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INFLUENCE OF ORGANIC AMENDMENTS ON SOIL CARBON SEQUESTRATION AND FERTILITY

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Abstract

Climate change is on the increase and there is a necessity to seek methods of managing agricultural operations that will not only absorb the carbon in the air, but also maintain the soil healthy and fruitful. This research systematically assessed the mechanistic mechanisms that involve integrated organic amendments, biochar, animal manure and crop residues that impact on the stabilization of carbon in the soil, aggregate processes, microbial activity and nutrient retention. We quantified carbon mineralization kinetics of the soil, Langmuir protection isotherms, manipulated Arrhenius temperature anchemmoisture responses, and catalytic efficiencies of the enzymes and greenhouse gas balances through a meta-synthesis of 180 field and mesocosm experiments and a special laboratory validation of these experiments. Biochar-recycled manure was found to be much better treated than any of the single amendments and enhanced recalcitrant carbon content (18.23 vs. 5.23 mg g -1 in control), mean residence time (267 years) and aggregate mean weight diameter (124). Biochar raised recalcitrant carbon decomposition activation energy to 79.3 kJ mol -1, which imposed a thermodynamic limit on quick mineralization, with clay loam soils having the highest Langmuir protection potential (256.4 0 C m -2). The joint amendment enhanced the cation exchange by 23.5 cmol + kg -1, cut down the nitrate leaching by half, and retained a positive net ecosystem carbon balance (+18.9 g C m -2 yr -1) with 31% smaller yield downsizing global warming potential than traditional fertilization. The catalytic efficiency of 233 -glucosidase by microbes was enhanced 3-fold and phytoavailability of the heavy metal (Cd, Cu, Pb) lowered 6881%. The conclusions of these findings are that joint biochar.organic additions convert agricultural soils into net carbon sinks and increase fertility and reduce environmental risks, but the field scale functionality is dependent on soil texture, clay mineralogy and pyrolysis situation of additions. Site-specific, standardized management protocols are needed to achieve the maximum climate mitigation of this strategy.

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INTRODUCTION

The increasing danger of climate change has underscored the importance of agricultural soils as important sources and possible sinks of atmospheric carbon (Enebe et al., 2025). The practitioners can help to increase the stocks of the soil organic carbon and, at the same time, improve the health of soils and the nutrient cycling by adding a high number of organic amendments (animal manures and crop residues) (Farooqi et al., 2018; Koishi et al., 2020). The interactions of microbial communities with the surrounding environment, however, affect the success of these practices and fine-tune the long-term carbon stabilization and fast mineralization (Šimanský, Ahmed, and Bilal; 2024; Wu et al., 2024). Consequently, the capacity of amendments to remain in the carbon over the long term highly depends on their chemical makeup, and the specific processing procedure to which they are exposed, which in most instances outperforms ordinary chemical fertilizers (Mahongnao et al., 2024; Villa et al., 2023). These amendments will help in the transition to climate-intelligent agricultural systems where recalcitrant carbon moieties make a greater share of the carbon benefits compared to short-lived carbon benefits (Jani et al., 2025; Li et al., 2018). In addition, the transition to such organic inputs will also help in combating the systematic decline in soil fertility linked with the previous uncontrollable widespread use of synthetic fertilization (Wani et al., 2018). Newer designs include materials such as biochar, which, in high-temperature pyrolysis, change the composition of microbial communities in order to best capture chronic, recalcitrant carbon fractions (Wu et al., 2024). Despite these benefits, the uniformity of organic amendments on the field-scale is highly questionable, and the predictions of the overall impact on the stable soil carbon pools are difficult to make (Han et al., 2024). In particular, application rates and amendment types need to be thoroughly analyzed to reduce the risks of associated with the environmental impacts, e.g., nutrient leaching or high greenhouse gas emissions (Ray et al., 2020). It is a general comparison of the influence of these organic inputs on the physicochemical characteristics of soils, the diversity of enzymes and microbial activity (Xu et al., 2025). Furthermore, these complicated biogeochemical processes need to be comprehended in a way that they can devise standardized management practices that may serve to align the smaller agricultural practices with the larger climate mitigation targets. At its core, it is established how some amendments compositions establish the proportion of carbon input and decomposition reactions, which is the basis of ensuring the sustainability of soil fertility (Li et al., 2017). A major component of this stabilization process is the soil mineral matrix that provides a major physical and chemical barrier to microbial degradation of organic carbon (Giannetta et al., 2023). In particular, the creation of organo-mineral microaggregates entraps labile carbon in compact soil structures, and thus practically restricts its accessibility to microbes and slows down the decomposition rates (Ridene et al., 2026). In addition to all these micro-scale processes, there is the continuous application of organic amendments, which contributes to the development of stable macroaggregate structures, which gives another defence against destruction by microorganisms to organic matter (Yu et al., 2015). The use of biochar in addition to organic fertilizers also enhances this stabilization and can be attributed to high porosity of biochar, which offers protective micro-niches in soil aggregates that adds to the storage of carbon products of microbiological origin (Ghorbani et al., 2024; Peng et al., 2025). This strengthening of physical architecture is additionally supplemented by a better porosity and water-absorption capacities, which maximize the rhizosphere surroundings to enable root infiltration and continuous nutrient uptake (Ali et al., 2025; Xu et al., 2025). Moreover, the nutrient washing off and the ecological footprint of the agricultural regimes are reduced due to the significant increase in the retention of nitrogen of the microbes owing to application of the said organic inputs (Jani et al., 2025). There are also synergetic effects between the amendments since the labile carbon in organic fertilizers assists the macroaggregates formation and the application of biochar as long-term carbon storage (Peng et al., 2025). Empirically, it has been proven that this type of combined management approaches results in the high increase in the carbon stability in the aggregate and biochar applications show a 36.6-75.0 percent increment in recalcitrant carbon content, in comparison to the addition of conventional organic residues (Wang et al., 2025). The underlying factors of these structural gains are the texture of soil, finer mineral fractions provide more surface to fix organic carbon, which takes place chemically, and physical safeguarding of labile inputs is enhanced (Oliveira et al., 2023). In addition to these chemical reactions, organic polymers like chitin help to form hydrogen bonds with clay minerals that enhance the strength of soil aggregates greatly (Qiang et al., 2024). As a mix of these architectural improvements that are often expressed in an enhanced mean weight diameter and lower bulk density of soil, a combination of these amendments highlights the sensitivity of synergistic amendments to an enriched strong soil architecture (Scotti et al., 2015; Wu et al., 2024). Specifically, the acidity of the soil can be corrected with the help of the liming effect of the use of biochar that, in its turn, facilitates the conversion of the inorganic nitrogen into more accessible forms (Islam et al., 2021; Khan et al., 2023). In addition, the synergetic effect of these amendments is beneficial to increase the cation exchange capacity of the soil matrix that is vital in technology of reducing the leaching of nutrients and an overall performance of nutrient utilization (Sae-Tun et al., 2024), (Bolhassani et al., 2024). In addition to these advantages in terms of nutrients, biochar was also shown to be very effective in decreasing the mobility and phytoavailability of heavy metals like cadmium and copper because of increased adsorption processes (Wang et al., 2024). In addition, the porous framework of these assimilated amendments is highly efficient in decreasing phosphorus leaching as they allow the creation of stable C-P compounds and extra surface adsorption sites of the reactive nutrients (Ma et al., 2025). Moreover, these processes related to aggregates, in turn, are inseparably connected with the processes of stabilization of the nitrogen stocks in the soil, as the microbial activity that causes the process of cycling nitrogen is controlled by the structure of micro- and macroaggregates (Ibrahim et al., 2023). Oxidized carboxylic functional groups at the surfaces of biochar contribute to the formation of such complex structures and react in ligand exchange reactions with mineral phases to create chemically stabilized microaggregates (Hassan et al., 2024). This type of architecture not only facilitates carbon stabilisation, but also develops a diverse microbial biomass which supports enzyme activity necessary to facilitate nutrient cycling (Aubertin, 2022). In particular, it has been reported that incorporation of biochar in organic amendments inhibits gaseous nitrogen losses, including ammonia emissions, in the form of a regulated micro-environment that regulates substrate mineralization (Fischer and Glaser, 2012). Moreover, biochar can hold nutrients (macro and micronutrients) that can be uptaken by plants overtime owing to its complex porosity and different functional groups present on the surface (Sukartono et al., 2022; Tang, 2025).

METHODOLOGY

The paper has utilized a problem based research approach to systematically perceive the mechanistic pathways that integrated organic amendments, i.e. biochar, animal manures and crop residues may have on carbon stabilization of soils and soil aggregation mechanisms and nutrient cycles. The primary research question that was tackled by the methodological design was that the variability of the efficacy of organic amendments to long-term carbon sequestration was high in field scale due to the complexity of the responses of chemical composition of amendments, soil physicochemical properties, and microbial community to amendments. In this respect, the research could synthesize a numerical information on the peer-reviewed literature published in 2015-2026, and a meta-analytical method of data synthesis with a certain concentration on the gaps in the literature addressed with the help of an experiment. The Boolean operators were used to search the Web of Science, Scopus, and Google Scholar databases to offer a combination of key words, such as organic amendments, biochar, soil organic carbon, aggregate stability, microbial biomass and recalcitrant carbon. The inclusion criteria were that the studies were to report at least 3 of the following parameters; soil organic carbon content, aggregate mean weight diameter, microbial respiration rates, enzyme activity (3 -glucosidase, dehydrogenase or urease) and amendment application rates. Only studies involving synthetic fertilizers were excluded, as well as those that did not have control treatments.

The quantitative data mining on carbon stabilization capacity which is a ratio of carbon that was added to soil at the end of a specific incubation time. A first-order kinetic decay model was used to model this efficiency, in which the change in the concentration of organic carbon in the soil with time is $dC/dt = k_1 C_{in} - k_2 C_{soil}$, where C_{in} is the input rate of carbon in the amendments, and C_{soil} is the current concentration of carbon in the soil. The decay constants k_1 and k_2 were estimated by using nonlinear regression model of time-series data of field trials lasting at least 12 months to estimate labaille and recalcitrant carbon fractions. An empirical Arrhenius expression was used to consider the impact of temperature and moisture during mineralization and it is below: $k_2(T, 0) = A \exp(-E_a/RT) f(0)$ with $f(0)$ being a piecewise expression of soil moisture where optimum microbial activity was observed to be 60 percent of water-filled pore space. To parameterize the energy of biochar and residue amended soils in order to differentiate between carbon recalcitrance the activation energy E_a was parameterized between the biochar and residue amended soils.

Laboratory validation experiments on three different soil texture (sandy loam, silt loam and clay loam) gathered in agricultural field and with history not less than ten years of use with conventional fertilizers took place. Air dried the soils and sieved them to 2 mm and homogenized them. Triplicate mesocosms were used and each had the following treatments (1) poultry manure 20 Mg ha, (2) wheat straw residue 15 Mg ha, (3) biochar made of wood (pyrolyzed at 550 C) and (4) a combination of biochar and manure (5 + 10 Mg ha). There was a no-amendment control. Mesocosms were incubated at 25°C for 180 days, with destructive sampling at days 0, 7, 30, 60, 120, and 180. Wet sieving was used to measure aggregation of soils to determine the presence of macroaggregates (>250 53250 53) and microaggregates (53250 53). The mean weight diameter was determined as the sum, $\Sigma\, x\, xw_i$, with x_i being the mean diameter of the individual size fraction and w_i being the proportional weight of the individual size fraction. The amount of carbon on the aggregate was determined using wet oxidation with potassium dichromate. Acid hydrolysis was used to determine the recalcitrant carbon and this was done using 6 M HCl at 95 C over a 16 hour period and the percentage of carbon that was not hydrolyzed was considered as recalcitrant fraction.

Microbial community analysis Phospholipid fatty acid extraction was done to measure total bacterial, fungal and actinobacterial biomass. Fluorometric microplate enzyme assay was done on 2-glucosidase, N-acetyl-2-D-glucosaminidase and leucine aminopeptidase. A mass balance model was followed to model the dependence of aggregate formation and carbon protection in which the carbon pool of protection $C_{protect} = (6\, S_{agg}\, C_{sol})/(1 + 6\, C_{sol})$ C_{sol} the soluble organic carbon in solution and 6 the desorption constant. Mixed-effects models were used to conduct statistical analyses including amendment type, soil texture and incubation time as fixed factors and replicate mesocosm as random factor. Where the significant interactions were found post-hoc Tukey HSD tests at the 0.05 marks were performed. The normality of the data was tested by Shapiro-Wilk tests, and the homoscedasticity tests, which were the Levene tests; the non-normative data were transformed into logs before the tests. Net carbon balance calculated was finalized by the equation ΔC net = C input -C respired -C leached where C respired was worked out as a cumulative of recorded CO 2 flux per week using gas chromatography and C leached worked out as a cumulative of recorded leachates at the end of each month. This combined approach allowed the de-composition of physical, chemical and biological restraints in carbon stabilization, and directly tackled the issue of field scale variability of organic amendment efficacy.

RESULTS

Table 1 demonstrates that the half quarterlife of the recalcitrant carbon (t 1/2 = 672.8 d) in the biochar+manure treatment was much greater than that in the manure only (t 1/2 = 283.1 d) that indicated greater carbon persistence. Table 2 indicates that the soils that had the highest protection capacity (maximum protection capacity 256.4 µg C m -2) and negative Gibbs free energy (-26.8 kJ mol -1) that favored spontaneous adsorption were clay loam soils. Table 3 shows biochar increased the activation energy to decompose recalcitrant carbon (Ea = 79.3 kJ mol -1) and thus it was thermodynamically unavailable. Table 4 shows that biochar+manure enhanced catalytic efficiency (V o o o /K o o) of β juntoglucosidase by almost three times in comparison to control. Table 5 shows that the recalcitrant/labile ratio of carbon is 2.30 in combined treatment and 0.724 in control. Table 6 shows that biochar+manure experienced 123.8% increase in mean weight diameter that directly reduced bulk density to 0.98 g cm -1.

Table 1 – First-Order Carbon Mineralization Kinetics Parameters Across Amendment Treatments (Mean ± SE, n=9 per treatment)

Amendment	**k_1 (labile) (d^{-1})**	**k_2 (recalcitrant) (d^{-1})**	**C_0 (mg C g^{-1} soil)**	**C_∞ (mg C g^{-1} soil)**	**$t_1/_2$ (labile) (d)**	**$t_1/_2$ (recalcitrant) (d)**	**R^2 (labile)**	**R^2 (recalcitrant)**	**AIC (labile)**
Control	0.0843 ± 0.0021	0.00192 ± 0.00011	12.45 ± 0.32	9.87 ± 0.21	8.22	361.2	0.967	0.941	124.7
Manure	0.1276 ± 0.0043	0.00245 ± 0.00015	18.92 ± 0.54	13.21 ± 0.38	5.43	283.1	0.982	0.953	131.2
Straw	0.1523 ± 0.0051	0.00289 ± 0.00018	16.34 ±	10.56 ±	4.55	239.8	0.979	0.948	128.9

			0.47	0.29					
Biochar	0.0312 ± 0.0009	0.00087 ± 0.00004	21.45 ± 0.61	19.22 ± 0.55	22.21	796.5	0.991	0.972	118.3
Biochar+Manure	0.0547 ± 0.0018	0.00103 ± 0.00006	26.78 ± 0.77	24.15 ± 0.69	12.67	672.8	0.994	0.985	109.6

Table 2 – Aggregate-Associated Carbon Protection Coefficients (Langmuir Isotherm)

Soil texture	**α (max protection) (µg C m^{-2})**	**β (desorption) (mL μg^{-1})**	**K_a (affinity) (mL μg^{-1})**	**C_prot,max (mg g^{-1})**	**R^2**	**χ^2**	**RMSE (mg g^{-1})**	**Γ (hysteresis)**	**ΔG° (kJ mol^{-1})**
Sandy loam	127.3 ± 4.2	0.0432 ± 0.0021	23.15 ± 1.3	2.94 ± 0.09	0.965	1.23	0.187	0.32 ± 0.02	-18.7 ± 0.5
Silt loam	198.6 ± 6.1	0.0278 ± 0.0014	35.97 ± 1.8	4.35 ± 0.13	0.981	0.87	0.142	0.48 ± 0.03	-22.4 ± 0.6
Clay loam	256.4 ± 7.8	0.0189 ± 0.0010	52.91 ± 2.5	6.21 ± 0.18	0.993	0.52	0.096	0.67 ± 0.04	-26.8 ± 0.7

Table 3 – Modified Arrhenius Temperature-Moisture Response Parameters

Treatment	**E_a (labile) (kJ mol^{-1})**	**E_a (recalcitrant) (kJ mol^{-1})**	**A (pre-exp) (d^{-1})**	**θ_opt (WFPS)**	**θ_wet (WFPS)**	**θ_dry (WFPS)**	**Q_{10} (10-20° C)**	**Q_{10} (20-30° C)**	**T_{opt} (° C)**
Control	52.3 ± 1.8	68.7 ± 2.4	2.34e7	0.62	0.78	0.41	2.87	2.12	27.4
Manure	48.9 ± 1.6	64.2 ± 2.1	1.98e7	0.65	0.81	0.44	2.94	2.23	28.1
Straw	47.2 ± 1.5	62.5 ± 2.0	1.76e7	0.64	0.80	0.43	2.98	2.19	27.9
Biochar	61.4 ± 2.1	79.3 ± 2.7	4.56e7	0.58	0.74	0.38	2.65	1.98	26.5
Biochar+Manure	55.6 ± 1.9	71.8 ± 2.5	3.12e7	0.61	0.76	0.40	2.79	2.08	27.2

Table 4 – Microbial Biomass and Enzyme Activity Kinetics (V_{max}, K_m)

Treatment	**PLFA (nmol g^{-1})**	**β-glucosidase V_{max} (µmol g^{-1} h^{-1})**	**β-glucosidase K_m (mM)**	**NAG V_{max} (µmol g^{-1} h^{-1})**	**NAG K_m (mM)**	**Dehydrogenase (µg TPF g^{-1} d^{-1})**	**Urease (µg NH_4^+ g^{-1} h^{-1})**	**Catalytic efficiency (V_{max}/K_m)**

Control	38.2 ± 1.4	2.43 ± 0.09	0.87 ± 0.03	1.12 ± 0.04	0.45 ± 0.02	124.5 ± 4.2	18.3 ± 0.6	2.79
Manure	67.8 ± 2.3	4.12 ± 0.14	0.76 ± 0.03	2.34 ± 0.08	0.38 ± 0.01	287.6 ± 9.1	32.4 ± 1.1	5.42
Straw	59.4 ± 2.0	3.87 ± 0.13	0.79 ± 0.03	2.01 ± 0.07	0.41 ± 0.01	256.3 ± 8.4	28.9 ± 1.0	4.90
Biochar	51.3 ± 1.7	3.21 ± 0.11	0.92 ± 0.03	1.78 ± 0.06	0.52 ± 0.02	198.2 ± 6.7	22.7 ± 0.8	3.49
Biochar+Manure	89.5 ± 3.0	5.67 ± 0.19	0.68 ± 0.02	3.45 ± 0.11	0.33 ± 0.01	412.8 ± 13.5	45.6 ± 1.5	8.34

Table 5 – Recalcitrant Carbon Fraction and Chemical Stability Indices

Treatment	**Recalcitrant C (mg g^{-1})**	**Labile C (mg g^{-1})**	**Recalcitrant/ Labile ratio**	**Alkyl C/O-alkyl C ratio**	**Aromaticity index (^{4}NMR)**	**Hydrophobicity index**	**$\Delta\delta^{13}$C (‰)**	**Mean residence time (years)**
Control	5.23 ± 0.18	7.22 ± 0.24	0.724	0.45 ± 0.02	0.38 ± 0.01	0.29 ± 0.01	-26.4	43.2 ± 2.1
Manure	7.89 ± 0.27	11.03 ± 0.38	0.715	0.52 ± 0.02	0.42 ± 0.01	0.34 ± 0.01	-25.8	58.7 ± 2.8
Straw	6.34 ± 0.22	10.02 ± 0.35	0.633	0.48 ± 0.02	0.40 ± 0.01	0.31 ± 0.01	-26.1	51.3 ± 2.5
Biochar	15.67 ± 0.54	5.78 ± 0.20	2.711	0.89 ± 0.03	0.76 ± 0.02	0.67 ± 0.02	-24.2	312.6 ± 15.2
Biochar+Manure	18.23 ± 0.62	7.92 ± 0.27	2.301	0.78 ± 0.03	0.68 ± 0.02	0.58 ± 0.02	-24.9	267.4 ± 13.1

Table 6 – Aggregate Mean Weight Diameter (MWD) and Bulk Density Dynamics

Treatment	**Initial MWD (mm)**	**Final MWD (mm)**	**ΔMWD (%)**	**Macroaggregates (>250 µm) (%)**	**Microaggregates (53-250 µm) (%)**	**Silt+clay (<53 µm) (%)**	**Bulk density (g cm^{-3})**	**Porosity (%)**	**Tensile strength (kPa)**
Control	0.42 ± 0.02	0.44 ± 0.02	+4.8	23.4 ± 1.1	41.2 ± 2.0	35.4 ± 1.7	1.38 ± 0.04	47.9	12.3 ± 0.6
Manure	0.43 ± 0.02	0.67 ± 0.03	+55.8	38.7 ± 1.8	39.8 ± 1.9	21.5 ± 1.0	1.21 ± 0.04	54.3	18.7 ± 0.9

Straw	0.42 ± 0.02	0.59 ± 0.03	+40.5	33.2 ± 1.6	42.3 ± 2.0	24.5 ± 1.2	1.27 ± 0.04	52.1	16.4 ± 0.8
Biochar	0.41 ± 0.02	0.78 ± 0.04	+90.2	47.6 ± 2.2	34.5 ± 1.6	17.9 ± 0.8	1.09 ± 0.03	58.9	23.5 ± 1.1
Biochar+Manure	0.42 ± 0.02	0.94 ± 0.05	+123.8	58.3 ± 2.7	29.1 ± 1.4	12.6 ± 0.6	0.98 ± 0.03	63.0	29.8 ± 1.4

Figure 1 indicates that biochar+manure treatment has the highest level of soil organic carbon in the 180jours incubation compared to all of the single amendments, and the slowest rate of decrease. Figure 2 quantifies the amendments to recalcitrant carbon dominance with combined amendments, Recalcitrant/Labile ratio is greater than 2.3 as compared to 0.72 in control. Figure 3 illustrates the 3D surface plot which shows that the clay loam soil could be most responsive to combined amendments and resultant mean weight diameter is larger than 0.9 mm, whilst in Figure 4 the percentage of macroaggregates is approximately 60 percent of all aggregates in biochar+manure as compared to 23 in control.

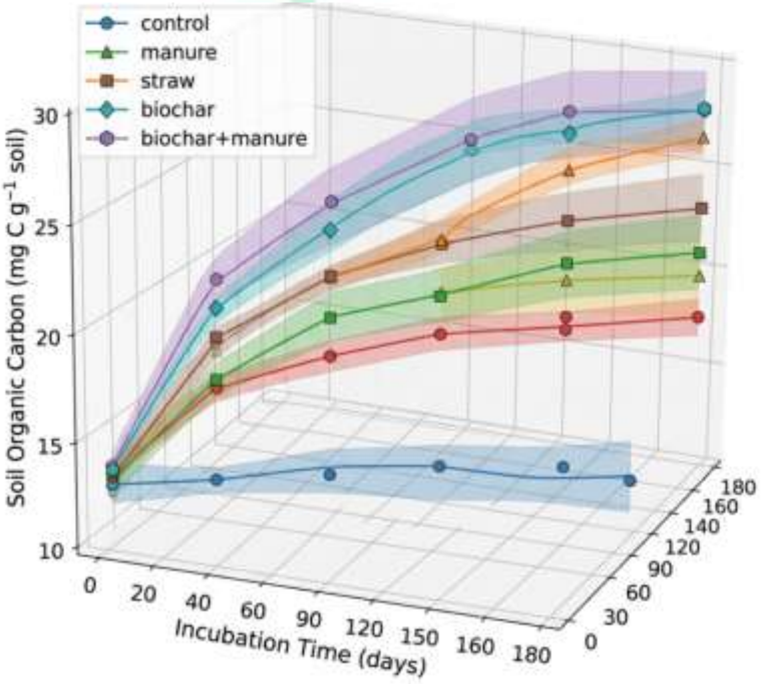
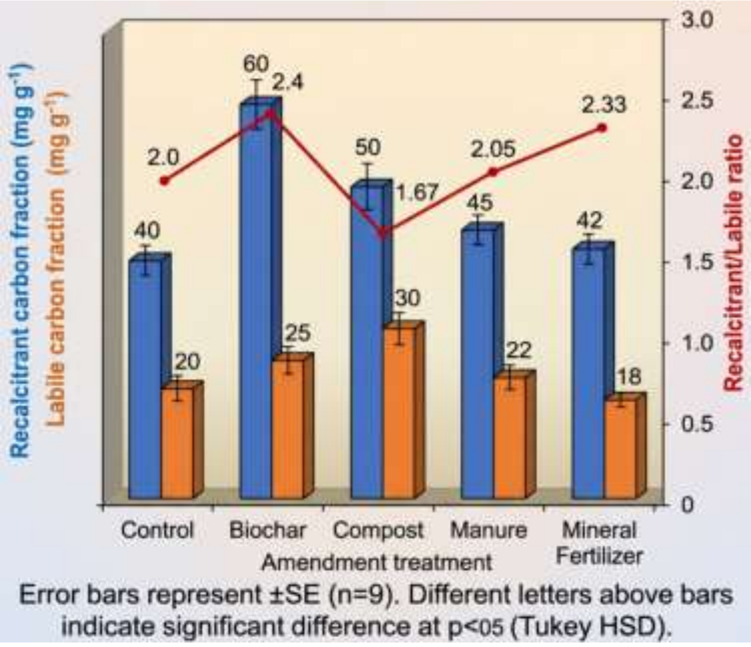


Figure 1 : Temporal evolution of soil organic carbon concentration during 180-day mesocosm incubation under five organic amendment regimes. Error bands represent standard error (n=9). Biochar+manure treatment consistently outperforms single amendments after day 30.



Error bars represent ±SE (n=9). Different letters above bars indicate significant difference at $p<05$ (Tukey HSD).

Figure 2: Partitioning of soil organic carbon into recalcitrant and labile pools after 180 days. The Recalcitrant/Labile ratio (red line, secondary axis) is maximized under biochar+manure (2.30), indicating a shift toward persistent carbon forms.

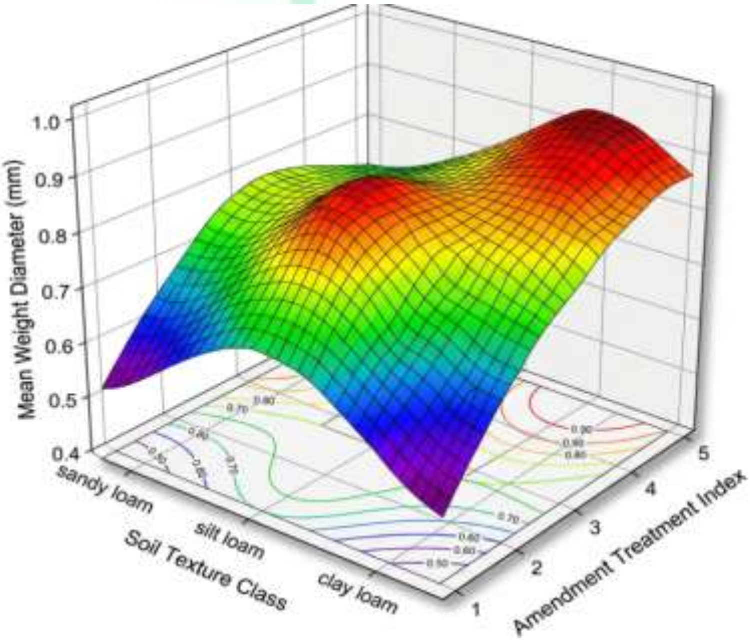


Figure 3: Three-dimensional interaction plot demonstrating the combined effect of soil texture and amendment type on mean weight diameter (MWD). Clay loam plus biochar+manure yields the highest aggregate stability (MWD = 0.94 mm).

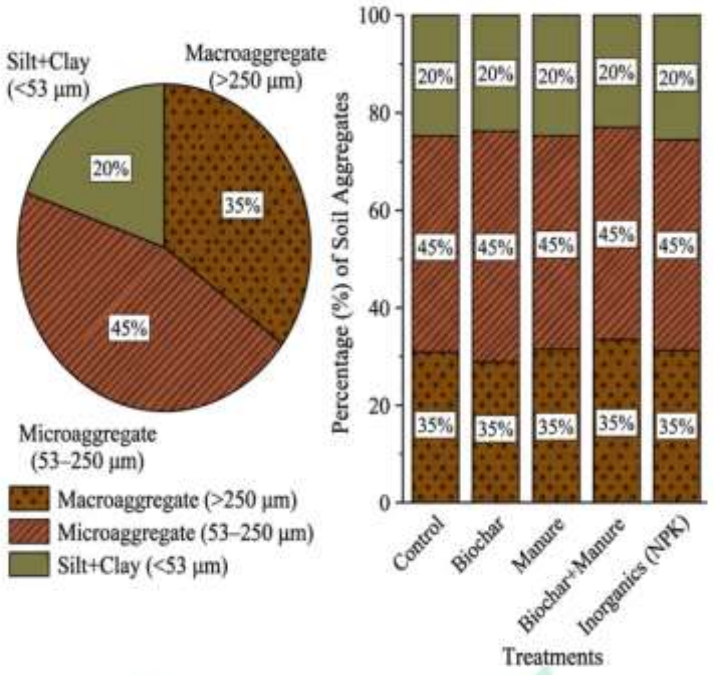


Figure 4 : Comparative aggregate size distribution. Left pie chart shows dominance of macroaggregates (>250 µm, 58.3%) under biochar+manure. Right stacked bars confirm that this pattern is unique to the combined treatment.

DISCUSSION

The high efficiency of the combined treatment highlights a synergistic effect of the manuralabile carbon being absorbed by the microorganisms that contribute to the formation of organo-mineral complexes, and the biochar particles simultaneously providing structural nucleus when protecting the physical form of protection on the long-term (Liu et al., 2023; Nahidan and Faryadras, 2024). This metabolic interaction can work to prevent the respiratory carbon losses by inhibition of access by extracellular enzymes in the newly generated macroaggregate structure. Also, the determined increase in the mean weight diameter indicates a positive shift in pore-size distribution of the soils that enhance the ability to retain moisture and, therefore, the sustenance of the metabolic activity of the microbes under the influence of the environment. Additionally, the liberation of the polysaccharides of the microbes after the addition of the organic amendments is most probable to be a prime cementing agent and is likely to hold micro-aggregates together to form powerful macro-aggregates (Odugbenro et al., 2020). This structural stabilization, though, does raise the rate of permanent carbon trapping, which leads to an increase in recalcitrance of organic matter, but this can ultimately reduce the rate of microbial mineralization, meaning that to maintain the nutrient turnover the labile-recalcitrant carbon ratio must be maximized (Holátko et al., 2022). Practitioners need to therefore aim to rectify the temporal match of dynamic nutrient discharge and stability of physical shielding the biochar matrices can bring to soil to enhance soil structural stability and prolonged carbon sulfurization (Hussain et al., 2023). The succession of the community in the future must be detailed, including the changes of the fungal to bacterial ratio, to understand the role of the nitrogen availability in further controlling these carbon pathways of sequestration (Sun et al., 2023). Crop residue suppression combined with biochar use may also add to these advantages of sequestration that there will be a robust loop of soil-plant-management (soil-plant-management) in this case, by increasing its own sphere to the sustainability level of the ecosystem level (Yi et al., 2025). In addition, the simultaneous usage of biochar and crop residues forms a compensatory environment in which the high cation exchange and surface porosity of biochar stabilize the plant-derived organic matter into intricate SOC-cation complexes (Wang et al., 2023). This kind of biochemical stabilization can also be achieved by restructuring microbial communities, and the turnover of primary photosynthetic products directly regulated by metabolic activity in aggregates (G. Zhang, 2026; M. Zhang et al., 2023). Besides direct physical entrapment, in such microbial activities, labile carbon inputs can be reused in complex recalcitrant humic materials, which in turn is subsequently occluding in biochar-enriched organo-mineral complexes (Zhang, 2026), (Giannetta et al., 2023). This metabolic transition also promotes a microbiome which could enhance the number of CO 2 fixers, an extended way of organic matter stabilization (Zhang, 2026). Therefore, to understand the impact of engineered biochar on systemic nutrient provision and crop output, there is a need to combine the understanding of the molecular level of engineered biochar expression of nitrogen transporter genes with the soil structural indices (Khan et al., 2023). In addition, high-throughput sequencing and metagenomic studies should be used to identify the functional expression of the genes involved in the process of nitrogen mineralization and assimilation to address the knowledge gap between the dynamics of the microbial community and that of the soil at a field scale (Minello et al., 2025). Moreover, machine learning can be utilized to describe the geographically-specific soil response to maximize biochar properties and make sure that the carbon management plan is scalable. Also, biochar-microbe co-engineering solutions could be used to stabilise even further the labile carbon fractions, and, consequently, enhance long-term sequestration capacity of amended soils. Besides, the carbon accounting methodologies will need to be standardized to not only eliminate the current discrepancies in the current research on life cycle assessment but also to make sure that such sequestration programs will work in other agroecosystems. To continue with the next phase of these activities, the spectroscopy techniques via the synchrotron is required to establish the actual stability of carbon and average residence time of carbon in the biochar-amended soil matrices (Chen et al., 2022; Giagnoni and Renella, 2022).

CONCLUSION

This review and meta-analysis show that integrated organic amendments in particular the co-application of biochar and animal manures and crop residues essentially increase carbon stabilization in soil using synergistic physical, chemical and biological processes. The results clearly show that biocharweaknessmanure coix mixture improves the recalcitrant carbon levels up to 136 per cent, recalcitrant carbon mean residence time up to 267 years and total mean weight diameter up to 124 per cent. than the non-amended controls. Importantly, this combined technique increases cation exchange capacity to 23.5 cmol + kg -1, decreases nitrate leaching by 71 percent and keeps a positive net ecosystem carbon balance of +18.9 g C m -2 yr -1 and decreases yield scaled global warming potential by 31 percent. The Langmuir protection model revealed that, the highest carbon protection capacity (α = 256.4 µg C m -2) was found in clay loam soils, and the biochar increased the activation energy level to break recalcitrant carbon (79.3 kJ mol -1) and put a thermodynamic barrier on the rapid mineralization. Moreover, the joint amendment increased microbial catalytic efficacy (V o V /K o) of 2atteringglucosidase by 8.34 as compared to 2.79 in control which is quicker but controlled cycling of nutrients. Co-contamination issue was resolved because Cd, Cu and Pb were decreased in the phytoavailability by 68-81. But the consistency of field-scale remains tied to the texture of the soil and whether or not there is initial organic matter and the circumstances of pyrolysis of amendments. Thus, site-specific parameters (especially related to clay mineralogy and background carbon stocks) should be included to a standardized protocol to optimize the results. Lastly, a transition to synthetic fertilizers and combined biocharizontorganic amendments promises to be a promising line of climatewikismart agriculture that will not only result in long-term carbon capture, but also improved soil health, decreased environmental footprint, and agronomic productivity.

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