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TECHNICAL PAPER

Sludge valorization towards sustainable concrete: a biochar-based framework integrating life cycle assessment, and socio-economic impacts

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Abstract

While recent studies have demonstrated that biochar supplementation to the cement mixture positively impacted the concrete mechanical properties, there is a research gap in exploring various environmental burdens, human health impacts, and resource consumption patterns accompanying biochar-concrete composite manufacturing. Hence, this study introduces a novel evaluation framework by integrating biochar-concrete properties, life cycle assessment (LCA) criteria, and economic considerations with sustainable development goals (SDGs) achievement. The control mix (C mix) was prepared using 100% cement, and the other mixtures were arranged using different sludge biochar (SB) replacement levels (5–20% w/w). A LCA model was employed to select the best sludge valorization approach, regarding two scenarios: (i) cement mixture (C mix) with sludge landfilling, and (ii) sludge biochar mixture (SB mix). The 5% SB mixture exhibited functional characteristics nearly comparable to those of the C mix, particularly in terms of compressive strength at 7 and 28 days, split tensile strength (3.5 MPa at 28 days), water penetration depth (≈2.8 mm), and durability. Applying this mixture in concrete maintained LCA endpoint categories of 0.005 DALY, 3.7×10^3 PDF m^2 yr, 7×10^3 kg CO_2 eq, and 70.6×10^3 MJ primary for human health, ecosystem quality, climate change, and resources, respectively. This mixture scenario could also fulfill 11 SDGs, including human health protection (SDG_3), resource recovery (SDG_12), climate change mitigation (SDG_13), and ecosystem preservation (SDG_14). Because the combined technical/LCA/SDG framework could maintain a sludge management approach for biochar-concrete industrialization, future work should focus on quantifying other scenarios related to energy, climate, urbanization, transport, and low-carbon cement development.

Graphical abstract

Graphical abstract shows a novel evaluation framework by integrating biochar-concrete properties, life cycle assessment (LCA) criteria, and economic considerations with sustainable development goals (SDGs) achievement. The control mix (C mix) was prepared using 100% cement, and the other mixtures were arranged using different sludge biochar (SB) replacement levels (5–20% w/w).

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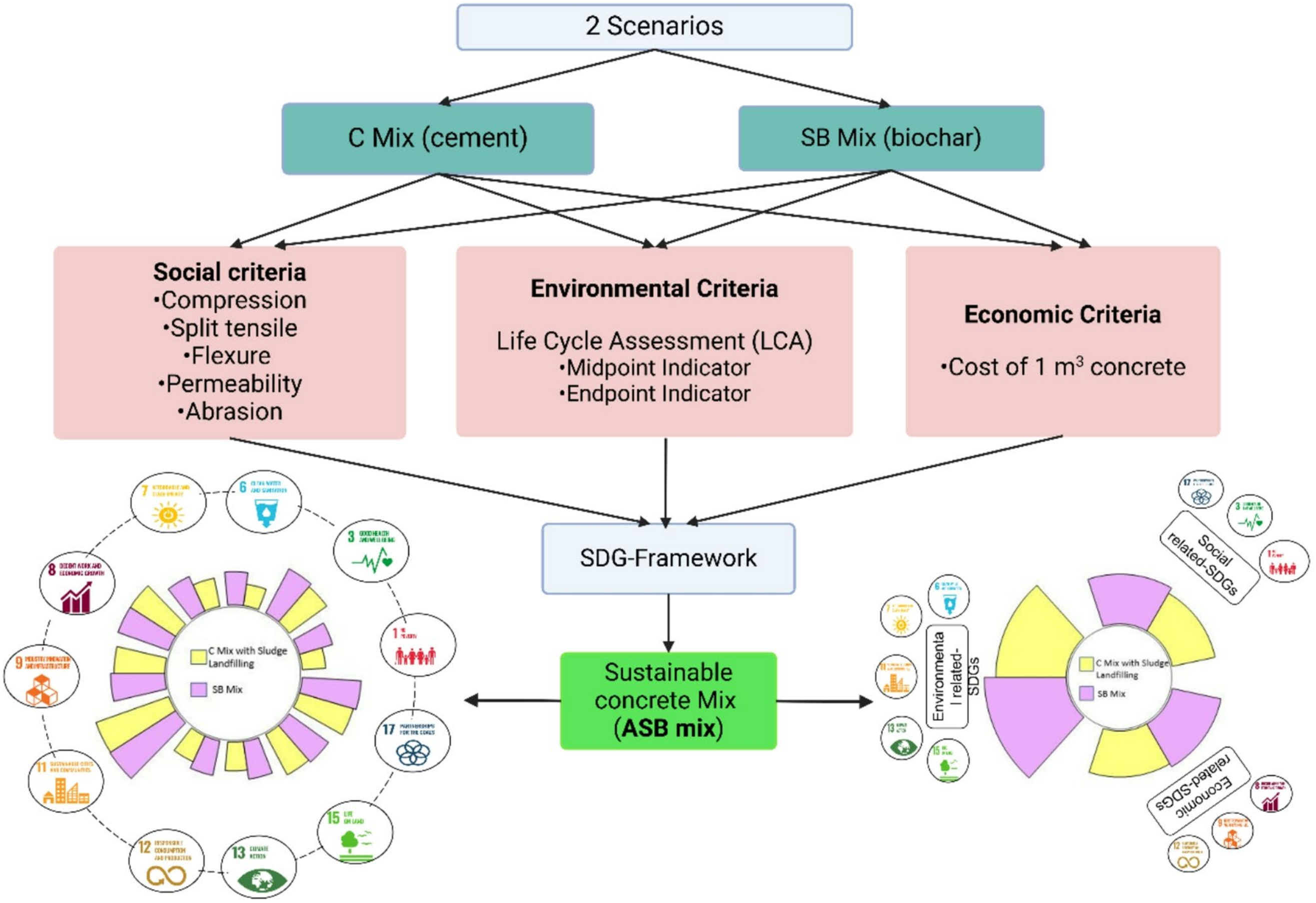

Keywords Biochar material · Midpoint LCA categories · SDG/targets · Sludge valorization · Sustainable concrete

Introduction

Biochar is a carbon-rich substance produced by the thermal treatment of biomass under a pyrolysis condition (e.g., oxygen-limited environment) [1]. Biochar captures and stores large amounts of carbon, further mitigating environmental pollution and CO_2 emissions that contribute to climate change [2]. Because the construction industry has a considerable carbon footprint, researchers have recently investigated biochar applicability as a concrete admixture [3]. This step is followed by determining the mechanical properties of the biochar-cement mixtures, considering both environmental and financial aspects [4]. Recently, a few studies have investigated the production of biochar from alum sludge and studied its effect on the structural properties of cement paste and concrete [5]. For instance, Gomes et al. [6] studied the effect of varying the percentages of sludge biochar (e.g., as a partial cement replacement in cement paste) on the material's mechanical performance. Their findings showed a slight improvement in compressive strength using 1–5% biochar in the as-prepared construction material, and the estimated biochar production cost (≈398 USD/ton) would overcome the socio-economic crisis caused by sending sewage sludge to landfills. Aziz et al. [7] also studied the effect of introducing sustainable materials into the construction sector by developing mortar from different biochar sources. Their study demonstrated that biochars obtained from date palm leaves (BioCl) and seeds (BioCs) could be used as cement additives to improve the material's mechanical properties due to the increased density and pozzolanic action of the mortar matrix. Wang et al. [8] illustrated that using biochar to partially substitute sand in concrete enhanced internal curing by extending the hydration process, resulting in a 56% increase in the time between hydration peaks and a 65% reduction in total shrinkage at 100% sand replacement. It also promotes the formation of calcium silicate hydrate (C-S-H) gel and $CaCO_3$ as essential hydration products, improving long-term behavior and durability for biochar-added concrete. Although the mentioned studies have decided that sludge biochar could be used as a partial cement substitute, there is a need to assess the environmental impacts (e.g., ecotoxicological potential of construction materials) arising from using biochar in concrete throughout the project's lifetime.

Various analytical approaches, including carbon footprint analysis and life cycle assessment (LCA), are available to assess the environmental impact, performance, and lifetime of the concrete industry and ensure the sustainable use of cement composites [9]. The LCA model is used to evaluate the environmental impacts (e.g., global warming potential, GWP) of cement concrete manufacturing during the product's life cycle, considering the four stages of goal and scope definition, inventory analysis, impact assessment, and interpretation [10]. Different computational-based tools, such as SimaPro, Open LCA, and GaBi software, can be used to assess the life cycle of concrete products based on the guidelines of ISO 14,040–14,044 [11]. Campos et al. [12] studied the environmental and health impacts of using biochar-concrete mixtures at different replacement percentages (0–20%), where increasing this substitutional ratio reduced the environmental risks related to CO_2 footprint, human health, and soil (terrestrial) ecology. Although this approach also depicted a positive effect on the concrete's physical strength, further studies should address the economic performance associated with using biochar as a partial cement replacement. While incorporating biochar into cementitious products at a 5% replacement percentage improved the final product's compressive strength and mitigated the concrete's detrimental effects on the environment [13], additional work should demonstrate public engagement with climate change as a social pillar of sustainability. Because the LCA tool is sufficient in making reliable decisions from an environmental perspective, it should be combined with other modeling techniques that focus on the well-being of people and communities. As such, the sustainable development goals (SDGs) of the 2030 agenda could explore how these environmental (e.g., water and air pollution) and socio-economic (capital expenditure and human health) characteristics interact in the biochar-cement industrialization sector.

Up-to-date research should correlate the "sustainable building" concept with clean water and sanitary facilities, personal safety, well-being, climate change, cheaper energy, and aquatic environment [14]. These items have shown great potential in achieving the main dimensions of SDGs announced by the United Nations [15], regarding waste management, sludge recycling, and low-carbon concrete manufacturing. These 17 SDGs and their associated 169 targets have been recently used to evaluate the sustainable building sector, especially in developing countries that lack the financial resources for providing cement minerals. For instance, Shehata et al. [16] demonstrated that geopolymer concrete could be used in the cement industry to fulfill the SDGs related to green material development, pollution reduction, and financial improvement. Wen et al. [17] defined the role and contribution of green buildings towards SDGs achievement, showing that the green building rating tools (GBRTs) exhibited considerable impacts on SDGs 3 "human health and well-being", 7 "cleaner energy", 11 "sustainable settlement and housing", and 12 "waste valorization". Furthermore, the SDG Target 7.3 "energy efficiency" was the key factor in endorsing the concept of "sustainability" in efficient, productive, and certified buildings. Although the relationship between construction materials and SDGs was given in the literature, comprehensive studies are still required to evaluate the implementation of water treatment sludge as a partial cement replacement in concrete that can pave the way for rapid deployment of renewable resources. This step is essential for policy development to implement and raise public awareness and to transform the SDGs framework from the global level to the construction projects level. While these studies have justified the technical viability of employing sludge biochar in cementitious material fabrication, more research is required to explore the correlation between specific performance indicators (e.g., mechanical strength) and the environmental footprint. The existing LCA-based studies recommend that biochar could reduce the environmental impact of concrete, but they rarely monitored the socio-economic dimensions of sustainability, such as cost-effectiveness, and public satisfaction, connected to the application of sludge derivatives in building materials.

To support good practice in implementing strategies for sustainable building development, this study attempts to create an innovative framework that synergistically incorporates multiple socio-environmental, financial, and functional criteria that can optimize concrete mixtures in civil infrastructure. The study objectives are fourfold (1) use sludge biochar (SB) as partial cement replacement at different percentages to study the compressive strength of concrete mixtures, (2) study mechanical properties and durability of concrete for the SB percentage that maintained the best compressive strength, (3) employ LCA analysis to evaluate the environmental impacts of these as-prepared concrete mixtures, and (4) develop an adequate framework to determine the achieved SDGs by partially replacing concrete components with alum sludge. This approach can be utilized by decision makers worldwide because the integrated LCA/SDG framework is flexible to incorporate additional indicators based on the available resources in the country.

Materials and methods

Raw materials

The cement used in the study was ordinary Portland cement (CEM-I; Grade 42.5 N). The fine and coarse aggregates were obtained from Egyptian local companies. Natural siliceous sand was used as fine aggregates, whereas natural dolomite of a 20 mm maximum nominal size was used as coarse aggregates. All these materials were used to produce normal concrete. The collected raw sludge (RS) was sieved, dried, and then underwent pyrolysis at 700 °C @ 17 °C/min for 2 h to produce sludge biochar (SB), following a recent study [6]. Tap water was utilized for mixing and curing the concrete specimens. ViscoCrete-3425 was used as a superplasticizer, meeting "ASTM C 494" as a standard specification for chemical admixtures used in concrete construction [18].

Mix proportions and preparation of specimens

Table 1 provides concrete mix proportions, where a total of five different concrete mixtures were prepared according to ACI 211.1–91 [19]; [20]. The target compressive strength was 30 MPa at the age of 28 days. The control mix (C mix) was prepared using 100% cement, and the other mixtures were arranged using different SB replacement levels (5, 10, 15, and 20% w/w) to identify the percentage that provided the highest compressive strength [6]. Cubes 100 × 100 × 100 × 100 mm were cast to determine compressive strength, and three samples were tested at 7-day and 28-day ages for each mixture. The split tensile test was performed on a 150 × 300 mm cylinder. The flexural strength test was conducted on 100 × 100 × 500 mm beams. For sample durability, the permeability test was conducted on (150 × 150 × 150) mm cubes, and the abrasion resistance was measured according to Egyptian Standard Specifications (ESS) 2005/1-269. Other tests were conducted according to ESS1658/2006 [21]. All tests were conducted on the samples of ages 28 and 90 days (see Supplementary Tables S1–S5).

Life cycle assessment (LCA) of concrete mixtures production

A LCA model was conducted for two scenarios to determine the environmental impacts of the concrete mixtures prepared from SB compared with those of the control specimen (C mix). These scenarios were (1) C mix and sludge landfilling, and (2) sludge valorization for SB mix production. The SimaPro 7.1 software and Ecoinvent database [22] were used to model the four stages: (i) goal and scope, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation of results, in the LCA methodology. The goal and scope of this project are to evaluate the environmental impacts of the previously mentioned two scenarios. Figure 1 illustrates the system boundaries of the two scenarios. A cradle-to-gate system framework was used to introduce the assessment of the environmental impact of the concrete mixtures, complying with the system boundary reported earlier [23]. This method started with the extraction of natural resources and finished with the manufacturing of concrete, ignoring the product's use and end-of-life. The functional unit (FU) was the unit volume of ready-mixed concrete (1 m^3) and compressive strength as reported earlier [24]. According to the inventory stage, the data were calculated per FU (see Supplementary Table S6). The records were retrieved from the Ecoinvent database. LCA was conducted via the IMPACT 2002 + V2.05 method [25], containing 15 impact categories to evaluate the environmental loads. Diesel usage, heating process, and transportation data were collected from the Agri-footprint and Ecoinvent-3 databases within the SimaPro software. Transportation distances for site locations were determined from Google Maps. The midpoint and endpoint LCA indicators used for the assessment stage are also defined (see Supplementary Tables S7 and S8).

Cost analysis

The price of the concrete mixture is one of the crucial factors that should be considered during concrete production. A material cost analysis was performed to evaluate the economic efficiency of concrete mixture preparation, as summarized in Table 2. Only transportation cost was considered to estimate the financial criteria of raw sludge because it is considered a zero-cost waste material, shifting towards

Table 1 Components and ingredients of the prepared concrete mixtures, using sludge biochar (SB) as partial cement replacement

Mixture ID	Cement (kg)	SB (kg)	Sand/Cement	Gravel/Cement	Water/Cement	Superplasticizer (%)
C mix	380	–	1.78	2.67	0.50	1.5
SB 5%	361	19	1.88	2.81	0.53	1.5
SB 10%	342	38	1.98	2.97	0.56	1.5
SB 15%	323	57	2.10	3.15	0.59	1.5
SB 20%	304	76	2.23	3.34	0.63	1.5

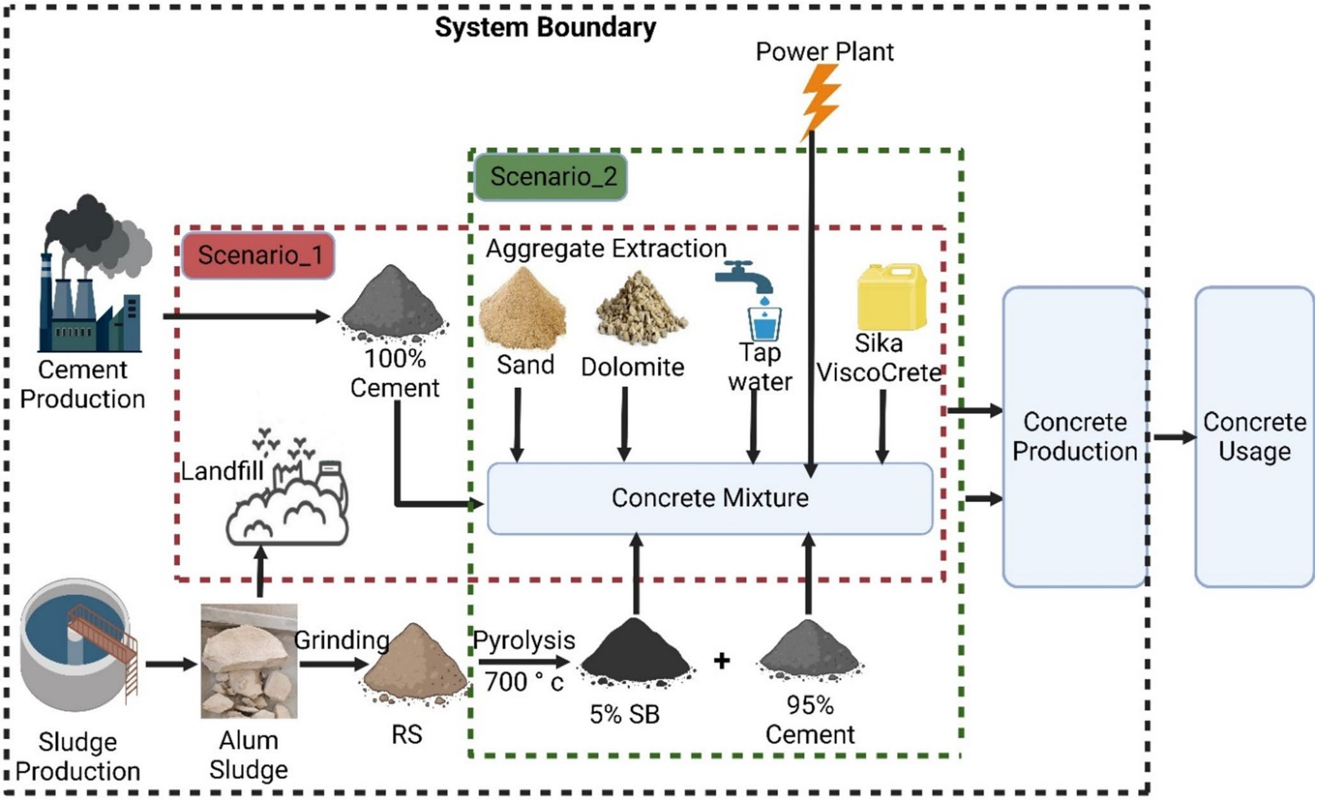

Fig. 1 Illustration of system boundary (cradle-to-gate), process, and material flow for two scenarios of concrete mixtures, showing scenario#1 “control mix and sludge landfilling”, and scenario#2 “sludge valorization for SB mix production”

Table 2 Market price per kg of each type of material and the price of each mixture for 1 m^3 concrete preparation, representing control (C) mixture and sludge Biochar (SB) mixture

Material	Cost (USD/kg)	Justification	Concrete mixture	
			C Mix	SB mix
Cement	0.078	According to market price (Egypt)	29.64	28.16
Sand	0.0046	According to market price (Egypt)	3.12	3.12
Dolomite	0.006	According to market price (Egypt)	6.1	6.1
Water	0.00026	According to market price (Egypt)	0.05	0.05
Sludge biochar (SB)	0.0065	According to market price (Egypt) (Transportation Price)	0	0.12
Electricity for SB production	0.06	[26]	0	1.44
Total cost			38.91	38.96

a circular economy approach. The cost of a cubic meter of concrete was estimated by Eq. (1), as previously reported [26]:

$$C_T = \sum (C_{MP} + C_{MT}) \times Q_i + C_{EU} \tag{1}$$

where, C_T is the total cost (USD), C_{MP} is the precursor material cost (USD/kg), C_{MT} is the material transportation cost (USD/kg), Q_i denotes the kilograms of each material used to produce 1 m^3 of concrete, and C_{EU} is the energy cost used for concrete manufacturing in USD, as estimated by Eq. (2):

$$C_{EU} = P \times T \times C \tag{2}$$

where, P represents the muffle furnace power (kWh/kg), T stands for the amount per burning period (kg/h), and C denotes the electricity price (USD/kW).

Framework for evaluating SDG achieved by each scenario

A framework was created to quantitatively evaluate the sustainability performance of the two proposed scenarios. This framework includes ten indicators to properly address the socio-environmental, financial, and technical aspects of sustainability in sludge recycling in concrete production (Table 3; see Supplementary Fig. S1). The framework was developed according to the methodology reported recently that has assigned scores to the achieved SDGs on wastewater treatment [27]. Firstly, a SDG-indicator matrix was created by identifying the SDG targets based on each indicator (see Supplementary Table S9). Secondly, an indicator-alternative matrix was constructed and then normalized by Eq. (3) to be in a standardized form (see Supplementary Table S10).

$$N = \frac{a}{\sqrt{a^2 + b^2}} \tag{3}$$

where, N is the normalized value, and a and b are the real indicator values for each alternative.

Finally, the SDG-indicator matrix was multiplied by the indicator-alternative matrix to get the SDG-alternative matrix. Some indicators have negative impacts on the achieved SDGs (e.g., using more energy for concrete production would reduce resource availability [28–32]), and hence their associated values were multiplied by (-1).

Table 3 Definition of indicators and their suggested sustainable development goal (SDG) targets for assessing the sustainability of sludge recycling and concrete production scenarios

	Socio-environmental	Economic	Technical
Indicator	Human health; Ecosystem quality; Climate change; Resources	Cost	Compressive strength; Split tensile strength; Flexure strength; Permeability; Abrasion
Main SDG's target	Targets (1.5; 1.a) build structure and infrastructure systems resilience to environmental shocks, such as climate-related extreme events; resource mobilization by managing sludge and acquiring biochar to achieve sustainable buildings [28]. Targets (3.8; 3.9) reduce CO_2 and particulate matter emissions from the cement industry to support essential health-care services; reduce health risks and the number of illnesses from hazardous chemicals and cement dust (i.e., fine particles that can be easily inhaled) [29]. Targets (6.1; 6.3; 11.6; 12.4; 15.1) utilize sludge derivatives as a replacement for cement to eliminate sludge dumping into landfills throughout their life cycle; avoid deterioration of groundwater quality; protect terrestrial ecosystems and drinking water from sludge landfill runoff [30]. Targets (7.1; 7.3; 9.4; 9.5) apply affordable, and modern energy services for sludge conversion into biochar under thermal treatment; reduce energy consumption by integrating biochar into cement mixtures; using biowaste as cement additive/alternative to maintain environmentally sound technologies [31]. Targets (13.1; 13.2; 13.3) use low-carbon strategies by partially replacing cement with biochar; raise climate awareness using green concrete solutions; enhance resilience to climate change using durable concrete; estimate the global warming potential (GWP) from the quantity of CO_2 produced during the manufacturing of cement [32].	Target (8.4): revenue diversification and financial sustainability in cement manufacturing companies; promote sustainable resource use in screw reactors and rotary kilns for biochar production. Targets (9.2; 9.4; 9.5) strengthen cement manufacturing and employment; reduce industrial emissions using alternative sources of supplementary cementitious materials; innovate greener concrete using sludge derivatives as a substitute for cement Target (11.6; 12.2; 12.5) reduce air pollution from cement production during raw material extraction and processing, clinker production, fuel combustion, and cement grinding and handling; conserve raw materials through sludge valorization for biochar production; integrate waste into cement and concrete mixture preparation. Target (17.16) foster collaboration for a circular economy and sustainable concrete production complemented by multi-stakeholder partnerships; maintain international support for developing countries by offering cheaper concrete prices, including the price of materials and a feed-in tariff as a price per unit of electricity [32].	Target (9.1) maintain resilient infrastructure with concrete that has higher compressive strength levels; enhance concrete's capacity to withstand weathering, permeability, chemical corrosion, and abrasion. Target (11.1; 11.b) improve concrete application for affordable, and secure housing and sustainable urbanization; enhance structural stability of the building elements and concrete capability to endure over time without notable degradation.

Results and discussion

Mechanical properties and durability of concrete mixtures

Figure 2a shows the results of the specimens' compressive strength values at 7 and 28 days of water curing. The compressive strength declined from 24 to 11 MPa after 7 days when the SB levels in the concrete mixtures increased from 5 to 20%, respectively. The cause of this reduction could be attributed to the agglomeration of SB particles around the cement grains due to the elevated replacement levels [33]. These values corresponded to a drop in the compressive strength levels from 32 to 22.5 MPa at the 28-day age. The pozzolanic activity of the mixture was adversely affected by the dilution effect, mainly caused by the insufficient cement concentration [34]. The 5% SB replacement ratio provided the highest compressive strength (32 MPa) among other percentages, which was better than the target strength (30 MPa). Moreover, this mixture demonstrated a minor difference compared to the C mix's compressive strength (33.5 MPa). The remaining mechanical properties and durability of the SB mixture were examined at the 5% replacement level, because it provided the highest compressive strength (see Supplementary Fig. S2). The split tensile strength and flexure strength patterns followed the same compressive strength trend (Fig. 2b). As such, the 5% SB mixture's tensile strength levels were 3.5 MPa at 28 days and 3.9 MPa at 90 days. These values were lower than the control sample by only 5.4% and 2.5%, respectively. The flexure strength levels were 6.0 MPa at 28 days and 6.4 MPa at 90 days, lower than the C mix case by 6.25% and 4.5%, respectively. The main reason for producing concrete with nearly the same mechanical properties as the control mixture could be the elimination of organic compounds from raw sludge during the pyrolysis process (e.g., organic substances could slow down and interfere with the mortar binding reaction). Gomes et al. [6] also demonstrated that the compressive strength behavior of the biochar-concrete composites was improved due to the removal of organic components from the sludge by pyrolysis, where the oxidation of this organic matter might be accompanied by the formation of open pores in the cement matrix.

Figure 2c displays the water penetration depth of permeability and loss of thickness of abrasion, describing the concrete's durability pattern. The durability of the concrete mixture exhibited better results compared with the mechanical properties after SB addition. The water penetration depth of the 5% SB and C mix was 2.7–2.8 mm at 28 days, where the fineness of biochar particles improved the concrete's ability to resist water penetration under pressure. A comparable pattern was noticed for the water penetration depth at 90 days, where the biochar particles avoided the creation of greater voids in the cement paste, and enhanced the effective bearing area. Figure 2c shows that the abrasion resistance followed the same trend as permeability. The loss of thickness was 1.3 mm at 28 days, with 7.1% enhancement, after biochar addition. This improvement in durability could be attributed to the fineness of the SB particles, initiating the pozzolanic reaction and filling the spaces between cement paste and aggregates [35]. The loss of thickness was 1.2 mm at 90 days, where this 7.7% improvement occurred because the SB material could build a dense structure to avoid the loss of fluidity within the elapsed time. While the proposed biochar-cement mixtures exhibited applicable compressive strength levels at early ages, more research is required to evaluate the sulfate attack or chloride ion penetration tests. This approach should comply with recent studies that justified the role of biochar derived from municipal solid waste [36] and waste rice straw [37] in preparing biochar-cement composites that exhibited strong sulfate resistance because biochar could regulate the pH levels under acidic environments and reduce chemical erosion inside the concrete.

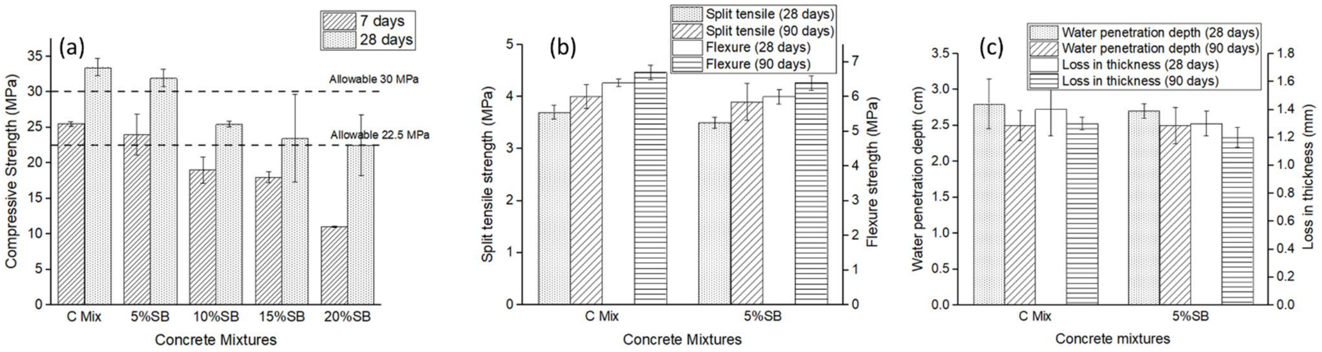

Fig. 2 Concrete properties for different sludge biochar (SB)/cement mixtures, showing **a** compressive strength at 7 and 28 days, **b** tensile strength and flexure strength, and **c** permeability and abrasion

Environmental LCA impact results for concrete mixtures

The LCA results of the two scenarios are summarized in Table 4 for the midpoint and endpoint environmental impact categories. This comparison highlights substantial differences in the LCA levels, where the C mix scenario exhibited the worst environmental profile due to the full use of cement and landfill disposal of sludge.

Control mix with sludge transfer to landfills (scenario#1)

The first scenario had a GWP midpoint indicator of 10.5×10^3 kg CO_2 eq (see Table 4), which is higher than the SB scenario (7×10^3 kg CO_2 eq). This result is similar to a previous study by Nakic [14], who found that there is an increase in CO_2 emissions from the chemical reactions during the heating and calcination of limestone in many cement plants. The C mix scenario had the highest respiratory inorganics impact (9.25 kg PM2.5 eq) and non-renewable energy use (102×10^3 MJ). This result could be attributed to the use of fossil fuels in cement kilns to provide higher temperatures (> 900 °C) needed to manufacture clinker [38]. These findings are justified by monitoring the endpoint LCA categories. The C mix and sludge landfilling scenario shared the highest human health impact (0.008 DALY) and climate change effect (10.5×10^3 kg CO_2 eq), as illustrated in Table 4. This scenario also showed greater damage in the resource depletion and ecosystem quality categories compared to the SB mix scheme. This finding could be because the released nitrogen oxides (NO and NO_2) from air combustion tended to increase the climate change risks associated with acid rain, photochemical smog, and hazy weather circumstances. The release of CO and CO_2 from $CaCO_3$ calcination of raw materials and fuel combustion could negatively impact life expectancy and mental health by entering the particulate matter into the lungs and bloodstream [39].

Table 4 Environmental impacts of control concrete sample (100% cement percentage) with sludge landfilling (scenario#1) and sludge Biochar (SB)-cement mixture Preparation (scenario#2) given by the life cycle assessment (LCA) tool

Impact category	Unit	Scenario#1	Scenario#2
Midpoint impact categories			
Carcinogens	kg C_2H_3Cl eq	250	165
Non-carcinogens	kg C_2H_3Cl eq	240	160
Respiratory inorganics	kg PM2.5 eq	9.25	6.25
Ionizing radiation	Bq C-14 eq	139×10^3	94×10^3
Ozone layer depletion	kg CFC-11 eq	0.00068	0.0005
Respiratory organics	kg C_2H_4 eq	3.25	2.25
Aquatic eco-toxicity	kg TEG water	595×10^3	428×10^3
Terrestrial eco-toxicity	kg TEG soil	190×10^3	128×10^3
Terrestrial acid/nutria	kg SO_2 eq	175	120
Land occupation	m^2 organic arable	3.55×10^3	2.35×10^3
Aquatic acidification	kg SO_2 eq	33	23
Aquatic eutrophication	kg PO_4 P-lim	0.19	0.13
Global warming	kg CO_2 eq	10.5×10^3	7×10^3
Non-renewable energy	MJ primary	102×10^3	69.7×10^3
Mineral extraction	MJ surplus	14×10^2	9.3×10^2
Endpoint impact categories			
Human health	DALY	0.008	0.005
Ecosystem quality	PDF m^2 yr	5.6×10^3	3.7×10^3
Climate Change	kg CO_2 eq	10.5×10^3	7×10^3
Resources	MJ primary	104×10^3	70.6×10^3

Sludge biochar (SB)-cement mix scenario#2 implementation

Replacing 5% of cement with SB significantly improved the overall environmental scoring performance, reducing GWP by 33.3% because about 800 kg of CO_2 could be released into the atmosphere from producing one ton of cement. This scenario also had the lowest impact on respiratory inorganics (6.25 kg PM2.5 eq) by diverting sludge from landfills and reducing landfill surface gas emissions, including CH_4, CO_2, N_2O, and sulfides [14]. A previous study by Hong and Li [40] also verified that the potential effect of the cement mixture with sludge on respiratory inorganics decreased to 0.29 kg PM2.5 eq compared with the 100% cement specimen (0.39 kg PM2.5 eq), owing to emitting particulates, NO_2, and SO_2 to the air. Other environmental impacts, including non-renewable energy use, land occupation, and terrestrial ecotoxicity, were also reduced due to scenario#2 implementation. These findings could be because the usage of SB as a supplementary cementitious material could prevent soil pollution from aluminum, representing the main component of alum sludge. This sludge type could pose a potential risk to human health, disturb aquatic life, and deteriorate the terrestrial plants and food crops grown on such contaminated soils. As a result, a reduction in terrestrial ecotoxicity could occur. According to the endpoint categories, incorporating SB as a partial cement replacement led to approximately a 34% reduction in the main environmental impacts. The SB scenario demonstrated a decrease in the human health impacts (0.005 DALY) because the bacteria attached to the aluminum species of sludge might be microbial pathogens and potentially resistant to antimicrobial treatment. Additionally, the SB mixture exhibited lower resource depletion and improved ecosystem quality indicators. These results could be returned to the incorporation of SB in concrete, further minimizing resource input and waste output (i.e., organic waste is considered one of the most readily available resources with economic potential).

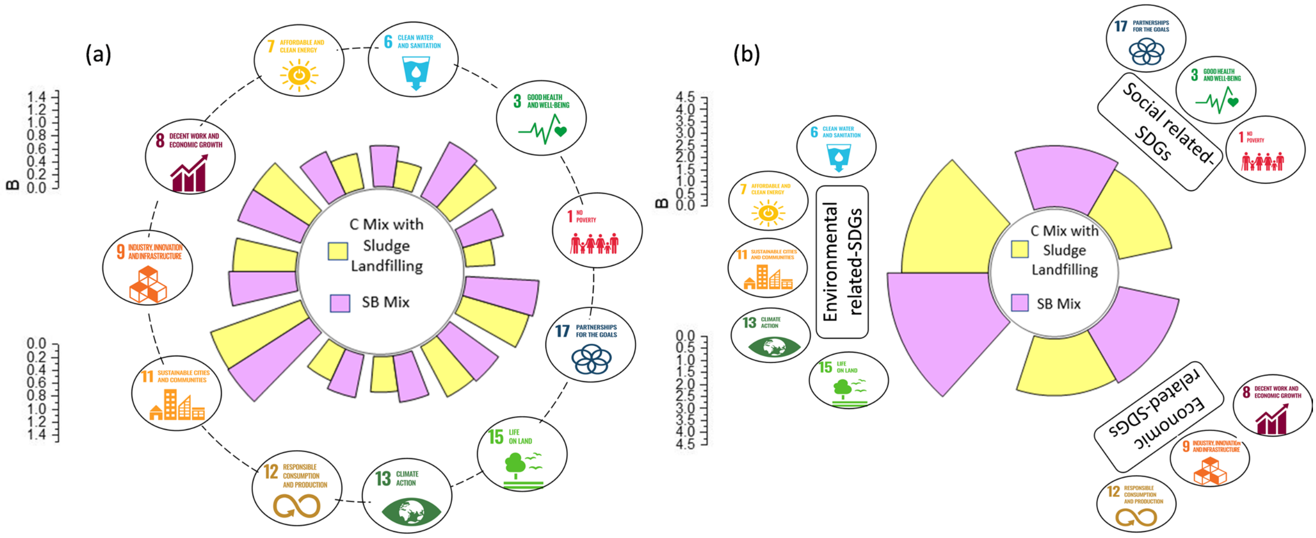

Fig. 3 Evaluation of the two scenarios, Scenario#1: control concrete mixture with sludge transfer to landfills, and Scenario#2: valorization of sludge to produce biochar used in greener concrete fabrication, based on sustainability criteria: **a** the fulfillment of sustainable development goals (SDGs), and **b** the socio-environmental and economic criteria of sustainability

Meeting sustainable development goals (SDGs) for each scenario

Figure 3a displays the degree of fulfillment for each SDG by the “C mix” and “SB concrete” scenarios. These SDGs could be illustrated as follows:

SDG1 “no poverty”

Employing SB in concrete production could fulfill Target 1.5 by reducing the exposure and vulnerability of poor groups to the climate-related extreme events associated with greenhouse gas (GHG) emissions from sludge landfills. The mitigation of this environmental impact was justified by reducing the score on the “human health” endpoint indicator by 37.5% through implementing well-structured social protection systems (e.g., reducing CO_2 emissions in the environment; see Table 4). As a result, the dumping of sludge waste could release various harmful pollutants, such as CH_4, NO_x, and CO_2, negatively impacting human physiology and health and the overall poverty status [41]. Furthermore, the achievement of Target 1.a by scenario#2 exceeded that of scenario#1 because sludge valorization for biochar production entails considerable mobilization of resources (e.g., electricity, feedstock, and reagents) from various input attributes (e.g., an energy grid network system).

SDG 3 “good health and Well-being”

Sludge recycling to produce a promising supplementary cementitious material could mitigate multiple environmental and public health concerns associated with the land application of solid wastes, such as the adverse effects highlighted by the “respiratory inorganics” indicator. Implementing environmentally friendly techniques in concrete production could meet Target 3.9 by reducing mortality from air pollution and soil contamination, as confirmed by the “carcinogens” and “non-carcinogens” LCA impact factors. Promoting high-paying jobs (e.g., management consultants) in the cement manufacturing industries would protect people from financial risks and improve access to healthcare, fulfilling Target 3.8 “maintain health coverage”. This achievement could be supported by Omer and Noguchi [42], highlighting the importance of the cement sector in manufacturing locally produced building materials that could guarantee equal rights to economic resources, basic services, and ownership. This finding also complies with Target 3.d by upgrading sustainable public procurement (e.g., to purchase a pyrolysis rotary kiln unit for biochar production) and maintaining risk reduction and management of the sludge dumping sites.

SDG 6 “clean water and sanitation”

Using SB as a supplementary cementitious material in concrete production could positively contribute to Target 6.1 (universal access to clean water) by preventing the disposal of sludge into water bodies. This benefit could prevent the transfer of harmful substances and toxins (e.g., metals in alum sludge) from water and sediments to aquatic life, as evidenced by the minimum “aquatic eco-toxicity” indicator in the SB scenario. Tawfik et al. [43] argued against the practice of RS dumping into water bodies or landfills due to its high heavy metal content, where utilizing this solid waste in construction materials like bricks and ceramics could meet Target 6.3 “improved water quality and reduced pollution”.

SDG 7 “affordable and clean energy”

According to Shehata et al. [16], producing building materials for construction and manufacturing currently accounts for about 40% of the global energy consumption. Converting sustainable biogenic waste sludge to biochar used as partial cement replacement presents a viable solution to this environmental-based challenge. Reducing the need for energy-intensive processes in the cement industry (e.g., clinker production in the rotary kiln) could maintain significant resource savings, aligning with the Target 7.3 “improve energy efficiency” achievement. This assertion could be noticed in the LCA impact category (see Table 4), where scenario#2 showed a better “non-renewable energy” midpoint level than scenario#1 by about 30%, suggesting the sustainable transition towards the biomass-based cement industry.

SDG 8 “decent work and economic growth”

The scoring performance for SDG_8 was almost comparable under the two scenarios, encouraging youth employment in labor-intensive industries (Target 8.6). This trend in economic growth might be associated with the higher price of cement compared with the small amount of cement replacement by SB (5% w/w). The two scenarios could also meet Target 8.4 “promoting sustainable resource consumption and production” by enhancing the utilization of resources and waste materials (e.g., sludge from water purification processes) for financial growth.

SDG 9 “industry, innovation, and infrastructure”

Utilizing sludge in the concrete industry contributes to the fulfillment of Target 9.1 “concrete infrastructure projects” and Target 9.2 “manufacturing employment in cement industries”, fostering gross domestic product to strengthen economic development and human welfare (e.g., green education and learning environments). According to Young et al. [44], determining the optimal cementitious content (0.110 USD/kg) that achieved the desired compressive strength (30–50 MPa) positively influenced the concrete mixture’s cost-effectiveness. Incorporating SB as a supplementary cementitious material in concrete to achieve satisfactory compressive strength (30 MPa) aligned with Target 9.4 by minimizing CO_2 emission per unit of value added, showing a cleaner and environmentally friendly approach [27]. Using treated alum sludge in sustainable concrete production could also address Target 9.5 by advancing scientific inquiry and fostering innovation in greener product manufacturing, further developing a deeper understanding of scientific concepts and the processes involved in circular economy applications.

SDG 11 “sustainable cities and communities”

Concrete emerges as a multifaceted solution, addressing the pressing need for vital social infrastructure and affordable and secure housing (Target 11.1: combating the proliferation of urban slums). Furthermore, the current study demonstrates the potential utilization of SB as a waste resource for concrete production, fostering the creation of sustainable and resilient buildings (Target 11.b; see Supplementary Table S11). The remarkable compressive strength (31.9 MPa) for the SB-concrete surpassed the allowable threshold of 30 MPa, underscoring the viability of utilizing biochar-cement composites in public infrastructure projects (Target 11.7: safeguard marginalized communities). The current investigation also underscored the imperative of optimizing the collection and management of RS within controlled environments to produce biochar, supporting the advancement of an eco-friendly alternative to the ordinary concrete material (Target 11.6). In alignment with Dadebo et al. [45], who advocated for repurposing water treatment sludge into valuable assets, the findings in Table 4 highlight the transformative potential of shifting the waste management paradigms from financial liabilities to lucrative ventures.

SDG 12 “responsible consumption and production”

An effective use of natural resources (e.g., water, sand, and crushed stone) and optimization of energy performance in the concrete manufacturing process would support the fulfillment of Target 12.2 “natural resource management”. The LCA outputs (see Table 4) depicted that avoiding the release of untreated sludge into the environment could achieve an environmentally sound management of waste treatment residues throughout their life cycle (Target 12.4). This hypothesis also supports the fulfillment of Target 12.5 through the valorization and recycling of raw sludge, minimizing the prevalence of infectious disease from pathogens and pollution from genotoxic agents and harmful organic chemicals.

SDG 13 “climate action”

Using 5% SB in concrete as a partial replacement of cement could attain Target 13.1 by maintaining suitable and cost-efficient risk mitigation strategies associated with GHG emissions. Countries should entail long-term strategies, and national adaptation plans to implement the biochar-cement scenarios, meeting Target 13.2 “include climate change data into national policies”. Improving education and institutional capacity towards CO_2 emission reduction in the concrete industry contributes significantly to achieving carbon neutrality within the frameworks of carbon markets, climate policy, and financial footprint (Target 13.3).

SDG 15 “life on land”

Synthesizing biochar and compost from municipal organic waste and further their application in the building industry under international agreements is appropriate for land conservation and ecosystem preservation (Target 15.1). Producing sustainable and environmentally friendly concrete is beneficial in reaching Target 15.3 “achieve a land degradation-neutral country” by avoiding the accumulation of cement dust in and on plants, animals, and soils.

SDG 17 “partnership for the goals”

Greener concrete production has the capacity to facilitate extensive cooperation among stakeholders, suppliers, and consumers, supporting investment in sustainable and eco-friendly structures. This beneficial aspect has been emphasized by Shehata et al. [16], underscoring the pivotal role of creating a collaborative enterprise atmosphere to develop a circular concrete sector and advance innovative sustainable construction practices (Target 17.16). Some developing countries that lack access to biomass energy substitutes should initiate collaborative momentum to enable circular material flows and attain circular supply chain management between the public and private sectors (Target 17.17).

Comparison between the alternatives according to three pillars of sustainable development

The LCA and SDGs scoring performances highlighted that using SB as a partial cement replacement significantly impacted the green finance and environmental quality changes. As shown in Fig. 3b, the synergetic interaction between the functional criterion and the economic and socio-environmental dimensions of sustainable development emphasized the importance of employing the SB mix scenario in the industrial sector. Selecting the best alternative cement replacement materials should comply with the LCA midpoint/endpoint impact categories related to climate change (in kg CO_2 eq), human health (in DALY), and resources (in MJ primary), as previously demonstrated [46]. Following the economic pillar of SDGs, the SB mix scenario would maintain a better financial effect on the country’s gross domestic product growth due to saving money on environmental taxes and regulations (safe sludge disposal: reusing and recycling; Target 12.c). The proportion of social-related SDGs was also higher for the SB-based concrete production scheme due to raising individual awareness and understanding towards sludge valorization in the fabrication of construction and building materials (see sensitivity analysis in Supplementary Table S12). Reducing cement usage and GHG emissions, and avoiding the consequent depletion of natural resources, make energy-intensive industry production consistent with the Paris Agreement (Target 17.4 support developing countries in achieving long-term debt sustainability).

Overcoming limitations for future investigations

While the study methodology effectively aimed at promoting the sustainability of SB concrete to contribute to environmental health and well-being, some areas require further exploration to ensure the feasibility of implementing the proposed LCA/SDG framework model:

- Further studies should focus on the long-term durability aspects, such as sulfate attack and chloride-ion penetration in concrete structures (see Supplementary Table S13). This item should be addressed by understanding the synergistic mechanism of biochar and cement carbonization reaction and its correlation to the carbon capture capacity of cement-based composites.
- Investigating biochar production from various feedstock wastes is pivotal in calling for immediate solutions and strategies to mitigate the adverse effects of climate change related to cement and concrete production (e.g., batching and mixing of the ingredients). Scaling up production not only bolsters the availability of this sustainable additive but also contributes to carbon sequestration efforts, thereby fostering a more environmentally resilient construction industry.
- Employing a combination of experimental studies and mathematical modeling tools would provide a robust framework to comprehensively assess the carbon sequestration mechanisms of biochar cement-based materials and cement mortar. By integrating empirical data with artificial intelligence models to accurately quantify the material’s capacity in the carbon sequestration mechanisms, the decision-makers could further improve the comprehensive performance of recyclable cement-based materials and maintain sustainable valorization of biomass.
- More studies should focus on determining the health risk of airborne and soilborne pathogens in sewage sludge, as an emerging contaminant in the environment, during its application in real-world construction projects,

fulfilling Target 9.4 “maintain environmentally sound industrial processes”.

- Future work should include a comprehensive economic analysis of biochar-based concrete, taking into consideration capital, maintenance, labor, and energy costs (see Supplementary Table S14). Because the current study focuses solely on direct material and energy inputs, a precise cost-benefit model is required for assessing large-scale implementations.

Conclusions

This study successfully represented an innovative framework to assess the fulfillment of sustainable development goals (SDGs) by using sludge valorization to produce biochar (SB) employed in concrete mixture preparation. The study outcomes were justified by incorporating multiple socio-environmental, financial, and functional criteria into a life cycle assessment (LCA) model, regarding the estimation of multiple midpoint and endpoint impact categories. The 5% SB-cement mixture exhibited a compressive strength of 32 MPa and its abrasion resistance levels were enhanced by about 7% compared with the control sample at the age of 28 and 90 days. Moreover, the global warming potential (GWP) and overall LCA environmental impacts of this mixture were reduced by almost 33% compared with the control specimen, highlighting that biochar-based concrete could be employed to achieve an eco-friendly industrialization approach. The proposed SDG-framework exhibited an optimal balance between the three pillars of sustainable development and the greener concrete composite performance. The results of this study could serve future investigations by integrating more socio-health, environmental, and financial indicators into the LCA/SDG model to implement sustainable construction and greener building techniques worldwide.

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Data availability All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Declarations

Conflict of 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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