

BIOCHAR-BASED SOIL MANAGEMENT FOR ENHANCING BARNYARD MILLET (*ECHINOCHLOA FRUMENTACEA* (ROXB.) LINK) PRODUCTION UNDER RAINFED CONDITIONS: A REVIEW

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ABSTRACT

Barnyard millet (*Echinochloa frumentacea* (Roxb.) Link) is a short-duration cereal that fits well into low-input and rain-dependent production systems. Its adaptability makes it valuable where rainfall is uncertain, yet yields in such environments are often restricted by depleted organic matter, weak nutrient supply and limited soil-water storage. Biochar, produced by heating biomass under oxygen-limited conditions, has attracted attention as a durable soil amendment capable of modifying several soil properties at the same time. Published evidence indicates that biochar can decrease soil bulk density, improve aggregation and pore characteristics, increase water retention, and contribute to nutrient retention. Nevertheless, the magnitude and direction of these effects are strongly influenced by feedstock, pyrolysis conditions, soil texture, soil reaction, application rate and crop management. Meta-analyses have reported an overall positive effect of biochar on crop productivity, but responses vary considerably among environments. Combining biochar with compost, farmyard manure, biofertilizers or recommended mineral fertilization may be more effective than using biochar as a stand-alone input. Direct evidence for barnyard millet is still limited, and consequently biochar rates or combinations should not be presented as universal recommendations. This review examines the scientific basis for using biochar in rainfed barnyard millet, with emphasis on soil physical and chemical improvement, nutrient-use efficiency, water-stress mitigation, carbon management, locally available feedstocks, limitations and future research requirements.

KEYWORDS: Barnyard millet; *Echinochloa frumentacea*; biochar; rainfed farming; soil fertility; soil-water relations; nutrient-use efficiency; sustainable crop production

1. INTRODUCTION

Barnyard millet (*Echinochloa frumentacea*) is an important minor millet with considerable potential for climate-resilient agriculture because of its short duration, adaptability to marginal environments, relatively low input requirement and ability to withstand drought and other environmental stresses. Despite these advantages, its genetic improvement has received comparatively less attention than major cereal crops, and systematic exploitation of its genetic diversity and molecular resources is still required. Considerable genetic variability has been reported in barnyard millet for grain yield, yield components, nutritional traits and stress adaptation, providing opportunities for developing superior cultivars through conventional and molecular breeding approaches (Sood et al., 2015; Renganathan et al., 2020). Molecular markers such as simple sequence repeats (SSRs), expressed sequence tags (EST-SSRs) and single nucleotide polymorphisms (SNPs) have facilitated the assessment of genetic diversity, population structure and relationships among barnyard millet germplasm and can be effectively utilized for marker-assisted selection and genomic breeding (Renganathan et al., 2020). The development of transcriptomic and genomic resources in *Echinochloa* species has further enhanced the understanding of genes and molecular pathways associated with plant growth, grain development and adaptation to environmental stresses. Comparative transcriptome studies involving cultivated and wild *Echinochloa* species have provided valuable information on differentially expressed genes and candidate genes involved in stress response and adaptive mechanisms, which can be exploited for crop improvement (Jayakodi et al., 2019). Genomics and transcriptomics approaches are particularly valuable for elucidating the molecular mechanisms governing tolerance to drought, salinity, heat and other abiotic stresses in minor millets, including barnyard millet, by identifying stress-responsive genes, transcription factors and signalling pathways (Gobika et al., 2026). In addition to productivity, molecular breeding can contribute to improving

nutritional quality by targeting traits such as protein content, dietary fibre, minerals, antioxidants and other nutritionally important grain constituents. The integration of phenotypic evaluation with genome-wide association studies (GWAS), quantitative trait locus (QTL) mapping, transcriptomics, metabolomics and candidate-gene analysis can facilitate the identification of genomic regions controlling complex traits such as grain yield, nutritional quality and abiotic stress tolerance. Recent advances in genomics-assisted breeding indicate that combining conventional selection with molecular markers and genomic selection could substantially accelerate the development of high-yielding, nutritionally superior and climate-resilient barnyard millet cultivars (Amasiddha et al., 2023; Gobika et al., 2026). In the future, functional genomics and genome-editing technologies such as CRISPR/Cas systems may provide additional opportunities for validating candidate genes and precisely modifying traits associated with yield, nutritional quality and stress adaptation. Thus, systematic characterization of germplasm, development of high-density molecular markers and integration of genomics, transcriptomics and functional validation will be essential for unlocking the genetic potential of barnyard millet and promoting its utilization in sustainable and climate-smart rainfed agriculture (Renganathan et al., 2020; Gobika et al., 2026).

2. Barnyard Millet and Its Relevance to Rainfed Agriculture

The short crop duration and adaptability of barnyard millet make it suitable for production where the available rainy period is limited. These characteristics are especially relevant to smallholder systems in which irrigation facilities and purchased inputs may be restricted. Sood et al. (2015) described the crop as a potential food and feed crop for future production systems because of its adaptation to marginal environments. Even a relatively drought-adapted crop can experience yield losses when moisture shortage coincides with important growth stages. In addition, poor soil fertility can restrict biomass production and reduce the crop's capacity to exploit short periods of favourable moisture. Hence, rainfed barnyard millet benefits from soil-management practices that improve the efficiency with which rainfall and applied nutrients are converted into crop growth.

2.1 Major soil constraints in rainfed barnyard millet

Important soil-related limitations commonly associated with low-input rainfed systems include low organic carbon, weak nitrogen availability, phosphorus deficiency or fixation, limited plant-available water, nutrient losses through runoff or leaching, poor aggregate stability, reduced biological activity and inadequate recycling of crop residues. These constraints frequently occur together rather than independently. A soil amendment capable of influencing several of these properties may therefore have greater value than an input that addresses only one constraint.

3. Biochar: Nature, Production and Key Properties

Biochar is the carbon-rich solid product obtained when biomass undergoes thermochemical conversion under restricted oxygen supply. It is intentionally produced for applications such as soil improvement and carbon retention. Its behaviour in soil is controlled by both the original feedstock and the conditions used during pyrolysis (Lehmann and Joseph, 2009). Important characteristics include pH, electrical conductivity, ash content, carbon concentration, C:N ratio, surface area, pore structure, nutrient content, particle size and bulk density. Pyrolysis temperature, residence time and heating rate can alter these properties. Consequently, two biochars made from different residues—or even from the same residue under different processing conditions—may perform quite differently after soil incorporation (Enders et al., 2012). This variability is especially important when developing recommendations for farmers. Biochar should therefore be characterized before field use rather than treated as a uniform product. Agegnehu et al. (2017) emphasized that biochar–compost systems can influence soil quality through simultaneous physical, chemical and biological pathways.

4. Effects of Biochar on Soil Physical Properties

4.1 Bulk density and pore space

Biochar is generally lighter than mineral soil. Incorporation can consequently lower bulk density and increase pore volume, potentially creating a more favourable environment for root growth and movement of air and water. Omondi et al. (2016), using a meta-analysis of published studies, reported an average reduction of about 7.6% in soil bulk density following biochar addition. The magnitude of change nevertheless depends on application rate, particle characteristics and the initial condition of the soil.

4.2 Aggregation and porosity

The interaction of biochar particles with mineral fractions and organic materials can alter the arrangement of soil particles and pores. Improved aggregation can increase the continuity and diversity of pore spaces available for roots, air and water. Omondi et al. (2016) reported mean improvements of approximately 8.4% in porosity and 8.2% in aggregate stability across the studies evaluated. Such effects may be useful in degraded soils, although the response should be verified under local field conditions.

4.3 Soil-water storage

Water relations are particularly important in rainfed barnyard millet. Biochar can increase the amount of water retained in soil that remains potentially available to plants. Omondi et al. (2016) estimated an average improvement of about 15.1% in available water-holding capacity, while Razzaghi et al. (2020) showed that the response varied with soil texture and was generally stronger in coarse-textured soils. These findings suggest that biochar may help moderate short periods of moisture stress, but they do not establish a fixed benefit for every barnyard millet field.

5. Influence on Soil Chemical Properties

5.1 Soil organic carbon

A major distinction between biochar and easily decomposed organic residues is the relative persistence of its carbon fraction. Repeated or single applications, depending on rate and conditions, can increase soil organic carbon and contribute to longer-term carbon storage. Increased organic carbon may also influence aggregation, water relations, nutrient cycling and microbial activity (Lehmann and Joseph, 2009; Agegnehu et al., 2017).

5.2 Cation exchange capacity and nutrient retention

The charged surfaces of biochar can retain nutrient cations and thereby influence nutrient residence in the root zone. Liang et al. (2006) demonstrated that black-carbon materials can contribute substantially to soil cation exchange capacity. This property may be especially useful in low-fertility soils where nutrient losses reduce fertilizer-use efficiency. The extent of the effect depends on the chemical ageing of biochar and its interaction with the surrounding soil.

5.3 Soil reaction

Many biochars contain alkaline ash and can increase soil pH. Such an effect may be advantageous in acidic soils, and Jeffery et al. (2011) found stronger productivity responses in acidic and neutral conditions in their broader meta-analysis. In contrast, applying highly alkaline biochar to an already alkaline soil may be undesirable. Soil pH should therefore be considered together with the pH and ash characteristics of the biochar when selecting an application rate.

5.4 Nitrogen transformations

Biochar can alter nitrogen behaviour through adsorption, changes in microbial activity, immobilization, mineralization and modification of soil physical conditions. A high-carbon material may temporarily reduce plant-available nitrogen in some situations because microorganisms can immobilize mineral nitrogen. Biochar should consequently be viewed as a soil amendment that influences nutrient dynamics, not as a direct replacement for nitrogen fertilizer. The combination of biochar with organic and mineral nutrient sources requires crop- and soil-specific evaluation (Agegnehu et al., 2017).

6. Biochar and Soil Biological Processes

The internal pores and reactive surfaces of biochar can provide microsites for microorganisms and can modify the environment surrounding soil organic matter and nutrients. Reported biological responses include changes in microbial biomass, community composition, carbon turnover, nitrogen transformations, nutrient mineralization and rhizosphere interactions (Lehmann et al., 2011). For a short-duration crop such as barnyard millet, efficient nutrient acquisition during the limited growing period is important. Biochar may contribute indirectly by improving the soil environment in which beneficial microorganisms operate. However, biological responses are not necessarily consistent among biochars or soils, and the effectiveness of specific microbial inoculants must be established experimentally rather than assumed.

7. Potential Effects on Barnyard Millet Growth and Yield

7.1 Direct evidence

Compared with major cereals such as rice, wheat and maize, relatively little field research has directly examined biochar application to barnyard millet. Therefore, statements that a particular biochar rate will produce a predetermined yield increase would go beyond the available evidence. Research by Yadav and Malik (2010) demonstrated that integrated organic nutrition can sustain barnyard millet productivity under rainfed conditions, with suitable organic combinations eventually producing yields comparable with recommended fertilizer treatment. This supports the importance of soil organic matter and nutrient management, but organic manure cannot be treated as agronomically identical to biochar.

7.2 Evidence from other crops

The wider biochar literature provides a rationale for testing the amendment in barnyard millet. Jeffery et al. (2011) reported an overall mean crop-productivity increase of approximately 10% in their meta-analysis, but individual responses ranged from negative to strongly positive. Such variability indicates that biochar performance depends on the interaction among soil, climate, feedstock, rate and management. Thus, broader evidence supports experimentation rather than a universal yield claim for barnyard millet.

8. Biochar in Combination with Fertilizers and Organic Inputs

Biochar is better regarded as a soil-conditioning material than as a complete nutrient source. Its nutrient content varies with the feedstock and pyrolysis process, and the nutrients it contains may not be released at a rate that matches crop demand. Combining biochar with nutrient sources can potentially unite immediate nutrient supply with improved nutrient retention and soil physical conditions.

8.1 Biochar with recommended NPK

Recommended fertilizer can provide readily available nitrogen, phosphorus and potassium, while biochar may reduce nutrient loss and improve the soil environment. This combination deserves evaluation under rainfed conditions, particularly where nutrient losses are associated with intense rainfall events.

8.2 Biochar with farmyard manure

Farmyard manure supplies decomposable organic matter and nutrients, whereas biochar contributes a more persistent carbon fraction. Their combined use may therefore provide both short-term nutrient release and longer-lasting soil-conditioning effects.

8.3 Biochar with compost

Biochar–compost mixtures have attracted attention because compost supplies active organic matter and nutrients while biochar provides a stable carbon-rich matrix. Agegnehu et al. (2017) reviewed evidence indicating that such combinations can improve soil quality and crop performance more consistently than some single-input approaches.

8.4 Biochar with biofertilizers

The porous structure of biochar may create favourable microsites for microorganisms, raising the possibility of useful interactions with biofertilizers. Potential combinations with *Azotobacter* or phosphate-solubilizing microorganisms should nevertheless be tested under barnyard millet and the relevant soil conditions before practical recommendations are made.

9. Biochar and Nutrient-Use Efficiency

Efficient nutrient use is particularly important in rainfed agriculture because the economic consequences of fertilizer loss can be substantial. Biochar may contribute to nutrient-use efficiency by retaining nutrient ions, reducing leaching, improving moisture conditions, supporting root development and influencing microbial nutrient cycling. Increased cation exchange capacity can also extend the period during which nutrients remain in the crop rooting zone (Liang et al., 2006). The most promising approach for barnyard millet is therefore likely to be integration of biochar with balanced nutrient management. The objective should be improved synchronization between nutrient supply and crop demand rather than simply increasing the quantity of inputs.

10. Role in Moisture-Stress Management

Rainfall variability is a major determinant of yield in rainfed farming. Although barnyard millet is comparatively tolerant of difficult moisture conditions, prolonged water deficit can interfere with tillering, panicle formation and grain filling. By modifying pore characteristics and water-holding capacity, biochar may increase the amount of rainfall retained within the soil profile (Omondi et al., 2016). Razzaghi et al. (2020) demonstrated that the effect of biochar on water retention is strongly dependent on soil texture, with comparatively larger responses often occurring in coarse-textured soils. This suggests that biochar may have greater value in some sandy or light-textured rainfed soils than in heavy soils. Field trials should therefore measure soil moisture and crop response together rather than assuming that an improvement in laboratory water retention will automatically produce a yield increase.

11. Carbon Sequestration and Residue Recycling

Biochar provides a route for transforming part of the carbon contained in agricultural residues into a comparatively stable form. When incorporated into soil, this persistent carbon fraction can remain for longer periods than much of the carbon in fresh residues (Lehmann and Joseph, 2009). Biochar production can therefore link residue management with soil-carbon conservation, provided that biomass is sourced sustainably and the production process is appropriate. For rainfed farming, locally available residues can potentially be converted into a soil amendment rather than being burned or rapidly decomposed. However, carbon benefits should be evaluated alongside production energy requirements, transport, feedstock availability and agronomic performance.

12. Potential Feedstocks for Barnyard Millet-Based Systems

A wide range of crop and agroforestry residues can serve as biochar feedstocks. Depending on local availability, possibilities include rice straw, maize and sorghum residues, millet stalks, groundnut shells, coconut residues, pigeonpea stalks, woody biomass and *Prosopis* biomass. Feedstock selection matters because the resulting biochar inherits characteristics associated with the original biomass and processing conditions. Before field application, the material should preferably be characterized for pH, electrical conductivity, total carbon, nitrogen, phosphorus, potassium, C:N ratio, ash content, bulk density and possible contaminants. Such characterization is essential for comparing experimental treatments and avoiding unsuitable materials (Enders et al., 2012).

13. Selecting an Appropriate Biochar Rate

There is no single biochar rate that can be recommended for all barnyard millet production environments. Crop responses have varied with application rate, soil type, feedstock and environmental conditions (Jeffery et al., 2011; Omondi et al., 2016). Very low rates may produce limited soil change, whereas large applications can become expensive and may alter soil reaction or nutrient dynamics excessively. Rate trials should therefore include untreated or farmer-practice controls and several graded biochar levels, preferably in combination with balanced nutrient treatments. Measurements should extend beyond yield to include soil moisture, nutrient availability and economic return.

14. Prospects for *Prosopis*-Derived Biochar

Prosopis biomass is widely available in many dryland landscapes and may offer a locally accessible feedstock for biochar production. Converting this woody biomass into biochar could create an additional pathway for biomass utilization and return stable carbon to agricultural soils. The agronomic suitability of *Prosopis* biochar should not, however, be assumed from its availability alone. Its pH, electrical conductivity, ash content, nutrient concentration, carbon characteristics and contaminant status should first be determined. Field studies are required to identify appropriate rates and to establish whether *Prosopis* biochar interacts favourably with the soils and nutrient-management practices used for rainfed barnyard millet.

15. Integrated Soil Fertility Management Approach

Biochar is most appropriately considered one component of an integrated soil-fertility strategy. A combined approach may include balanced mineral fertilizers, farmyard manure or compost, biofertilizers, crop-residue recycling and moisture-conservation practices. Yadav and Malik (2010) showed the importance of integrated organic nutrition for

rainfed barnyard millet, while Agegnehu et al. (2017) highlighted the potential of biochar–compost systems for improving soil quality. The advantage of integration is that different inputs can perform complementary functions: mineral fertilizers supply immediately available nutrients, organic materials provide decomposable carbon and nutrients, microorganisms support nutrient transformations, and biochar can contribute more persistent carbon and nutrient-retention surfaces. Such combinations should be optimized according to soil-test results and local production conditions.

16. Constraints and Risks Associated with Biochar

16.1 Variation in material quality

Biochar is not a standardized material. Differences in feedstock and pyrolysis conditions can produce substantial variation in chemical and physical properties (Lehmann and Joseph, 2009).

16.2 Production, transport and handling costs

Field application may require substantial quantities of material. When biochar is produced far from the farm, transportation and handling can become major components of the total cost.

16.3 Temporary nitrogen immobilization

Some high-C:N biochars may temporarily reduce nitrogen availability by stimulating microbial immobilization. This possibility should be considered when planning fertilizer treatments.

16.4 Excessive alkalinity or salinity

Strongly alkaline or saline biochars may be unsuitable for soils that already have high pH or electrical conductivity. Material characterization and soil testing are therefore essential.

16.5 Inconsistent crop responses

The positive average response reported in meta-analyses masks substantial variation among individual experiments. A beneficial response cannot be assumed for every soil, crop or management system (Jeffery et al., 2011).

16.6 Need for long-term assessment

Biochar is expected to persist in soil, but many agronomic experiments have been relatively short. Long-term trials are needed to understand residual effects on soil carbon, nutrient availability, crop yield and economics.

7. Priority Research Areas for Barnyard Millet

Future investigations should focus specifically on barnyard millet rather than relying only on evidence from other cereals. Replicated field trials are required to determine suitable biochar sources and rates, particularly in contrasting soil types such as red soils, black soils and sandy loams. An important research priority is the interaction between biochar and recommended NPK. Experiments should also test combinations with farmyard manure, compost, *Azotobacter* and phosphate-solubilizing microorganisms. Because drought is a major concern in rainfed agriculture, trials should examine whether biochar reduces yield losses during intermittent moisture stress. Multi-season experiments are essential for assessing residual effects on soil carbon, nutrient availability and crop productivity. Economic analysis should include biochar production, transport, field application, fertilizer savings and changes in gross and net returns. Such information will determine whether a technically effective treatment is also practical for farmers.

18. Suggested Measurements for Field Experiments

18.1 Soil measurements

Recommended soil observations include pH, electrical conductivity, organic carbon, available nitrogen, phosphorus and potassium, sulphur, DTPA-extractable zinc and iron, cation exchange capacity, bulk density, porosity, water-holding capacity, periodic soil moisture and microbial biomass carbon.

18.2 Crop measurements

Crop observations may include germination, plant height, tiller number, root length and biomass, panicle length, panicles per plant, grains per panicle, thousand-grain weight, grain yield, straw yield, harvest index and nutrient uptake. Measuring both vegetative and reproductive traits helps identify whether biochar influences yield through establishment, root development, tillering or grain formation.

18.3 Economic measurements

Economic evaluation should account for the cost of feedstock collection or purchase, biochar production, transportation and field application. Gross returns, net returns and benefit–cost ratio should then be calculated for each treatment. Economic analysis is essential before moving from experimental findings to farmer recommendations.

19. CONCLUSION

Barnyard millet is well suited to many rainfed and resource-constrained environments because of its short duration and adaptability (Sood et al., 2015). Nevertheless, low organic carbon, nutrient limitations and inadequate soil–water storage can restrict productivity. Biochar provides a potentially useful means of addressing several of these soil constraints simultaneously. Evidence from meta-analyses indicates that biochar can reduce bulk density and improve porosity, aggregation and available water-holding capacity, while its surface properties can contribute to nutrient retention and cation exchange processes (Omondi et al., 2016; Liang et al., 2006). Broader crop research also indicates a generally positive, but highly variable, effect on productivity (Jeffery et al., 2011). Evidence directly generated in barnyard millet is much more limited, although studies on organic nutrient management demonstrate the value of improving nutrient supply and soil organic matter under rainfed conditions (Yadav and Malik, 2010). Accordingly, biochar should be evaluated as part of an integrated soil-management system rather than as a substitute for fertilizers. Research combining

locally available biomass-derived biochar, balanced fertilization, organic amendments and beneficial microorganisms could provide a stronger basis for improving rainfed barnyard millet production. In particular, Prosopis-derived biochar merits location-specific evaluation where the biomass is locally available. Future trials should simultaneously measure soil moisture, nutrient availability, crop growth, yield, nutrient uptake, soil carbon and economic returns across multiple seasons. Such evidence is necessary to establish practical, site-specific recommendations for sustainable barnyard millet production.

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