WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal Homepage: www.ijrpr.com ISSN 2582-7421

Performance-Based Multi-Objective Optimization of Biochar-Modified Recycled Aggregate Vegetation Concrete Using AI

N. Yasaswini Bhavya[1], P. Gnana Jyothi[2], P. Archana[3], R. Manmadha[4], Dr. G. Ganesh Prabhu[5]

1,2,3,4 Third-Year B.Tech Students, Department of Civil Engineering, GMR Institute of Technology (Deemed to be University), Rajam, Vizianagaram, Andhra Pradesh, India

5 Academic Dean and Professor, Department of Civil Engineering, GMR Institute of Technology (Deemed to be University), Rajam, Vizianagaram, Andhra Pradesh, India

** E-mail: gnanajyotipathina@gmail.com*

A B S T R A C T

Vegetation concrete is an eco-friendly porous material used for slope protection, soil-erosion control and plant-growth support. Its interconnected voids allow water and air to pass and provide space for root development, but conventional mixes can be limited in compressive strength, water retention and durability. This term paper reviews how recycled aggregates (RA) from construction and demolition waste and biochar can improve vegetation concrete while reducing its environmental impact, and proposes an Artificial Intelligence (AI) based framework for optimizing biochar-modified recycled aggregate vegetation concrete (BRAVC). The framework uses machine-learning models (Random Forest, XGBoost and Artificial Neural Networks) trained on experimental and literature data to predict compressive strength, porosity, permeability, pH and plant-growth performance. The Non-dominated Sorting Genetic Algorithm II (NSGA-II) is then used for multi-objective optimization, and TOPSIS ranks the resulting Pareto-optimal mixes. Findings from the reviewed studies indicate typical vegetation-concrete design ranges of 25–30% porosity, pH 8–10 and a water–cement ratio of 0.30–0.35, and that about 1–5% biochar replacement is commonly reported as beneficial, while excessive biochar reduces strength and workability. Laboratory validation of the predicted optimum mix is proposed to confirm model reliability.

Keywords: Biochar, recycled aggregate, vegetation concrete, Artificial Intelligence, multi-objective optimization, NSGA-II, TOPSIS, compressive strength, sustainability.

1. INTRODUCTION

Porous vegetation (planting) concrete is used for slope protection, riverbank stabilization, embankments and erosion control because its void structure supports water flow, air exchange and root growth [6]. Its design is a balancing act: excessive porosity lowers strength, whereas insufficient porosity impedes water movement and root penetration [6]. At the same time, the construction industry generates large volumes of construction and demolition waste (CDW) and consumes large quantities of natural aggregate, which motivates the use of recycled aggregates [4, 5].

Biochar, a carbon-rich material produced by pyrolysis of organic matter under limited oxygen, has a porous structure that can influence water retention, strength and durability of cementitious materials [12, 14]. Combining biochar and recycled aggregates in vegetation concrete is therefore attractive, but the interacting effects of aggregate quality, biochar dosage, porosity and water–cement ratio make trial-and-error mix design costly. AI and multi-objective optimization offer a systematic route to predict performance and select balanced mixes [1, 3, 13, 14].

1.1 Purpose of the study

This study seeks to enhance the performance and sustainability of vegetation concrete by adding biochar and recycled aggregates and by applying AI for optimization. It aims to determine material proportions that balance concrete strength, water movement, water retention and plant growth, for use in slope protection, erosion control, embankments and other sustainable civil-engineering applications.

1.2 Objectives

- To evaluate how biochar and recycled aggregates influence compressive strength, porosity, water absorption, permeability, water retention and plant growth.
- To reduce reliance on natural aggregates by using CDW-derived aggregates.

- To build AI models from experimental data that forecast concrete properties for various mix designs.
- To apply NSGA-II to find material combinations that balance mechanical strength, hydraulic performance, vegetation needs and environmental sustainability, and to use TOPSIS to rank alternatives.
- To validate the optimized mix experimentally and quantify prediction error.

2. LITERATURE REVIEW

2.1 Vegetation concrete

Vegetation concrete is a porous material whose void structure permits water and air flow and creates space for root development. Earlier investigations address mix design, porosity, compressive strength, pH and suitability for various plant species, and show that balancing mechanical strength with vegetation needs is essential [6]. Reviews report typical design ranges of 25–30% porosity, pH 8–10 and a water–cement ratio of 0.30–0.35 [6]. The alkalinity of cement paste is a particular obstacle: fly ash and silica fume have been shown to reduce alkalinity and improve plant root length and leaf relative water content by 7.91% and 4.95%, with silica fume also improving strength [20]. Spent coffee grounds improved water absorption and sustained water release and moderated root-zone alkalinity, although higher dosages weakened the cementitious skeleton [16].

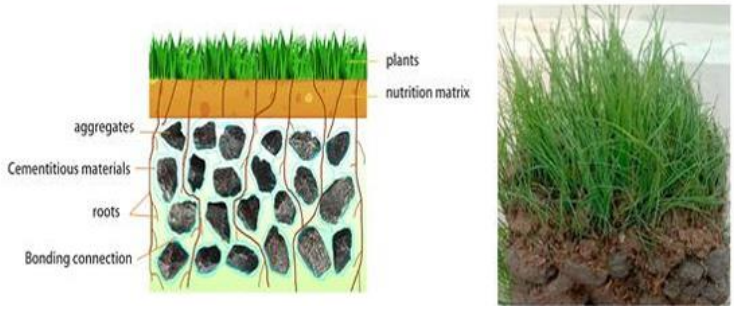


Fig. 1. Vegetation concrete (adapted from Rao & Shi [21])

2.2 Recycled aggregate concrete

Recycled aggregates derived from CDW can replace natural aggregates, lowering waste disposal and resource consumption. They usually retain attached mortar and absorb more water than natural aggregates, with the effect varying with source and processing [4, 5]. Reported average water absorption values are 5.13% [4] and about 4.9% for recycled concrete aggregate [5]. Batch variability is significant: across 12 industrial batches, mixed recycled aggregate concrete showed 22.8% higher permeability and 46.8% higher porosity but 28.9% lower compressive strength than the natural-aggregate control [18]. Mix design must therefore account for both aggregate quality and substitution level.

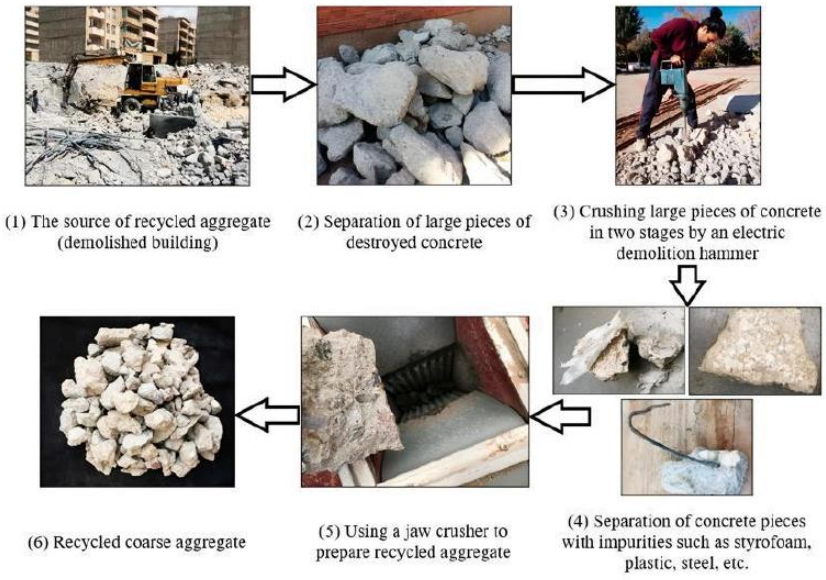


Fig. 2. Production of recycled aggregate from demolition waste (adapted from Ulsen et al. [22])

2.3 Biochar-modified concrete

The influence of biochar depends on its feedstock, production temperature, particle size and dosage. Appropriate amounts can yield benefits, whereas excessive quantities impair workability and compressive strength [12]. For sawdust-biochar concrete, an optimal cement replacement of about 1–5% is reported, with higher contents reducing strength and workability [14], and about 2% biochar was reported as useful in a biochar–recycled-fibre composite [7]. A nutrient-rich biochar eco-concrete achieved 10.5 MPa strength with about 27% porosity and pH 9.7 [2], and biochar pervious concrete reached 14.7 MPa with 27.3% porosity and 4.21 mm/s permeability, with reported emissions reduced by 21.6% [10]. In recycled-aggregate systems, 5% coconut-shell biochar raised the compressive strength of a geopolymer concrete from 79.6 to 85.6 MPa, and 25% recycled concrete aggregate raised it further to 87.2 MPa [17]; sugarcane-bagasse biochar refined pore structure and improved durability [19]. Biochar also increases soil water content (132.3% for wheat-straw biochar, a soil-test result) [9]. Marine field tests found no significant ecotoxicological response at up to 10 wt.% biochar, but these results should not be assumed to transfer to vegetation concrete [15].

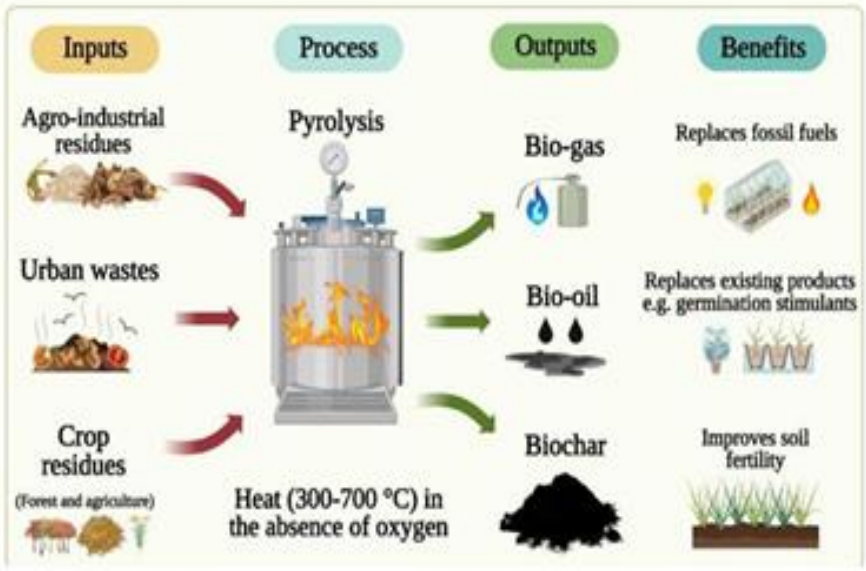


Fig. 3. Manufacturing of biochar by pyrolysis (300–700 °C, absence of oxygen)

2.4 AI in concrete technology

Machine-learning models such as Artificial Neural Networks, Random Forest, Support Vector Regression and XGBoost can predict compressive strength and permeability and reduce the number of experimental trials needed, although accuracy depends on data quality, quantity and scope. An explainable machine-learning study of planting concrete reported R^2 of 0.93 for pH, 0.97 for porosity and 0.94 for strength [1], and AI-based mix design of recycled aggregate concrete identified alternatives with strengths of 37.0–67.4 MPa [3]. A hybrid XGB–HistGB model reached a testing R^2 of 0.958 for predicting strength, cost and embodied CO_2 of biochar concrete, and partial-dependence analysis showed that biochar dosage needs careful optimization [14]. For recycled aggregate concrete, LightGBM reached $R^2 = 0.9523$ for compressive strength, and the AGE-MOEA-II algorithm combined with hybrid AHP–TOPSIS was used for multi-objective optimization and decision-making [13]. Experimental testing remains necessary to validate predictions.

2.5 Multi-objective optimization

Enhancing one property of vegetation concrete often degrades another, so mix selection involves balancing strength, porosity, permeability, water retention, plant growth, cost and CO_2 emissions. NSGA-II generates a set of Pareto-optimal solutions, and TOPSIS ranks these alternatives against chosen criteria to identify a preferred mix, supporting systematic decision-making in sustainable mix design.

2.6 Summary

The literature indicates that recycled aggregates reduce waste, biochar can influence water retention and concrete properties, and vegetation concrete must balance strength with plant growth. AI and multi-objective optimization provide tools for forecasting performance and selecting mix proportions. No reviewed study combines all of these elements for BRAVC, which defines the gap addressed here.

3. METHODOLOGY

The proposed methodology has eight stages: material selection, mix preparation, property testing, data preparation, AI modelling, multi-objective optimization, optimum-mix selection and experimental validation.

3.1 Material selection and characterization

Materials are cement (binder), recycled aggregates from processed CDW, biochar as a supplementary material, water, admixtures for workability as needed, and a growing medium with seeds to assess vegetation performance.

3.2 Preparation of concrete mixes

Several mixes are produced by varying the percentages of recycled aggregate and biochar while keeping the remaining ingredients within comparable limits. A reference mix with natural aggregate and no biochar provides a baseline. Quantities of all components are documented, and specimens are cast and cured under controlled conditions.

3.3 Testing of concrete properties

Table 1. Properties tested and their purpose

Property	**Purpose**
Compressive strength	Load-bearing capacity
Porosity	Amount of void space
Water permeability	Ease of water passage
pH	Alkalinity and suitability for vegetation
Plant growth	Seed germination and plant growth
Cost and CO_2	Economic and environmental performance

3.4 Data collection and preparation

Experimental results from all mixes are collected and supplemented with data from the reviewed papers where data and testing conditions are comparable. Data are organized into input and output variables, checked for missing values, errors and inconsistent units, and divided into training and testing sets.

3.5 Development of AI models

Table 2. Input and output variables

Input variables	**Output variables**
Cement content	Compressive strength
Recycled aggregate %	Porosity
Biochar %	Water permeability
Water–cement ratio	pH
Admixture content	Plant growth performance
Aggregate properties, curing age	—

Random Forest, XGBoost and ANN models are tested, and predictions are compared with experimental results using R^2 and RMSE; the model giving reliable predictions is selected.

3.6 Multi-objective optimization

The selected model predicts the performance of candidate mixes, and NSGA-II is applied to identify combinations of recycled aggregate, biochar, water and cement that simultaneously balance the objectives. The final mix must meet both strength and vegetation requirements.

3.7 Selection of the optimum mix

Optimized mixes are compared on predicted performance, and TOPSIS is applied if needed to rank the alternatives. The mix offering the best compromise among strength, permeability, vegetation performance, cost and environmental impact is chosen.

3.8 Experimental validation

A fresh batch is produced at the chosen proportions and tested in the laboratory. Experimental results are compared with AI predictions, prediction errors are computed, and the mix or model is adjusted if required performance is not met.

4. RESULTS AND DISCUSSION

This paper is a literature-based study; the experimental programme and AI modelling are proposed rather than completed. Table 3 therefore summarizes numerical results reported in the reviewed studies and their relevance to BRAVC. These values are specific to the materials and test conditions of each study and must not be treated as results of the present work.

Table 3. Key results reported in the reviewed literature

Focus	Reported result	Ref.
AI prediction, planting concrete	R^2 = 0.93 (pH), 0.97 (porosity), 0.94 (strength)	[1]
Biochar eco-concrete	10.5 MPa; ~27% porosity; pH 9.7; 5.51 mm/s permeability	[2]
AI mix design, RAC	Strength 37.0–67.4 MPa across optimized alternatives	[3]
RA review	Average water absorption 5.13%	[4]
RCA production	RCA absorption about 4.9%	[5]
Planting concrete review	25–30% porosity; pH 8–10; w/c 0.30–0.35	[6]
Biochar + recycled fibres	~2% biochar useful; resistivity reduced ~70%	[7]
Nutrient aggregates	High porosity improved water retention; lower porosity improved fertility	[8]
Straw biochar (soil)	Soil water content +132.3%	[9]
Biochar pervious concrete	14.7 MPa; 27.3% porosity; 4.21 mm/s; emissions −21.6%	[10]
ML, RAC	LightGBM R^2 = 0.9523 (strength), 0.9286 (carbonation depth); XGBoost R^2 = 0.8985 (charge passed)	[13]
ML, biochar concrete	XGB–HistGB testing R^2 = 0.958 (strength, cost, CO_2); 1–5% replacement reported optimal	[14]
Marine concrete	Up to 10 wt.% biochar: no significant ecological change in 6-month test	[15]
Spent coffee grounds	Better water release and plant compatibility; high dosage weakened skeleton	[16]
Biochar + RCA geopolymer	79.6 → 85.6 MPa (5% biochar); 87.2 MPa (+25% RCA)	[17]
MRA batch variability	+22.8% permeability, +46.8% porosity, −28.9% strength vs. control	[18]
Bagasse biochar in RAC	Improved strength and durability; refined pore structure	[19]
Fly ash/silica fume	Root length +7.91%; leaf water content +4.95%	[20]

4.1 Discussion

- **Strength versus porosity.** Reported vegetation-type concretes cluster around 25–30% porosity with strengths of roughly 10–15 MPa [2, 6, 10], confirming the trade-off between ecological function and strength.
- **Biochar dosage.** Benefits are most often reported at low dosages (about 1–5%), and higher dosages risk reduced workability and strength [12, 14]; spent-coffee-ground work shows the same pattern for another porous organic additive [16].
- **Recycled aggregate quality.** Higher absorption and batch-to-batch variability [4, 5, 18] make absorption checks, fresh-density monitoring and hardened-concrete testing necessary in BRAVC mix design.
- **Combining biochar and RA.** Geopolymer results show biochar and RCA can jointly increase strength and cut carbon footprint [17], but the values apply to that mixture only.
- **AI suitability.** High R^2 values for pH, porosity and strength [1], and for strength of recycled-aggregate and biochar concretes [13, 14], support the use of ML for BRAVC, provided models are trained on data comparable to the target mixes.
- **Evidence limits.** Some evidence is indirect (soil water retention [9], wastewater treatment [11], marine exposure [15]) and cannot be assumed to apply to vegetation concrete.

5. PROBLEM STATEMENTS

- How can recycled aggregates and biochar be combined in vegetation concrete while maintaining sufficient compressive strength?
- How do recycled aggregate content, biochar percentage, porosity and water–cement ratio affect mechanical, hydraulic and vegetation performance?
- How can Random Forest, XGBoost and ANN models predict the strength, porosity and pH of BRAVC?
- How can multi-objective optimization balance compressive strength, permeability, plant growth, cost and CO_2 emissions?
- How can AI-predicted results be verified through laboratory testing?
- How can the combined use of recycled aggregates, biochar and AI-based optimization improve resource efficiency and reduce environmental impact?

6. CONCLUSION

Recycled aggregates can reduce CDW and the demand for natural aggregates, but their higher water absorption and variable quality must be considered in mix design. Biochar has the potential to improve certain concrete properties and support plant growth depending on its type and dosage, and vegetation concrete requires an appropriate balance between strength, porosity and permeability. Previous studies show that AI can predict compressive strength, pH and porosity with good accuracy, and multi-objective optimization can identify mixes that balance strength, permeability, plant growth, cost and CO_2 emissions. Combining recycled aggregates, biochar and AI may therefore improve the sustainability and performance of vegetation concrete.

However, results of previous studies cannot be applied directly to every BRAVC mixture because material properties and testing conditions vary. Further laboratory work is needed to evaluate different biochar and recycled aggregate proportions and to validate AI predictions. The proposed research aims to identify an optimized BRAVC mix providing suitable mechanical strength, hydraulic performance, vegetation support and environmental benefits.

REFERENCES

[1] Duan, X., Zhang, M., & Zhou, R. (2026). Evaluating parameter influences on planted concrete properties via explainable machine learning models. Applied Sciences, 16(2), 761.

[2] Zeng, H., et al. (2025). A novel nutrient-rich biochar modified eco-concrete with simultaneously enhanced mechanical and planting performance. Case Studies in Construction Materials, 23, e05382.

[3] Mohammadi Golafshani, E., Kim, T., Behnood, A., Ngo, T., & Kashani, A. (2024). Sustainable mix design of recycled aggregate concrete using artificial intelligence. Journal of Cleaner Production, 442, 140994.

[4] Piccinali, A., Diotti, A., Plizzari, G., & Sorlini, S. (2022). Impact of recycled aggregate on the mechanical and environmental properties of concrete: A review. Materials, 15(5), 1818.

[5] Pacheco, J., & de Brito, J. (2021). Recycled aggregates produced from construction and demolition waste for structural concrete: Constituents, properties and production. Materials, 14(19), 5748.

[6] Liu, Y., Wang, B., Qian, Z., Yu, J., Shi, T., Fan, Y., Zhou, Y., Ning, Y., & Zhou, X. (2024). State-of-the-art on preparation, performance, and ecological applications of planting concrete. Case Studies in Construction Materials, 20, e03131.

[7] Mobili, A., et al. (2023). Biochar and recycled carbon fibres as additions for low-resistive cement-based composites exposed to accelerated degradation. Construction and Building Materials, 376, 131051.

[8] Yang, Y., et al. (2024). Mechanical and vegetative performance of ecological concrete with nutrient aggregates. Case Studies in Construction Materials, 20, e03210.

[9] Huang, C., et al. (2024). Properties of biochars derived from different straw at 500°C pyrolytic temperature: Implications for their use to improving acidic soil water retention. Agricultural Water Management, 301, 108953.

[10] Bualuang, T., et al. (2025). Corn waste-derived biochar as a sustainable fine aggregate in pervious concrete for climate-resilient urban pavement applications. Developments in the Built Environment, 23, 100735.

[11] Mnyango, J. I., & Hlangothi, S. P. (2026). Biochar for wastewater remediation and circular water management in low-resource settings. Biomass Futures, 4, 100074.

[12] Barbhuiya, S., Das, B. B., & Kanavaris, F. (2024). Biochar-concrete: A comprehensive review of properties, production and sustainability. Case Studies in Construction Materials, 20, e02859.

[13] Zhao, Z., Liu, Y., Lu, Y., Wu, K., Meng, Y., Wang, Z., & de Brito, J. (2026). Strength and durability prediction and multi-objective mix design optimization of recycled aggregate concrete based on machine learning. Case Studies in Construction Materials, 24, e06111.

[14] Uddin, M. A., Sobuz, M. H. R., Ghalla, M., Kabbo, M. K. I., Khatun, M., Lal, R., Hossain, M., & Abubakar, S. A. (2026). Mechanical assessment with data-driven hybrid machine learning-based optimization of compressive strength of sustainable biochar-concrete composite. Scientific Reports (in press). https://doi.org/10.1038/s41598-026-59827-7

[15] Piccardo, M., et al. (2025). Biochar-based concrete as biocompatible building material for marine artificial structures. Journal of Environmental Management, 394, 127518.

[16] He, M., et al. (2026). Spent coffee grounds as a multifunctional modifier for vegetation concrete: Coupled regulation of water retention, alkalinity and plant growth compatibility. Developments in the Built Environment, 27, 101026.

[17] Xie, Y. (2026). Development of a carbon-negative geopolymer concrete with biochar and recycled concrete aggregates: Mechanical properties, resistance to thermal fatigue, and carbon footprint. Powder Technology, 483, 122842.

[18] Gratão, U., Simão, L., & Innocentini, M. D. M. (2026). Industrial batch variability and quality control of mixed recycled aggregates for pervious concrete. Construction and Building Materials in Transportation, 3, 100025.

[19] Ahamed, M. L., Rayeesulhaq, M. R., Khushnood, R. A., Kanwal, M., & Khan, H. A. (2026). Enhanced durability of recycled aggregate concrete with sugarcane bagasse biochar. Next Materials, 13, 103224.

[20] Ganapathy, G. P., et al. (2023). Effects of fly ash and silica fume on alkalinity, strength and planting characteristics of vegetation porous concrete. Journal of Materials Research and Technology, 24, 5347–5360.

[21] Rao, C., & Shi, M. (2023). Research and application progress of vegetation porous concrete. Materials, 16(21), 7039.

[22] Ulsen, C., et al. (2019). Concrete aggregates properties crushed by jaw and impact secondary crushing. Journal of Materials Research and Technology, 8(1), 494–502.