Discover Sustainability

https://doi.org/10.1007/s43621-026-04416-x

Article in Press

Biochar amendments as a regenerative agriculture strategy for soil health restoration and sustainable millet production

Received: 16 January 2026

Accepted: 12 August 2026

Published online: 22 August 2026

Cite this article as: Subudhi L., Behera S.K., Panda A.K. *et al.* Biochar amendments as a regenerative agriculture strategy for soil health restoration and sustainable millet production. *Discov Sustain* (2026). https://doi.org/10.1007/s43621-026-04416-x

Lopamudra Subudhi, Sandeep Kumar Behera, Alok Kumar Panda & Shibani Mohapatra

Biochar Amendments as a Regenerative Agriculture Strategy for Soil Health Restoration and Sustainable Millet Production

Lopamudra Subudhi[1], Sandeep Kumar Behera[2], Alok Kumar Panda[2*], Shibani Mohapatra[1*]

[1]Centre for Biotechnology, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha

[2]Environmental Science Laboratory, School of Applied Sciences, Kalinga Institute of Industrial Technology (Deemed to be University), Bhubaneswar-751024, India

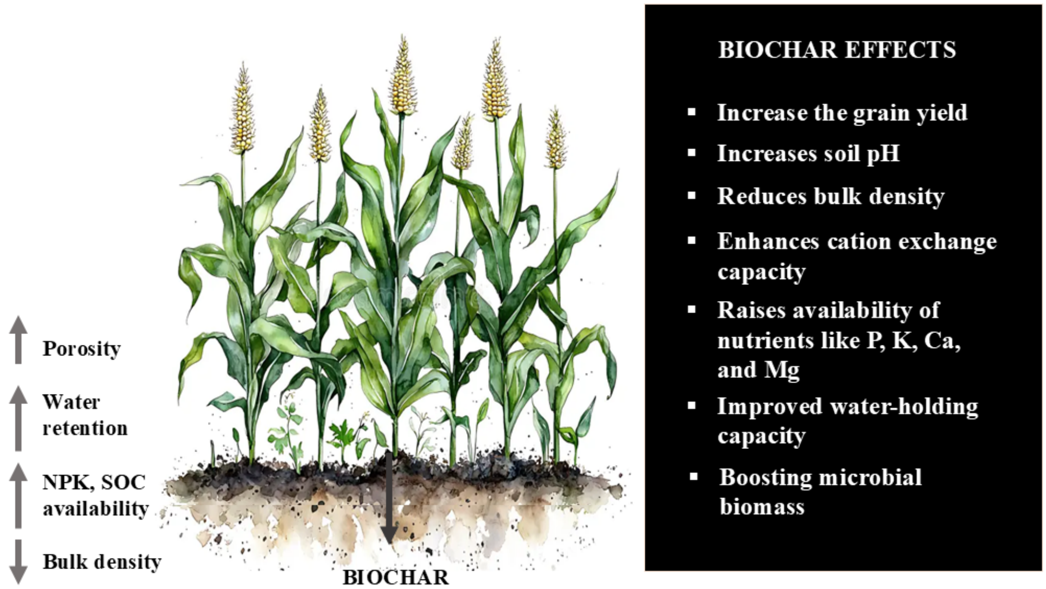
Corresponding authors: shibanimohapatra@soa.ac.in , alokpanda.fch@kiit.ac.in

Abstract

Millet crops are primarily grown in marginal, nutrient-deficient, and increasingly arid regions, where declining soil health significantly limits productivity. Biochar is a carbon-rich byproduct of biomass pyrolysis that is being researched as a promising soil amendment to improve degraded soils. This systematic review has been conducted through an in-depth analysis of 14 peer-reviewed papers from 2014 to 2025, including a synthesis of the literature that describes the changes to soil physical, chemical, and biological properties, as well as the impacts on cultivar growth and grain yield that can be attributed to biochar amendment. Results indicate that biochar significantly reduces bulk density, improves soil porosity and water-holding capacity, and enhances soil structure, which are important and necessary indicators of soil for new millet establishment in sandy or compacted soils. In addition, biochar chemically increased organic carbon in soils, optimized pH levels, increased cation exchange capacity, and enhanced the availability of macro- and micronutrients. We also describe how biochar biologically increases microbial biomass, enzyme activities, and beneficial microbial taxa, while decreasing the effects of salinity and heavy metals via improved rhizosphere function. Constructively, these improvements contributed to better germination and root establishment, improved stress tolerance, and significantly greater biomass and grain yields for pearl, foxtail, finger, and proso millet. In summary, biochar is a viable, inexpensive, and climate-resilient practice for restoring soil functionality and increasing millet production in susceptible agroecosystems.

Keywords: Biochar, Millet cultivation, Soil health, Soil fertility, PRISMA 2020

Graphical abstract:



1. Introduction

Soils are an important interface connecting the Earth's layers (bedrock), atmosphere, plants, and animals, and supporting the growth of many species through their role in exchanging nutrients with the environment (biogeochemistry) and storing materials needed for survival for both humans and natural systems. Agriculture's greatest challenge in the tropics is land degradation and soil fertility, which includes soil erosion, nutrient depletion, biomass competition, the lack of inorganic fertilizer use, and farmers' inability to recognize how soil quality affects productivity (Agegnehu and Amede 2017). The most effective way to combat land degradation and restore soil fertility in tropical agriculture begins with soil improvement techniques that incorporate the application of the correct types of soil amendments.

Biochar is commonly used as a soil improver and refers to the charcoal derived from heating high-carbon biomass, which has been heated with little or no oxygen present. Biochar may provide an alternative method for enhancing the soil organic carbon (SOC) content in agricultural soils (Ok, Uchimiya et al. 2015). The benefits of biochar have been investigated extensively in various studies. The attributes of biochar include a predominantly alkaline pH, excellent pore sizes and surface areas, as well as stability and high cation exchange capacity (Basak, Sarkar et al. 2022). Thus, it can be utilized to enhance soil properties, such as fertility and nutrient availability, as well as provide favorable conditions for microorganisms in the soil and immobilize contaminants. Unlike other organic methods of amending soil, which tend to degrade easily, the recalcitrance of biochar will help to maintain its benefits in the soil for an extended period (Lima, da Penha Simon et al.

2025).Millets are cereal grain crops that can be resilient to changing climates. They are typically grown in dry regions (arid and semi-arid) and provide good nutrition and food security with low inputs compared to many other types of crops, especially in stressful climate conditions. Despite the increasing importance of sustainable agriculture, no documented PRISMA-compliant systematic reviews have evaluated all aspects of how biochar applications interact with millet production. There is published literature suggesting that biochar can improve nutrient availability, decrease soil bulk density, promote beneficial microorganisms, and increase millet growth and yield under marginal and/or stressful growing conditions. As climate change continues to pose challenges for agricultural practices and sustainable soil restoration, knowledge of the interactions between biochar amendments and millet productivity is particularly relevant. Therefore, this systematic review will provide an overview of peer-reviewed experimental research conducted from 2014-2025 and will assess the current state of research, provide direction on future agronomic practices and evaluate the overall impact of biochar amendments on soil health and millet production. Specifically, this review addresses the following research question: "How does biochar application influence soil physical, chemical, and biological properties, and how do these changes affect millet growth and yield under different environmental conditions?"

This review will synthesize peer-reviewed experimental millet studies published internationally between 2014 and 2025, to evaluate how biochar-amended practices improve soil health and yield in millet cultivation. (Fig. 1)

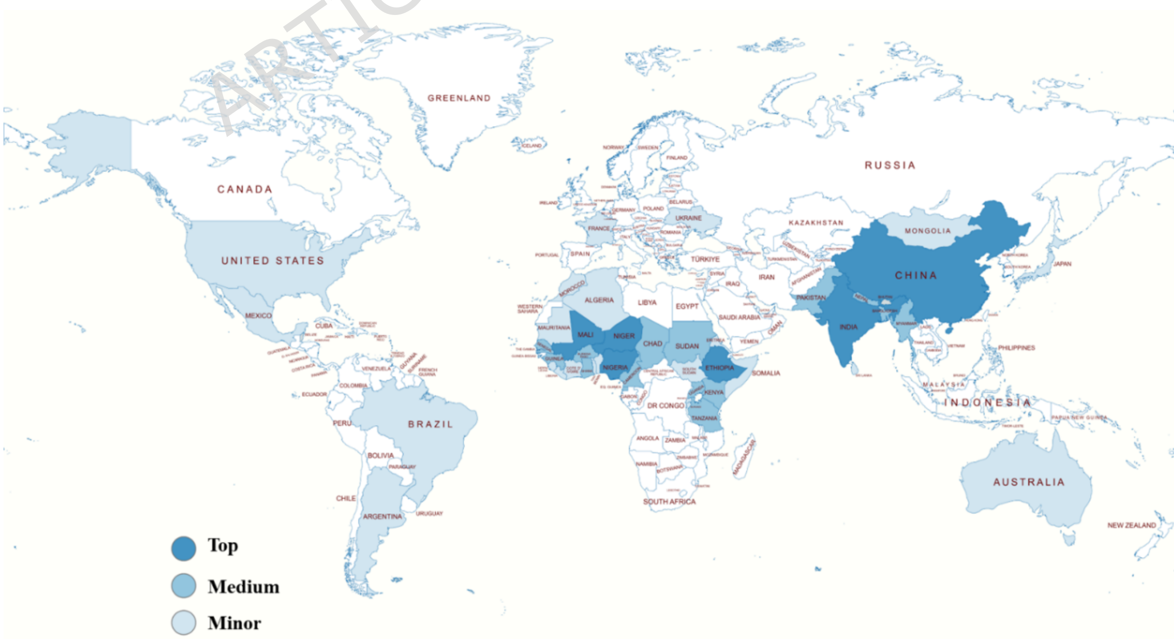


Figure 1: Millet Distributions throughout the world

2. Materials and Methods

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Page et al., 2021) to ensure transparency, reproducibility and methodological rigor.

2.1. Literature Search Strategy

A comprehensive literature search was conducted using four major electronic databases: Scopus, Web of Science, ScienceDirect and Google Scholar. Studies published between 2014 and 2025 were considered for inclusion in the review. The search strategy used Boolean operators and combinations of keywords to identify studies investigating biochar application in millet crop production systemsThe primary search string was ("biochar") AND ("millet" OR "pearl millet" OR "foxtail millet" OR "finger millet" OR "proso millet") AND ("soil properties" OR "soil health" OR "soil fertility" OR "crop productivity" OR "yield"). Additional database-specific modifications were made as necessary to improve search results.

The search resulted in a total of 12,707 records (Scopus: 2686; Web of Science: 396; ScienceDirect: 425; Google Scholar: 9200 screened).

2.2. Eligibility Criteria

Studies were included if they:

1. Evaluated the effects of biochar application on millet crops.

2. Reported soil health parameters/yield outcomes are measurable in millet crop studies only

3. Were Peer reviewed experimental research involving millet studies including biochar only

4. Were published between 2014 to 2025

5. Only peer-reviewed publications written in English were considered for inclusion.

Studies were excluded if:

1. Focused exclusively on non-millet crops.

2. Were review articles, conference abstracts, or lacked primary data.

3. Did not report or soil performance indicators

4. Lacked adequate methodological and/or quantitative information

5. Studies before 2015 were not considered

2.3. Study Selection Process

Process of Study Screening and Selection were imported into the reference manager Endnote 20 and duplicate entries were identified and removed (n=10,205). The remaining 2,502 records were screened against pre-specified PICOS criteria using titles and abstracts (Fig 2):

- Population: Millet crops (pearl, foxtail, finger, proso millet)
- Intervention: Soil application of biochar
- Comparison of control vs. fertilizer-only treatment
- Results: soil physical, chemical, biological properties and/or crop production
- Study Design: Experimental studies (field, pot or controlled environment)

After this first screening, 2001 studies were excluded because they did not address millet systems, did not involve a biochar intervention, or did not report any measurable outcomes on soil or yield. A total of 501 full text articles were assessed for eligibility. Of these, 483 studies were excluded for incomplete data reporting, missing quantitative results, review articles, or non-millet crop focus. Finally, 14 studies met all inclusion criteria and were included in the qualitative synthesis.

2.4. Data Extraction

Data were extracted from each eligible study using a standardized data collection framework. These shared the following data types: species of millet used; type of soil where the millet was grown; type of biochar used and its attributes; rate at which biochar was applied; design of the experiment; information regarding physical, chemical, and biological measurements made on the soil; growth response of the millet plant; yield of millet; and any key conclusions relevant to this review.

2.5. Quality Assessment of Included Studies

To evaluate the methodological quality of the studies considered in this review process, we used a modified JBI critical appraisal checklist for experimental biochar-millet studies. The checklist consisted of eleven criteria that were used to evaluate the following: clarity of research objectives, adequacy of experimental design, biochar characterization, reproducibility of experimental conditions, appropriateness of analytical method, comparability of treatment groups, statistical analyses, completeness of outcome reporting and relevance to the objectives of this systematic review. Criteria were rated as Yes (1 point), No (0 points), or Unclear (0 points), based on information explicitly stated in the original publication. The maximum score available was 11 points. Studies that scored 10-11 points were rated as high methodological quality, 7-9 points were rated as moderate methodological quality, and ≤6 points rated as low methodological quality.

2.6. Data Synthesis

Due to heterogeneity among scientific studies relating to the biochar source, the types of soil used, millet varieties tested, the established experimentation protocol, and the outcomes reported, there was no possibility to conduct a quantitative meta-analysis. Thus, the literature was synthesized based on the available evidence, with all studies sorted according to the type of soil physical/chemical/biological condition(s) tested and their subsequent impacts upon millet growth and yield measurement to perform a PRISMA-compliant systematic review.

2.7. Bibliometric Analysis

Using VOSviewer software, we conducted a bibliometric keyword co-occurrence analysis of the literature retrieved from this search to identify major research themes and conceptual relationships found within that literature. This was done by choosing the "All Keywords" option and the method of Full Counting, which allowed us to create a network of keyword co-occurrence (Fig-3).

2.8. Statistical and Graphical Analysis

Visual representations using heatmap and box plots were created from the fourteen studies to allow comparisons to the response patterns exhibited in each of the included studies. The data used to create these visual representations was extracted from the fourteen studies utilized in the qualitative synthesis of those studies.

In the heatmap analysis, we considered variables that showed changes in soil physical, chemical, biological, and productivity responses. The physical variables were bulk density, porosity, available water capacity, soil moisture, aggregate stability, and saturated soil water. The chemical variables were pH, EC, SOC, CEC, total nitrogen, available phosphorus, available potassium, exchangeable calcium, exchangeable magnesium, and salinity measurement. The biological variables were microbial biomass carbon, microbial diversity, dehydrogenase enzyme activity, urease enzyme activity, catalase enzyme activity, sucrase enzyme activity, phosphatase enzyme activity, basal respiration, and other microbial variables that were reported. The productivity-related variables were grain yield, straw yield, total biomass, germination percentage, stress alleviation and indices of physiologic response.

Quantitative variables were measured similarly across all of the studies in order to create a box plot for visualization: biochar pH, pyrolysis temperature, biochar application rate, yield response of the grain grown, carbon sequestration response, and nutrient availability indicators were included as variables if they were numerically measured. Any variables with inadequate quantitative measurements were cut from the analysis.

Data extraction was performed manually from the included studies, and variables reported in non-uniform units were synchronized prior to analysis. Results from studies where the reporting was insufficient were not included in graphical analyses to limit the risk of having incomplete datasets which would introduce bias. Due to the heterogeneity of the biofeedstocks, experimental designs, rate of application and the measurement of the outcomes, the visualizations that were generated are for the purpose of identifying general trends and correlations across studies rather than for quantitative inference.

Data was standardised prior to visualisation by normalisation procedures, helping to decrease scale-dependent variation among types of measurements being made. Distance algorithms and clustering algorithms were employed to perform heatmap cluster analysis. Box plots were created to summarise the measures of centre, distribution, and variability associated with the extracted variables. OriginPro24 was used for all statistical analysis and visualisation of the data.

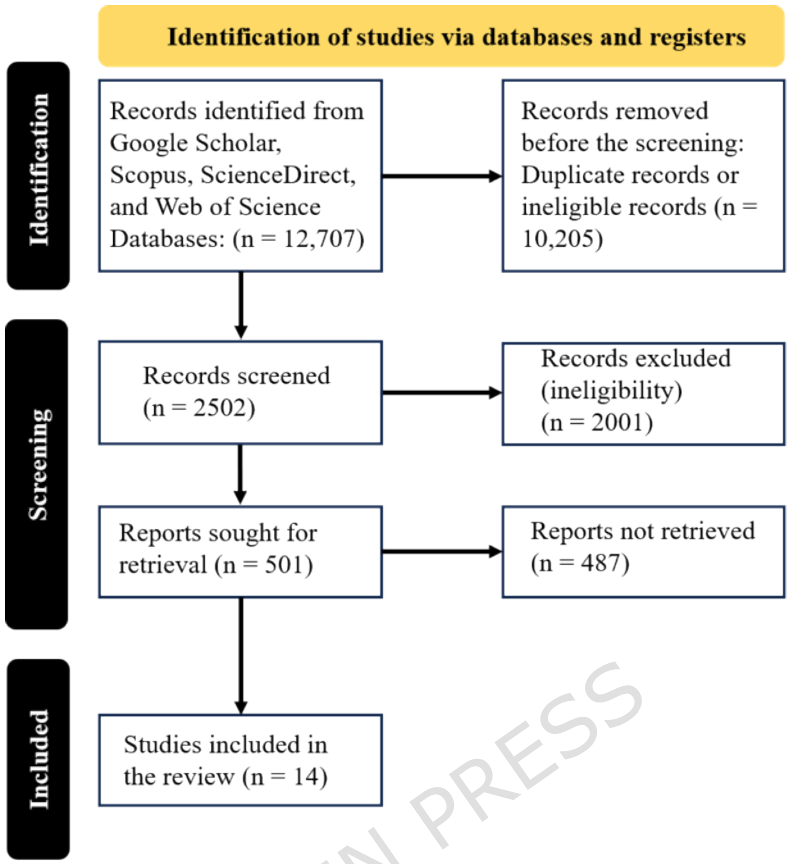
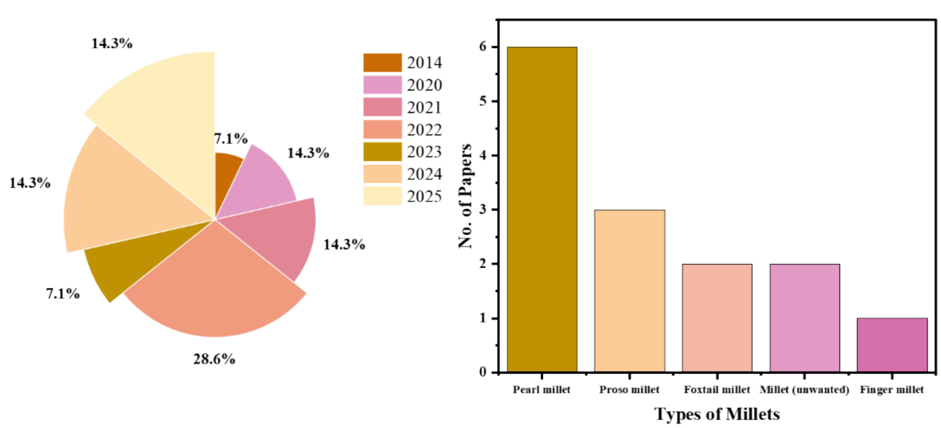


Figure 2: This figure represents the study selection process showing identification, screening, and inclusion steps. From 12,707 records retrieved, 14 studies met the eligibility criteria and were included in the systematic review (Page, McKenzie et al. 2021).

Figure 3. Number of articles in the systematic review.



Study ID	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11
Abo-Elyousr et al. (2022)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Ali et al. (2022)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Ali, Al-Yasi et al. (2021)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Boostani et al. (2025)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Ding et al. (2022)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Faye et al. (2021)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
He et al. (2020)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Hou et al. (2024)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Kang et al. (2022)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Ogunremi et al. (2023)	Y	Y	N	Y	Y	Y	Y	Y	N	Y	Y
Singh et al. (2020)	Y	N	N	N	Y	Y	N	Y	N	Y	Y
Taheri et al. (2024)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Tian et al. (2025)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Zhao et al. (2014)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y

This is a summary representation of the total articles included in the systematic review and their distribution within major study categories. The pie diagram gives an indication of the percentage of studies included in each biochar category. The categories include physical properties of the soil, chemical composition, biological effects, plant physiology, nutrient uptake, yield response, and stress responses. The bar graph shows the number of studies that focus on different types of millets in the systematic review. It is shown from the graph that the most common types of millet studied were pearl millet, foxtail millet, finger millet, and proso millet.

Using VOSviewer software (version 1.6.18), we conducted a visual analysis of the keywords associated with published articles related to the topic of this research. The keyword co-occurrence analysis shows how the authors of these articles have classified their research using both author and index keywords, based on the ‘All keywords’ option. VOSviewer software uses ‘Full Counting’ methodology, which treats each keyword co-occurrence equally, regardless of the actual number of times a given keyword has co-occurred with another keyword in the same paper. Out of 146 total keywords, 20 were selected for analysis based on the minimum number of times each keyword appeared (greater than or equal to 5 occurrences). These keywords were then grouped into 2 clusters. As can be seen from the 2 cluster diagrams in Fig. 4, the size of the node corresponds to how frequently a particular keyword appears compared to other keywords. The lines connecting the two nodes indicate the number of times both keywords appear together within the same paper, and the strength of the connection indicates how many times both keywords appeared together in that paper. The keywords with the highest number of occurrences were as follows: Saline soil (n = 14), biochar (n = 12), nutrient uptake (n = 10), and soil aggregation (n = 10).

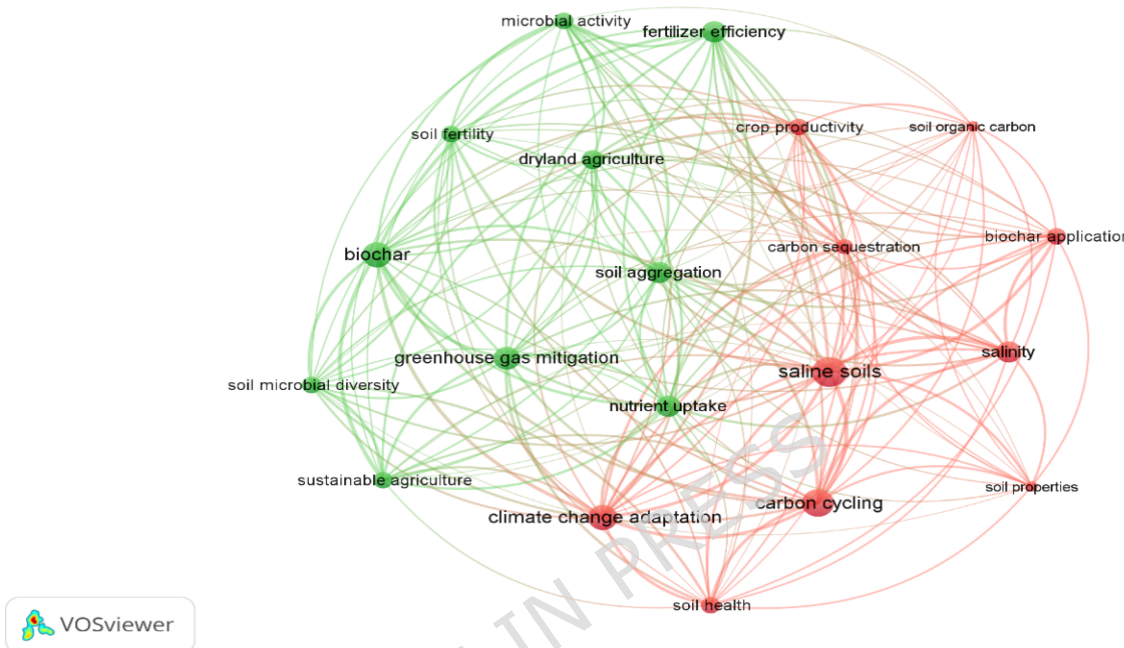


Figure 4. Keyword co-occurrence and cluster analysis of articles included in the systematic review. VOSviewer analysis of the co-occurrence of keywords presents two main clusters. Green color indicates soil fertility related to biochar, microbial activity, fertilizer effectiveness, drought-resistant farming, greenhouse gases mitigation, and sustainability. Red color indicates soil health, salinity, carbon turnover, soil organic carbon, nutrients uptake, plant yield, and biochar utilization.

The clusters identified in Fig. 4 through the use of cluster analysis show that there is a relationship between keywords. Four groups can be seen in the analysis: Group 1 (Red) has 10 keywords; these keywords are mostly related to biochar application, carbon sequestration, climate change change, carbon cycling, crop productivity, soil health, salinity, saline soils, soil organic carbon, and soil properties. Group 1 relates directly to the addition of biochar to improve soil conditions to help grow plants. Group 2 (Green) has 10 keywords most closely related to biochar, dryland agriculture, fertilizer efficiency, greenhouse gas mitigation, microbial activity, nutrient uptake, soil aggregation, soil fertility, soil microbial diversity, and sustainable agriculture.

3.1 Feedstock selection and pyrolysis considerations in biochar production

The selection of feedstock is crucial for the manufacture of biochar because it determines the feasibility of pretreatment, the efficiency of the production process, and the physicochemical characteristics of the final product (Amarasinghe, Gunathilake et al. 2016). There are many possibilities for biomass sources to produce biochar like agricultural crop wastes, woody biomass, livestock and poultry manure, industrial and municipal solid waste, sewage, and fermentation byproduct wastes (Wang, Zhu et al. 2018). Of these sources of biomass, microalgae have recently become recognized as a potentially environmentally friendly feedstock with desirable inorganic nutrient content, ease of cultivation, and excellent ion-exchange capacity making microalgae an ideal choice for stabilizing soil and supplying plant nutrients (Yu, Lau et al. 2017). Conversely, using plant-based feedstocks produces biochar with lower nutrient content, thus resulting in reduced biochar fertilizer effectiveness when used as a direct source for growing crops. In addition, the presence of hazardous materials (e.g. metals), the availability of the feedstock, and the economic feasibility of obtaining the feedstock must be carefully assessed to determine whether the feedstock is appropriate for the intended application (Murtaza, Ahmed et al. 2021).

Pyrolysis refers to the thermal breakdown of biological material under conditions of limited supply of oxygen and is the principal method of producing biochar. Pyrolysis can be further divided into three categories of slow, transitional and fast based on the speed at which heat is applied and the residence time of biochar in the reactor. "Slow" and "transitional" pyrolysis methods have been shown to produce more stable biochars with greater carbon retention compared to "fast" pyrolysis (less than two seconds of residence time) which produces mainly bio-oils having less than adequate amounts of carbon (Murtaza, Ahmed et al. 2021). The temperature of the pyrolysis process is one of the most significant factors affecting the composition and stability of the produced biochar; when the pyrolysis process is conducted at elevations above 500 degrees Celsius, biochar can exhibit a half-life exceeding 1,000 years and have long-term potential for the sequestration of carbon (Ippolito, Cui et al. 2020). However, as the pyrolysis temperature is raised, the cation-exchange capacity and the adsorptive capacity of the biochar will be adversely affected, as well as the chemical composition (Domingues, Trugilho et al. 2017). Additionally, increased pyrolysis temperatures result in a decrease in pore volume, pore-area and an increase in the amount of ash produced (Rafiq, Bachmann et al. 2016). Therefore, selecting the right feedstock for pyrolysis and using appropriate pyrolysis conditions to create biochar with specific properties is necessary to produce biochar that can benefit the environment and agriculture.

3.2 Quality Assessment of Included Studies

"The critical assessment of the studies supporting this evidence revealed that the included 14 studies showed an adequate level of methodological quality in terms of their clear definition of objective, experimental design, reporting of biochar characteristics, and analytical measurements. However, a limited number of studies provided a clear assessment of study limitations or factors confounding the results.

Thus, while the overall quality of literature supporting the impact of biochar on millet production systems is high, caution must be exercised when attempting to extrapolate these results into differing agro-ecological settings, differing biochar feedstocks and differing management practices. Detailed critical appraisals of the individual studies supporting this evidence are summarized in table 3."

3. Effects of Biochar in Soil Applications on Millet Growth and Productivity

Biochar has become a transformative approach to soil management for boosting millet productivity, especially in marginal, nutrient-poor, and stress-prone agroecosystems. Across all studies reviewed, biochar improved diverse aspects of soil health physical structure, nutrient availability, and biological function to ultimately improve millet growth, resistance to stress, and yield. Because biochar is a porous and carbon-rich material, it improves water storage and retention, pH moderation, and increases the activity of beneficial microbes in the soil, to create a more favorable soil habitat in the rhizosphere for millet crops, e.g. pearl, foxtail, finger, or proso millet. The following sections summarize evidence across the physical, chemical, and biological improvements in soil health leading to increased millet productivity (fig. 5)(Table. 1).

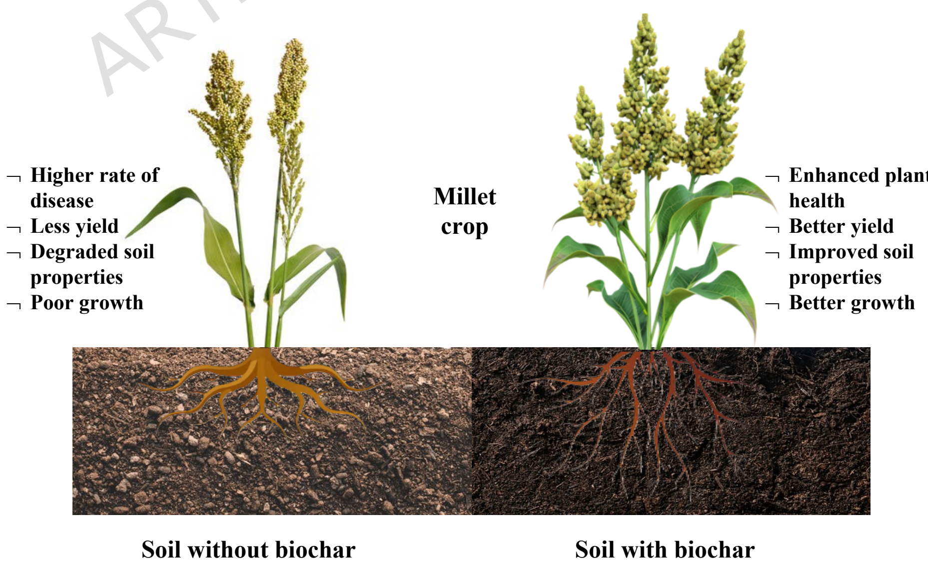


Figure 5: Effects of Biochar on Millet Growth and Soil Condition

Table 1. Summary of Studies Included in the Systematic Review

Sl no.	Millet species	Soil type	Biochar Feedstock and Synthesis Conditions	Biochar application rate	Biochar properties	Soil pro
1.	Millet	Oxisols (acidic subtropical soil) and Cambosols (alkaline calcareous soil)	Rice straw, 500°C for 8 hours	0 (control), 2.25 Mg ha⁻¹, 22.5 Mg ha⁻¹ applied before each crop season	pH 9.16, Total C 620 g kg⁻¹, N 13.3 g kg⁻¹, CEC 18.9 cmol kg⁻¹, ash 131 g kg⁻¹, P 4.40 g kg⁻¹, K 20.9 g kg⁻¹, Na 7.70 g kg⁻¹, Ca 13.9 g kg⁻¹, Mg 5.70 g kg⁻¹	**Oxisols** • to 5.92. • by 1.8 c • reduced **Cambo** • reduced • increase
2.	Finger millet	Sandy loam soil	Not reported	Not reported	pH 9.90, EC 3.53 dS m⁻¹, BD 0.19 Mg m⁻³, PD 0.58 Mg m⁻³, WHC 58.5%, P 0.09%, K 3.22%, Na 0.99%, Fe 0.28%, Ca 0.38%, Mg 0.25%, Zn 157 mg kg⁻¹, Mn 214 mg kg⁻¹, Cu 54 mg kg⁻¹,	• 1.28→1 • increase • 0.65→0 • 24.12→ • 130.25–

					Pb 45.5 mg kg^{-1}, Cd 1.84 mg kg^{-1}	
3.	Millet	Acidic red soil	Rice straw, 500°C for 8 hours	0 (Control), 2.25 and 22.5 Mg ha^{-1} per crop season	pH 9.16, ash 131 g kg^{-1}, CEC 18.9 cmol kg^{-1}, TOC 620 g kg^{-1}, total N 13.3 g kg^{-1}, total P 4.40 g kg^{-1}, SSA 51.3 m^2 g^{-1}, pore width 5.88 nm, available K 13.4 g kg^{-1}, Ca 5.41 g kg^{-1}, Mg 1.24 g kg^{-1}	• by 3.29 • by 5.66 • increase • 306%. • 182%. • 241%. • 513%. • 245%. • 265%. • decrease
4.	Pearl millet	Saline-sodic clay loam soil	Corn-cob biochar, 350°C for 2.5 hours	0, 5, 10, 15, and 20 t ha^{-1}	pH 10.5, EC 4.2 dS m^{-1}, organic C 522 g kg^{-1}, total N 22 g kg^{-1}, P 3.5 g kg^{-1}, K 30 g kg^{-1}	• from 8.0 • 43%. • • • sequestr • increase

5.	Pearl millet	Sandy soil	Rice husk and *Typha australis* biochar, 500°C	5 and 10 t ha^{-1}	**Rice husk:** pH 8.9, organic C 0.1%, total N 0.2%, OM 2%, available P 4.1 ppm, available K 107.4 ppm; ***Typha australis*:** pH 10.9, organic C 0.9%, total N 0.2%, OM 3%, available P 3.2 ppm, available K 268.8 ppm	• from 5.5 • increase • 27.2 t C
6.	Foxtail millet	Cd/Zn-contaminated weakly alkaline soil	Corn straw, 300°C, 400°C, and 500°C	2% (w/w) mixed with contaminated soil (5 kg soil per pot)	**BC300:** pH 7.96, C 44.59%, N 1.56%, C/N 28.59. **BC400:** pH 9.64, C 49.34%, N 1.63%, C/N 30.21. **BC500:** pH 10.30, C 59.13%, N 1.41%, C/N 41.84, SEM and FTIR characterization performed	• bioavail • decrease • decrease

7.	Pearl millet	Saline sandy soil	Shrimp waste, 300°C for 4 hours	0, 5, 10, 15, 20, 25 g kg^{-1} soil, equivalent to 0-2.5% w/w	N 6.4%, P 5.2%, K 3.2%, Ca 30%, organic C 40%, pH 6.20, EC 3.50 dS m^{-1}	• response • soil qua • uptake a
8.	Pearl millet	Loam soil	Poultry manure and Farmyard manure biochar, 500°C for 5 hours	5, 10, and 15 t ha^{-1}	**FYMB:** pH 8.67, EC 1.34 dS m^{-1}, OM 1.29%, TOC 507 g kg^{-1} **PMB:** pH 7.59, EC 1.25 dS m^{-1}, OM 1.37%, TOC 492 g kg^{-1}	NPK tre
9.	Pearl millet	Saline sandy soil	Maize stalk biochar, 400°C for 2.5 hours	0, 5, and 10 t ha^{-1}	pH 10, EC 5 dS m^{-1}, organic C 530 g kg^{-1}, total N 25 g kg^{-1}, P 4 g kg^{-1}, K 32 g kg^{-1}	• moisture • water-us • SOC. • CEC. • availabl • volatiliz
10.	Pearl millet	Sandy loam soil contaminated	Rice straw, Sorghum straw,	1%, 2%, and 3% (w/w), corresponding	pH 8.15-8.54, high porosity, increased	Not repo

		with spent engine oil (50 mL kg⁻¹; 5% v/w)	Standard biochar	to 30, 60, and 90 g biochar per 3 kg soil	mineral content, low heavy metal concentration	
11.	Proso millet	Saline-sodic and calcareous soil	Sunflower stalk, 400°C	Biochar was mixed with 5% inorganic sulfur solution (80% purity) for 24 h, filtered, and oven-dried at 70°C for 24 h to produce sulfur-modified biochar	B: pH 10.31, C 61%, N 0.32%, CEC 36 cmol (+) kg^{-1}, WHC 400%; BS: pH 7.56, C 57%, N 0.43%, S 1.4%, CEC 39 cmol(+) kg^{-1}, WHC 250%; FTIR characterization performed	• content • 17%. • increase • increase • organic • increase • increase • increase • increase
12.	Foxtail millet	Newly reclaimed sandy land covered with 30 cm uncultivated loess, saline-alkaline context; low fertility.	Maize straw, 450°C	0 (Control), 3000, 4500, and 6000 kg ha^{-1}.	pH 8.55, TN 14‰; TP 4.6‰; total C 50.6%; pore size ~100–200 nm	• decrease • increase • increase • to 5.78 • urease a

13.	Proso millet	Sandy-loam soil	Wheat straw biochar, maize residue biochar, cotton residue biochar, 400°C for 4 hours	0, 1.5%, and 3% (w/w)	WB: pH 10.4, EC 6.97 dS m^{-1}, total C 51.0%, ash 28%, FTIR Si-associated band at 1100 cm^{-1}; MB: pH 10.0, EC 4.03 dS m^{-1}, total C 52.6%, ash 11%; CB: pH 10.0, EC 0.70 dS m^{-1}, total C 74.4%, ash 7.0%	• reduced • residual • by 78%
14.	Proso millet	Sandy loam soil	Wheat straw biochar, 500°C	10^4 kg ha^{-1} (10 t ha^{-1})	Organic matter 617.96 g kg^{-1}; TN 1.65 g kg^{-1}; total K 5.65 g kg^{-1}; total P 20.14 g kg^{-1}; pH 10.39	• increase • up to 6. • increase • richness • complex

4. Properties of Biochar

a. Effects of Biochar on Soil Physical Properties in Millet Cultivation

i. Influence on Soil Bulk Density and Compaction

Bulk density (BD) is a highly responsive physical indicator when biochar is added to soils planted with millet crops. The most notable physical effect found was the reduction in bulk density. After the wheat-millet rotation, an application of 22.5 Mg/ha biochar led to a 15.9% and 10.3% decrease in bulk density for oxisols and cambosols, respectively, compared to the control plots with suggesting better looseness and reduced compaction. (Zhao, Wang et al. 2014). Under sandy loam soil in finger millet cultivation conditions, BD decreased from 1.28 Mg m^{-3} to 1.15 Mg m^{-3} with applications of NPK with biochar (Singh, Thomas et al. 2020). He,Zhao et al described that biochar greatly decreased bulk density. As compared to BC0, BC2.25 decreased bulk density by 0.06 g cm^{-3}, whereas BC22.5 decreased it by 0.52 g cm^{-3} (He, Zhao et al. 2020). In another study, under the treatment of biochar during 2021, Soil bulk density ranged from 1.56 to 1.66 g cm^{-3}, and Biochar 3 significantly decreased SBD but during 2022, control had the highest SBD of 1.58 g cm^{-3}, and the biochar treatments had lower values (Hou, He et al. 2024). These studies demonstrate that even small amounts of biochar can significantly influence bulk density and packing density in soil. Therefore, millets, which are often cropped in marginal and dry soils, it's decreasing compaction can be directly translated into better tillering and root biomass, along with increased yield potential.

ii. Enhancement of Soil Porosity and Aeration

In this study with finger millet, showed that porosity improved from 45.7% to 54.5% at various rates of biochar application, which is a clear indication of the physical improvements . In millet-based systems, often planted in semi-arid and tropical regions, improved soil porosity reduced hard-setting soils and surface crusting due to rainfall .In another study by He, Zhao et al the results revealed greater porosity and connectivity within intra-aggregate pores in biochar-treated aggregates. Porosity rose cumulatively from 9.8% in Biochar 0, to 14.5% in Biochar 2.25 and 21.1% in Biochar 22.5. Biochar provides an internal pore network and restructures the soils, leading to improvements in pore distribution, especially with connected macropores for greater benefits in water infiltration and gaseous exchange.The results of other evaluated research studies also support the contribution of biochar to increasing soil porosity and structuring soil. showed that porosity was increased from 45.76% to 58.93% with the application of combination of NPK with biochar. Although the porosity of the studied soils was not measured by , they found pores from 100 to 200 nm by SEM analysis in maize-straw biochar, and at the same time the soil bulk density was reduced. (Tian, Wang et al. 2025) observed an increase in large macroaggregates (>2 mm) and a decrease in microaggregates (<0.25 mm).

iii. Improvement in Soil Water Retention and Moisture Dynamics

Water retention is one of the most beneficial physical aspects of biochar use in millet production, notably in arid and semi-arid environments. In this study biochar was reported for having a 58.5% water-holding capacity but treatment-wise soil moisture was not studied here (Singh, Thomas et al. 2020) .In a study by He, Zhao et al. 2020 they reported that the biochar used in the treatment along with controls shows that BC22.5 significantly increased field capacity, wilting point, and plant available water capacity (He, Zhao et al. 2020) . Another study reported that during the year 2019, it was compared that between biochar, Sand + soft rock , and all three in soil moisture control with Control. The biochar had the water retention capacity which was significantly more than the control by about 200% (Sun, Zhang et al. 2020).Kone et al described biochar as a improving agent for soil water retention its effect in drought resistance which leads to the reduction of irrigation (Koné and Galiegue 2023) . Another study demonstrate the improvement with the soil water retaintion with the help of biochar by 47% which was compared with control at 20 days after irrigation (Taheri, Astaraei et al. 2024). This study has been done for two consecutive years, and both years showed a significant increase in soil water retaintion capacity. At the flowering stage, B3 which is 6000 kg/h^{-1} dose had significantly higher soil water content, with 10.7% SWC in 2021 and 15.94% in 2022; in comparison with control treatment (Hou, He et al. 2024). These studies indicates the agronomic evaluations that biochar increases pore space, hydraulic conductivity, and water-holding capacity for a range of coarse-textured soil types, affirming biochar's well-established ability to bolster soil moisture dynamics in dryland crops like millet .

iv. The Enhancement of Physical Characteristics of Soil Texture

Biochar normally does not affect the initial soil texture category, including the ratio of sand, silt, and clay, in a short experimental duration; nevertheless, it greatly affects the physicochemical behavior of diverse soil textures through reducing compaction, enhancing porosity, improving soil aggregation, and increasing soil water holding capacity. In the context of growing millets, these properties become highly relevant since millets are normally grown in sandy, acidic, saline-sodic, degraded, and nutrient-deficient soils. Specifically, for instance, in acid oxisol and cambisol soils, rice straw biochar decreased bulk density by 15.9% and 10.3%, respectively, which shows that biochar is effective in loosening compacted soil in the structural constraint soil matrix (Zhao, Wang et al. 2014). Additionally, when used alongside the application of NPK fertilizer, finger millet grown in sandy-loamy soils exhibited decreased bulk density from 1.28 to 1.08 Mg m^{-3} and enhanced soil pore volume from 45.76% to 58.93% (Singh, Thomas et al. 2020).

In red soils of acidic nature, rice straw biochar improved the structural aggregation of soils, tensile strength, porosity, field capacity, wilting point, and plant-available water content, leading to improved hydraulic property of soils in wheat-millet rotation (He, Zhao et al. 2020)In new reclamation sandy/loess soils, biochar derived from maize straw decreased soil bulk density and increased soil water content from 6.10% to 10.7% in 2021 and 9.48% to 15.94% in 2022, thus demonstrating its benefits in coarse-textured soils having poor water retention properties (Hou, He et al. 2024). In saline-sodic and calcareous soils, biochar of sunflower plant species increased soil moisture by about 47%, while that of sulfur modified biochar increased soil moisture content by 35%. Both the biochars have been found to modify physical properties of soils under salinity stress conditions (Taheri, Astaraei et al. 2024). In African soils characterized by degraded sand particles and poor fertility level, biochar has been claimed to increase porosity, water retention, and soil structure although most of the data available is derived from reviews (Koné and Galiegue 2023). Thus, biochar must be considered as a soil structure modifying agent and not a soil texture modifier.

b. Effects of Biochar on Soil Chemical Properties in Millet Cultivation

The chemical properties of the soil define nutrient availability, pH, ion exchange capacity, and overall soil fertility all of which can significantly influence millet response in stressed and marginal environments. Across all of the reviewed studies on millet and biochar, there were always improvements to the chemical quality of the soil due to biochar by way of changing pH, improving organic carbon, enhancing cation exchange capacity (CEC), and increasing macronutrient and micronutrient availability and the immobilisation of toxic metals. The improvements in soil chemistry almost always led to significant increases in millet nutrient uptake, physiological performance, and final yield.

i. Effect on Soil pH and Salinity Management

In a study the in acidic oxisols the use of biochar increased the soil pH. The highest pH was reported 5.92 which occurred after two successive applications of 22.5 Mg/ha biochar. In alkaline cambosols, pH showed no significant change (He, Zhao et al. 2020). Another study also reported that the biochar increases the soil pH by 0.76 unit in the BC 2.25 and 3.29 units in BC22.5 as comparable to BC0 (He, Zhao et al. 2020). The study conducted by Ali et al 2021 reported a slight increase in the pH with the application of biochar (Faye, Stewart et al. 2021). This study indicated that the treatment with biochar and manures helps in increasing the soil ph here in this study the pH increased from 5.5

to 6.3 and this increase was maintained upto five to eight years (Faye, Stewart et al. 2021). The liming effect of biochar has been thoroughly examined in acidic, neutral, and saline millet-growing soils. In the case of pearl millet grown in saline conditions, biochar made with shrimp wastewith calcium reduced the soil pH as compared to the control.(Abo-Elyousr, Mousa et al. 2022). The biochar in this study slightly increased the soil pH, and the EC was also increased from 17-22% in BC5, and 24-27% in the BC 10 (Ding, Majrashi et al. 2022). Another study also found that the rice biochar in 3% concentration increased the soil pH from 6.76 to 8.04 (Ogunremi, AMUBIEYA et al. 2023). Taheri et al reported that the normal biochar increased the pH as compaire to the biochar sand composite and the control (Taheri, Astaraei et al. 2024). In a study conducted by Boostani et al. 2025 also reported the hincrese in soil Ph with the application of 2 different type of biochar one made of wheat and another is cotton (Boostani, Hardie et al. 2025).Unlike the above reports experiment, giving different results, here the pH is decreasing; the control significantly has the highest pH as compared to the other 3 variants of biochar in different concentrations (Hou, He et al. 2024). The above studies suggested that mostly the biochar is helping in increasing the soil pH and the EC.

ii. Improvement of Soil Organic Carbon (SOC)

ii. One of the principal benefits of biochar is to increase in SOC that results from the application of a recalcitrant and aromatic carbon structure. In foxtail millet fields, growing on newly reclaimed sandy land, maize-straw biochar produced significant increases in SOC over two growing seasons, which enhanced nutrient cycling and soil stability (Zhao, Wang et al. 2014). In another study conducted by Singh et al 2020 they reported that the application of biochar in the soil is helping in increasing the SOC (Singh, Thomas et al. 2020). A study also reported that the SOC increased in 3 different concentrations of biochar respectively BC0 4.06 g kg-1, BC2.25 5.48 g kg-1, BC22.5 16.5 g kg-1(He, Zhao et al. 2020). Ali et al. 2021 also reported that the application of biochar increases the SOC (Faye, Stewart et al. 2021). Abo-Elyousr et al. 2022 reported about the increase in the SOC with the help of Shrimp waste biochar (Abo-Elyousr, Mousa et al. 2022). Another Study reported that biochar increases the SOC significantly as compared to the control(Ding, Majrashi et al. 2022). In a study with porso millet they have reported that the biochar is helping in increasing the SOC (Tian, Wang et al. 2025). So with the help of the studies we can say that the biochars are having beneficial effect on Soil organic carbon content increment in soil. ***Increase in Cation Exchange Capacity (CEC)***

In a study on oxisols, CEC increased with increasing biochar application rate at the end of the millet season, a 1.8 cmol/kg increase in CEC was observed with 22.5 Mg/ha. In cambosols, the increase was minimal, at only 0.47 cmol/kg reported by (Zhao, Wang et al. 2014) . According to Zhao et al.

(2014), the use of biochar led to increased cation exchange capacity (CEC) of the soil. For instance, CEC was 0.34 cmol kg⁻¹ more for BC2.25 compared to the control (BC0) (He, Zhao et al. 2020) . In this study there was a significant increase in CEC due to biochar application in different type of biochars like BC400 and BC500 had higher values compared to BC300 and control. There was significant increase in CEC due to biochar application; BC400 and BC500 had higher values compared to BC300 and control (Kang, Geng et al. 2022). In Ding et al.,2022 biochar significantly increased soil cation exchange capacity with CEC increasing from approximately 14.6-15.0 cmol kg⁻¹ in the control to about 16.7-17.0 cmol kg⁻¹ (Ding, Majrashi et al. 2022). CEC determines the soil's capacity to retain nutrients such as Ca^{2+}, Mg^{2+}, K^{+}, and NH_4^{+}. Multiple studies have evaluated the ability of biochar to improve CEC in soils that produce millet. (Taheri, Astaraei et al. 2024) found considerable increases in CEC after additions of biochar to soils, suggesting improved retention of nutrients and an increase in microbial respiration due to changes in porosity.

iii. Macronutrient Availability: Nitrogen, Phosphorus, and Potassium Nitrogen (N)

Zhao et al. (2014) reported that rice straw biochar could enhance the availability of macro nutrients by increasing the soil's nutrient retention capacity and providing additional nutrients to the soil. The application of higher amounts of biochar at the rate of 22.5 Mg ha⁻¹ significantly increased the total soil nitrogen content at the same time, extractable phosphorus and potassium contents also increased post-harvest (Zhao, Wang et al. 2014). He et al. (2020), rice straw biochar amendment of red acidic soil resulted in significant enhancement of secondary macronutrients and nutrient availability. BC2.25 improved the available P, K, Ca and Mg content by 25.3%, 53.2%, 30.8% and 32.4%, respectively and BC22.5 improved the available P, K, Ca and Mg content by 241%, 513%, 245% and 265%, respectively, a huge boost to the ability of the soil to supply nutrients (He, Zhao et al. 2020). Another study also reported the increment of N,P,K content with the application of biochar (Faye, Stewart et al. 2021). The use of biochar significantly increased nutrient availability of the soil, especially with the two high-temperature treatments BC400 and BC500. The increase in the available P was pronounced, and the available K was increased by 59.30% in BC400 and 70.51% in BC500 treatment (Kang, Geng et al. 2022). Abo-Elyousr et al. (2022), the biochar extracted from shrimp waste enhanced the availability of nutrients in saline sandy soils. The amount of available nitrogen content was elevated from 48 mg kg⁻¹ in the control treatment to 60 mg kg⁻¹ in the case of 25 g kg⁻¹ SWB application. Similarly, the level of available phosphorus content was increased from 5.6 mg kg⁻¹ to 7.4-7.5 mg kg⁻¹ at a rate of 20-25 g kg⁻¹ SWB application (Abo-Elyousr, Mousa et al. 2022). Biochar significantly increased macroelement availability in saline sandy soil, as observed by Ding et al. (2022). The available N, P and K in the BC5 treatment were increased by 20-32%, 33-39% and 15-23% compared with control, respectively. The impact of the high-rate biochar (BC10) on the soil nutrients was even higher, with the available N, P and K increased by 36-42%, 73-84% and 20% respectively (Ding, Majrashi et al. 2022). Their et al. 2024reported that the both modified and unmodified biochar improved soil availability if the K in saline-sodic calcareous soil (Taheri, Astaraei et al. 2024). The biochar in this study improved the soil phosphorous and nitrogen availability, with B3 biochar having the highest total phosphorus across the year (Hou, He et al. 2024). All studies determined that millet yield was improved most by biochar combined with NPK application, indicating a synergistic effect.

c.Effects of Biochar on Soil Biological Properties in Millet Cultivation

i. Variations in the Soil Microbial Biomass and Diversity

The introduction of biochar in all the reviewed millet production systems invariably promoted the levels of microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and the overall microbial functional diversity. The application of biochar increases in the microbial biomass carbon , which is showing the improved microbial activity in the soilThe results indicate that biochar improved microhabitats and carbon substrate for microbial growth (Taheri, Astaraei et al. 2024). In the current study biochar regulated soil microbial community structure as the major phyla of bacteria and fungi which determined and compared among treatments. This clearly shows that biochar not only affected soil chemical fertility, but it also affected soil microbial community structure (Kang, Geng et al. 2022). Microbial biomass carbon increased significantly with shrimp waste-derived biochar (SWB) application, indicating enhanced microbial growth and biological activity in the amended soil (Abo-Elyousr, Mousa et al. 2022). The increases in MBC and respiration observed in this research were strongly associated with higher dissolved organic carbon levels and improved nitrogen and phosphorus availability, further supporting the notion that biological activity is a direct target of enhanced soil chemical environments.

Biochar in the presence of sorbitol further increased both microbial biomass and soil enzyme activity in millet-based saline soils, due to an increased amount of carbon substrate available for soil microbes (Taheri, Astaraei et al. 2024). Pearl millet grown in salinity-affected systems with Ca-rich biochar showed increased microbial activity and efficiency of soil nutrient cycling in the presence of PGPR, confirming biochar's intrinsic value as both a habitat for microbial activity and soil conditioner (Singh, Thomas et al. 2020). Diversity of soil microbes exhibited little variability, since neither the bacterial nor the fungal alpha diversities differed among the LN, MN, and HN treatments. Nevertheless, there was a change in the composition of the communities, in which Proteobacteria, Gemmatimonadota, Acidobacteriota, and Actinobacteriota dominated among bacteria, and Ascomycota (Guo, Ren et al. 2025).

Effects of Biochar on Rhizosphere Microbial Communities

Multiple studies in the dataset indicated that biochar dramatically alters the rhizosphere microbial community structure in millet. The greatest change was seen in foxtail millet planted in multi-metal–contaminated soils where biochar made from wheat straw enriched beneficial bacteria such as Sphingomonas, Pseudomonas, and several Actinobacteria with known functions for metallic immobilization, P-soluble capability, and matter decomposition (Faye, Stewart et al. 2021). Such modifications negatively affected the local toxicity in the root zone and simultaneously improved plant nutrient status. In saline–sodic and calcareous soils, rhizosphere microbial diversity and activity were significantly increased for sunflower, while soil moisture and organic carbon became more available, contributing to a more favorable microenvironment for millet root–microbe interactions (Taheri, Astaraei et al. 2024). The rhizosphere soil characteristics were enhanced by applying biochar, resulting in elevated pH, total carbon, and a higher C/N ratio. Moderate amounts of biochar decreased the concentration of nitrate and nitrification potential, thereby increasing the retention of nitrogen (Pang, Huang et al. 2022). Biochar has reduced CO_2 emissions from the environment and has promoted beneficial microbial activity. However, some declines in SOM, SOC, phosphorus, and exchangeable nutrients with time suggest that the nutrient dynamics associated with biochar are complex and long-term in nature (Jia, Zhang et al. 2025).

ii. Influence on Soil Enzyme Activity

Faye et al. (2021) reported that enzyme activity in the soil was measured using the FDA assay, which measures the hydrolytic capacity of all microorganisms in the soil. Thus, it can be concluded that the addition of biochar affected the functioning of soil microorganisms; however, because no specific enzymes were tested, it cannot be determined exactly how biochar affected the enzymes like such as urease, phosphatase, catalase, sucrase, or dehydrogenase (Faye, Stewart et al. 2021). In this study soil enzymes were measured directly based on their respective roles of catalase, urease, alkaline phosphatase, and sucrase activities. The role of each enzyme mentioned is to serve as a good measure for controlling oxidative stress, nitrogen metabolism, phosphorus metabolism, and carbon breakdown (Kang, Geng et al. 2022). Another study reported dehydrogenase activity which measured as an indicator of overall soil microbial activity, and its increase under biochar application suggests improved biological functioning of the soil. This response indicates that biochar created a more favorable microbial habitat, likely by improving organic carbon availability, nutrient status, and soil conditions (Abo-Elyousr, Mousa et al. 2022). Taheri et al. 2024 reported enzyme activities in soils using catalase, dehydrogenase, urease, and alkaline phosphatase tests. Catalase and dehydrogenase activities relate to general biology of soils because these enzymes are involved in oxidation and metabolism, respectively, while urease relates to nitrogen metabolism, and alkaline phosphatase to phosphorus metabolism (Taheri, Astaraei et al. 2024).Overall, the findings show that increases in activities of DHA, urease, phosphatase, and β-glucosidase increased nutrient turnover and improved rhizosphere fertility and directly contribute to greater yield of millet and vigor.

iii. Reducing Biotic and Abiotic Stress via Microbial Stimulation

Biochar increases stress resistance of millet due to its stimulatory effect on soil microbiology. Biochar creates small pores for soil microorganisms and provides quick and prolonged carbon source, as well as improved nutrient retention and accessibility, thus enhancing microbial growth and activity and promoting soil enzymatic nutrient cycling. In case of salt/sodic and calcareous soil, application of sunflower biochar and sulfur-modified biochar significantly increased microbial biomass carbon by 113% and 50%, respectively; basal respiration was stimulated by 75% and 108%; catalase, urease, alkaline phosphatase, and dehydrogenase were activated. These results indicate increased microbial metabolic activity and enhanced soil fertility in conditions of salt stress (Taheri, Astaraei et al. 2024). Application of Ca-enriched shrimp biochar in salty sandy soil increased microbial biomass carbon by 43% and dehydrogenase activity by 47%. This biochar application promoted pearl millet antioxidant defense system, osmoprotectant production, and reduced Na^+ and Cl^- accumulation. Thus, an enhancement in microbial activity can be associated with improved nutrition and reduced oxidative stress, enhanced ionic homeostasis of the plants in conditions of salinity (Abo-Elyousr, Mousa et al. 2022). Also, application of biochar obtained from maize stalks significantly reduced ammonia volatilization by up to 36%, which indicates enhanced nitrogen availability and thus more beneficial nutrient regime for the pearl millet in salty sandy soil (Ding, Majrashi et al. 2022). Under conditions of heavy metals exposure, biochar enhanced soil microbial activity and promoted microbial diversity while simultaneously improving nutrient regime and metal bioavailability. In contaminated foxtail millet soil, biochar application significantly improved bacterial and fungal diversity and some of the enzyme activities. Also, biochar reduced DTPA-extractable Cd and Zn content and increased plant antioxidative capacity (Kang, Geng et al. 2022). Similarly, biochar application in proso millet contaminated with Pb decreased concentration of soluble/exchangeable form of Pb in the soil and converted Pb in the stable form, thereby decreasing metal toxicity (Boostani, Hardie et al. 2025). There was no evidence of biochar effect on disease/pathogen development. So, it could be assumed that the role of biochar is mostly connected with reduced abiotic stress and rhizosphere function improvement.

iv. Soil Biological Restoration of Degraded Ecosystems

Millets are commonly grown in degraded, nutrient-poor, saline, and drought-prone regions, where biological activity is often severely inhibited. Research on the saline-sodic and calcareous millet system indicated that biochar could act as both a microhabitat and a source of carbon for microorganisms, thereby stimulating increases in MBC, basal respiration, and enzyme activity even under the most severe soil conditions. Co-amendments of biochar sorbitol further stimulated microbial processes, indicating that the structural benefits of biochar can be synergised by organic substrate. Biochar also restructured microbial communities, restoring rhizosphere function and biological resilience in heavy-metal soils. Manure-derived biochar in millet systems also enhanced biological functioning and soil fertility, and shows promise in restoring microbial life within semi-arid, low-carbon soils (Taheri, Astaraei et al. 2024).

Overall, the combined evidence suggests that biochar is a powerful biological restoration agent in millet agroecosystems and that increased microbial biomass, increased and active enzymes, a restructured rhizosphere community, and improved plant antioxidative system biological health. Biochar is a key support mechanism for restoring the biological health of soils and associated resilient millet production under adverse conditions (Faye, Stewart et al. 2021).

5. Discussion and Future Prospects

A review of the literature reveals that the majority of the currently available data of the effect of biochar is obtained from clearly defined controlled experiments. However, there are still major limitations like, inconsistencies in the reporting of the physicochemical properties of biochar, variability in the duration of different experiments, and insufficient discussion regarding limitations of each study which makes it difficult for direct and quantitative comparisons between studies. The heterogeneity within the studies additionally supports the use of qualitative synthesis instead of a quantitative meta-analysis of biochar research. Future research should concentrate on improving the consistency of reporting on the conditions used in producing biochar, including the rate at which biochar is applied to soils, as well as the conditions in which biochar is being used, through standardization of experimental design and data collection methods, to improve reproducibility and allow for comparative analysis across multiple studies."

The reviewed studies show that biochar has generally had positive effects on millet production systems but these effects can be highly variable. The most compelling evidence for the effectiveness of biochar in millet production comes from those systems under stress, such as those with acidic, saline/sodic, saline/sandy, reclaimed sandy/loess, degraded sandy, and contaminated with heavy metals. In acidic soils, the addition of biochar made from rice-straw increased soil pH, cation exchange capacity, organic carbon, available nutrients and bulk density, all supporting increased productivity from wheat-millet crop rotations. (Zhao, Wang et al. 2014)found bulk density reductions of 15.9% with biochar addition in acidic oxisols and 10.3% in cambosols, but substantial increases in total carbon, total nitrogen, cation exchange capacity (CEC), and with available nutrients. Similarly, (He, Zhao et al. 2020) reported that addition of rice-straw biochar over a long-term period improved the physical properties of red soils, in terms of structure, aggregation and porosity, while also improving water-holding capacity, nutrient availability and cumulative productivity of grain/straw. Collectively, these pieces of evidence indicate that the effect of biochar on acidic soils is enhanced due to the liming effect of biochar, its capacity to retain nutrients, and its ability to contribute to stable pools of carbon in the soil.

Biochar can be used to condition degraded soils and to overcome problems related to structural stability, water and nutrient retention and organic matter. Faye et al. (2021) showed that biochar applied to degraded sandy soil in Senegal improved soil pH, total carbon and fertiliser use efficiency (Faye, Stewart et al. 2021). The use of biochar alone did not increase the yield of millet and so it would be reasonable to conclude that the combination of biochar with manure or fertiliser would produce the best results. Koné & Galiegue (2023) reported that biochar increases the carbon sequestration, water and nutrient retention and crop yields in degraded soils. However, its effectiveness was highly dependent on the feedstock and substrate types. It is also depended on the application rate and soil type (Koné and Galiegue 2023).

Crop-straw biochar increased foxtail millet yield by 54.6% in sandy soils by improving water retention, organic matter, nutrient availability and photosynthesis during flowering (Sun, Zhang et al. 2020). Further, maize-straw biochar improved the yield of foxtail millet, while decreasing the soil bulk density and pH, and increasing the soil moisture, field capacity, organic matter, the essential nutrients total and available nitrogen and phosphorus, organic acids and enzymatic activity (Hou, He et al. 2024). The results of these studies provide evidence that biochar can be beneficial in offsetting limitations associated with coarse-textured degraded environments. The chemical nature of biochar has been well documented, but biological benefits have also been shown, although fewer in-depth studies are available. For example, Taheri et al. (2024) reported that the sulfur modified biochar showed significant increases in microbial biomass carbon (113% increase) for the basal respiration and enzyme activity (Taheri, Astaraei et al. 2024). Another report by Abo-Elyousr et al. (2022) stated the addition of shrimp waste-derived biochar to the soil increased dehydrogenase activity and microbial biomass carbon (Abo-Elyousr, Mousa et al. 2022).

Tian et al. (2025) showed that the use of wheat-straw biochar in combination with organic fertilizer had beneficial biological effects such as increased complexity of the bacterial community, macroaggregate size, soil organic carbon stock and activities of a variety of enzymes related to C, N and P acquisition . Nevertheless, few studies have investigated the biological effects of biochar in soils on millet and most biochar studies do not measure microbial diversity, respiration or biomass(Tian, Wang et al. 2025) .Biochar provides physiological stress tolerance, nutrients acquisition, biomass production and crop quality/quantity when applied to plants. In saline environments, biochar has been demonstrated to enhance forage production, chlorophyll level, crude protein and primary nutrients (N, P, K), and reduce oxidative damage while reducing levels of damaging Na^{+}/Cl^{-} in the plant's environment. Kang et al. (2022) reported that biochar application reduced DTPA extractable Cd and Zn in highly metal contaminated soils and their accumulation into roots, shoots and grains, decreasing oxidative stress markers and increasing head biomass (Kang, Geng et al. 2022). Boostani et al. in wheat biochar. (2025) found reduced shoot Pb levels by 23.4% and soluble or exchangeable Pb by 36.7% while increasing residual Pb levels by 60.3%. Although final yield data were not reported, these data indicate biochar's ability to markedly improve the safety of crops (Boostani, Hardie et al. 2025). Based on multiple reports, the past yield from cropping systems will result in significant yield increase due to biochar application. Therefore, biochar is not to be considered as an every cropping system/growth enhancer; rather, it should be viewed as an extremely effective yield producing soil amendment to support crops that are being subjected to high stress, acidic, sandy, saline, contaminated or severely degraded soil types.

The box plot representing that the biochar added to soil can lead to significant or substantial changes (generally positive) in different characteristics and soil chemical properties; this change will benefit different soils which is reported by studies conducted at different locations. Of the four soil chemical properties shown in Figure 6, the soil nutrient phosphorus is the one with the highest number of studies and great results (i.e., the mean value of available phosphorus is higher than either the potassium or nitrogen mean values). In addition, many studies have documented a large improvement in phosphorus (medium-high degrees of added phosphorus), which also reflects the biochar's ability to supply nutrients by reducing the retention of phosphorus in the soil, by buffering the soil from changes in acidic environments, increasing the nutrient holding capacity in sandy/acid saline soils, etc (He, Zhao et al. 2020, Ding, Majrashi et al. 2022, Hou, He et al. 2024).

Potassium is the most variable of the nutrient parameters (with the largest outlier - i.e., magnitudes of added potassium which were extremely high compared to other research studies). The number of studies indicates that some biosynthetic nutrient-related biochars (like those generated from plant waste) may directly supply potassium while many others (non-nutrient type or carbon-only biochars) will enhance potassium retention (e.g., rice straw and maize stalk biochars produced some studies with large increases in available potassium while others produced only moderate increases). (Zhao, Wang et al. 2014, Ding, Majrashi et al. 2022, Kang, Geng et al. 2022).

The increases in nitrogen have been moderate compared with phosphorus and potassium. Biochar increases nitrogen availability mainly through reduction of leaching, improvement of ammonium retention in soil, increasing microbial populations and/or improvement of nitrifying bacteria retention and/or reduction of ammonia emissions (Ding, Majrashi et al. 2022, Taheri, Astaraei et al. 2024). The availability of the SOC/SOM/C category has also improved (indicating the improvement of soil organic matter and long-term carbon storage by biochar), but the distribution of the variables shows that the amount of carbon in the SOL (both in biochar and by biochar application respectively) depends on many factors such as: the amount of biochar applied, conditions of pyrolysis, physical properties of the soil (e.g. sand, clay) and time of application (Faye, Stewart et al. 2021, Hou, He et al. 2024) . Overall, the analysis of the graph indicates that biochar has improved phosphorus, potassium, and soil carbon status to the greatest extent (with the exception of nitrogen, where biochar had positive effects, but the effects of nitrogen were by far less than nutrient phosphorus or potassium).

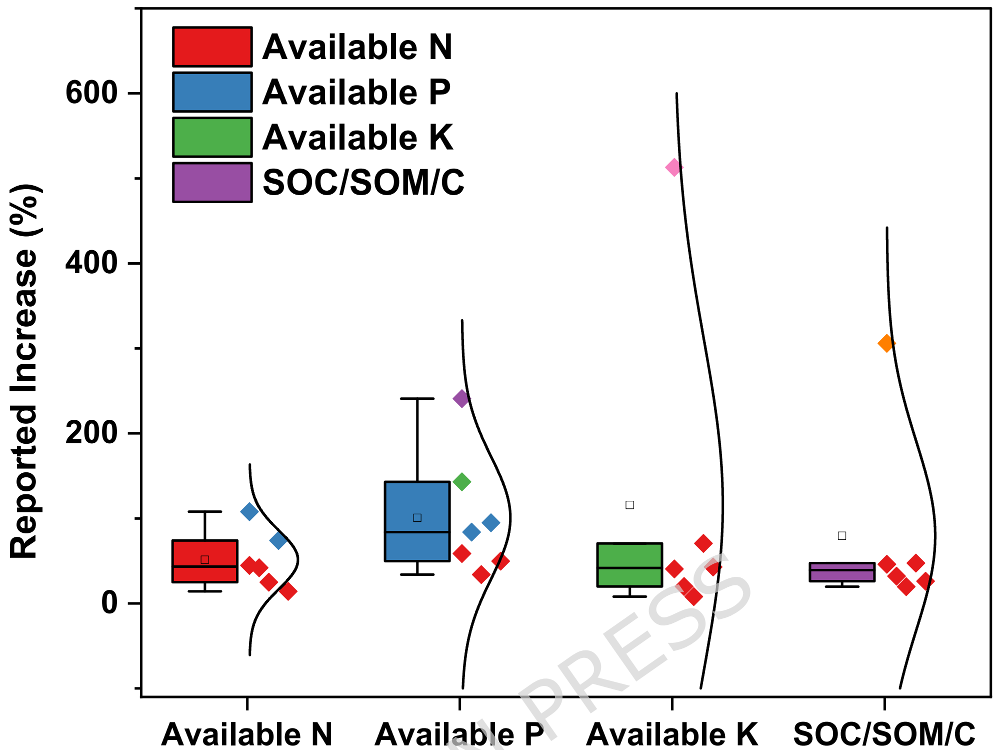


Figure: 6 **The distribution of how each study reviewed improved chemical properties after adding biochar to fields planted with millet**

The semi-quantitative heatmap below has been created to compare the degree of evidence reported in a sample of 14 published studies. The studies are assessed on a scale of 0–3 with the following meanings: 0 = not reported; 1 = Qualitatively reported on; 2 = Quantitatively measured directly and; 3 = Quantified results provided and there are clear signs of biological activity related to a specific treatment. Overall, the heatmap shows that studies reporting quantitative results from direct measurements are primarily related to soil chemical properties, soil yield, and biomass response, as most studies reported that soil chemistry changed in response to biochar or were affected by biochar. The most frequently reported aspects of soil chemistry include pH, SOM/SOC, CEC, available N-P-K, salinity, available crop nutrients/biomass/yield ((Ali, Al-Yasi et al. 2021, Ding, Majrashi et al. 2022, Hou, He et al. 2024, Zhang, Zhang et al. 2025). In contrast, the degree of advanced biochar characterization (i.e., high levels of sophistication in how biochar was analysed) by quantitative measurements is limited, as few studies reported measurements using SEM, FTIR, etc, and there were virtually no examples of the use of XRD, BET, Raman, XPS and TGA in studies published before 2020 (Kang, Geng et al. 2022, Hou, He et al. 2024, Taheri, Astaraei et al. 2024, Boostani, Hardie et al. 2025). The moderating data on evidence from soil physical property studies showed evidence of aggregates, bulk densities, porosity, and water retention (He, Zhao et al. 2020, Singh, Thomas et al. 2020, Tian, Wang et al. 2025). The soil biological measurements data have generally been limited relative to the other two categories; however, recent studies that measured microbes (microbial biomass), enzymes, and the number of bacteria in response to biochar produced more quantitative results across all three categories (Abo-Elyousr, Mousa et al. 2022, Kang, Geng et al. 2022) . The results of the heatmap indicate that biochar improves soil chemistry and productivity, while mechanistic biochar characterization (i.e. how biochar operates) through soil biological pathways remains under-studied in terms of creation of yield.

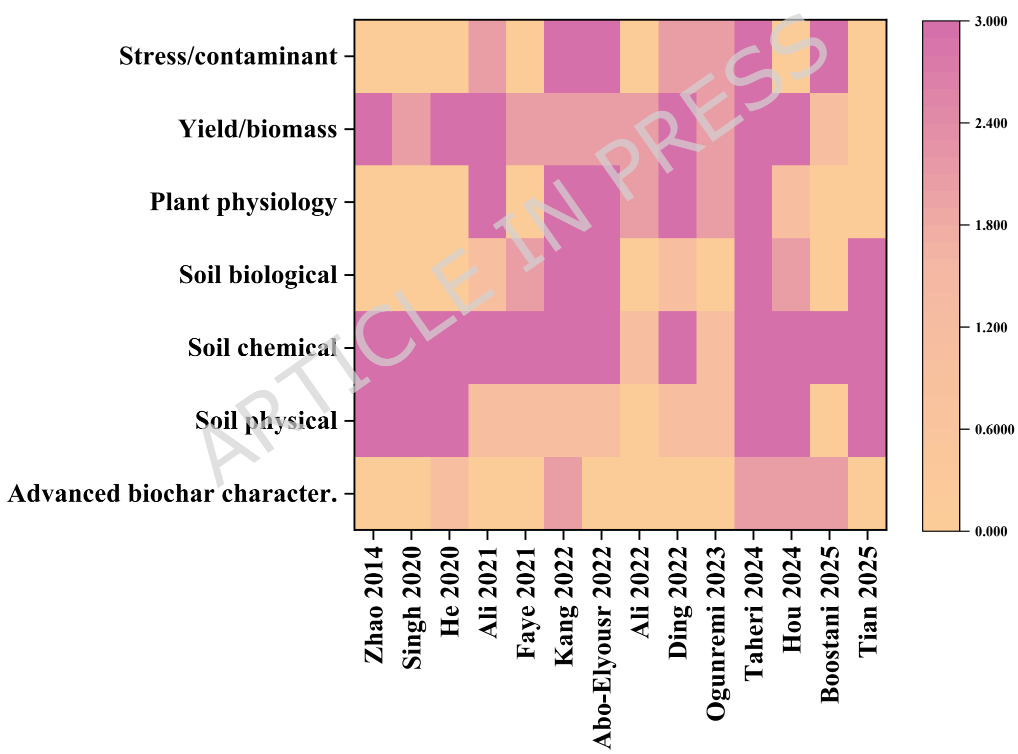


Figure:7 **This visual representation of the evidence shows how strong the reporting is among the 14 biochar-millet studies.**

6. Conclusion

The results of this systematic review demonstrate that biochar is a valuable and sustainable amendment for improving soils on which millet is commonly grown. Biochar, across different environments, improved soil structure, improved soil water retention, nutrient availability, and biological activity. Such improvements contributed to better establishment of the millet plants with higher stress tolerance and improved yields. As biochar can be produced from commonly available agricultural residues, the treatment becomes less expensive and more environmentally sustainable for resource-limited farmers working with challenging soils. With proper application, biochar has strong potential to promote long-term soil restoration and improve technology for the millet-based farming systems in resource-limited contexts.

Author Contribution

A.K.P. and S.M. conceptualized and designed the study. LS. performed the literature search, data extraction, and formal analysis. S.M. supervised the methodological framework and validated the PRISMA screening process. LS. prepared the first draft of the manuscript, including writing the introduction, methodology, results, and graphical components. S.M. and AKP critically reviewed, edited, and refined the manuscript for intellectual content and coherence. Both authors contributed to data interpretation, approved the final version of the manuscript, and agreed to be accountable for all aspects of the work. SKB helped in analysis.

Acknowledgements

The authors gratefully acknowledge Prof. Sanghamitra Nayak, HOD, Centre for Biotechnology, Prof. Debajyoti Das, Dean, Centre for Biotechnology, and Dr. Manojranjan Nayak, President, Siksha 'O' Anusandhan (Deemed to be University) for providing the necessary facilities for carrying out the work.

Funding

No outside funding used in preparation of the manuscript

Data Availability

Not applicable

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Consent to Publish declaration: not applicable

Consent to Participate declaration: not applicable

Ethics declaration: not applicable

Clinical trial number: not applicable.

Third party material: 'No'

Reference:s

Abo-Elyousr, K. A., M. A. Mousa, O. H. Ibrahim, N. O. Alshareef and M. A. Eissa (2022). "Calcium-rich biochar stimulates salt resistance in pearl millet (Pennisetum glaucum L.) plants by improving soil quality and enhancing the antioxidant defense." Plants **11**(10): 1301.

Abo-Elyousr, K. A., M. A. Mousa, O. H. Ibrahim, N. O. Alshareef and M. A. J. P. Eissa (2022). "Calcium-rich biochar stimulates salt resistance in pearl millet (Pennisetum glaucum L.) plants by improving soil quality and enhancing the antioxidant defense." **11**(10): 1301.

Agegnehu, G. and T. J. P. Amede (2017). "Integrated soil fertility and plant nutrient management in tropical agro-ecosystems: a review." **27**(4): 662-680.

Ali, E. F., H. M. Al-Yasi, A. M. Kheir and M. A. Eissa (2021). "Effect of biochar on CO2 sequestration and productivity of pearl millet plants grown in saline sodic soils." Journal of Soil Science and Plant Nutrition **21**(2): 897-907.

Ali, E. F., H. M. Al-Yasi, A. M. Kheir, M. A. J. J. o. S. S. Eissa and P. Nutrition (2021). "Effect of biochar on CO2 sequestration and productivity of pearl millet plants grown in saline sodic soils." **21**(2): 897-907.

Ali, M. F., U. Ali, S. Bilal, U. Zulfiqar, S. Sohail and T. J. A. J. o. G. Hussain (2022). "Response of sorghum and millet to poultry and farmyard manure–based biochar treatments." **15**(20): 1592.

Amarasinghe, H., S. Gunathilake and A. J. P. f. s. Karunarathna (2016). "Ascertaining of optimum pyrolysis conditions in producing refuse tea biochar as a soil amendment." **6**: 97-102.

Basak, B., B. Sarkar, A. Saha, A. Sarkar, S. Mandal, J. K. Biswas, H. Wang and N. S. J. S. o. t. T. E. Bolan (2022). "Revamping highly weathered soils in the tropics with biochar application: What we know and what is needed." **822**: 153461.

Boostani, H. R., A. G. Hardie, A. Mahmoodi and A. J. D. A. S. Tavili (2025). "Correction: Crop residue biochar modifies Pb fractionation and bioavailability to proso millet in calcareous soil." **7**(12): 1375.

Boostani, H. R., A. G. Hardie, A. Mamoodi and A. Tavili (2025). "Crop residue biochar modifies Pb fractionation and bioavailability to proso millet in calcareous soil." Discover Applied Sciences **7**(11): 1298.

Ding, Z., M. A. Majrashi, A. M. Ghoneim, E. F. Ali, M. A. Eissa and R. E. Shal (2022). "Irrigation and biochar effects on pearl millet and kinetics of ammonia volatilization from saline sandy soils." Journal of Soil Science and Plant Nutrition **22**(2): 1546-1558.

Ding, Z., M. A. Majrashi, A. M. Ghoneim, E. F. Ali, M. A. Eissa, R. E. J. J. o. S. S. Shal and P. Nutrition (2022). "Irrigation and biochar effects on pearl millet and kinetics of ammonia volatilization from saline sandy soils." **22**(2): 1546-1558.

Domingues, R. R., P. F. Trugilho, C. A. Silva, I. C. N. d. Melo, L. C. Melo, Z. M. Magriotis and M. A. J. P. o. Sánchez-Monedero (2017). "Properties of biochar derived from wood and high-nutrient biomasses with the aim of agronomic and environmental benefits." **12**(5): e0176884.

Faye, A., Z. P. Stewart, K. Diome, C.-T. Edward, D. Fall, D. K. K. Ganyo, T. M. Akplo and P. V. Prasad (2021). "Single application of biochar increases fertilizer efficiency, C sequestration, and pH over the long-term in sandy soils of Senegal." Sustainability **13**(21): 11817.

Faye, A., Z. P. Stewart, K. Diome, C.-T. Edward, D. Fall, D. K. K. Ganyo, T. M. Akplo and P. V. J. S. Prasad (2021). "Single application of biochar increases fertilizer efficiency, C sequestration, and pH over the long-term in sandy soils of Senegal." **13**(21): 11817.

Guo, R., Y. Ren, G. Ren, S. Zhang and J. Feng (2025). "Impacts of Fertilizers with Varying Nitrogen Contents on Millet Yield and Rhizosphere Soil Microbial Communities: Implications for Sustainable Agricultural Development." Sustainability **17**(4): 1557.

He, L., J. Zhao, S. Yang, H. Zhou, S. Wang, X. Zhao and G. Xing (2020). "Successive biochar amendment improves soil productivity and aggregate microstructure of a red soil in a five-year wheat-millet rotation pot trial." Geoderma **376**: 114570.

He, L., J. Zhao, S. Yang, H. Zhou, S. Wang, X. Zhao and G. J. G. Xing (2020). "Successive biochar amendment improves soil productivity and aggregate microstructure of a red soil in a five-year wheat-millet rotation pot trial." **376**: 114570.

Hou, X., W. He, Y. Zhang, N. Zhang, J. Yan and Y. Chen (2024). "Maize-straw biochar enhances soil properties and grain yield of foxtail millet in a newly reclaimed land." Agronomy **14**(11): 2465.

Hou, X., W. He, Y. Zhang, N. Zhang, J. Yan and Y. J. A. Chen (2024). "Maize-straw biochar enhances soil properties and grain yield of foxtail millet in a newly reclaimed land." **14**(11): 2465.

Ippolito, J. A., L. Cui, C. Kammann, N. Wrage-Mönnig, J. M. Estavillo, T. Fuertes-Mendizabal, M. L. Cayuela, G. Sigua, J. Novak and K. J. B. Spokas (2020). "Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review." **2**(4): 421-438.

Jia, Y., L. Zhang, Z. Pang, L. Mo, H. Fu, Z. Yuan and C. Hu (2025). "Effects of biochar on sugarcane growth and rhizosphere microecosystem under reduced nitrogen fertilization: a 5‐year field experiment study." Biochar **7**(1): 121.

Kang, X., N. Geng, X. Li, J. Yu, H. Wang, H. Pan, Q. Yang, Y. Zhuge and Y. Lou (2022). "Biochar alleviates phytotoxicity by minimizing bioavailability and oxidative stress in foxtail millet (Setaria italica L.) cultivated in Cd-and Zn-contaminated soil." Frontiers in Plant Science **13**: 782963.

Kang, X., N. Geng, X. Li, J. Yu, H. Wang, H. Pan, Q. Yang, Y. Zhuge and Y. J. F. i. P. S. Lou (2022). "Biochar alleviates phytotoxicity by minimizing bioavailability and oxidative stress in foxtail millet (Setaria italica L.) cultivated in Cd-and Zn-contaminated soil." **13**: 782963.

Koné, S. and X. Galiegue (2023). "Potential development of biochar in Africa as an adaptation strategy to climate change impact on agriculture." Environmental Management **72**(6): 1189-1203.

Lima, J., C. J. I. J. o. E. S. da Penha Simon and Technology (2025). "Biochar–soil–plant interfaces: a systematic review of the crop performance in tropical climate." **22**(3): 1995-2020.

Murtaza, G., Z. Ahmed, M. Usman, W. Tariq, Z. Ullah, M. Shareef, H. Iqbal, M. Waqas, A. Tariq and Y. Wu (2021). "Biochar induced modifications in soil properties and its impacts on crop growth and production." Journal of plant nutrition **44**(11): 1677-1691.

Ogunremi, O. O., O. F. AMUBIEYA and P. O. FATOBA (2023). "BIOCHAR EFFECT ON SEED GERMINATION AND GROWTH OF MONOCOTS IN SPENT-OIL-CONTAMINATED SOIL." South-Western Journal of Horticulture Biology & Environment **14**(2).

Ogunremi, O. O., O. F. Amubieya and P. O. J. S. W. J. H. B. E. Fatoba (2023). "Biochar effect on seed germination and growth of monocots in spent-oil-contaminated soil." **14**: 77-93.

Ok, Y. S., S. M. Uchimiya, S. X. Chang and N. Bolan (2015). Biochar: Production, characterization, and applications, CRC press.

Page, M. J., J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl and S. E. Brennan (2021). "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews." bmj **372**.

Pang, Z., J. Huang, N. Fallah, W. Lin, Z. Yuan and C. Hu (2022). "Combining N fertilization with biochar affects root-shoot growth, rhizosphere soil properties and bacterial communities under sugarcane monocropping." Industrial Crops and Products **182**: 114899.

Rafiq, M. K., R. T. Bachmann, M. T. Rafiq, Z. Shang, S. Joseph and R. J. P. o. Long (2016). "Influence of pyrolysis temperature on physico-chemical properties of corn stover (Zea mays L.) biochar and feasibility for carbon capture and energy balance." **11**(6): e0156894.

Singh, M., T. Thomas, A. A. David and N. Swaroop (2020). "Effect of Different Level of NPK and Biochar on Soil Physico-chemical Properties, Yield and Attributes of Finger Millet (Eleusine Coracana) Var.–KM 65." Int. J. Curr. Microbiol. App. Sci **9**(9): 1904-1911.

Singh, M., T. Thomas, A. A. David and N. J. I. J. C. M. A. S. Swaroop (2020). "Effect of Different Level of NPK and Biochar on Soil Physico-chemical Properties, Yield and Attributes of Finger Millet (Eleusine Coracana) Var.–KM 65." **9**(9): 1904-1911.

Sun, Y., N. Zhang, J. Yan and S. Zhang (2020). "Effects of soft rock and biochar applications on millet (Setaria italica L.) crop performance in sandy soil." Agronomy **10**(5): 669.

Taheri, M. a.-R., A. R. Astaraei, A. Lakzian and H. Emami (2024). "The role of biochar and sulfur-modified biochar on soil water content, biochemical properties and millet crop under saline-sodic and calcareous soil." Plant and Soil **499**(1): 221-236.

Taheri, M. a.-R., A. R. Astaraei, A. Lakzian, H. J. P. Emami and Soil (2024). "The role of biochar and sulfur-modified biochar on soil water content, biochemical properties and millet crop under saline-sodic and calcareous soil." **499**(1): 221-236.

Tian, L., Y. Wang, D. Jin, Y. Zhou, B. Mukhamed, D. Liu and B. Feng (2025). "The application of biochar and organic fertilizer substitution regulates the diversities of habitat specialist bacterial communities within soil aggregates in proso millet farmland." Biochar **7**(1): 6.

Tian, L., Y. Wang, D. Jin, Y. Zhou, B. Mukhamed, D. Liu and B. J. B. Feng (2025). "The application of biochar and organic fertilizer substitution regulates the diversities of habitat specialist bacterial communities within soil aggregates in proso millet farmland." **7**(1): 6.

Wang, M., Y. Zhu, L. Cheng, B. Andserson, X. Zhao, D. Wang and A. J. J. o. E. S. Ding (2018). "Review on utilization of biochar for metal-contaminated soil and sediment remediation." **63**: 156-173.

Yu, K. L., B. F. Lau, P. L. Show, H. C. Ong, T. C. Ling, W.-H. Chen, E. P. Ng and J.-S. J. B. t. Chang (2017). "Recent developments on algal biochar production and characterization." **246**: 2-11.

Zhang, Y., X. Zhang, Z. Zhou, G. Liu and C. Wang (2025). "A review of the conversion of wood biomass into high-performance bulk biochar: Pretreatment, modification, characterization, and wastewater application." Separation and Purification Technology: 131448.

Zhao, X., J. Wang, H. Xu, C. Zhou, S. Wang and G. Xing (2014). "Effects of crop-straw biochar on crop growth and soil fertility over a wheat-millet rotation in soils of C hina." Soil Use and Management **30**(3): 311-319.