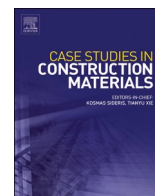


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## Case Studies in Construction Materials

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## Carbon dioxide emission evaluation of biochar based vegetation concrete for ecological restoration projects

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## ARTICLE INFO

## Keywords:

Vegetation concrete  
 CO<sub>2</sub> emissions  
 Biochar  
 Cost analysis  
 Compressive strength  
 Portland cement  
 Sulfoaluminate cement

## ABSTRACT

Vegetation concrete is increasingly being used for slope stabilization in highways, green roofing in urban developments, and erosion control in coastal areas due to its sustainable solutions for enhancing landscape aesthetics, mitigating pollution, and protecting the environment. However, the environmental and economic impacts of different mix proportions, particularly concerning CO<sub>2</sub> emissions, remain insufficiently explored. This study aimed to identify the optimal mix proportions of vegetation concrete through laboratory testing that minimize CO<sub>2</sub> emissions while ensuring compatibility with plant growth and cost-effectiveness. The vegetation concrete mix were prepared using different quantities of biochar (5 %, 10 %, and 15 %) and cement content (4 %, 8 %, and 12 %) by weight to evaluate their impact on porosity, unconfined compressive strength (UCS), alkalinity, plant compatibility, cost-effectiveness, and CO<sub>2</sub> emissions from raw materials. The results indicate that increasing the biochar content from 0 % to 15 % led to a 16 % reduction in porosity and a 92 % increase in UCS of vegetation concrete. Similarly, increasing the cement content from 0 % to 12 % resulted in an 11 % decrease in porosity and a substantial 200 % increase in the UCS of vegetation concrete. Moreover, the addition of 5 % biochar had a beneficial effect on plant growth, however, increasing the biochar content beyond this level adversely impacted plant development. Based on laboratory test results, the recommended optimal mix for vegetation concrete includes a mix of 5 % biochar, 8 % low-alkaline sulfoaluminate cement, 6 %

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<https://doi.org/10.1016/j.cscm.2024.e03874>

Received 13 May 2024; Received in revised form 23 September 2024; Accepted 14 October 2024

Available online 16 October 2024

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sawdust, and 6 % ferrous sulfate. The analysis of CO<sub>2</sub> emission of the materials studied showed that cement contributed the most to CO<sub>2</sub> emissions, followed by biochar, sawdust, water, and soil. Notably, the utilization of sulfoaluminate cement led to a 31.8 % reduction in CO<sub>2</sub> emissions compared to Portland cement, while also lowering the overall cost of vegetation concrete by 24.7–33.8 %. This research underscores the necessity of scientifically establishing relationships between the composition of plant-based concretes and their environmental and economic performance. In summary, this study identifies optimal mix proportions for vegetation concrete, leveraging low-alkaline sulfoaluminate cement and biochar to minimize CO<sub>2</sub> emissions, enhance landscape aesthetics, and ensure compatibility with plant growth, thus emphasizing its potential as a sustainable and cost-effective construction material.

## 1. Introduction

Engineering slopes, formed during projects like hydropower, roadways, railways, and urban development, often lead to ecological and environmental issues. These include deforestation, changes in hydrology and terrain, soil erosion, and slope slide incidents [1–3]. Retaining walls and shotcrete effectively improve slope stability but often leave large exposed areas, negatively impacting ecology and landscape aesthetics. Ecological rehabilitation efforts for concrete slopes not only aim to reinforce slope stability, thus reducing the risk of landslides and debris flows but also seek to restore natural habitats and preserve landscape integrity [4,5]. Additionally, these efforts aim to enhance microclimates, diminish soil erosion, and elevate landscape functionality [6,7]. Seed germination and seedling growth on slopes are challenging due to direct factors like temperature, soil nutrients, humidity, and light, as well as indirect factors like slope angle and orientation.

Carbon dioxide (CO<sub>2</sub>) is the primary greenhouse gas driving the greenhouse effect, accounting for 72 % of human-induced emissions [8,9]. Its levels have risen alarmingly, with the International Energy Agency (IEA) [10] reporting that global CO<sub>2</sub> emissions increased from 30 billion tons in 2010–36.3 billion tons by 2021. Correspondingly, atmospheric CO<sub>2</sub> concentrations have surged from 280 ppm in 1750 to 419 ppm in 2021 [11]. Among the largest contributors to these emissions is the cement manufacturing sector, known for its high energy consumption and significant emissions. The industry accounts for 12–15 % of total industrial energy use [12] and emitted 2.4 gigatons of CO<sub>2</sub> in 2019, representing 7.2 % of global human-related carbon emissions and over a quarter of the carbon output from industrial activities [13]. Given its considerable impact, the cement industry has been actively seeking ways to reduce its carbon footprint as part of broader efforts to mitigate climate change. Cement production is responsible for 5–10 % of global CO<sub>2</sub> emissions, primarily due to the combustion of fossil fuels and the thermal decomposition of limestone during production. On average, producing one ton of cement releases approximately 0.9 tons of CO<sub>2</sub>, contributing to a staggering annual total of 3.15 billion tons, given the global production volume of 3.5 billion tons. This high rate of emissions accelerates climate change and depletes the ozone layer. As population growth and urbanization continue to drive increased demand for cement, its contribution to CO<sub>2</sub> emissions is expected to rise further [14,15].

Portland cement (PC) clinker production is a major source of CO<sub>2</sub> emissions in the cement sector. To mitigate these emissions, it is important to explore the use of alternative binders like calcium aluminate cement (CAC), calcium sulfoaluminate (CSA) cement, alkali-activated binders, and super-sulfated cement. These alternatives offer a promising way to lower the environmental footprint of cement manufacturing [16,17]. Therefore, this research utilized sulfoaluminate cement (SAC) as the cement material because it has lower pore fluid alkalinity than PC, which is beneficial for plant growth [18,19]. The manufacturing process of SAC provides various benefits, such as a lower calcination temperature (around 1250°C), decreased CO<sub>2</sub> emissions, and relatively simple clinker grinding [20,21]. The primary constituents of SAC clinker are C<sub>4</sub>A<sub>3</sub>S and C<sub>2</sub>S. Consequently, the pore fluid alkalinity of hydrated SAC is lower compared to ordinary Portland cement (OPC) [22]. The quick hardening and high-strength properties of SAC could lead to a shortened construction period [23]. Thus, SAC proves to be a suitable choice as a cementitious material for planting, especially when compared to OPC.

Using plant-based materials like straw, sawdust, rice husk, and wood chips in concrete has been widely studied to boost sustainability and lower construction's carbon footprint. These natural additives replace some traditional aggregates, improving thermal insulation, moisture retention, and workability while reducing cement use [24,25]. Another study examines palm fiber reinforcement in vegetation-growing concrete (VC) substrates, showing that fibers enhance ductility and strength, shifting the substrate's behavior from softening to elastoplastic, making it suitable for slope eco-protection [25]. Xia et al. [26] explore methods to enhance the erosion resistance of vegetation concrete on slopes, finding that PAM and palm fiber reduce erosion effectively, making them suitable for high-rainfall steep slope restoration. Biochar, however, increased runoff and erosion rates.

Vegetation concrete can hinder plant growth due to its predominantly weakly alkaline environment, contrary to the slightly acidic conditions preferred by plants. To address this, studies have explored methods like using low-basicity cement or incorporating additives such as fly ash and slag to reduce the alkalinity [18,23,27]. Some research has focused on directly enhancing plant growth by adding fertilizers or soil amendments to the concrete. Gong et al. [28] found that adding urea improved plant growth but slightly decreased concrete strength. Yuan et al. [29] improved the concrete's adsorption capacity for pollutants and supported plant growth by adding activated carbon. However, there's limited research on biochar-modified vegetation concrete.

Biochar, a refractory fine granular charcoal derived from the pyrolysis of vegetation or waste materials [30], stands out not only for its soil conditioning properties but also for its cost-effectiveness and environmental practicality compared to activated carbon [31,32]. Numerous studies have demonstrated that adding biochar as an amendment improves soil fertility, which in turn improves the soil's

capacity to sustain the growth of agricultural plants [33]. Biochar’s significant trait lies in its slow decomposition rate compared to the original biomass, leading to extended presence in soil [34]. This characteristic boosts carbon sequestration in the biosphere and lowers CO<sub>2</sub> emissions, adhering to a “fast in, slow out” approach to carbon cycling. Biochar also impacts GHG emissions directly and indirectly by influencing soil organic matter decomposition and carbon/nitrogen cycling processes. However, field applications of biochar have produced inconsistent results regarding its effect on GHG emissions, suggesting variable outcomes based on environmental factors [35].

Recent studies have emphasized the environmental benefits of using sulphoaluminate cement (SAC) and biochar in concrete, supported by Life Cycle Assessment (LCA) analyses [36,37]. Chen et al. [38] found that SAC significantly reduces CO<sub>2</sub> emissions by 30–50 % compared to traditional Portland cement due to its lower production temperature and use of recycled materials. Similarly, Lehmann and Joseph [39] reported that biochar from organic waste pyrolysis is carbon-negative, reducing concrete emissions by up to 40 %. These LCAs highlight the potential of SAC and biochar to significantly lower concrete’s carbon footprint, promoting sustainable construction alternatives.

Moreover, the amount of cement in the vegetation concrete matrix is vital to the entire process. It needs to reach a certain level, usually between 0 % and 15 %, depending on the slope, to enhance slope stability without hindering seed germination or the establishment of seedlings [40–42]. Therefore, comprehending how various cement contents affect the germination and establishment of specific plant species is essential for determining the suitable range of cement content in vegetation concrete applications.

This study aims to develop a sustainable vegetation concrete mix that reduces CO<sub>2</sub> emissions, enhances slope stability, and supports plant growth. By optimizing biochar and sulphoaluminate cement proportions, the research evaluates their impact on porosity, compressive strength, pH levels, and plant growth. The study compares CO<sub>2</sub> emissions from the proposed mixes with conventional alternatives, highlighting the environmental benefits of biochar and low-carbon cement. It also conducts a cost-benefit analysis to assess the economic feasibility of large-scale ecological restoration. Addressing the high emissions from traditional cement and its poor support for vegetation, this research offers practical insights for policymakers and construction professionals on utilizing biochar-based vegetation concrete in large-scale ecological restoration projects to reduce CO<sub>2</sub> emissions and enhance sustainability.

**2. Materials and methods**

This section provides an in-depth explanation of the materials, their composition, the testing methods employed, and the variables considered to determine the optimal mix for vegetation concrete, that balances cost-effectiveness with environmental sustainability. Fig. 1 presents the methodology flowchart outlining the procedural steps undertaken in this study.

**2.1. Materials**

**2.1.1. Soil**

The raw material of sprayed-type vegetation concrete includes soil, cement, organic matter, water and nutrient retaining agent, and

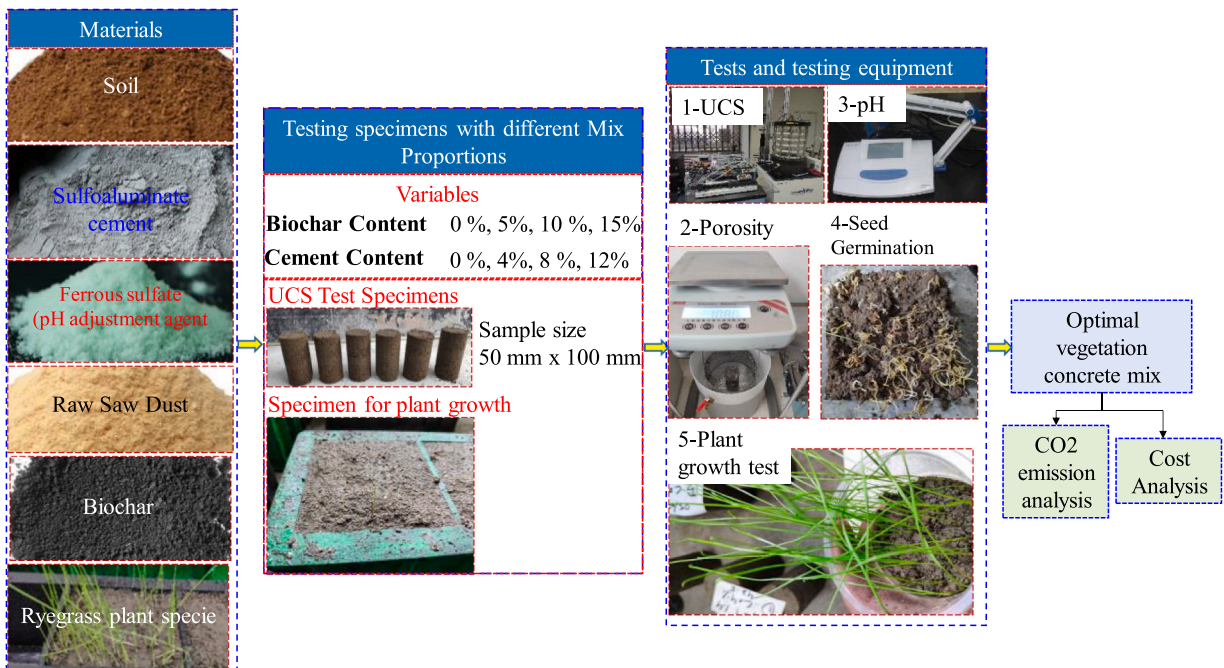


Fig. 1. : Methodology flow chart.

pH adjusting agent. The soil used in the indoor experiment was obtained from Taoshan Mountain, Tai'an City, Shandong Province. The soil type was clay loam with the pH and natural moisture content of 7.43 and 8.9 %, respectively. The gradation curve of the soil is given in Fig. 2. Prior to the experiments, the soil was sieved through a 4.75 mm mesh size. The sieved soil was oven-dried at a temperature of 105°C for 24 h to achieve an initial gravimetric water content.

### 2.1.2. Sulfoaluminate cement

The adhesive agent utilized in this study was low-alkaline Sulfoaluminate cement (Grade 42.5 as per Chinese National Standards GB20472–2006), supplied by Jianhua Cement Company in China. The chemical properties of the SAC used in this study are given Table 1.

### 2.1.3. Draw sawdust

Dry sawdust was used as organic matter in the soil to improve the soil texture, help to retain moisture, and keep roots cooler. The particle size of the sawdust was 0.1–2 mm.

### 2.1.4. Biochar

Biochar was used as a water and nutrient retention agent which is manufactured by Lize Henan, China. Biochar used in this experiment is a kind of carbon-rich solid substance produced by slow pyrolysis of wood (sawdust) at a high temperature of 500°C under anoxic conditions. The particle sizes of this material were 0.250 mm.

### 2.1.5. Ferrous sulfate

Ferrous sulfate was used in the vegetation concrete to adjust pH levels. It releases the ferrous ions to lower the pH, which is beneficial for promoting plant growth and maintaining nutrient availability in vegetation concrete. Its buffering effect helps maintain stable conditions in varying environmental exposures. Ferrous sulfate also acts as an iron supplement, addressing potential deficiencies in the concrete matrix that can affect plant health [43].

### 2.1.6. Plant species

Ryegrass typically adapts to local climates and soil conditions over time in the study area. Consequently, they typically demand less upkeep, such as watering and fertilization, once established, and they exhibit greater resilience compared to non-native species. Therefore, Ryegrass plant species were selected to observe the plant growth.

## 2.2. Mix proportion and experiment design

In this study, the fundamental mix ratio was established through trial experiments and a thorough review of previous research on vegetation concrete. A comparative experiment was conducted to analyze the impact of cement and biochar content on the physical properties of vegetation concrete, plant species growth, and CO<sub>2</sub> emissions. All other variables were held constant except for variations in cement and biochar content. Three varying concentrations of cement content (4 %, 8 %, and 12 %) and biochar content (5 %, 10 %, and 15 %) were added to the soil by weight. The mixture proportions of each raw material are outlined in Table 2 and Table 3. Table 2 presents the mix proportion for samples with varying cement content, while Table 3 shows details of the samples with varying content of biochar.

Following the mix proportions, the dry blending of raw materials (including soil, cement, organic matter, biochar, and pH adjusting

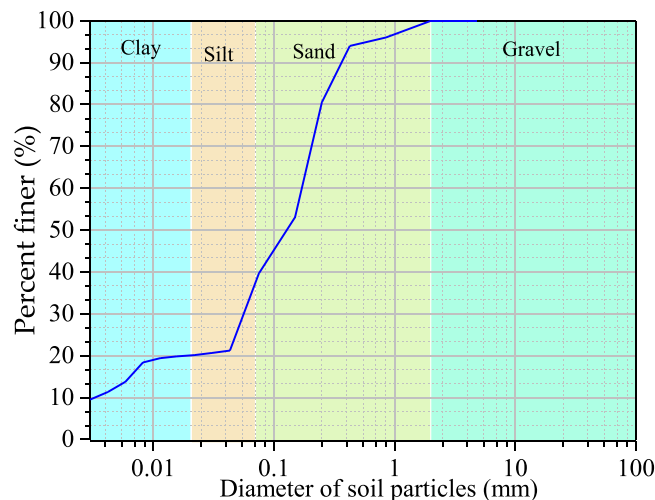


Fig. 2. gradation curve of the soil.

**Table 1**  
composition of Sulfoaluminate cement (SAC).

Oxide	SiO <sub>2</sub>	CaO	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	K <sub>2</sub> O	Na <sub>2</sub> O	TiO <sub>2</sub>	SO <sub>3</sub>	Los
% by Wt.	9.58	45.42	21.6	2.48	1.28	1.36	0.18	1.05	10.67	6.39

agent) was carried out for 30 seconds using a concrete mixer. After the dry blending, water was added, and the mixture was stirred for an additional 90 seconds. Subsequently, the material was filled into cylindrical molds according to specified density for testing porosity and unconfined compressive strength. The molds were then placed in a curing room maintained at 20°C temperature and 95 % relative humidity. Disposable glasses were utilized for planting the seeds.

The water absorption of biochar affects mix consistency as its content increases. To address this, we carefully adjusted mixing time and speed, maintaining a consistent 20 % water content for uniformity. Reflecting typical field application, the biochar was used without any pre-treatment. The aim of this methodology was to evaluate the direct effects of biochar as it would be applied in construction and ecological contexts.

### 2.3. Test methods

#### 2.3.1. Porosity

The porosity of the vegetation concrete test cubes, each measuring 150 × 150 × 150 mm<sup>3</sup>, was assessed using the drainage method, with each group consisting of three test blocks. The experimental procedure can be summarized as follows:

1. The specimen was oven-dried at 60°C until the mass remained constant and the weight ( $W_1$ ) of the specimen was measured.
2. The diameter, height, and volume of the cylindrical specimen were calculated.
3. The specimen was immersed in water for 24 hours and the weight of the saturated specimen ( $W_2$ ) was measured using the hydrostatic balance method.
4. The porosity ( $P$ ) of the specimen was determined according to the following Eq. (1) given by [44].

$$P = \left( 1 - \frac{W_1 - W_2}{\rho_w V} \right) * 100 \quad (1)$$

Where,  $\rho_w$  is the density of water, and  $V$  is the volume of the sample.

#### 2.3.2. Unconfined compressive strength

In many ways, vegetation-concrete is comparable to the soil-cement that is extensively employed in the area of civil engineering [6]. Both materials are primarily composed of soil and cement, and the cement proportions in soil-cement and vegetation concrete are also quite comparable. The mechanical characteristics of these two materials are highly dependent on curing time, soil texture, and cement content [45]. This type of test offers a suitable basis for testing and is a fast and easy method for comparison of results [46]. Thus, when no specific standard or regulation for vegetation-concrete exists, it is acceptable to reference soil or concrete testing standards [47]. In this experiment, the apparatus was computer-controlled. The loading rate was 1.2 mm/min under strain-controlled mode. The test specimens were 76 mm in height and 38 mm in diameter.

#### 2.3.3. Alkalinity

The pH of vegetation concrete was measured according to the procedure suggested by Zhao et al. [48]. Samples were crushed and sieved through a 2 mm mesh to remove the roots, stone, and other debris. The pH value of samples was measured in a soil-water suspension (soil: water = 1:2.5) using an acidometer. The pH value determination method of plant substrates refers to NY/T1377–2007 (determination of pH in soil).

**Table 2**  
Mix proportion of vegetation concrete with different cement content.

Sample ID.	Soil (%)	Cement (%) (Low alkaline sulfoaluminate cement)	Sawdust (%)	Ferrous sulfate (%)	Water (%)	Density g/cm <sup>3</sup>	Seeds (Num. of seeds)
0 % Cement content	100	0	6	6	20	1.4	70
4 % Cement content	100	4	6	6	20	1.4	70
8 % Cement content	100	8	6	6	20	1.4	70
12 % Cement content	100	12	6	6	20	1.4	70

**Table 3**  
Mix proportion of vegetation concrete with different biochar content (BC).

Sample ID	Soil (%)	Cement (%) (Low alkaline sulfoaluminate cement)	Sawdust (%)	Biochar (%)	Ferrous sulfate (%)	Water (%)	Density g/cm <sup>3</sup>	Seeds (Num. of seeds)
0 % BC	100	8	6	0	6	20	1.4	70
5 % BC	100	8	6	5	6	20	1.4	70
10 % BC	100	8	6	10	6	20	1.4	70
15 % BC	100	8	6	15	6	20	1.4	70

### 2.3.4. Plant growth test

The vegetation concrete was divided into two portions including the base material and surface material. The thickness of the base material and surface material was 8 cm and 2 cm, respectively. The Ryegrass plant seeds were mixed in the surface material. The plant growth test was performed in the lab under a temperature of 20°C and humidity of 95 % RH. The effect of different biochar and cement content on the plant growth was observed. The plants were watered twice a day. The plant height was recorded at regular intervals. Moreover, the germination coverage was calculated by the ratio of the number of germinated seeds to the total number of seeds in each pot. The germination coverage was measured after 20 days as the maximum number of seeds could germinate within 20 days.

### 2.3.5. Cost analysis and CO<sub>2</sub> emissions analysis

The cost analysis aimed to assess the economic feasibility of using sulphoaluminate cement (SAC) and biochar in the proposed vegetation concrete relative to traditional Portland cement concrete. This analysis concentrated on material costs, considering the prices of SAC, biochar, sawdust, and other components. Labor costs were calculated based on the time required for mixing, placing, and curing the vegetation concrete, which were estimated according to standard rates in the construction industry. The costs associated with machinery usage included expenses for concrete mixers, curing equipment, and other necessary tools. Additional engineering works, such as site preparation, surface treatment, and slope stabilization, were considered to ensure the practical application of vegetation concrete. Cost information was sourced from local suppliers and market surveys to align with current industry standards.

There are three steps to the production of general-purpose concrete, which are as follows: the materials stage, the transportation stage, and the manufacturing stage [49]. In this research, the analysis employed a cradle-to-gate approach, and CO<sub>2</sub> emissions were solely evaluated from the materials. The CO<sub>2</sub> emissions of vegetation concrete were determined using a standard mix of 1 m<sup>3</sup>.

CO<sub>2</sub> emissions from the manufacturing of cement, sawdust, biochar, ferrous sulfate, and water are included in the materials stage as a source of vegetation concrete's primary ingredients. The CO<sub>2</sub> units for each item were used to compute the total amount of CO<sub>2</sub> released. Eq. (2) was used to determine CO<sub>2</sub> emissions at the material stage [49].

$$Em = \sum (EM * a) \quad (2)$$

Here, Em denotes the total CO<sub>2</sub> emissions (kg.CO<sub>2</sub>/m<sup>3</sup>) from the material stage, EM denotes the weight of each component material (kg) in the 1 m<sup>3</sup> porous vegetation concrete mix, and a denotes the CO<sub>2</sub> emissions from each material (Kg.CO<sub>2</sub>/Kg).

CO<sub>2</sub> emissions for each raw material are listed in Table 4. The amount of CO<sub>2</sub> emitted from Portland cement and sulfoaluminate cement represents the total CO<sub>2</sub> emissions at all stages in the cement production process. The amount of CO<sub>2</sub> emissions from the production of the Portland cement and sulfoaluminate cement was assumed 944 kg.CO<sub>2</sub>/ton and 644 kg.CO<sub>2</sub>/ton respectively [50,51]. Carbon dioxide is released from the soil through soil respiration, and the value of CO<sub>2</sub> emissions from soil was assumed 50.9 mg CO<sub>2</sub>/kg [52]. The CO<sub>2</sub> emissions during the production of sawdust were assumed 25.949 kg CO<sub>2</sub>/ton including all the production processes in the sawmill. Furthermore, biochar production through pyrolysis emits 0.273 tons CO<sub>2</sub>/ton [53]. The production of water causes a CO<sub>2</sub> emission of 0.332 kg CO<sub>2</sub>/ton [50].

## 3. Results and discussion

### 3.1. Effect of biochar and cement content on the porosity of vegetation concrete

Fig. 3 demonstrates the influence of biochar on the porosity of vegetation concrete, revealing that biochar significantly impacts the porosity (p) of vegetation concrete. The increase in biochar content increases the weight of the sample and a decrease in the porosity of the vegetation concrete linearly, for instance, the increase in biochar content from 0 % to 15 % results in a decrease in the porosity of

**Table 4**  
CO<sub>2</sub> Emission amounts of materials.

Material	CO <sub>2</sub> Emission Amounts (Kg.CO <sub>2</sub> /Kg)
Cement	0.644
Soil	0.0000509
Sawdust	0.02594
Biochar	0.273
Ferrous sulfate	0
water	0.000332

the concrete from 50 % to 34 %. The proposed correlation for the biochar used in the study with the porosity of vegetation concrete is  $p(\%) = -5.52 \text{ BC}(\%) + 55.95$  ( $R^2 = 0.98$ ). The decrease in the porosity of vegetation concrete with biochar could be due to its physical properties and interactions with other components in the mixture. When biochar is added to the concrete mix, it fills up some of the pore spaces that would otherwise be present. Additionally, biochar particles can create a more compact structure within the concrete matrix, reducing the overall void space available. As a result, the porosity of the vegetation concrete decreases as the biochar content increases. This decrease in the porosity of vegetation concrete with biochar is well-reported in the literature by many researchers [54]. The presence of biochar particles bound to certain cementitious materials may perform a function comparable to fine aggregate to some extent [55]. Zhao, et al. [48] reported that adding a small amount of fine particles or tiny coarse aggregates to vegetation concrete improves its performance. In contrast, some studies reported that the porosity of vegetation concrete treated with biochar increased significantly with time I-e., Liu et al. [56]. The reason may be that the activated additives greatly increased the species and quantity of microorganisms in vegetation concrete compared with ordinary soil. Moreover, the developed pore structure and adhesion ability of biochar provide favorable conditions for the growth and reproduction of many microorganisms.

Fig. 4 shows the effect of cement content on the porosity of vegetation concrete. The results indicate that similar to the impact of biochar on vegetation concrete, the increase in cement content in the vegetation concrete porosity decreases linearly. For instance, adding 4 % to the cement content in the vegetation concrete results in a decrease of porosity by 4.81 %. While further increasing the cement content in the vegetation concrete further reduces the porosity of the soil I-e., increasing the cement content from 4 % to 8 % results in an increase in the porosity of the vegetation concrete by 11 %. The addition of cement into vegetation concrete leads to a reduction in porosity due to cement functions as a binding agent, filling gaps between particles and resulting in a denser arrangement within the concrete mixture. Additionally, the hydration process of cement generates hydration products such as calcium silicate hydrates (C-S-H) and calcium hydroxide (CH), which further occupy pore spaces, contributing to decreased porosity. Moreover, the formation of cementitious bonds between cement and other components enhances the cohesion of the mixture, promoting a more compact and less porous material overall. As a result, the addition of cement effectively reduces the porosity of vegetation concrete by filling voids, producing hydration products that occupy pores, and enhancing the cohesion of the mixture.

### 3.2. Effect of biochar and cement content on the strength of vegetation concrete

The strength characteristics of vegetation concrete with different biochar content and cement content were evaluated by conducting unconfined compression strength (UCS) test. The UCS test results of specimens amended with 5 %, 10 %, and 15 % biochar content are shown in Fig. 5, while Fig. 6 shows the results of unconfined compressive strength of vegetation concrete with different cement content. The results indicated that an increase in biochar content significantly improved the unconfined compressive strength of vegetation concrete. When compared with the specimen with 0 % biochar content, the amendment using 5 %, 10 %, and 15 % biochar resulted in a 15.4 %, 39.3 % and 92 % increase in UCS, respectively. The curve fitting through the conducted UCS test indicates that the addition of biochar exponentially increases the UCS of the vegetation concrete. During the tests, it was observed that adding biochar enhanced the soil's elastic nature, resulting in some height rebound upon unloading. However, the addition of biochar weakens and brittles the specimens when subjected to tensile stress. This, along with a weak section, caused some specimens to collapse prematurely in the unconfined condition. The reason for these changes might be attributed to the biochar's rigid structure, which can withstand higher loads while being kept together by the soil material.

The results of the UCS of vegetation concrete at different cement content (CC) (Fig. 6) demonstrated that the UCS of vegetation concrete increased significantly with increasing the cement content. The substantial increase in peak axial stress was noticed as a result

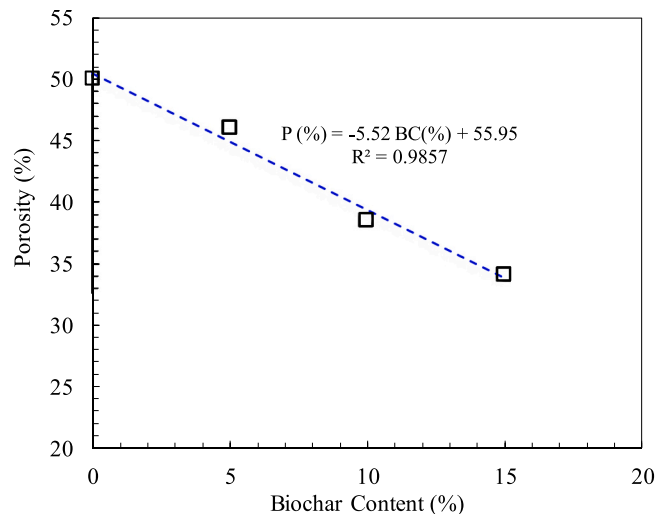


Fig. 3. : Effect of biochar content (BC) on porosity (p) of vegetation concrete.

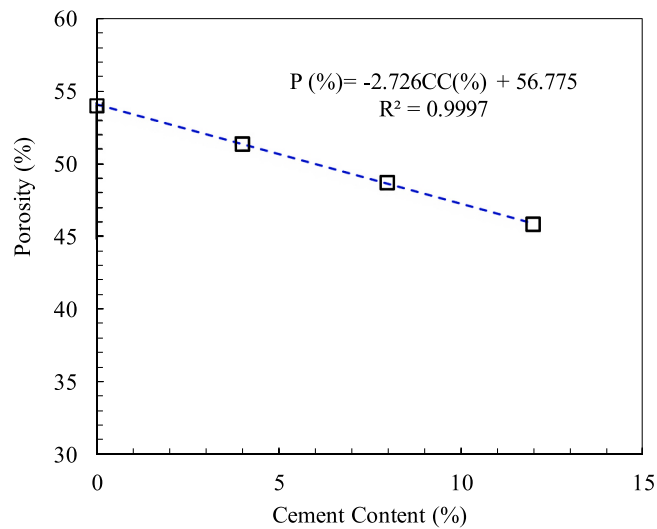


Fig. 4. Effect of cement content (CC) on porosity (p) of vegetation concrete.

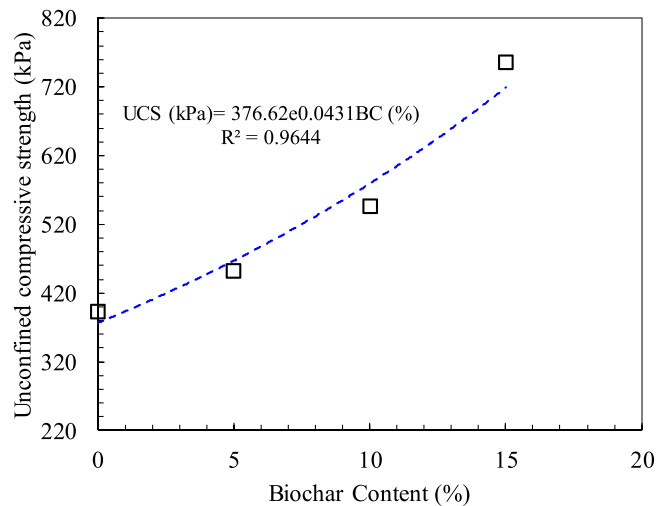


Fig. 5. : Effect of biochar content (BC) on unconfined compressive strength (UCS) of vegetation concrete.

of cement treatment. The cement stabilization increased UCS considerably while decreasing axial strains. Soil treated with cement is more brittle than untreated soil. Balasubramaniam, et al. [57] and Pakbaz and Alipour [58] also noted that the cement-treated soil specimens become more brittle at greater cement and lower water concentrations.

### 3.3. The influence of biochar and cement content overtime on the pH levels of vegetation concrete

The pH level of soil significantly impacts fertility and plant growth, serving as a crucial indicator reflecting soil characteristics [59]. As depicted in Fig. 7 there is a clear upward trend in the pH value of vegetation concrete as the biochar content increases. For instance, at 0 days, the addition of 4 % biochar into the vegetation concrete increases the pH from 8.77 to 8.94 (1.94 % increase), which further increases with an increase in biochar content. However, over the period of time, the pH values of samples containing 5 % and 10 % biochar content were lower than that of the specimen with 0 % biochar. Whereas the pH of the sample containing 15 % biochar content was relatively higher as compared to the vegetation concrete having 0 % biochar.

Fig. 7 also depicts that, over time, the pH value of each specimen exhibited a declining trend. For instance, the specimen with 0 % biochar at 0 days had having pH value of 8.77, which is decreased to 8.17 at 28 days (6.84 % decrease), while the specimen with 15 % biochar had a pH value of 9.25 at 0 days, which is reduced to 8.35 at 28 days (9.73 % decrease). The reason for the high pH value of vegetation concrete in the initial stage is that the cement hydration reaction will be completed within 10 h after adding water, accompanied by a large number of hydroxyl ions; with the end of the reaction, plant roots continuously secrete organic acids or

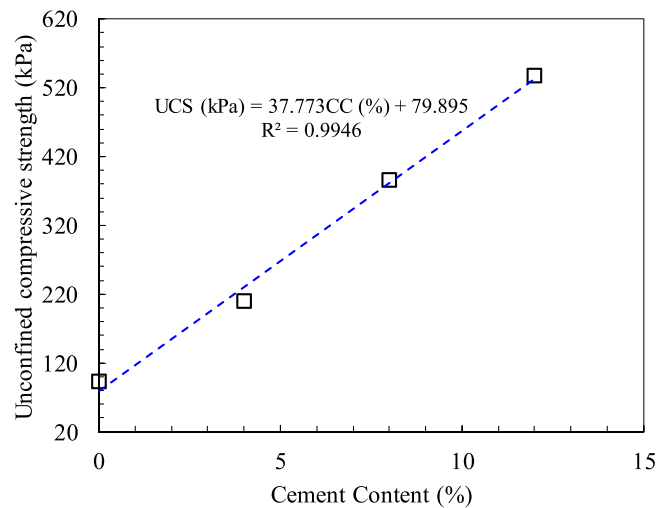


Fig. 6. Effect of cement content (CC) on unconfined compressive strength (UCS) of vegetation concrete.

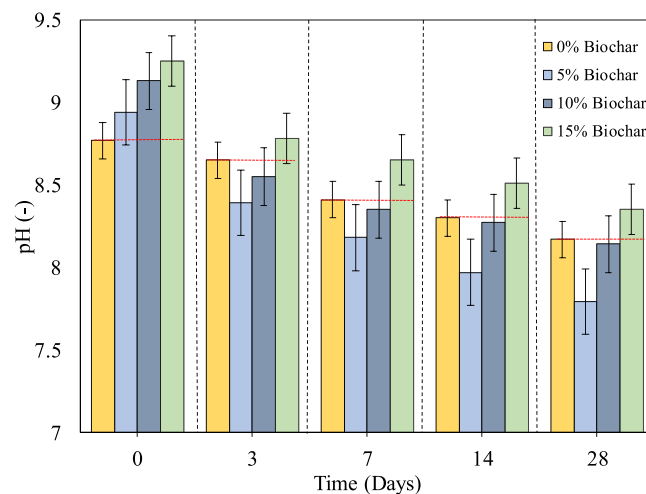


Fig. 7. : Effect of biochar content (BC) on pH of vegetation concrete with different curing age.

hydrogen ions during development [60]. At the same time, hydroxyl ions will also form more stable compounds with other cations in the sample, and then cooperate with the dilution of irrigation to reduce the concentration of hydroxyl ions, resulting in the continuous reduction of the pH value of vegetation concrete.

Fig. 8 shows the effect of cement content on the alkalinity of vegetation concrete. The figure depicts that the alkalinity of vegetation concrete is enhanced by increasing the cement content. By adding 4 % cement content to the soil at the age of 0 days, the pH value increased from 6.88 to 7.18 (4.38 % increase), which is further increased to 8.9 by increasing the cement content to 12 %. A similar trend of increase in pH of the soil with an increase in cement content was observed at other investigated curing times I-e., 3, 4, 14, and 28 days. This can be implied that cement increases the pH of the soil at any curing time.

Fig. 8 also shows that the pH of vegetation concrete significantly decreased with time. For instance, the vegetation concrete with 12 % cement content has having pH of 8.9 at 0 days curing time, which is reduced to 8.25 at 28 days curing time. The reason for this might be the curing of cement, which produces a decreasing amount of free OH<sup>-</sup>.

### 3.4. The influence of biochar and cement content on the growth of ryegrass

Fig. 9 illustrates the impact of varying biochar concentrations and cement content on ryegrass growth. Fig. 9(a) displays the ryegrass under different biochar concentrations, while the corresponding grass lengths at various growth stages are detailed in Table 5 and Fig. 10. The results indicates that biochar is having a significant impact on plant growth. The grass length exhibited a rising trend upon the addition of 5 % biochar content to the vegetation concrete. However, increasing the biochar content beyond 5 % negatively impact plant growth. Thus it can be implied from the experiment that within a certain range of biochar contents, the planting

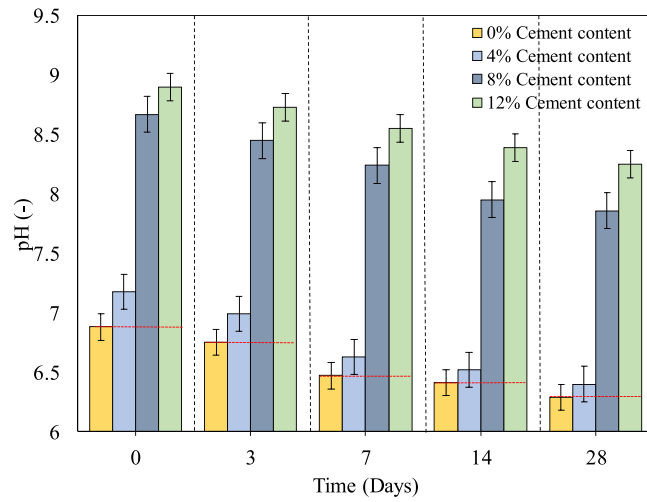


Fig. 8. : Effect of cement content on pH of vegetation concrete with different curing age.

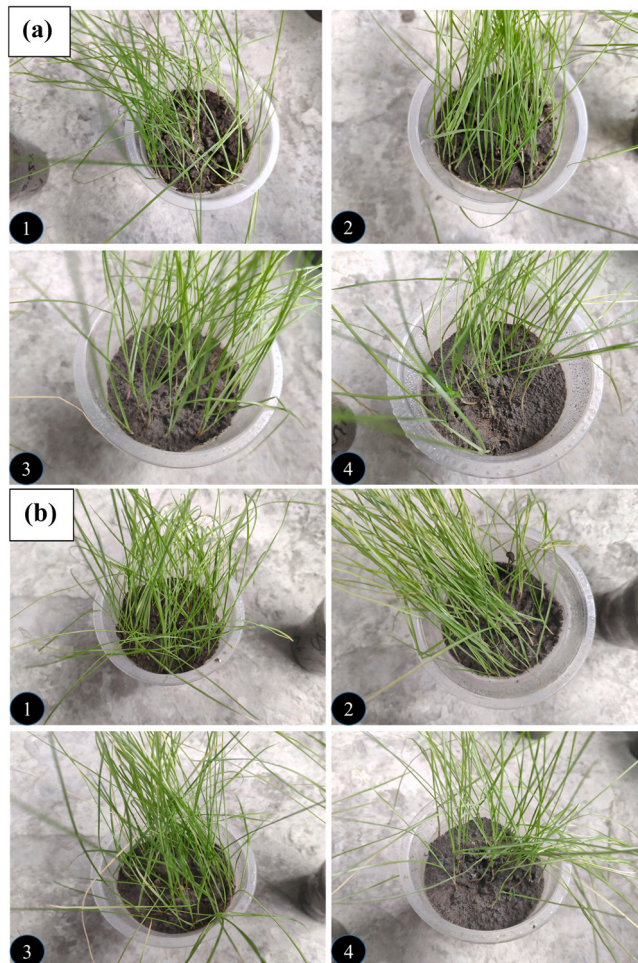


Fig. 9. : Effect of biochar and cement content on plant growth (a) Biochar content (1) 0 % (2) 5 % (3) 10 % (4) 15 % (b) Cement content (1) 0 % (2) 4 % (3) 8 % (4) 12 %.

properties of vegetation concrete will be improved to a point and will show a certain regularity. This is because the root system of the plant began to extend into the test block, and the presence of biochar helped the plant to grow. Chen et al. [61] reported similar results that the biomass of ryegrass reached the optimal value under 15 % biochar treatment and then decreased.

Furthermore, the application of biochar holds the potential to extend growth days [62]. Biochar has a large surface area and abundant micropore structures, which can enhance the water-holding capacity and nutrition maintenance of soil, improve the utilization efficiency of fertilizers, and thus promote the growth of ryegrass [62]. Evidence shows that although biochar contains low concentrations of nutrients such as nitrogen, phosphorus, and potassium, its stabilized pore structure can improve nutrient preservation capacity and nutrient utilization efficiency via increasing soil organic carbon, total nitrogen, available phosphorus, and ammonium [63].

Fig. 11 shows the germination coverage and plant height with different biochar content at a growth period of 30 days. Fig. 11 depicts that the germination coverage as compared to the specimen with 0 % biochar content was increased by 18.7 % and 8.3 % with 5 % and 10 % of biochar content respectively, whereas decreased by 8.3 % with 15 % of biochar content (Table 5). Fig. 11 also illustrates that the plant reached maximum growth at a biochar content of 5 % I-e., which increased from 23.4 cm to 25.6 cm, after which it declined I-e., decreased from 23.4 cm to 21.8 cm when biochar content increased to 15 %. This can be implied that the optimum biochar content for plant growth and germination is 5 %.

The influence of cement content on the growth of plants at different growth periods is shown in Fig. 12 and Table 6. It can be noted that the grass length decreased with increasing the cement content at all the growth period. However, the difference is negligible up to 8 % of the cement content, whereas the grass length significantly decreased with 12 % of cement content as compared to the specimen with 0 % cement content. Fig. 13 displays the effect of cement content on the germination coverage for a growth period of 30 days. The figure depicts that the germination coverage of the vegetation and plant height decreased with increasing the cement content at observation on 30 days of growth period I-e, the germination coverage decreases from 90 % to 87 % when the cement content is increased from 0 % to 4 %, which is further reduced to 62.86 % when the cement content is increased to 62.86 %. While the plant height is reduced from 23.4 cm to 22.4 with the addition of 4 % cement content which is further reduced to 20.8 cm by increasing the cement content to 12 %. The reason for this might be the addition of a higher amount of cement hardened the vegetation concrete samples and water could not reach to the seeds for sprouting the grass. Which also causes the low germination coverage of plants. The excess addition of cement makes it more difficult for plant roots to penetrate into the internal pores of vegetation concrete. Moreover, the higher amount of cement content makes the vegetation concrete more alkaline, which is also not suitable for plant growth.

However, in addition to the fact that biochar can improve the soil environment and promote the growth of plants, it also closes the pores of vegetation concrete and causes adverse results, including a reduced porosity and permeability coefficient. Therefore, 5 % of biochar content is suitable for the growth of plants considering the appropriate unconfined compressive strength (425.7Kpa) and porosity (46 %). Besides, the 8 % cement content is suitable for plants considering the appropriate porosity (48.7 %) and unconfined compressive strength (385.68Kpa) of samples. Based on all the properties analyzed in this research including porosity, unconfined compressive strength, alkalinity, and plant growth, the optimum mix design of vegetation concrete is shown in Table 7.

### 3.5. Effect of biochar and SAC cement on cost and CO<sub>2</sub> emission

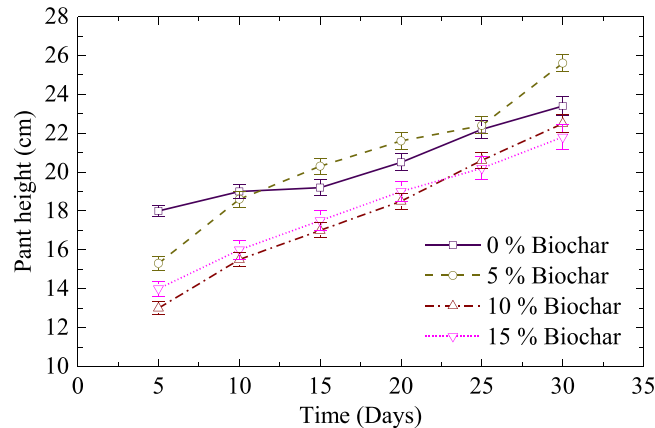
The cost analysis of the vegetation concrete application was evaluated as follows. The initial cost of the vegetation concrete was approximately 91.10 – 103.66 RMB/m<sup>2</sup> (US\$ 14.34 - US\$ 16.31/m<sup>2</sup>), as shown in Table 8, which was 66.2 % - 75.3 % of that of CBS vegetation concrete technique.

As described above, the initial cost of vegetation concrete was 91.10 – 103.66 RMB/m<sup>2</sup> (US\$ 14.34 - US\$ 16.31 per square meter), which was a little higher than that of the general vegetation works in China. However, the methods with cheaper prices usually are not applicable to the steep concrete-face slopes. Additional engineering treatments are needed. It should be noted that the application of the traditional methods does not ensure successful vegetation work, even if extra efforts are provided. The combined material cost for the proposed vegetation concrete was estimated between 5140 and 5516 RMB for 100 m<sup>2</sup>, compared to 6800–7200 RMB for traditional Portland cement concrete, reflecting a 24.7–33.8 % reduction in costs. This substantial reduction demonstrates the economic viability of the mix, highlighting the cost benefits of incorporating SAC and biochar.

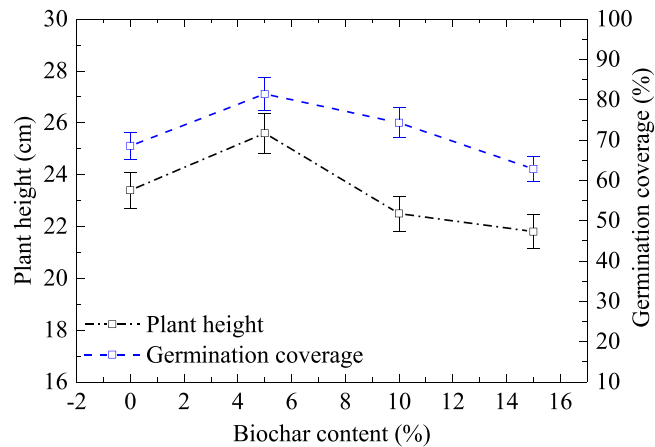
In this study, the LCA primarily focused on the material production stage, assessing CO<sub>2</sub> emissions related to the manufacturing of SAC, biochar, and other mix components. The CO<sub>2</sub> emissions for each raw material were calculated based on the optimum mix design of 1 m<sup>3</sup> of vegetation concrete. The results are shown in Fig. 14. CO<sub>2</sub> emissions for the included materials were highest for the cement, followed by biochar, sawdust, water, and soil. In this experiment, Portland cement was not used, however for comparison purposes, the CO<sub>2</sub> emissions data for Portland cement were included; when sulfoaluminate cement was used, CO<sub>2</sub> emissions were reduced by ~31.8 % versus Portland cement. Hanein et al. [51] reported that incorporating sulfoaluminate cement in concrete reduced CO<sub>2</sub> emissions by about 25–35 % compared to conventional Portland cement, aligning with the findings of this study. Similarly, Gartner and Sui [64] indicate that SAC's innovative clinker composition contributes to a 50–60 % reduction in carbon emissions during production, further validating its environmental benefits in concrete applications. The overall reduction of carbon dioxide emissions was 26.4 % in the optimum mix design. In the future, the use of sulfoaluminate cement in vegetation concrete would have a significant CO<sub>2</sub> emissions-reducing effect. Moreover, biochar is considered as soil additive, which contributes to an increase of carbon sequestration through the decrease of CO<sub>2</sub> production [65]. The biochar application in the vegetation concrete may mitigate climate change by reducing greenhouse gases (GHG) emissions and increasing soil C sequestration, but the precise effects of biochar application on soil GHG emissions remain controversial and vary among different studies [66,67]. Soil CO<sub>2</sub> fluxes have been shown to exhibit significant increases in some studies [68], while others report substantial decreases or negligible changes [69–71]. For example, biochar

**Table 5**  
The results of the plant growth based on different biochar content.

Sample ID	Grass length (cm)						Germination coverage (%) 30d
	5d	10d	15d	20d	25d	30d	
0 % BC	18	19	19.2	20.5	22.2	23.4	68.57
5 % BC	15.3	18.6	20.3	21.6	22.4	25.6	81.43
10 % BC	13	15.5	17	18.5	20.6	22.5	74.29
15 % BC	14	16	17.5	19	20.2	21.8	62.86



**Fig. 10.** : Effect of biochar content on grass length at different growth period.



**Fig. 11.** : Effect of biochar content on grass length and germination coverage at 30 days growth period.

application to paddy soils induces a 12 % increase in CO<sub>2</sub> emissions [72]. Another field experiment showed no significant effects of biochar application on soil CO<sub>2</sub> emissions in a pasture ecosystem [73]. Bovsun et al. [74] investigated the CO<sub>2</sub> flux in the field experiment with biochar application to clay soil and found 28.2 % reduction in CO<sub>2</sub> emissions using 3 kg/m<sup>2</sup>. Moreover, studies have shown that biochar-amended concrete can achieve CO<sub>2</sub> emission reductions of up to 40 %, depending on the biochar type and content. Additionally, biochar’s ability to enhance carbon sequestration and improve soil organic matter cycling has been noted in various LCAs, such as those by Liu et al. [75], which found that biochar can mitigate emissions significantly through soil integration. Thus, the impacts of biochar application are still uncertain due to these variable effects on soil GHG emissions. The LCA shows that using SAC and biochar reduces CO<sub>2</sub> emissions significantly, aligning with other studies and highlighting their potential in sustainable construction.

The conclusions of this study were primarily based on laboratory-scale experiments, which may not fully reflect the complexities of real-world environmental conditions and the long-term performance of vegetation concrete. Field trials and long-term monitoring could provide critical insights into the practical feasibility and effectiveness of the proposed mix proportions, particularly regarding slope stability, plant growth, and CO<sub>2</sub> emissions reduction. The study was limited to specific biochar types and low-alkaline

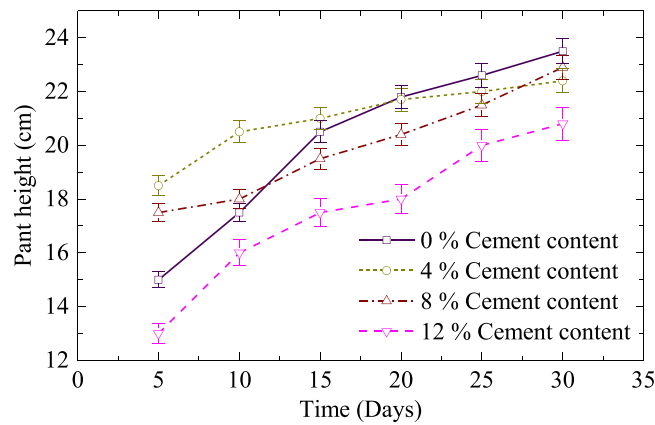


Fig. 12. : Effect of cement content on grass length at different growth period.

Table 6

The results of the plant growth based on different cement content.

No.	Grass length (cm)						Germination coverage (%) 30d
	5d	10d	15d	20d	25d	30d	
0 % Cement content	15	17.5	20.5	21.8	22.6	23.5	90
4 % Cement content	18.5	20.5	21	21.7	22	22.4	87
8 % Cement content	9.5	15	18	20.4	21.5	22.9	71.43
12 % Cement content	13	16	17.5	18	20	20.8	62.86

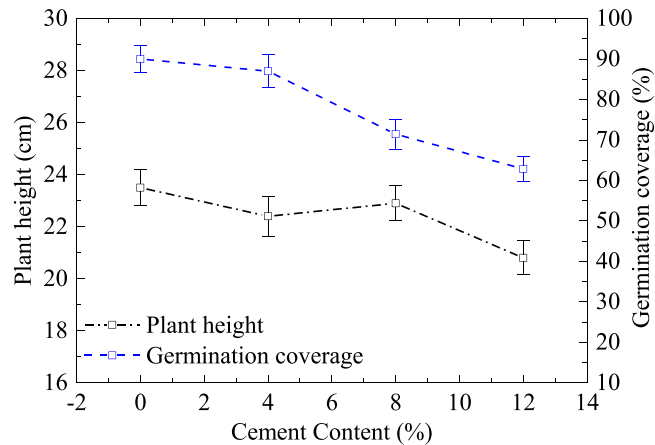


Fig. 13. : Effect of cement content on grass length and germination coverage at 30 days growth period.

Table 7

Optimum and economical mix proportion of vegetation concrete.

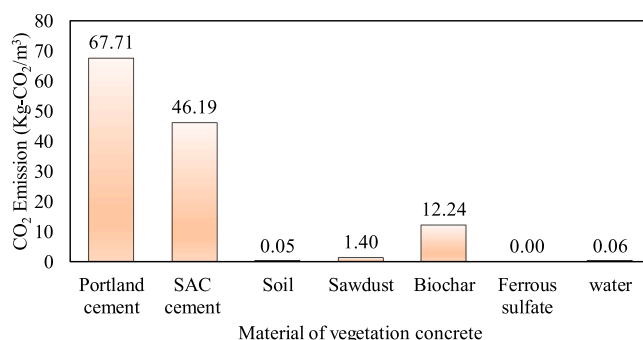
Soil (%)	Cement (%) (Low alkaline sulfoaluminate cement)	Sawdust (%)	Biochar (%)	Ferrous sulfate (%)	Water (%)
100	8	6	5	6	20.5

sulfoaluminate cement, which restricts the generalizability of the findings to other biochar varieties and low-carbon cement. The analysis focused on short-term effects, such as porosity, compressive strength, and plant growth, without considering long-term durability in diverse environmental conditions. Moreover, the environmental impact assessment was confined to the material stage, lacking a full life cycle assessment (LCA) that would account for transportation, manufacturing, and end-of-life phases.

Future research should address these limitations by incorporating field trials, comprehensive LCA studies, and exploring a wider range of biochar types, cements, plant species, and ecological contexts to enhance the robustness and generalizability of the results.

**Table 8**Initial cost analysis of vegetation concrete estimated for 100 m<sup>2</sup>.

Item	Description	Frequency of application	Unit: Chinese Yuan (RMB) (1US\$ = 6.355 RMB)
Initial cost	Material cost	Once	5140–5516
	Labor cost		2130 – 2500
	Machinery usage cost		620–900
	Additional engineering works		1220 – 1450
	Subtotal		9110 – 10,366 (US\$ 14.34 - US\$ 16.31/m <sup>2</sup> )

**Fig. 14.** : CO<sub>2</sub> emissions of material stage.

#### 4. Conclusion

In this study, extensive laboratory testing was carried out to examine the influence of cement and biochar content on vegetation concrete porosity, unconfined compressive strength (UCS), alkalinity, plant compatibility, and CO<sub>2</sub> emissions. The observations lead to the following conclusions:

- The addition of biochar and cement into the concrete significantly reduced the porosity of vegetation concrete and increased its UCS, increasing biochar content from 0 % to 15 % resulted in a 16 % reduction in porosity while increasing UCS by 92 % and increasing cement content from 0 % to 12 % led to an 11 % decrease in porosity and a substantial 200 % increase in UCS.
- The addition of both biochar and cement initially increased the pH of the vegetation concrete; however, over time, the pH demonstrated a declining trend. Further, at a biochar content of 5 % the vegetation concrete exhibited the lowest pH value at 28 days.
- Plant growth promotion and seed germination coverage increased with biochar content up to 5 %; however, with further increases in biochar content, both showed a gradual decline.
- The recommended optimal design mix for vegetated concrete, based on observations from laboratory testing, consists of 5 % biochar, 8 % low-alkaline sulfoaluminate cement, 6 % sawdust, and 6 % ferrous sulfate.
- The CO<sub>2</sub> emissions of the raw materials were highest for the cement, followed by biochar, sawdust, water, and soil. Sulfoaluminate cement showed a 31.8 % CO<sub>2</sub> emissions-reducing effect as compared to Portland cement. Whereas the overall reduction of carbon dioxide emissions was 26.4 % in the optimum mix design.
- The result of the cost analysis shows that the initial cost of the vegetation concrete was about 66.2 % - 75.3 % of that of the CBS vegetation concrete technique.

In the future, the use of sulfoaluminate cement in vegetation concrete could lead to significant reductions in CO<sub>2</sub> emissions. However, to evaluate the feasibility and effectiveness of the proposed mix proportions, field trials and monitoring are essential. Additionally, future research should take into account factors such as soil types, climate conditions, and vegetation species to gain a deeper understanding of their effects on slope stability, plant growth, and CO<sub>2</sub> emissions reduction.

#### Funding

This study was supported by Grant No. YUTP 015 LCO-550.

#### CRedit authorship contribution statement

**Mehtab Alam:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization, Supervision. **Serina Ng:** Writing – review & editing, Resources, Conceptualization. **Dennis Ling Chuan Ching:** Writing – review & editing. **Hamid Faiz:** Writing – original draft, Investigation, Formal analysis, Writing – review & editing. **Ilyas Khan:** Funding acquisition, Project

administration, Writing – review & editing. **Mohsen Bakouri:** Visualization, Writing – review & editing, Funding acquisition. **Mahfuzur Rahman:** Writing – review & editing, Validation. **Faisal Javed:** Writing – review & editing.

### Declaration of Competing Interest

I acknowledge that no conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all the authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

### Acknowledgements

The author Mohsen Bakouri extends the appreciation to the Deanship of Postgraduate Studies and Scientific Research at Majmaah University for funding this research work through the project number (R-2024-1361). The authors thankfully acknowledge the support provided by the National Natural Science Foundation of China (Grant No. 42350410441). The authors are also thankful to editors and reviewers for their valuable comments, which helped to improve the quality of the paper.

### Data Availability

Data will be made available on request.

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