

REVIEW

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Carbon sequestration potential of climate smart finger millet for sustainable food and nutritional security

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Abstract

Finger millet is emerging as a climate-smart cereal with strong potential for carbon farming and sustainable food systems. As an underutilized crop with inherent drought tolerance, low input requirements and superior nutritional quality, it supports agricultural resilience while contributing to carbon sequestration in marginal environments. Its extensive root architecture, delayed senescence and sustained photosynthetic activity under stress conditions promote biomass production and belowground carbon inputs. This mini review evaluates the capacity and role of finger millet to transform agri-food systems through improved carbon capture, enhanced nutrient cycling and strengthened food and nutritional security. Recent advances in breeding, genomics and agronomy have generated nutrient-dense and stress-resilient varieties optimized for low-carbon production systems. Integrating conservation agriculture, residue retention and intercropping can further enhance soil organic carbon accumulation and system sustainability. Despite its potential, adoption remains constrained by limited policy support, weak market incentives and low awareness of carbon farming opportunities. Therefore, targeted research, participatory breeding and carbon credit frameworks are essential for mainstreaming finger millet in climate-smart agriculture.

Keywords Finger millet, Carbon farming, Climate-smart agriculture, Drought tolerance, Nutritional quality, Underutilized crops, Climate mitigation

1 Introduction

Finger millet (*Eleusine coracana* L.) is a resilient and nutrient-rich cereal recognized as a critical crop for sustainable agriculture in semi-arid and marginal environments [1]. Its remarkable adaptability to drought stress, high temperatures and poor soils positions it as a climate-smart crop capable of addressing food insecurity under changing climatic conditions. In addition, finger millet offers opportunities for climate mitigation through carbon farming [2], particularly via root-derived carbon inputs and residue-mediated soil organic matter enhancement. Nutritionally, its grains are rich in calcium, iron, dietary fiber and essential amino acids, offering significant benefits for human health in



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communities with limited access to diversified diets [3]. This combination of stress tolerance, nutritional density and low external input demand aligns finger millet with the objectives of sustainable intensification and low-emission agriculture. Despite its significance, finger millet has historically received limited research and policy attention relative to major cereals, constraining its optimization and wider adoption.

The resilience of finger millet arises from its unique physiological and morphological adaptations, which confer drought tolerance and support carbon sequestration [4] (Ekwangu et al., 2023). These traits support sustained photosynthesis and biomass accumulation under water-limited conditions, directly linking stress tolerance with carbon-use efficiency. The fibrous root systems improve soil carbon input through rhizodeposition and root turnover [5], while efficient water use ensures sustained biomass accumulation under limited water environments. The osmotic adjustment and stomatal regulation enable maintenance of turgor and photosynthetic efficiency during drought stress [6], linking physiological performance to carbon-use efficiency. Delayed leaf senescence and rapid post-stress recovery allow continued carbon assimilation and resilience to fluctuating environmental conditions [7, 8]. Genotypic variation in these traits provides a strong foundation for targeted breeding programs aimed at improving both stress tolerance and carbon capture. Modern phenotyping and high-throughput screening techniques facilitate the identification of superior genotypes for climate-smart systems [9]. In addition, the ability of finger millet to thrive in marginal soils reduces dependence on synthetic inputs [3], thereby lowering its carbon footprint. Therefore, integrating physiological insights with sustainable agronomic practices enhances the crop contributes to both productivity and environmental sustainability.

Carbon farming principles emphasize the role of crops and management practices in enhancing carbon sequestration and mitigating climate change [10]. Finger millet's potential for high biomass production combined with low input requirements makes it well suited to such systems. Nevertheless, uncertainties remain regarding the magnitude, stability and long-term permanence of carbon stored under finger millet-based systems. Despite growing interest in millets, most studies treat finger millet primarily as a drought-resilient or nutrient-rich crop, with limited integration of its physiological traits, carbon allocation strategies, and management-driven sequestration potential into a unified carbon farming framework. The existing reviews lack explicit consideration of trade-offs among yield and nutritional quality. In light of the above background, this mini review highlights the role of finger millet in transforming agri-food systems through improved carbon capture, enhanced nutrient cycling and strengthened food and nutritional security.

2 Drought tolerance and carbon-related physiological adaptations

Finger millet exhibits remarkable drought tolerance [11], which is closely linked with its carbon assimilation and sequestration potential. Its deep and fibrous root systems allow efficient extraction of water from subsoil layers [12], while simultaneously contributing to soil organic carbon through root exudates and turnover. The root-to-shoot ratios (R:S) of 1.2–1.5 can indicate that plants are allocating a relatively large proportion of their biomass and carbon resources to their belowground root systems.

Photosynthesis is maintained under water stress through stomatal regulation and osmotic adjustment, supporting sustained carbon fixation and biomass accumulation.

Delayed leaf senescence enhances the duration of photosynthetic activity [13], which supports grain filling and promotes carbon storage in root and shoot biomass. Compared with shallow-rooted cereals such as rice and wheat, finger millet demonstrates greater resilience in maintaining biomass production under water-limited conditions [14], suggesting a relatively higher carbon retention potential in marginal environments. Furthermore, finger millet produces compatible solutes such as proline and sugars [15], which maintain cell turgor and support photosynthetic efficiency under drought stressed conditions. Its antioxidant systems, including superoxide dismutase and catalase [15], mitigate oxidative stress and protect photosynthetic machinery, indirectly enhancing carbon assimilation. The high root-to-shoot ratio contributes to soil carbon sequestration by channeling assimilated carbon belowground, while fine root turnover improves soil structure and microbial activity. The physiological plasticity enables rapid post-stress recovery, preserving biomass and carbon stocks, while genotypic variation in these traits provides opportunities for selecting lines with improved carbon-use efficiency and drought resilience.

3 Nutritional quality and carbon–nutrition nexus

Finger millet's grains are rich in calcium, iron, zinc, and essential amino acids, making it a critical crop for nutritional security in resource-limited regions [3]. The crop's low glycemic index and high fiber content support healthy diets and reduce the risk of diabetes, linking human health outcomes with sustainable food systems [16]. Increasing evidence indicates that soil organic carbon plays a critical role in improving micronutrient availability by enhancing soil structure, cation exchange capacity and microbially mediated nutrient cycling. Carbon-smart practices such as residue retention and organic amendments enhance micronutrient availability, demonstrating a positive relationship between soil carbon and nutrient density. This enables the concept of “nutrition per unit carbon footprint,” whereby higher nutritional value is achieved without proportional increases in greenhouse gas emissions. Genetic variation in accessions provides opportunities to breed cultivars and lines that simultaneously enhance nutrient content and carbon-use efficiency [17]. However, potential trade-offs among yield, nutritional quality and biomass allocation require further investigation to ensure balanced breeding outcomes.

4 Breeding and genomic advances for carbon-smart finger millet

Breeding for carbon-smart varieties requires integrating drought tolerance, nutritional quality and carbon-use efficiency into selection programs. Conventional breeding has improved yield and resilience [18], but molecular tools have accelerated the development of genotypes optimized for climate-smart systems. Marker-assisted selection, genome-wide association studies and QTL mapping allow targeted improvement of root traits and photosynthetic efficiency in cereals [19, 20]. Furthermore, genomic resources have identified regulatory pathways associated with carbon metabolism, drought resilience and nutrient accumulation in finger millet [21], although functional validation under field conditions remains limited. Transcriptomic studies identify stress-responsive genes, including those regulating osmotic adjustment, antioxidant defense and root development [22], which influence carbon-use efficiency. Proteomic and metabolomic analyses provide insights into metabolic pathways that support biomass production and stress tolerance [3], but their direct linkage to long-term carbon sequestration is not yet

fully explored. These approaches reduce the time required to develop climate-resilient and carbon-efficient varieties. Integration of molecular breeding with high-throughput phenotyping enhances the identification of superior lines. However, translating molecular gains into measurable field-scale carbon sequestration remains challenging, highlighting the need for integrated phenotyping, long-term field trials and robust carbon accounting approaches.

5 Agronomic and climate-resilient carbon farming practices

Agronomic management is crucial for optimizing productivity and climate resilience in finger millet systems [23]. Conservation agriculture practices including minimum tillage, residue retention and crop rotation can enhance soil organic carbon and improve water retention. The incorporation of organic residues, compost and green manures increases soil fertility while stabilizing carbon pools. Intercropping with legumes enhances nitrogen availability, improves soil structure and supports soil carbon accumulation while increasing system diversity. Mulching reduces soil temperature fluctuations and moisture loss, supporting consistent growth and carbon assimilation [24, 25]. Short growth cycles allow finger millet to fit efficiently into multi-crop systems, increasing land-use efficiency and carbon capture. Organic and biofertilizer applications reduce dependence on synthetic inputs and associated carbon emissions. For instance, the application of 10 Mg ha⁻¹ of farmyard manure increased the soil SOC pool by 41.2–73.0 Mg ha⁻¹ [26]. Improved residue management, including retention of stubble and incorporation of root biomass, contributes to long-term soil carbon accumulation, although outcomes depend strongly on soil type, climate, and management intensity. These climate-smart agronomic interventions ensure sustainable productivity while contributing to greenhouse gas mitigation. Therefore, expanding research and policy support is necessary to scale up these practices across semi-arid and marginal landscapes.

6 Conclusion

Finger millet is a climate-smart and nutrient-dense cereal with substantial potential to support sustainable agriculture, food security and climate change mitigation. Its drought-adaptive physiological traits including extensive root systems and delayed leaf senescence support biomass production and carbon uptake under water-limited conditions, positioning the crop as a promising component of carbon farming systems. In addition, its high content of essential micronutrients strengthens its role in addressing nutritional insecurity in marginal environments. The advances in conventional breeding, genomics and high-throughput phenotyping have accelerated the development of stress-resilient and nutrient-dense finger millet genotypes but translating these genetic gains into quantifiable field-scale carbon sequestration remains a key challenge. When integrated with conservation agriculture, residue retention, intercropping and organic nutrient management, finger millet-based systems can enhance soil health, stabilize soil carbon pools and improve climate resilience. Furthermore, these findings support the inclusion of finger millet in national climate-smart agriculture frameworks, carbon farming initiatives and low-emission food system strategies targeting smallholder farmers in semi-arid regions. The promotion of finger millet-based systems directly contributes to the achievement of Sustainable Development Goal 2 (Zero Hunger) through improved food and nutritional security and Sustainable Development Goal 13 (Climate

Action) by enhancing on-farm carbon sequestration and climate resilience. Therefore, capacity building and the integration of indigenous knowledge are essential for translating research evidence into scalable and farmer-centered climate mitigation.

7 Way forward

Future research should prioritize the following:

- (i) The development of robust and standardized carbon accounting frameworks tailored to smallholder systems.
- (ii) Improved understanding of genotype $\times$ environment $\times$ management interactions influencing carbon allocation and nutrient density.
- (iii) Socio-economic and policy mechanisms enabling farmer participation in carbon-smart agriculture.
- (iv) The quantification of trade-offs between yield, nutritional quality and carbon sequestration.

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Data availability

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