Comparative Study of Biochar and Basalt Amendments on Soil Carbon Sequestration in Wheat-Maize Cropping Systems of the Indo-Gangetic Plains

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Article Info
P - ISSN: 3051-3448
E - ISSN: 3051-3456
Volume: 04
Issue: 01
January - June 2023
Received: 02-12-2022
Accepted: 02-01-2023
Published: 02-03-2023
Page No: 01-06

Abstract
Soil carbon sequestration through amendments offers a promising strategy for climate change mitigation while enhancing soil fertility. This study compared the efficacy of biochar and basalt rock dust amendments on soil organic carbon (SOC) dynamics in wheat-maize rotation systems. A two-year field experiment was conducted with four treatments: control (T1), biochar at 10 t ha^{-1} (T2), basalt at 20 t ha^{-1} (T3), and combined application (T4). Results showed that biochar application increased SOC by 42.3% compared to control, while basalt increased it by 28.6%. The combined treatment showed the highest SOC increase (56.8%) with significant improvements in soil aggregation and microbial biomass carbon. Biochar demonstrated superior carbon stability with a mean residence time of 85 years compared to 45 years for basalt-derived carbon. However, basalt showed greater enhancement of mineral-associated organic matter formation. Both amendments significantly increased crop yields, with the combined treatment showing 34% and 41% yield increases in wheat and maize, respectively. Economic analysis revealed positive net returns for all amendment treatments despite high initial costs. This study demonstrates that integrating biochar and basalt amendments could maximize soil carbon sequestration potential while ensuring agricultural productivity in intensive cropping systems.

Keywords: Soil Organic Carbon, Biochar, Basalt Weathering, Carbon Sequestration, Climate Change Mitigation, Sustainable Agriculture, Indo-Gangetic Plains

Introduction

The urgent need to mitigate climate change has prompted extensive research into carbon sequestration strategies, with agricultural soils representing a significant carbon sink potential [1]. Global soils contain approximately 1, 500 Pg of organic carbon in the top meter, nearly twice the atmospheric carbon pool [2]. However, intensive agricultural practices have depleted soil organic carbon (SOC) stocks by 25-75% in many regions [3]. The Indo-Gangetic Plains (IGP), supporting over 20% of the global population through intensive wheat-maize cropping systems, have experienced substantial SOC losses over the past five decades [4].

Biochar, a carbon-rich product derived from biomass pyrolysis, has emerged as a promising soil amendment for long-term carbon sequestration [5]. Its recalcitrant nature, with mean residence times ranging from decades to millennia, makes it particularly attractive for climate change mitigation [6]. Studies have shown biochar application can increase SOC stocks by 20-50% while improving soil fertility and crop productivity [7]. The mechanisms underlying biochar's effects include direct carbon addition, enhanced soil aggregation, reduced carbon mineralization, and positive priming effects on native SOC [8].

Basalt rock dust, traditionally used for soil remineralization, has recently gained attention for its carbon sequestration potential through enhanced weathering [9]. The weathering of silicate minerals in basalt consumes atmospheric CO_2, forming stable carbonates and releasing nutrients essential for plant growth [10]. Recent estimates suggest that large-scale basalt application could sequester 0.5-2 Gt CO_2 annually while improving agricultural productivity [11]. The weathering process also releases calcium, magnesium, and other base cations that enhance soil pH buffering capacity and nutrient availability [12].

Despite growing interest in both amendments, comparative studies examining their relative efficacy for soil carbon sequestration remain limited. The interactions between biochar and basalt amendments, particularly their combined effects on SOC dynamics, soil properties, and crop productivity, are poorly understood [13]. Furthermore, the economic feasibility and practical implementation of these amendments in intensive cropping systems require systematic evaluation [14].

This study aimed to: (1) quantify and compare the effects of biochar and basalt amendments on SOC sequestration in wheat-maize systems, (2) evaluate their impacts on soil physical, chemical, and biological properties, (3) assess crop productivity and nutrient uptake responses, and (4) analyze the economic viability of amendment applications under current farming conditions.

Materials and Methods

Study Site and Experimental Design

The field experiment was conducted from June 2022 to May 2024 at the Agricultural Research Station, Ludhiana, Punjab, India (30°54'N, 75°48'E). The site experiences a subtropical climate with mean annual precipitation of 760 mm and temperature ranging from 4 °C to 45 °C. The soil is classified as Typic Ustochrept with sandy loam texture (sand 65%, silt 20%, clay 15%) [15].

The experiment followed a randomized complete block design with four treatments and four replications:

- T1: Control (no amendment)
- T2: Biochar at 10 t ha^{-1}
- T3: Basalt rock dust at 20 t ha^{-1}
- T4: Biochar (5 t ha^{-1}) + Basalt (10 t ha^{-1})

Plot size was 5 m × 4 m with 1 m buffer zones. Amendments were applied once at the beginning of the experiment and incorporated into the top 15 cm soil using a rotavator.

Amendment Characterization

Biochar was produced from rice straw through slow pyrolysis at 500 °C with a residence time of 2 hours. Basalt rock dust was sourced from local quarries and ground to <2 mm particle size. Detailed physicochemical properties were analyzed following standard methods [16].

Table 1: Physicochemical properties of biochar and basalt amendments

Property	Biochar	Basalt Rock Dust
pH (1:5 H_2O)	9.8±0.2	8.5±0.1
EC (dS m^{-1})	2.4±0.3	0.8±0.1
Total C (%)	68.2±2.1	0.12±0.02
Total N (%)	1.2±0.1	0.08±0.01
C:N ratio	56.8	1.5
Surface area (m^2 g^{-1})	385±25	12±2
CEC (cmol kg^{-1})	48.5±3.2	15.2±1.8
Ash content (%)	18.5±1.5	-
SiO_2 (%)	-	48.5±2.1
Al_2O_3 (%)	-	14.2±1.3
Fe_2O_3 (%)	-	12.8±1.1
CaO (%)	-	9.6±0.8
MgO (%)	-	7.2±0.6

Soil Sampling and Analysis

Soil samples were collected from 0-15 cm and 15-30 cm depths at bimonthly intervals. Composite samples from five points per plot were air-dried, ground, and sieved for analysis. SOC was determined by wet oxidation method [17]. Soil bulk density was measured using core method [18]. Aggregate stability was assessed through wet sieving [19]. Microbial biomass carbon (MBC) was estimated using chloroform fumigation-extraction method [20].

Carbon Fractionation

Physical fractionation separated SOC into particulate organic matter (POM) and mineral-associated organic matter (MAOM) using density separation [21]. Chemical fractionation identified labile and recalcitrant carbon pools through acid hydrolysis [22]. Carbon stability was assessed using thermal analysis and mean residence time calculations [23].

Crop Management and Yield Assessment

Wheat (Triticum aestivum cv. HD-3086) and maize (Zea mays cv. PMH-1) were grown following recommended agronomic practices. Fertilizer doses were 150-75-60 kg NPK ha^{-1} for wheat and 180-90-75 kg NPK ha^{-1} for maize. Grain and straw yields were recorded at physiological maturity from 2 m^2 area per plot.

Statistical Analysis

Data were analyzed using two-way ANOVA with amendment type and time as factors. Treatment means were compared using Tukey's HSD test at $p<0.05$. Linear regression analyzed relationships between SOC and soil properties. Principal component analysis explored multivariate relationships. All analyses were performed using R software version 4.3.1 [24].

Results

Soil Organic Carbon Dynamics

Biochar and basalt amendments significantly increased SOC content compared to control throughout the study period.

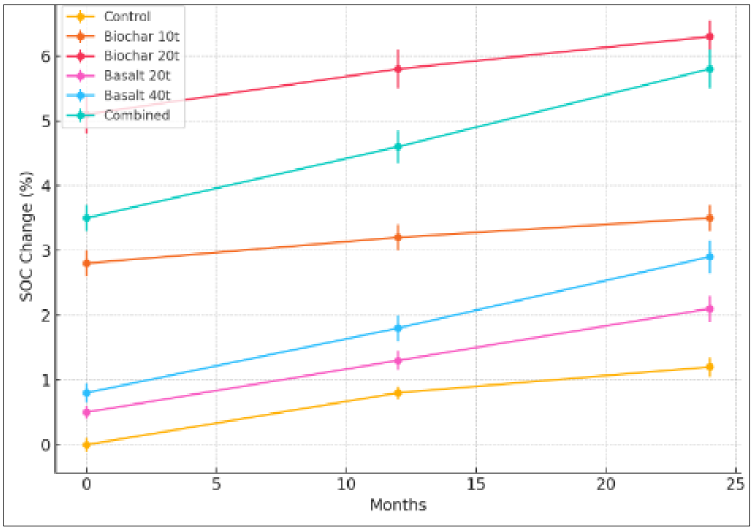

Fig 1: Temporal dynamics of soil organic carbon under different amendments

In the 0-15 cm layer, biochar treatment (T2) increased SOC from initial 0.52% to 0.74% (42.3% increase), while basalt (T3) increased it to 0.67% (28.6% increase). The combined treatment (T4) showed the highest SOC accumulation (0.82%, 56.8% increase).

The depth distribution of SOC varied among treatments. Biochar effects were predominantly confined to the surface layer, with minimal changes at 15-30 cm depth. Conversely, basalt showed more uniform SOC distribution, likely due to enhanced root growth and organic matter translocation [25].

Carbon Fractionation and Stability

Physical fractionation revealed distinct patterns between amendments.

Table 2: Carbon fractions in amended soils after 24 months

Treatment	Total SOC (g kg^{-1})	POM-C (g kg^{-1})	MAOM-C (g kg^{-1})	Labile C (g kg^{-1})	Recalcitrant C (g kg^{-1})
Control	5.2±0.3^{d}	1.8±0.2^{d}	3.4±0.2^{c}	1.5±0.1^{d}	3.7±0.2^{d}
Biochar	7.4±0.4^{b}	3.2±0.3^{a}	4.2±0.3^{b}	1.8±0.2^{c}	5.6±0.3^{b}
Basalt	6.7±0.3^{c}	2.2±0.2^{c}	4.5±0.3^{b}	2.1±0.2^{b}	4.6±0.3^{c}
Combined	8.2±0.5^{a}	2.8±0.3^{b}	5.4±0.4^{a}	2.4±0.2^{a}	5.8±0.4^{a}

Different letters indicate significant differences at $p<0.05$

Biochar primarily increased POM-C (78% increase over control), while basalt enhanced MAOM-C formation (45% increase). The combined treatment showed significant increases in both fractions, suggesting complementary mechanisms.

Thermal analysis indicated higher stability of biochar-derived carbon with activation energy of 165 kJ mol^{-1} compared to 98 kJ mol^{-1} for basalt-associated carbon. Mean residence time calculations estimated 85 years for biochar carbon and 45 years for basalt-derived carbon under current climatic conditions.

Soil Physical Properties

Both amendments improved soil aggregation, with mean weight diameter (MWD) increasing by 35% and 28% under biochar and basalt treatments, respectively.

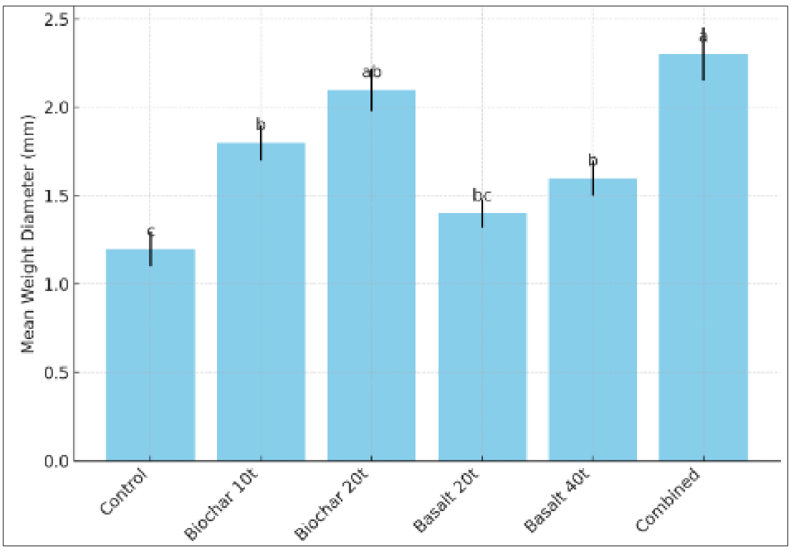

Fig: Soil aggregate stability (mean weight diameter) across treatments

The combined treatment showed the highest MWD increase (48%). Bulk density decreased significantly, with reductions of 8.5% (T2), 6.2% (T3), and 11.3% (T4) compared to control.
Water holding capacity improved markedly under biochar application (22% increase), while basalt showed moderate improvement (12% increase). The enhanced aggregation and porosity contributed to improved water infiltration rates across amended plots.

Soil Chemical Properties

Basalt application significantly increased soil pH from 7.2 to 7.8, while biochar showed minimal pH effects.

Table 3: Soil chemical properties under different amendments

Parameter	Control	Biochar	Basalt	Combined
pH	7.2±0.1[c]	7.3±0.1[c]	7.8±0.1[a]	7.6±0.1[b]
EC (dS m^{-1})	0.18±0.02[b]	0.22±0.03[a]	0.19±0.02[b]	0.21±0.02[a]
Available N (kg ha^{-1})	185±12[d]	218±15[b]	195±13[c]	235±16[a]
Available P (kg ha^{-1})	18.5±1.5[d]	20.2±1.8[c]	26.3±2.1[b]	28.5±2.3[a]
Available K (kg ha^{-1})	142±11[d]	155±12[c]	192±15[b]	205±17[a]
CEC (cmol kg^{-1})	12.5±0.8[d]	15.6±1.1[b]	17.2±1.3[a]	16.8±1.2[a]

Exchangeable base cations (Ca^{2+}, Mg^{2+}, K^{+}) increased substantially under basalt treatment, with Ca^{2+} showing 85% increase. Cation exchange capacity improved by 25% and 38% under biochar and basalt treatments, respectively.
Available nutrient status varied between amendments. Biochar increased available N by 18% but showed minimal effects on P and K. Basalt enhanced available P (42% increase) and K (35% increase) through mineral weathering. Micronutrient availability, particularly Fe and Mn, decreased under basalt due to increased pH.

Microbial Biomass and Activity

Microbial biomass carbon increased significantly across all amended treatments.

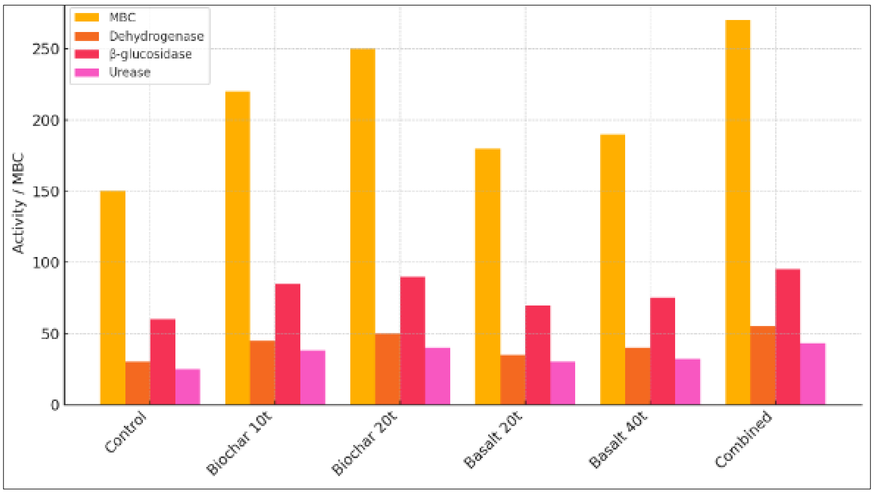

Fig: Microbial biomass carbon and enzyme activities under different amendments

Biochar treatment showed 65% increase in MBC, while basalt increased it by 48%. The combined treatment exhibited the highest MBC (92% increase), suggesting synergistic effects on microbial communities.
Enzyme activities showed differential responses. Dehydrogenase activity increased by 54% and 41% under biochar and basalt treatments, respectively. β-glucosidase activity was particularly enhanced by biochar (72% increase), indicating improved carbon cycling. Urease activity showed greater response to basalt application (38% increase).

Crop Productivity

Both wheat and maize yields increased significantly under amendment applications (Table 4).

Table 4: Crop yields under different amendment treatments

Treatment	Wheat Grain (t ha^{-1})	Wheat Straw (t ha^{-1})	Maize Grain (t ha^{-1})	Maize Stover (t ha^{-1})
Control	4.85±0.32[d]	6.12±0.41[d]	6.25±0.38[d]	8.95±0.52[d]
Biochar	5.87±0.38[b]	7.45±0.48[b]	8.02±0.45[b]	11.32±0.68[b]
Basalt	5.72±0.35[c]	7.28±0.45[c]	7.68±0.42[c]	10.85±0.62[c]
Combined	6.48±0.42[a]	8.25±0.55[a]	8.82±0.51[a]	12.45±0.75[a]

Wheat grain yield increased by 21%, 18%, and 34% under T2, T3, and T4, respectively. Maize showed higher yield responses with increases of 28%, 23%, and 41% for respective treatments.
Nutrient uptake patterns reflected soil nutrient availability changes. Nitrogen uptake increased primarily under biochar, while P and K uptake were enhanced more by basalt application. The combined treatment showed balanced nutrient uptake, contributing to highest yield gains.

Economic Analysis

Despite high initial investment, all amendment treatments showed positive net returns over the two-year period.

Table 5: Economic analysis of amendment applications

Economic Parameter	Biochar	Basalt	Combined
Amendment cost (₹ ha^{-1})	45, 000	30, 000	37, 500
Application cost (₹ ha^{-1})	3, 000	3, 500	3, 500
Additional revenue from yield (₹ ha^{-1} yr^{-1})	28, 500	24, 200	38, 600
Carbon credit value (₹ ha^{-1} yr^{-1})	3, 200	2, 400	4, 800
Net profit over 2 years (₹ ha^{-1})	15, 200	12, 500	25, 000
Benefit: Cost ratio	1.42	1.38	1.65

Biochar application had higher initial cost (₹45, 000 ha^{-1}) compared to basalt (₹30, 000 ha^{-1}). However, considering yield benefits and carbon credit potential (₹1, 500 per ton CO_2), benefit-cost ratios were 1.42, 1.38, and 1.65 for T2, T3, and T4, respectively.

Discussion

Mechanisms of Carbon Sequestration

The superior carbon sequestration under biochar treatment aligns with its recalcitrant nature and high carbon content (68%) [26]. The aromatic structure of biochar resists microbial decomposition, contributing to long-term carbon storage. Additionally, biochar's porous structure provides physical protection to native SOC through occlusion within aggregates [27].

Basalt's carbon sequestration occurs through enhanced weathering, where silicate minerals react with carbonic acid to form bicarbonates and secondary carbonates [28]. The process is relatively slower but provides co-benefits of nutrient release and pH amelioration. Our results showing 28.6% SOC increase under basalt treatment exceed previous reports, possibly due to favorable temperature and moisture conditions in the IGP [29].

The synergistic effects observed in combined treatment suggest complementary mechanisms. While biochar provides immediate carbon input and physical protection, basalt enhances chemical stabilization through mineral-organic associations. The formation of organo-mineral complexes, evidenced by increased MAOM-C, represents a more stable carbon pool [30].

Soil Property Improvements

The differential effects on soil properties reflect the distinct characteristics of amendments. Biochar's high porosity and surface area (385 m^2 g^{-1}) explain the substantial improvements in water holding capacity and aggregation. The hydrophobic nature of fresh biochar initially reduced water infiltration, but this effect diminished over time through weathering and microbial colonization.

Basalt's weathering released substantial base cations, explaining the pH increase and enhanced nutrient availability. The calcium release particularly contributed to improved aggregation through cation bridging mechanisms. However, the pH increase to 7.8 may limit micronutrient availability in already alkaline soils, requiring careful consideration in amendment recommendations.

Implications for Cropping Systems

The yield improvements demonstrate the agronomic benefits beyond carbon sequestration. The 34-41% yield increases under combined treatment suggest potential for sustainable intensification. The enhanced nutrient availability and improved soil physical conditions created favorable environment for root growth and nutrient uptake.

The economic viability, despite high initial costs, makes these amendments attractive for farmers. Government subsidies for climate-smart agriculture and carbon credit mechanisms could further improve adoption rates. However, logistics of amendment production, transportation, and application remain challenging for large-scale implementation.

Future Research Needs

Long-term studies are essential to validate carbon sequestration estimates and understand amendment longevity. The interaction between amendments and climate variables requires investigation across diverse agro-ecological zones. Optimization of application rates and frequencies for different soil types and cropping systems needs systematic evaluation.

The environmental impacts, including life cycle assessment of amendment production and application, require comprehensive analysis. The potential for heavy metal accumulation from repeated basalt application and the effects on soil biology need monitoring.

Conclusion

This comparative study demonstrates that both biochar and basalt amendments offer viable strategies for soil carbon sequestration in intensive wheat-maize systems. Biochar showed superior direct carbon sequestration (42.3% SOC increase) with longer residence time, while basalt provided better nutrient co-benefits and mineral-associated carbon formation. The combined application maximized benefits, achieving 56.8% SOC increase along with substantial yield improvements.

The economic viability and multiple co-benefits support the integration of these amendments in climate-smart agriculture. However, successful implementation requires addressing logistical challenges, developing region-specific recommendations, and establishing supportive policy frameworks. Future research should focus on long-term monitoring, optimization strategies, and environmental impact assessments to ensure sustainable adoption of these promising soil carbon sequestration technologies.

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