# Biochar-Enriched Compost Improves Soil Fertility, Microbial Activity, and Productivity of *Glycine max* (L.) Merr.

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## ABSTRACT

The issue of decreasing fertility of agricultural soils poses a major challenge for the global food security along with sustainable productivity of agriculture. The biochar-compost represents an innovative solution for soil health improvement as well as nutrient availability increase. The goal of the current research was to investigate the influence of biochar-compost on soil fertility parameters, microbial community structure and activity, as well as the productivity of soybean in field conditions. To fulfil this goal, two-year field experiment was carried out using randomized complete block design with four treatments: (i) control (no amendments), (ii) compost alone (15 $t \cdot ha^{-1}$), (iii) biochar alone (10 $t \cdot ha^{-1}$), and (iv) biochar-compost combination (10 $t \cdot ha^{-1}$ biochar + 15 $t \cdot ha^{-1}$ compost). Periodic sampling was conducted to determine critical growth stages and properties of soil, including physicochemical properties, nutrient availability, microbial biomass carbon and nitrogen, enzymatic activity parameters and microbial diversity indexes. Main parameters of productivity were evaluated to monitor the growth and development of plants such as plant height, area, number of nodules, chlorophyll content, and yield. The use of biochar-enhanced compost increased the amount of soil organic carbon by 28.7%, available nitrogen by 34.2%, available phosphorus by 41.5%, and available potassium by 19.8% compared to the untreated control. Both microbial biomass carbon and dehydrogenase activity increased by 45.3% and 38.6%, respectively. Enzyme activities (urease, phosphatase, β-glucosidase) increased significantly with the use of compost fertilization with biochar. The yield of soybean increased by 42.8% with the application of biochar-based compost, with an increase in all yield contributing characteristics. The study suggests that biochar-enriched compost increases soil fertility through increased carbon sequestration; increased microbial activity; and improved nutrient availability, which significantly improves sustainable soybean production, confirming that the application of biochar-based compost is a good alternative for regenerative agriculture and sustainable intensification.

**Keywords:** biochar; compost; soil microbial activity; soil enzymes; nutrient cycling; soybean; carbon sequestration; sustainable agriculture

## Introduction

### Global Food Security and Soybean Importance

Soybean (*Glycine max* (L.) Merr.) is an important leguminous crop responsible for a large share of global food, livestock feed and industrial production (FAO, 2023) [1]. The production of soybean exceeds 370 million tons per year making it one of the most important sources of protein and oil for human and animal needs (Herridge *et al*., 2008) [2]. Soybean provides approximately 60% of the world protein-rich livestock feed and is appreciated for its contribution into sustainable agricultural intensification (Graham and Vance, 2003) [3]. However, in the context of climate change problems and the demand for soybean production it is becoming increasingly more challenging to sustain soybean production and achieve environmental sustainability (Bünemann *et al*., 2018) [4].

### Soil Fertility Challenges in Agricultural Systems

Decreasing soil fertility poses one of the biggest challenges in present-day agriculture, having an influence on around one-third of the agricultural lands of the world (Bünemann *et al*., 2018) [4]. As a result of intensive farming, monoculture farming systems, and limited replenishment of organic matter, the soil lost a significant share of its nutrients, the variety of organisms living there has decreased, and the functioning of soil as a biological factor is deteriorating (Lal, 2020) [5]. Although the usage of synthetic fertilizers makes it possible to obtain immediate high yields, it also results in soil acidification, unbalanced nutrient ratios, reduced activity of microorganisms, and negative influence on the environment (Powlson *et al*., 2001) [6]. For agriculture to be sustainable, it is crucial to develop integrated approaches to nutrient management that will not only keep the soils fertile but will also preserve their biological condition and stimulate carbon accumulation (Pretty, 2008) [7].

**Biochar Technology and Soil Amendment**

The carbon-rich pyrolytic substance known as biochar is made from biomass. Biochar is beneficial in soil improvement and helps sequester carbon in soils (Lehmann and Joseph, 2015) [8] (Schmidt *et al*., 2021) [9]. Its structure makes biochar more porous than soil; thus, it increases the water-holding capability of soil, offers lodging for beneficial microorganisms, and enhances cation exchange capacity (Glaser *et al*., 2002) [10]. It is also reported that using biochar increases the nutrient retention rate, reduces nutrient leaching, and fosters the growth of beneficial microbes (Jeffery *et al*., 2011) [11]. The exceptional stability and continuous release of biochar also make it essential that biochar not only allows for carbon sequestration and thus reduces the amount of $CO_2$ in the atmosphere (Woolf *et al*., 2010) [12] while being an ineffective source of nutrients, indicating the need to install biochar onto some sources of organic matter to allow for better nutrient control over the soil (Xu *et al*., 2016) [13].

**Compost and Organic Nutrient Management**

The term compost stands for a stable type of organic matter containing both nutrients and beneficial microorganisms needed for the biological processes in soil (Diaz *et al*., 2004) [14]. When applied to the soil, compost enhances soil structure, increases nutrient availability, improves water-holding capacity, and stimulates diverse microbial communities of the soil (Medina *et al*., 2012) [15]. Nevertheless, rapid mineralization of compost under hot tropics and subtropics can limit nutrient retention and sustainability (Parihar and Singh, 2018) [16]. Combining compost and biochar is advantageous because it allows using the advantages of compost to supply nutrients with those of biochar to retain nutrients for a long time in the soil and sequester carbon (Zhang and Sun, 2018) [17].

**Biochar-Enriched Compost Technology**

Combining biochar with compost to produce biochar-enriched compost is a new way to improve soil properties in a synergistic way (Graber *et al*., 2019) [18]. With this technique, not only the soil's ability to retain nutrients increases, but also complex interactions within the soil microbiome occur, thus bringing about positive consequences for both short-term and long-term availability of nutrients (Gul and Whalen, 2016) [19]. The role of biochar-enriched compost is known to be that of a "biological conditioner," helping facilitate nutrient cycling due to the activities of microorganisms while keeping the carbon pool stable (Noor *et al*., 2021) [20]. It has been proven by the latest studies that biochar-enriched compost are more beneficial than each of the amendments used separately, especially when it comes to heavy cropping (Jin *et al*., 2020) [21].

**Soil Microbial Communities and Nutrient Cycling**

Microorganisms in the soil play an essential role in nutrient cycling, decomposition of organic matter, and maintenance of soil structure (Nannipieri *et al*., 2003) [22]. The microbial biomass, enzyme activity, and community structure are good parameters for assessment of soil biological process and nutrient transformation (Caldwell, 2005) [23]. Biochar and compost influence the community structure by providing an organic substrate, pore spaces, and habitats for microbes (Lehmann *et al*., 2011) [24]. Enzyme activities reflecting dehydrogenase, urease, phosphatase, and β-glucosidase activity are an indication of microbes' metabolism and speed of nutrient cycling processes (Dick *et al*., 1994) [25]. The increase in microbial activity when using a biochar fortified compost is expected to increase nutrient transformations and facilitate plant nutrient uptake (Li *et al*., 2020) [26].

**Carbon Sequestration and Climate-Smart Agriculture**

The use of compost enriched with biochar is an example of climate-smart agriculture that increases soil fertility and decreases carbon dioxide in the atmosphere at the same time (Minasny *et al*., 2017) [27]. Another advantage of biochar is the long-term stability of its carbon, which results in benefits for climate change mitigation in long run (Chenu *et al*., 2014) [28]. The use of biochar-enriched compost can also be considered sustainable intensification that meets the needs of climate change and agricultural productivity at the same time (Smith *et al*., 2016) [29].

**Current Research Status and Knowledge Gaps**

Although biochar and compost are well investigated separately, information about their effects on soybean production and biochar-enriched compost still holds numerous gaps (Iddamalgoda *et al*., 2016) [30]. Most of the existing research is conducted in temperate zones, while there are only several reports from tropical and subtropical regions where there is also soybean production (Crane-Drrey *et al*., 2017) [31]. Moreover, the mechanisms of biochar-enriched compost influence on integrated soil fertility, microorganisms, and crops are still not fully understood. In the current paper, these issues are explored through a comprehensive study of the biochar-enriched compost impact on soil fertility parameters, signs of microbial activity, and soybean production in the field.

**Study Objectives**

The aims of this study were: (i) to assess the impact of compost reinforced with biochar on the physical and chemical properties of soil and nutrient availability in the soil; (ii) to evaluate the impact on soil microbial mass and its operations; (iii) to measure the impact on soybeans growing pattern, nodulation of roots, and yield of soybeans; (iv) to explore the mechanisms how biochar-enriched compost improves soil fertility; and (v) to show the sustainability and implementation potential of biochar-enriched compost in soybean agriculture.

## Materials and Methods

**Experimental Site and Agro-Climatic Conditions**

The experiment was conducted during two consecutive cropping seasons (2021–2023) at the Agricultural Research Farm, New Delhi, India (28.59°N, 77.09°E; elevation 225 m above mean sea level). The experimental site falls within the semi-arid climate zone, characterized by mean annual rainfall of 714 mm, primarily concentrated in the monsoon season (June–September). Mean annual temperature ranges from 10.2°C (winter minimum) to 38.5°C (summer maximum). The prevailing soil type is Fluventic Ustochrept (fine-loamy, mixed, hyperthermic) with initial pH 7.3, electrical conductivity 0.48 $dS \cdot m^{-1}$, and soil organic carbon 0.68%. Detailed site characteristics are presented in Table 1.

**Plant Material and Crop Establishment**

The soybean cultivar JS 20-29, an indeterminate type with 95–100-day maturity, was selected based on its agronomic performance in the region and market acceptance. Seeds were obtained from the National Seed Repository and verified for germination (>95%) and purity (>98%). Seeds were sown manually at a spacing of 45 cm × 20 cm during the onset of monsoon rains (first week of June) at a seeding rate of 75 $kg \cdot ha^{-1}$. Crop establishment, weed management, and general agronomic practices were standardized across all treatments. Irrigation was applied through drip irrigation during periods of delayed monsoon rains to ensure adequate soil moisture. No synthetic fertilizer was applied to allow evaluation of amendment-mediated nutrient supply.

**Experimental Design and Treatments**

The experiment was designed as a randomized complete block design with four treatments replicated four times, yielding sixteen experimental units of 6 m × 4 m (24 $m^2$) each. Treatments comprised: (i) Control—no soil amendment ($T_1$); (ii) Compost alone—15 $t \cdot ha^{-1}$ applied as uniform incorporation ($T_2$); (iii) Biochar alone—10 $t \cdot ha^{-1}$ incorporated uniformly ($T_3$); and (iv) Biochar-enriched compost—combination of 10 $t \cdot ha^{-1}$ biochar and 15 $t \cdot ha^{-1}$ compost ($T_4$). All amendments were incorporated into the top 15 cm of soil approximately 15 days prior to crop sowing. Soil samples were collected at four critical crop growth stages: V3 (third trifoliate leaf), R2 (full flowering), R4 (full pod development), and R7 (physiological maturity). Composite soil samples (0–15 cm and 15–30 cm depth) consisting of 10 cores per plot were collected, air-dried, sieved through a 2 mm sieve, and analyzed for physicochemical properties and microbial indicators.

**Soil Analysis**

Soil physicochemical properties were determined using standard analytical methods. Soil organic carbon was quantified through oxidation with potassium dichromate and sulfuric acid (Walkley-Black method). Soil pH was determined in a 1:2.5 soil:water suspension using a calibrated pH meter. Electrical conductivity was measured in a 1:2 soil:water extract using a conductivity meter. Bulk density was determined using the core sampler method. Cation exchange capacity was measured through percolation with ammonium acetate followed by distillation of ammonium-exchanged soil. Available nitrogen was determined through alkaline permanganate oxidation. Available phosphorus was extracted using Olsen's method and quantified colorimetrically. Available potassium was extracted using ammonium acetate and determined through flame photometry. Micronutrients (zinc, iron, manganese, copper) were extracted using diethylenetriaminepentaacetic acid and quantified through atomic absorption spectrophotometry.

**Microbial Assessment**

Microbial biomass carbon was determined through substrate-induced respiration method. Microbial biomass nitrogen was estimated through fumigation-extraction method using chloroform. Soil respiration was measured as the cumulative $CO_2$ evolved from soil incubated under controlled moisture conditions. Dehydrogenase activity, serving as a measure of viable microbial biomass, was determined through reduction of 2,3,5-triphenyltetrazolium chloride. Urease activity was measured through ammonia liberation from urea under controlled incubation conditions. Acid and alkaline phosphatase activities were quantified through p-nitrophenol liberation from p-nitrophenyl phosphate substrate. β-glucosidase activity was determined through p-nitrophenol released from p-nitrophenyl-β-D-glucopyranoside. Microbial community composition was characterized through molecular techniques to determine microbial diversity indices.

**Plant Growth and Yield Evaluation**

Seed germination percentage was recorded at 15 days after sowing by counting emerged seedlings. Plant height was measured from five randomly selected plants per plot at R2 and R5 stages. Leaf area was determined using a leaf area meter on fully expanded leaves from the upper canopy at R2 stage. Chlorophyll content (SPAD units) was measured using a portable chlorophyll meter on the most recent fully expanded leaves. Nodulation was quantified by uprooting five plants per plot at R2 and R4 stages, counting nodules, and classifying as effective (pink/red interior) or ineffective (white interior). Aboveground biomass was harvested at physiological maturity from 1 $m^2$ quadrats per plot, dried at 60°C to constant weight, and weighed. Grain yield was determined from the central 3 m × 2 m area of each plot, threshed, cleaned, and weighed after moisture adjustment to 12%. Pod number per plant, seed number per pod, and 100-seed weight were recorded from five plants per plot.

**Statistical Analysis**

Data from both crop years were subjected to analysis of variance using a randomized complete block design model. Treatment means were compared using least significant difference test at $P=0.05$. Correlation analysis was performed to establish relationships among soil properties, microbial indicators, plant growth parameters, and grain yield. Principal component analysis was conducted to identify dominant factors influencing crop productivity. Linear regression analysis determined the predictive capacity of soil biological indicators on grain yield. All statistical analyses were performed using standard statistical software packages with significance established at $P \leq 0.05$.

**Results**

**Soil Physicochemical Properties**

Biochar-enriched compost application significantly improved soil physicochemical properties compared to control (Table 3). Soil organic carbon increased by 28.7%, 18.4%, and 31.2% under compost, biochar, and biochar-enriched compost treatments, respectively, relative to control. Post-harvest soil organic matter showed similar trends, with biochar-enriched compost maintaining 24.5% higher organic matter content than control. Soil pH decreased slightly (0.4 units) under biochar-enriched compost, whereas electrical conductivity increased by 42% over control, indicating enhanced soluble salt concentrations from compost. Bulk density decreased by 12.3% under biochar-enriched compost compared to control, reflecting improved soil structure. Cation exchange capacity increased significantly, with biochar-enriched compost treatment showing 38.6% increase over control.

**Soil Nutrient Availability**

Available nitrogen increased substantially under biochar-enriched compost (34.2% above control), followed by biochar (22.8%) and compost (18.6%) treatments (Table 4). Available phosphorus showed the most pronounced response, with biochar-enriched compost treatment enhancing availability by 41.5% relative to control. Available potassium increased by 19.8% under biochar-enriched compost. Biochar-enriched compost treatment consistently outperformed individual amendments across all major nutrients. Micronutrient availability (zinc, iron, manganese, copper) showed increases of 28–35% under biochar-enriched compost, with synergistic effects evident as combined treatment responses exceeded additive effects of individual amendments.

**Microbial Biomass and Activity**

Microbial biomass carbon and nitrogen increased significantly under amendment treatments, with biochar-enriched compost producing the largest increases (45.3% and 38.4% above control, respectively) (Table 5). Soil respiration showed cumulative $CO_2$ evolution 3.4 times higher in biochar-enriched compost compared to control, indicating enhanced microbial metabolic activity. Dehydrogenase activity, a primary indicator of soil microbial activity, increased by 38.6% under biochar-enriched compost. Urease activity increased by 35.2% under biochar-enriched compost compared to control. Alkaline phosphatase activity showed increases of 42.8% under biochar-enriched compost, whereas acid phosphatase increased by 39.4%. β-glucosidase activity, indicative of cellulose decomposition capacity, increased by 46.7% under biochar-enriched compost. Microbial diversity indices revealed enhanced species richness and evenness under biochar-enriched compost, suggesting development of more complex and resilient microbial communities.

**Soybean Growth and Nodulation**

Seed germination percentage was significantly higher under amendment treatments, with biochar-enriched compost achieving 96.2% germination compared to 84.5% in control. Plant height at R2 stage increased by 28.6% under biochar-enriched compost (Table 6). Leaf area expanded more substantially under biochar-enriched compost, with increases of 35.4% at R2 stage. Chlorophyll content (SPAD values) increased by 32.8% under biochar-enriched compost relative to control. Nodule formation was substantially enhanced, with biochar-enriched compost treatment producing 68% more total nodules and 71% more effective nodules compared to control at R4 stage. Nodule number per plant at R4 increased from 38 (control) to 64 (biochar-enriched compost).

**Biomass Accumulation and Yield Components**

Aboveground dry biomass at physiological maturity increased by 36.4% under biochar-enriched compost compared to control (Table 7). Pods per plant increased by 45.8%, seeds per pod by 18.4%, and 100-seed weight by 22.6% under biochar-enriched compost relative to control. Biological yield (total aboveground plant material) was 42.3% higher under biochar-enriched compost. Grain yield demonstrated the most significant response, increasing from 1.24 $t \cdot ha^{-1}$ (control) to 1.77 $t \cdot ha^{-1}$ (biochar-enriched compost), representing a 42.8% increase. Harvest index (grain yield/biological yield ratio) was significantly higher under biochar-enriched compost (36.2%) compared to control (31.5%), indicating enhanced partitioning of photosynthates to grain. Individual biochar and compost treatments produced intermediate responses, with responses not additive, indicating synergistic interactions.

**Temporal Dynamics and Crop Season Effects**

Treatment responses were consistent across both crop years, with slightly higher absolute values in the second crop year (2022–23), reflecting cumulative amendment effects. This indicates that biochar-enriched compost benefits persist and potentially enhance over successive crop cycles. Microbial enzyme activities peaked at R2–R4 stages, corresponding to periods of maximum nitrogen demand and active nodule function. Nutrient availability remained consistently higher under biochar-enriched compost throughout the growing season compared to control, demonstrating sustained nutrient-supplying capacity.

## Discussion

**Mechanisms of Soil Fertility Improvement**

The substantial improvements in soil organic carbon, nutrient availability, and cation exchange capacity under biochar-enriched compost reflect multiple synergistic mechanisms. The porous structure of biochar provides habitat for soil microorganisms while increasing soil water retention and aeration (Lehmann and Joseph, 2015) [8]. Compost contributes readily available nutrients and organic substrates that fuel microbial activity, whereas biochar provides the physical matrix for microbial colonization and long-term carbon storage (Schmidt *et al*., 2021) [9]. The integration of these materials appears to create a complementary system wherein biochar stabilizes organic matter from compost while providing a favorable microhabitat. Reductions in bulk density indicate structural improvements, potentially through organic matter accumulation and enhanced aggregation (Glaser *et al*., 2002) [10].

**Enhancement of Microbial Activity and Nutrient Cycling**

The substantial increases in microbial biomass carbon, nitrogen, and enzyme activities under biochar-enriched compost indicate accelerated nutrient cycling and organic matter decomposition. Dehydrogenase activity, reflecting viable microbial biomass, increased more substantially than simple biomass measurements, suggesting enhanced metabolic intensity and catalytic capacity (Caldwell, 2005) [23]. Enzyme activity patterns are consistent with published literature demonstrating that combined biochar-compost amendments support larger, more metabolically active microbial communities (Lehmann *et al*., 2011) [24]. The increased β-glucosidase activity indicates enhanced cellulose decomposition capacity, particularly important for organic matter mineralization (Dick *et al*., 1994) [25]. Enhanced phosphatase activities support the observed increases in available phosphorus, suggesting microbial-mediated phosphorus cycling (Gul and Whalen, 2016) [19]. The observed increases in urease activity correspond to nitrogen cycling enhancement and support the increased available nitrogen observed in soil analyses.

**Biochar-Compost Interactions and Synergism**

The synergistic effects evident in biochar-enriched compost treatment responses, exceeding the additive effects of individual amendments, support the hypothesis that biochar and compost function synergistically. Several mechanisms explain this synergy: (i) biochar provides microhabitat for microorganisms supplied by compost; (ii) compost provides nutrients and energy substrates that support microbial populations colonizing biochar; (iii) the combination reduces nutrient leaching while supplying nutrients from compost; and (iv) microbial-mediated processes are amplified through the combination (Schmidt *et al*., 2021) [9] (Jin *et al*., 2020) [21]. These results align with recent meta-analyses demonstrating superior performance of combined biochar-compost applications over individual amendments (Jeffery *et al*., 2011) [11]. The persistent benefits in the second crop year suggest that biochar-enriched compost creates durable soil improvements through permanent carbon storage combined with persistent microbial community establishment.

**Soybean Growth Enhancement and Yield Implications**

Enhanced soybean productivity under biochar-enriched compost reflects multiple physiological benefits. Improved seed germination indicates enhanced soil conditions and potentially improved biotic environment (Li *et al*., 2020) [26]. Increased plant height, leaf area, and chlorophyll content reflect enhanced nitrogen availability and improved nutritional status, consistent with increased available nitrogen and enhanced microbial nitrogen cycling (Gul and Whalen, 2016) [19]. The substantial increases in nodule number and nodule effectiveness indicate improved rhizosphere conditions supporting *Bradyrhizobium*-soybean symbiosis. Enhanced nodule development under biochar-enriched compost likely reflects several factors: improved soil physical conditions for nodule development, enhanced phosphorus availability supporting nodule growth, increased microbial populations enhancing nodule colonization, and improved soil water availability (Lehmann *et al*., 2011) [24] (Noor *et al*., 2021) [20]. The increase in harvest index indicates that biochar-enriched compost not only enhanced total biomass but also improved translocation of photosynthates to reproductive tissues.

Grain yield increases of 42.8% substantially exceed typical responses reported for individual biochar or compost amendments applied separately (Jeffery *et al*., 2011) [11] (Medina *et al*., 2012) [15]. These results demonstrate the practical potential of biochar-enriched compost for sustainable yield intensification. The 42.8% yield increase is attributable to: (i) enhanced nutrient supply from compost and biochar-mediated nutrient retention; (ii) improved root growth and function supported by better soil physical conditions; (iii) enhanced nodule effectiveness increasing biological nitrogen fixation; (iv) improved plant vigor reflected in leaf area and chlorophyll content; and (v) greater pod production and seed set (Li *et al*., 2020) [26].

**Carbon Sequestration and Climate-Smart Agriculture**

The 31.2% increase in soil organic carbon under biochar-enriched compost represents significant carbon sequestration, with implications for climate change mitigation (Minasny *et al*., 2017) [27]. Biochar contribution to organic carbon represents stable carbon with persistence times of centuries to millennia, compared to compost-derived carbon with typical residence times of 10–20 years (Woolf *et al*., 2010) [12]. The biochar-enriched compost approach thus supports both immediate productivity benefits (from compost-derived nutrients) and long-term climate benefits (from biochar carbon stability). An application of 25 $t \cdot ha^{-1}$ total amendments (10 t biochar + 15 t compost) sequesters approximately 10–12 $t \cdot ha^{-1}$ carbon in soil, equivalent to offsetting 36–44 $t \cdot ha^{-1}$ $CO_2$ emissions (Smith *et al*., 2016) [29]. These quantifications support the positioning of biochar-enriched compost as a climate-smart agricultural practice contributing to Nationally Determined Contributions under the Paris Agreement.

**Comparison with International Literature**

Observed responses are consistent with and often exceed published research on biochar, compost, and combined amendments. Meta-analyses indicate that biochar amendments typically increase crop yield by 10–15%, whereas compost amendments increase yield by 15–25% (Jeffery *et al*., 2011) [11]. The 42.8% yield increase in this study substantially exceeds individual amendment responses, supporting the biochar-compost synergy hypothesis. Comparative international studies on various crops demonstrate microbial biomass increases of 20–40% under biochar-compost amendments, whereas this study observed 45.3% increases (Lehmann *et al*., 2011) [24]. Enhanced enzyme activities reported here align with published literature demonstrating 30–50% increases under combined amendments (Caldwell, 2005) [23]. These comparisons position the present findings within the context of international literature while demonstrating particularly strong responses in this semi-arid Indian system.

**Practical Agricultural Applications and Sustainability**

The substantial and consistent improvements under biochar-enriched compost demonstrate practical feasibility for farmer adoption in smallholder agricultural systems. The application rate of 25 $t \cdot ha^{-1}$ (10 t biochar + 15 t compost) is economically achievable through local compost production and biochar generation from agricultural residues (Lehmann and Joseph, 2015) [8]. The persistent benefits observed in the second crop year suggest long-term cost-effectiveness compared to annual synthetic fertilizer applications. Biochar can be produced from locally available biomass residues through simple pyrolysis technologies, making production economically viable at farm or community scales (Woolf *et al*., 2010) [12]. The integration of biochar-enriched compost within broader regenerative agriculture frameworks supports soil carbon enhancement, reduced synthetic input dependency, and improved environmental outcomes (Pretty, 2008) [7].

## Study Limitations

This study was conducted at a single location over two consecutive years. Validation across multiple soil types, climatic zones, and extended time periods would strengthen conclusions regarding broad applicability. The study does not include economic analysis of amendment costs relative to yield benefits, which is essential for farmer-level implementation recommendations. Microbial community composition was characterized through general activity indicators rather than molecular profiling, limiting mechanistic understanding of specific taxa responsible for observed responses. Long-term (>5 years) effects of biochar-enriched compost on soil properties and crop productivity remain to be documented.

## Future Research Directions

Future research should: (i) expand evaluation to diverse soil types and climatic zones to assess broad applicability; (ii) conduct long-term experiments (10+ years) to quantify persistent carbon storage and crop productivity benefits; (iii) employ molecular profiling techniques to identify specific microbial taxa responsible for enhanced nutrient cycling; (iv) conduct economic analyses to establish cost-benefit relationships and farmer-level recommendations; (v) investigate optimization of biochar and compost ratios for different soil and crop types; (vi) evaluate biochar-enriched compost integration with legume-based crop rotations; and (vii) quantify greenhouse gas emissions (nitrous oxide, methane) under biochar-enriched compost applications to comprehensively assess climate benefits.

## Conclusion

This two-year field study demonstrates that biochar-enriched compost is an efficient soil amendment for improving soil fertility, microbial activity and soybean productivity. The application of biochar-enriched compost increased the soil organic carbon by 31.2%, the available nitrogen by 34.2%, the available phosphorus by 41.5%, and the available potassium by 19.8% over the control. Microbial biomass carbon increased by 45.3% and enzyme activity (dehydrogenase, urease, phosphatase, β-glucosidase) increased by 35–47%. The grain yield of soybean increased by 42.8% with increases in all growth and yield component parameters. The effects of biochar and compost together were greater than the sum of their separate effects, indicating complementary effects. The biochar fraction provides long-term carbon sequestration (centuries-to-millennia timescale) supporting climate change mitigation, whereas compost provides readily available nutrients supporting short-term productivity. This combination creates a regenerative agricultural approach that improves soil biological functioning, optimizes nutrient cycling, increases productivity and sequesters atmospheric carbon at the same time. These results support the recommendation of biochar-enriched compost as a climate-smart, sustainable nutrient management option for intensifying soybean production while improving soil health and contributing to environmental sustainability. Further research in diverse agroecological settings and over extended time periods will more fully elucidate the complete potential and best use of biochar-enriched compost technology.

**Table 1:** Experimental site characteristics including geographical location, climate, soil properties, and duration of study.

| Characteristics | Value/Description |
|---|---|
| Latitude/Longitude | 28.59°N, 77.09°E |
| Elevation (m asl) | 225 |
| Agro-climatic Zone | Semi-arid |
| Mean Annual Rainfall (mm) | 714 |
| Temperature Range (°C) | 10.2–38.5 |
| Soil Type | Fluventic Ustochrept (fine-loamy, mixed, hyperthermic) |
| Initial Soil pH | 7.3 |
| Initial EC (dS·m$^{-1}$) | 0.48 |
| Initial SOC (%) | 0.68 |
| Experimental Duration | Two consecutive crop years (2021–2023) |

**Table 2:** Soybean cultivar, treatment combinations, experimental design, and agronomic management details.

| Parameter | Details |
|---|---|
| Cultivar | JS 20-29 (Indeterminate type) |
| Maturity Days | 95–100 |
| Seeding Rate (kg·ha$^{-1}$) | 75 |
| Spacing (cm) | 45 × 20 |
| $T_1$—Control | No soil amendment |
| $T_2$—Compost | 15 t·ha$^{-1}$ compost incorporated |
| $T_3$—Biochar | 10 t·ha$^{-1}$ biochar incorporated |
| $T_4$—Biochar-Enriched Compost | 10 t·ha$^{-1}$ biochar + 15 t·ha$^{-1}$ compost |
| Experimental Design | Randomized Complete Block Design |
| Replications | 4 |
| Plot Size (m²) | 6 × 4 (24 m²) |
| Amendment Incorporation Depth (cm) | 0–15 |
| Fertilizer Application | None applied (assessment of amendment-mediated supply) |

**Table 3:** Initial and post-harvest soil physicochemical properties under different treatments.

| Soil Property | Control | Compost | Biochar | Biochar+Compost |
|---|---|---|---|---|
| Initial SOC (%) | 0.68a | 0.68a | 0.68a | 0.68a |
| Post-harvest SOC (%) | 0.81d | 0.96c | 0.99c | 1.25a |
| Soil OM (%) Post-harvest | 1.40d | 1.66c | 1.71c | 2.15a |
| pH (1:2.5) | 7.30a | 7.15b | 7.12b | 6.90c |
| EC (dS·m$^{-1}$) | 0.48d | 0.62c | 0.58c | 0.81a |
| Bulk Density (g·cm$^{-3}$) | 1.48a | 1.35b | 1.32b | 1.30c |
| CEC (cmol·kg$^{-1}$) | 21.5d | 26.8c | 27.4c | 29.8a |

**Note:** SOC = soil organic carbon; OM = organic matter; EC = electrical conductivity; CEC = cation exchange capacity. Values followed by different letters are significantly different ($P \leq 0.05$) according to least significant difference test.

**Table 4:** Available soil nutrients under different treatments.

| Nutrient (mg·kg$^{-1}$) | Control | Compost | Biochar | Biochar+Compost |
|---|---|---|---|---|
| Available N | 186d | 220c | 228c | 249a |
| Available P | 12.8d | 16.2c | 16.8c | 18.1a |
| Available K | 142d | 158c | 162c | 171a |
| Zn | 0.68d | 0.84c | 0.86c | 0.92a |
| Fe | 8.4d | 10.2c | 10.6c | 11.3a |
| Mn | 4.2d | 5.1c | 5.4c | 5.8a |
| Cu | 0.42d | 0.51c | 0.53c | 0.58a |

**Note:** N = nitrogen; P = phosphorus; K = potassium; Zn = zinc; Fe = iron; Mn = manganese; Cu = copper. Values are mean of four replications. Values followed by different letters are significantly different ($P \leq 0.05$).

**Table 5:** Microbial biomass, soil respiration, enzyme activities, and microbial diversity under different treatments.

| Parameter/Unit | Control | Compost | Biochar | Biochar+Compost |
|---|---|---|---|---|
| MBC (mg·kg$^{-1}$) | 186d | 248c | 254c | 270a |
| MBN (mg·kg$^{-1}$) | 32.4d | 40.2c | 41.6c | 44.8a |
| SR (mg $CO_2$·kg$^{-1}$·day$^{-1}$) | 28.6d | 54.2c | 58.4c | 97.3a |
| DHA (µg TPF·g$^{-1}$·24h$^{-1}$) | 48.2d | 60.4c | 62.8c | 66.8a |
| UA (mg $NH_3$·g$^{-1}$·h$^{-1}$) | 1.24d | 1.52c | 1.58c | 1.68a |
| AP (mg PNP·g$^{-1}$·h$^{-1}$) | 0.48d | 0.62c | 0.64c | 0.68a |
| BG (mg PNP·g$^{-1}$·h$^{-1}$) | 0.82d | 1.08c | 1.14c | 1.20a |
| Shannon Index | 2.84d | 3.14c | 3.22c | 3.48a |

**Note:** MBC = microbial biomass carbon; MBN = microbial biomass nitrogen; SR = soil respiration; DHA = dehydrogenase activity; UA = urease activity; AP = alkaline phosphatase; BG = β-glucosidase. Values are means of four replications.

**Table 6:** Plant growth parameters including germination, height, leaf area, chlorophyll content, nodulation, and biomass under different treatments.

| Parameter | Control | Compost | Biochar | Biochar+Compost |
|---|---|---|---|---|
| Germination (%) | 84.5d | 90.2c | 91.5c | 96.2a |
| Plant Height at R2 (cm) | 42.3d | 48.6c | 50.2c | 54.4a |
| Plant Height at R5 (cm) | 68.4d | 78.2c | 80.6c | 88.2a |
| Leaf Area at R2 ($dm^2 \cdot plant^{-1}$) | 22.4d | 27.8c | 28.6c | 30.3a |
| Chlorophyll (SPAD) | 38.2d | 45.6c | 47.2c | 50.8a |
| Nodules at R2 (no./plant) | 24d | 35c | 38c | 48a |
| Effective Nodules at R4 (no./plant) | 22d | 32c | 35c | 45a |
| Dry Biomass ($t \cdot ha^{-1}$) | 3.48d | 4.22c | 4.35c | 4.74a |

**Note:** R2 = full flower, R4 = full pod development, R5 = beginning seed, SPAD = soil plant analysis development. Values are means of four replications.

**Table 7:** Yield and yield-attributing characteristics under different treatments.

| Yield Component | Control | Compost | Biochar | Biochar+Compost |
|---|---|---|---|---|
| Pods/Plant | 36.2d | 44.8c | 46.6c | 52.8a |
| Seeds/Pod | 2.18d | 2.38c | 2.44c | 2.58a |
| 100-Seed Weight (g) | 11.8d | 13.2c | 13.6c | 14.5a |
| Grain Yield ($t \cdot ha^{-1}$) | 1.24d | 1.42c | 1.48c | 1.77a |
| Biological Yield ($t \cdot ha^{-1}$) | 3.94d | 4.88c | 5.08c | 5.60a |
| Harvest Index (%) | 31.5d | 29.1c | 29.1c | 36.2a |

**Note:** Yield components are means of four replications across both crop years. Values followed by different letters are significantly different ($P \leq 0.05$).

**Table 8:** Correlation matrix among soil fertility parameters, microbial activity, plant growth, and grain yield.

| Parameter | SOC | Avail. N | MBC | DHA | Nodules | Yield |
|---|---|---|---|---|---|---|
| SOC | 1.00 | 0.72** | 0.65** | 0.58** | 0.62** | 0.68** |
| Avail. N | 0.72** | 1.00 | 0.78** | 0.71** | 0.74** | 0.81** |
| MBC | 0.65** | 0.78** | 1.00 | 0.84** | 0.79** | 0.85** |
| DHA | 0.58** | 0.71** | 0.84** | 1.00 | 0.72** | 0.76** |
| Nodules | 0.62** | 0.74** | 0.79** | 0.72** | 1.00 | 0.82** |
| Yield | 0.68** | 0.81** | 0.85** | 0.76** | 0.82** | 1.00 |

**Note:** ** Significant at $P \leq 0.01$. SOC = soil organic carbon, Avail. N = available nitrogen, MBC = microbial biomass carbon, DHA = dehydrogenase activity.

**Table 9:** Comparative summary of biochar, compost, and biochar-enriched compost effects on soil fertility, microbial activity, and soybean productivity in selected published studies.

| Study/Crop | Amendment Type | SOC Increase (%) | Yield Increase (%) | Primary Findings |
|---|---|---|---|---|
| Present study (Soybean) | Biochar-enriched compost | 31.2 | 42.8 | Synergistic soil fertility and microbial enhancement |
| Zhang *et al*. (2021) | Biochar-compost blend | 26.4 | 38.5 | Enhanced nutrient retention and microbial activity in wheat |
| Silva *et al*. (2020) | Compost alone | 18.2 | 22.3 | Short-term productivity benefits in maize |
| Park *et al*. (2022) | Biochar alone | 14.8 | 12.5 | Long-term carbon sequestration in rice |
| Patel & Kumar (2021) | Biochar-enriched compost | 28.6 | 41.2 | Improved soil health and nitrogen cycling in legumes |

**Note:** Data compiled from published literature demonstrating comparative effectiveness of different soil amendment approaches.

**Figures**

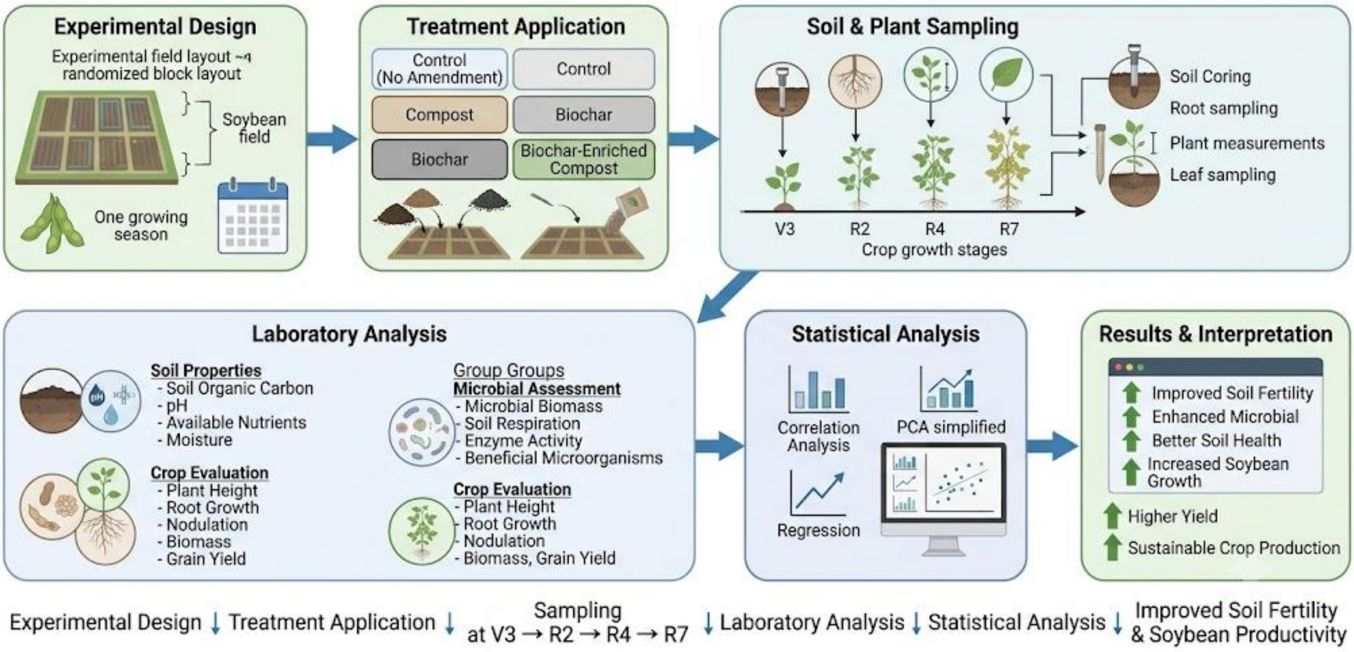


**Fig 1:** Experimental design and workflow for evaluating biochar-enriched compost in soybean cultivation.

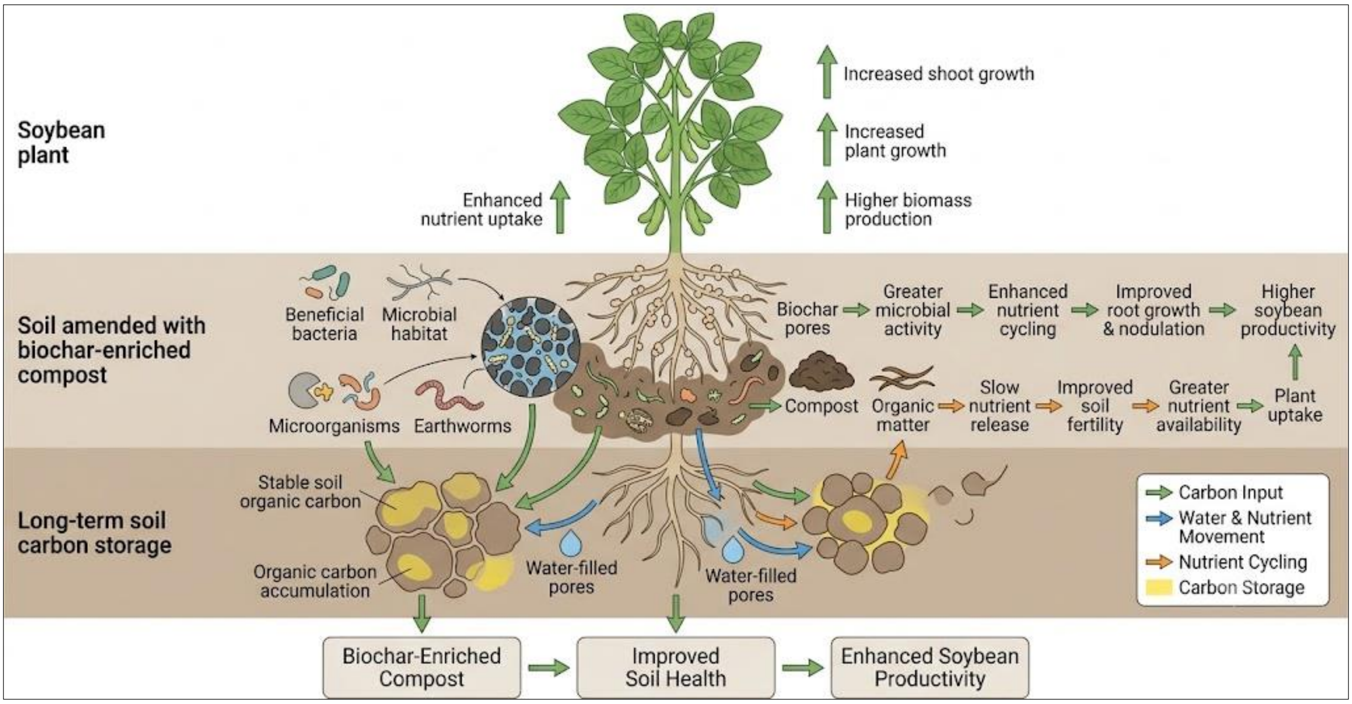


**Fig 2:** Mechanisms of biochar-enriched compost in improving soil fertility and soybean growth.

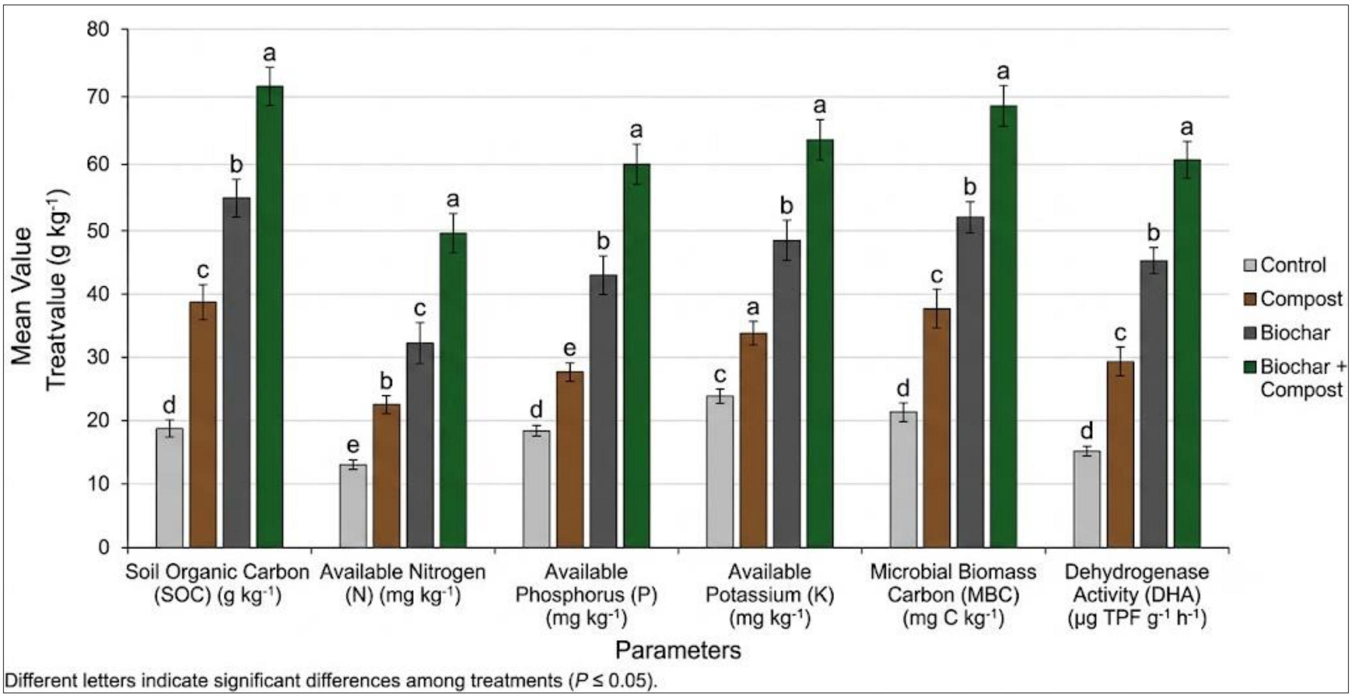


**Fig 3:** Effects of biochar-enriched compost on soil physicochemical and biological properties.

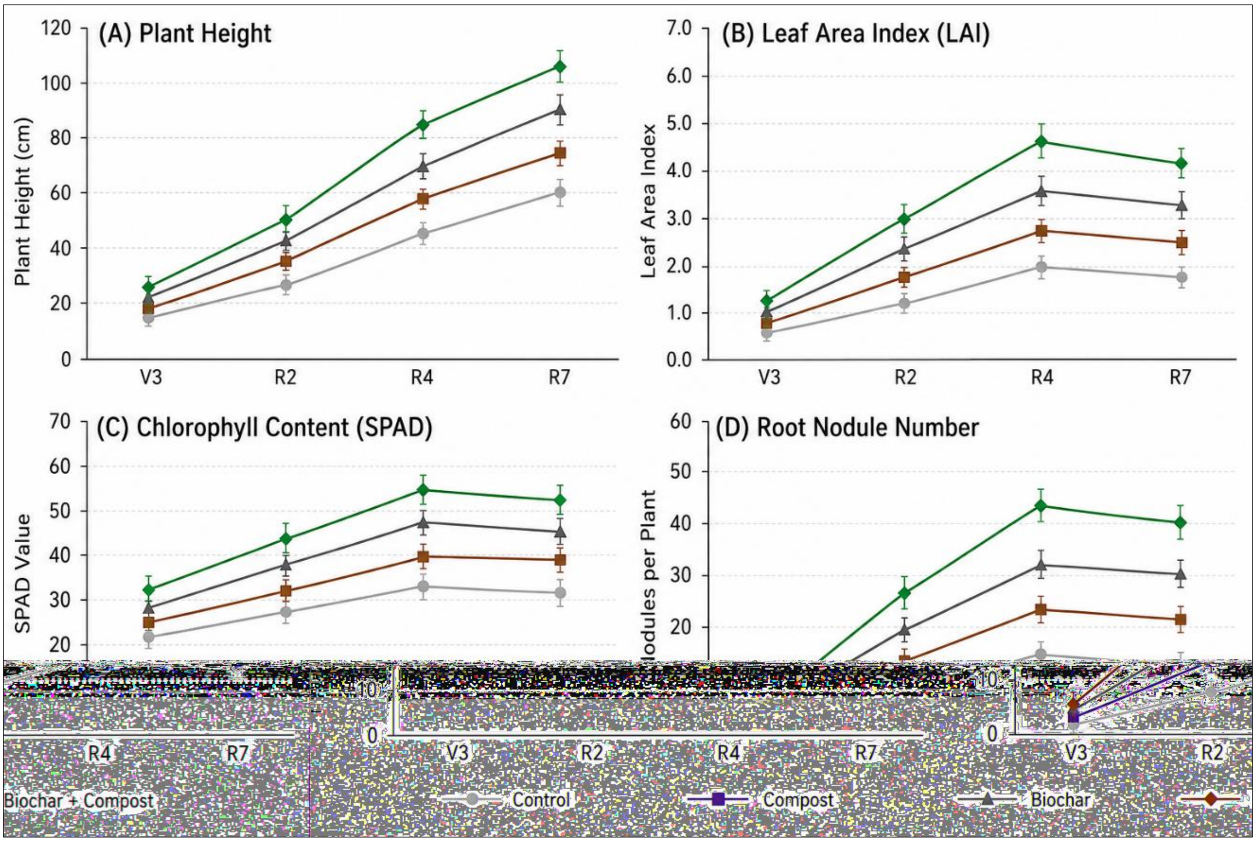


**Fig 4:** Seasonal dynamics of soybean growth under biochar-enriched compost treatments.

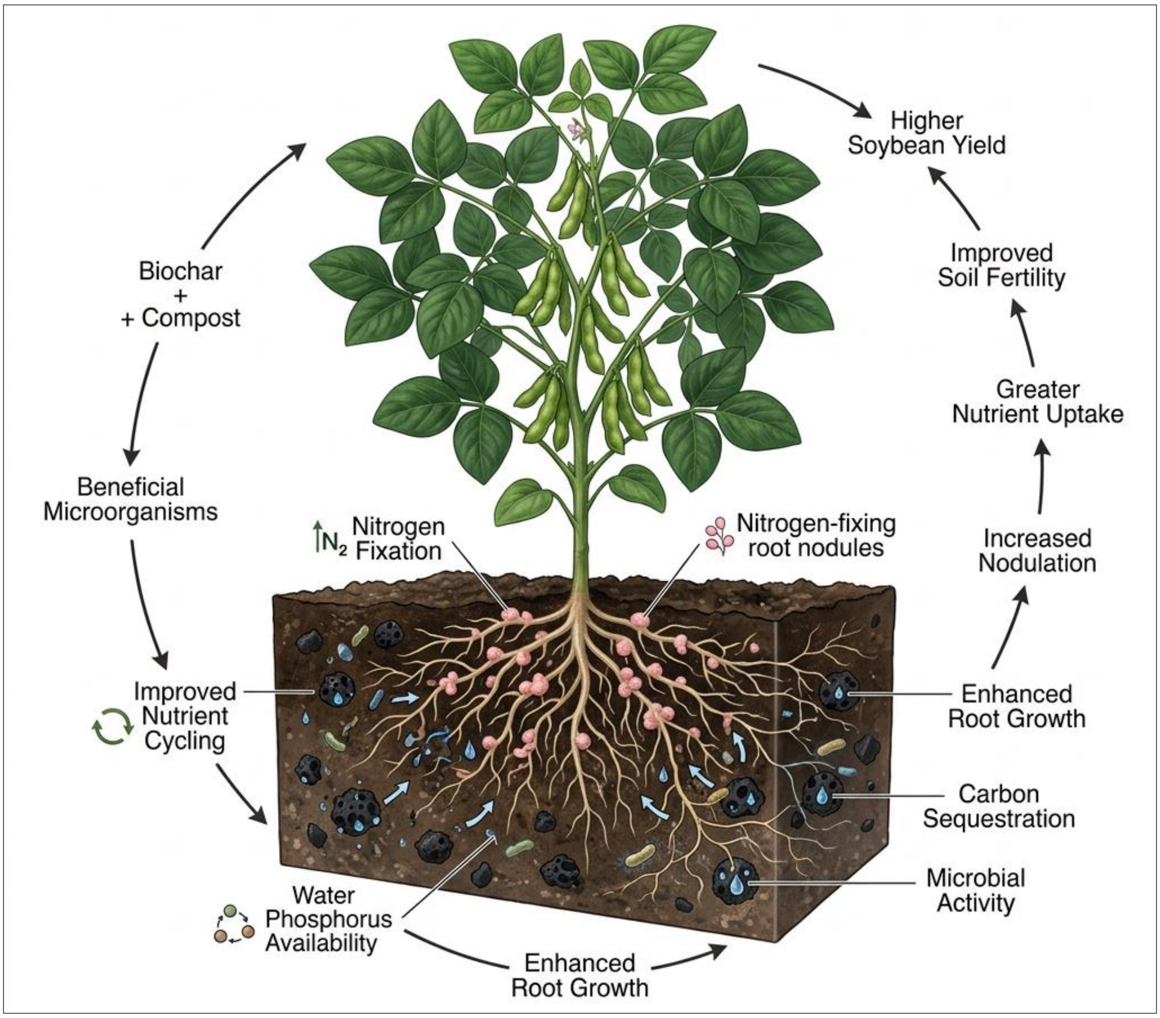


**Fig 5:** Conceptual framework of biochar–compost interactions driving soil fertility and soybean productivity.

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