biochar application to concrete production though. The MSW-biochar at an optimum of 5 wt% substitution rate, lowered the cradle-to-gate global warming potential by approximately 5 wt%. When considering global concrete production, such a decrease would equal approximately 0.12–0.15 Gt CO_2-eq year^{-1}. Although there is a lesser reduction than from global biochar mitigation estimates, the comparison is still important for the construction industry. Only agricultural and forestry residues give rise to a waste biomass generation of about 140 Gt per year with considerable untapped potential. Developing only a small fraction of this resource could sequester up to 500 million tons CO_2 each year, or 1.5 wt% of global greenhouse gas emissions and also mitigate environmental pollution from uncontrolled waste streams.

Furthermore, MSW can provide a more reliable and abundant feedstock for biochar than agricultural residues since it is generated daily in households and factories around the globe. The world produced 2.01 billion tonnes of MSW in 2017, making it an estimated to become 3.40 billion tonnes by the year 2050 while agricultural residues are approximately as high as about 4.3 billion but seasonal and difficult to collect (World Bank, 2017) (FAO; the United Nations, 2017). MSW can generate 0.2–0.5 kg of biochar per kg of waste, representing a potential for 0.68–1.7 Gt pa by 2050 (assuming pyrolysis). But this conservative yield would already provide over three times the 0.2 billion tonnes required for a 5 wt% global cement substitution. This validates the -practicality of integrating biochar from MSW at a large scale. Upcoming priorities are optimization of low-energy pyrolysis, product quality standardization, and integrating renewable heat with life cycle monitoring to ensure tangible carbon-negative, cost-effective concrete production.

In terms of conversion, 1 kg MSW can potentially produce 0.2–0.5 kg of biochar depending on feedstock and pyrolysis conditions (temperature, heating rate). At low conversion efficiencies (20 wt%), such estimated 2050 MSW generation could yield 0.68–1.7 Gt of biochar annually. Such a volume of biochar would account for 3.15 times the world-wide demand of 0.2 Gt per year of slag/biochar, i.e., its use as 5 wt % replacement for cement Supplementary Material A, Fig. 9. This capacity ensures biochar from MSW can possibly serve low-level substitution cement demands globally without competing with the resources of agricultural biomass and other types of biomasses.

Perpetual and optimally scattered accumulation of MSW provides abundant carbon that can be incorporated in bio-char soil amendments, diverting the waste from a destructive path to a beneficial one where carbon is sequestered and protected in long-lived construction products. Future studies should consider methodologies to enhance pyrolysis efficiency, energy demands, and the development of quality standards for biochar derived from MSW. The role of renewable energy integration into pyrolysis and the development of robust life cycle approach will be important to ensure economic viability as well as verifiable net-negative emissions in the production of sustainable concrete.

Combining biochar with concrete provides a double environmental benefit: carbon store and replacement of cement, i.e., clinker demand and impact are reduced. Furthermore, the upcycling of waste biomass into sustainable construction materials is in line with a circular economy approach for deep decarbonization. However, its scalability relies on the optimization of production technologies, quality control of biochar and policy mechanism in place for industrial up-scaling.

Although the use of biochar in construction materials is being explored, its integration still generally occurs at low substitution levels, limiting its potential to contribute significantly to carbon-neutral goals. Novel strategies such as pretreatment of the source biomass, post-pyrolysis activation, and co-activation with additional materials are under investigation to improve biochar as a raw material that can provide longer-lasting effects in cementitious composites. At the same time, machine learning (ML) remains an underexplored opportunity to accelerate adoption by predicting material performance, uncovering hidden property–performance relationships, and automating biochar integration throughout its life cycle. Industrial-scale ML models, supported by expanding datasets from the cement industry, could help enable deployment in challenging real-world scenarios. At small amounts (1–5 wt wt.%), biochar can make construction materials stronger, less prone to shrinkage, and more resistant to chemical attack. When produced using renewable energy, it can also cut carbon emissions and support circular economy goals. Its use is not limited to concrete it could work in geopolymers, asphalt, and lightweight composites too. Advances in biomass pretreatment, post-pyrolysis modification, and data-driven optimization may further support its use in cementitious systems.

Overall, the use of biochar in construction materials offers combined benefits in terms of carbon storage and reduced clinker demand. Although challenges related to energy use, cost, and material variability remain, targeted technological improvements and coordinated research efforts could enable biochar to become a practical option for reducing the environmental footprint of the construction sector (Barbhuiya et al., 2024; Irshidat et al., 2021; Wani et al., 2021; Campion et al., 2023; Gupta et al., 2018b,a; Lin et al., 2023).

4. Conclusion

This study demonstrates an integrated sustainability assessment of municipal solid waste (MSW)-derived biochar as a partial cement replacement is performed by combining mechanical, environmental, economic, and social performance. With only 5 wt% replacement biochar concrete had higher compressive strength (45.5 MPa vs. 43.3 MPa), lower global warming potential (−5 wt%) and similar life-cycle costs. It was particularly convincing when it determined the social life cycle results (−45 wt%, health-related impact) and contributed almost all of the advantages (99.9 wt%) in the sustainability assessment. According to the multi-criteria decision-making (AHP-TOPSIS) methodology, biochar concrete emerged as the most sustainable solution, primarily due to social impacts (weight = 0.76). Social impact showed the largest improvement: health-related damage, expressed in terms of societal willingness to pay to avoid these effects, decreased from an estimated USD 6487 for conventional concrete to USD 3538 for biochar-enhanced concrete. When the three sustainability pillars were integrated, the social life cycle assessment accounted 99.9 wt% of the total sustainability gap, emphasizing the dominant role of social factors.

The sensitivity analysis confirms this pattern. Health related impacts, measured through willingness to pay, are the primary drivers of the sustainability profile, showing very strong correlations for both conventional concrete (0.94) and biochar concrete (0.89). At the same time, the biochar mixture is more sensitive to environmental indicators, with a correlation of −0.48 compared with −0.34 for conventional concrete. This indicates that improvements in environmental performance have a stronger influence on the overall sustainability score of biochar concrete than on the reference mix. In contrast, cost related parameters play a relatively minor role, suggesting that sustainability outcomes in this assessment are shaped mainly by social and environmental considerations rather than economic variability.

In summary a 5 wt% MSW-biochar substitution reduced global warming potential by approximately 5%, lowered monetized health-related impacts by about 45.5%, and decreased the overall life cycle sustainability cost by roughly 44%, despite a moderate increase in production cost of around 9%. Furthermore, a moderate 5 wt% MSW-biochar replacement provides the most favourable strength-cost-sustainability compromise.

Energy demand in pyrolysis, feedstock availability variability, and long-term durability currently limit large scale deployment. However, coupling biochar production with renewable energy sources and further optimizing concrete mix design could change these challenges to opportunities, opening realistic path toward scalable, low-carbon and truly circular concrete for the construction industry.

CRediT authorship contribution statement

Teklit Gebregiorgis Ambaye: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tao Liu:** Writing – review & editing. **Charilaos Paraskevoulakos:** Writing – review & editing. **Ruichang Mao:** Writing – review & editing. **Zheng Lu:** Writing – review & editing. **Ashal Tyurkay:** Writing – review & editing. **Georgia Psyrri:** Writing – review & editing. **Ana T. Lima:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.147839.

Data availability

No data was used for the research described in the article.

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