P-ISSN: 2618-0723
E-ISSN: 2618-0731

NAAS Rating (2025): 5.04
www.extensionjournal.com

International Journal of Agriculture Extension and Social Development

Volume 8; Issue 9; September 2025; Page No. 480-483

Received: 16-06-2025
Accepted: 18-07-2025

Indexed Journal
Peer Reviewed Journal

The impact of biochar amendment on wheat (*Triticum aestivum*) productivity: A review

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DOI: https://www.doi.org/10.33545/26180723.2025.v8.i9g.2446

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Abstract

The global peer-reviewed data on the impact of biochar on wheat yield from 2000 to 2024 is summarized in this review. The combined results of meta-analyses and field research indicate an average yield increase of 10-15%, with the greatest benefits occurring in soils that are coarse-textured or fertile and under stress circumstances (such as salt or drought) when 5-15 t ha⁻¹ of biochar is added. Feedstock (crop residue or animal waste outperforms woody sources), moderate pyrolysis temperatures (400-550 °C), fertilizer co-application, and critical enhancements in soil physical, chemical, and biological factors all significantly influence yield benefits. After three years, long-term efficacy declines, and standardization, environmental hazards, and cost-benefit ratios need to be carefully considered. Agronomic recommendations, research needs, and the potential of biochar for sustainable wheat production in the face of climate change challenges are highlighted in the paper's conclusion.

Keywords: Biochar, wheat yield, meta-analysis

Introduction

Biochar's Role in Sustainable Wheat Production: Historical Context, Global Trends, and Objectives

Originating in the Amazonian Terra Preta, biochar is an ancient soil amendment that has recently attracted attention as a carbon sequestration and sustainable agriculture input (Wikipedia, 2025). Early research in the 2000s concentrated on soil conditioning, but throughout the last 20 years, attention has shifted to crop-specific results, especially for wheat, a staple crop that is essential to the world. Wheat yields increased by 13.5%, according to meta-analyses, including the 2021 study by Ma *et al.*, especially on acidic, coarse-textured soils. This demonstrated the agronomic potential of biochar in poor settings. After 2015, research funding and publications increased dramatically due to a range of climatic applications, especially in China, Pakistan, Canada, and Australia. Given the pressing problems facing wheat production, such as soil degradation, water scarcity, and nutrient losses, research into biochar-driven soil improvements (such as improved nutrient retention, water holding capacity, and soil structure) is highly pertinent. The primary goals of this review are to critically evaluate performance outcomes and trends.

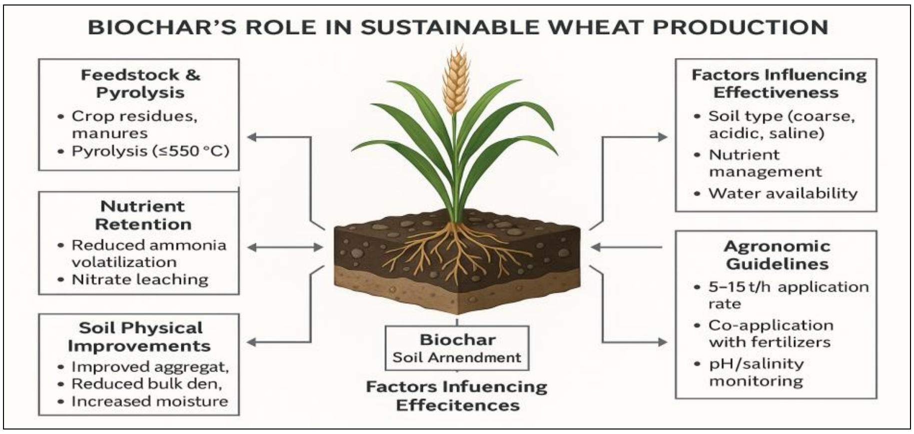

Fig 1: Image depicting biochar's role in sustainable wheat production

Quantitative Effects on Wheat Yield: Aggregated Field and Experimental Evidence

Studies conducted worldwide have shown that biochar increases wheat yield by 8-15%, with differences depending on the soil and environment. According to Ma *et al*. (2021) [11], there was a 13.5% increase in field conditions, especially in desert and subtropical agroecosystems. This pattern was supported by Xiao *et al*. (2017) [13], who discovered a 10% average yield increase across grains, with clay and acid showing the strongest responses. According to Zulfiqar *et al*. (2022) [3], drought stress pot experiments using 3-5% wheat-straw biochar showed a 13-16% increase in yield, which was backed by increased physiological resistance. In comparison to organic fertilizers, longer-term field trials in the Yellow River Delta (5-20 t ha^{-1} annually, over three years) demonstrated improvements in salinity and water status as well as yield increases of 10-14%. Co-applying biochar with NPK fertilizers resulted in 15-30% yield improvements in treatment integration studies conducted in Pakistan utilizing nutrient-rich treatments. All things considered, the statistics continuously show modest but significant yield gains, especially when combined with fertilizer and under stress.

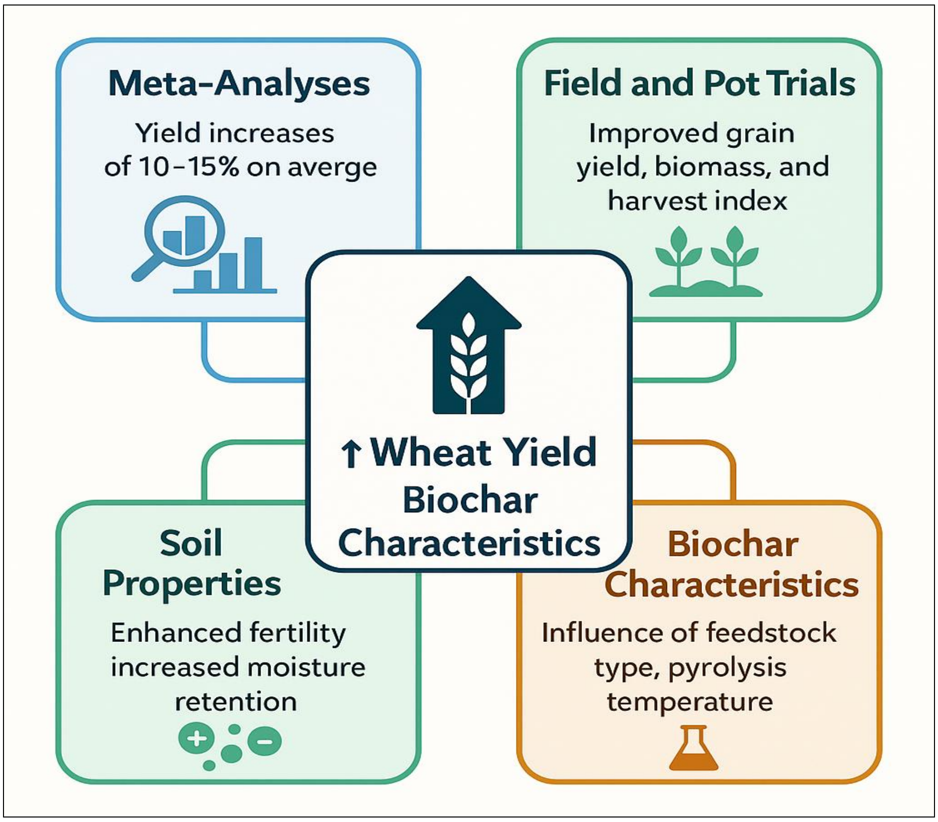

Fig 2: Quantitative effects of Biochar on wheat yield

Mechanisms Enhancing Wheat Yield: Soil-Plant-Microbe Pathways

The stimulatory effect of biochar on wheat stems from four interconnected pathways.

Biochars made from crop residues and manure offer a continuous release of N, P, and K while lowering nitrate leaching and ammonia volatilization. Grain and shoot N increases of 50-60% are demonstrated by meta-analyses and pot experiments, which directly contribute to the creation of yields (Ali *et al*., 2022) [1]. Biochar increases plant-available moisture, decreases bulk density, and improves soil aggregation-all of which are crucial in areas that are prone to drought (Hyvaluoma *et al*., 2018; Zulfiqar *et al*., 2022) [6, 3].

Biochar increased water content and decreased EC and sodium in the saline-alkaline Yellow River Delta soils, improving yield by 0.5 to 0.7 t ha^{-1} (Lashari *et al*., 2024) [8]. Research conducted on acidic soils confirms that biochar has an alkalizing impact that promotes nutrient availability. In order to promote plant stress resilience, biochar raises microbial biomass C/N ratios, enzyme activities (like dehydrogenase), and antioxidant enzyme responses (SOD, CAT) (Bilal Zulfiqar *et al*., 2022; Asai *et al*., 2011) [3, 2]. Under stressful environmental conditions, their contributions help to maintain yield stability. The properties of biochar and its agronomic results are influenced by the feedstock source, pyrolysis temperature, and application rate. Because of their higher nutrition and ash content, crop-residue and animal-waste biochars continuously function better than woody chars (Ma *et al*., 2021; Xiao *et al*., 2017) [11, 13]. According to research, pyrolysis between 400 and 550 °C offers the best balance between nutrient release and structural integrity; higher temperatures boost stability while lowering the amount of volatile nutrients (Li *et al*., 2019; Hyvaluoma *et al*., 2018) [9, 6]. In coarse, degraded soils, application doses of 5-15 t ha^{-1} optimize yield benefits; greater dosages are not cost-efficient because of diminishing returns (Xiao *et al*., 2017; Ma *et al*., 2021) [13, 11]. 15 t ha^{-1} provides the best salt mitigation in saline soils, whereas >20 t ha^{-1} adds minimal benefit (Lashari *et al*., 2024) [8].

Cooperation with Water-Saving Techniques and Fertilizers

The agronomic benefits of combining charcoal with fertilizers are substantial. In clay-loam soils, nutrient-rich biochars enhanced nitrogen uptake by 16-27% and enhanced wheat biological and grain yield by 26-29% when paired with chemical fertilizers (Improvements via PMB/FM pilot trials). In calcareous soils, co-applying wheat-straw biochar and NPK increased the concentration of nitrogen and grain protein (Ali *et al*., 2022) [1]. Furthermore, in semi-arid wheat systems, the combination of biochar with conservation-tillage and water-retentive polymers greatly increased yield and water-use efficiency (WUE) (Zulfiqar *et al*., 2022) [3]. These complementary approaches demonstrate how biochar can enhance water management and soil fertility systems.7. Agronomic Guidelines for Effective Biochar Use in Wheat Farming, When using biochar, farmers and agronomists should take into account important considerations. Choose crop-residue or manure feedstocks that have been pyrolyzed at ≤550°C and apply at moderate rates (5-15 t ha⁻¹) that are appropriate for the fertility and texture of the soil. Co-application of NPK fertilizers is necessary in coarse, acidic, or saline soils in order to maximize nutrient delivery and structural enhancement. Adaptive management is ensured by tracking soil pH (goal range 6.5-7.5), salinity, and nitrogen dynamics. To prevent impurities and guarantee consistent outcomes, quality standards (such as IBI) must be adhered to. Being aware of the risks is essential. Biochar works best on deteriorated or stressed soils, while compost may be more economical in fertile, temperate climates.

Environmental Considerations, Economic Feasibility, and Future Research Needs

Economic and environmental obstacles stand in the way of the broad application of biochar, despite its yield improvements. In low-value grain systems, production, transportation, and application can be prohibitively expensive unless localized pyrolysis units are practical. The carbon balances in life-cycle assessments (LCAs) vary based on logistics and scale, and they are constrained. Field experiments must take environmental concerns such heavy metal contamination, pH changes, and disturbance of the soil microbiome into consideration. The majority of positive yield responses decrease in later years, and there are crucially little long-term (>3 years) field data (Xiao *et al*., 2017) [13]. Standardized reporting on feedstock, pyrolysis, and soil-interaction parameters, multi-year, multi-site experiments, and integrated agronomic-economic-environmental assessments are all essential components of future study. Meaningful scale will require socioeconomic research and farmer uptake programs.

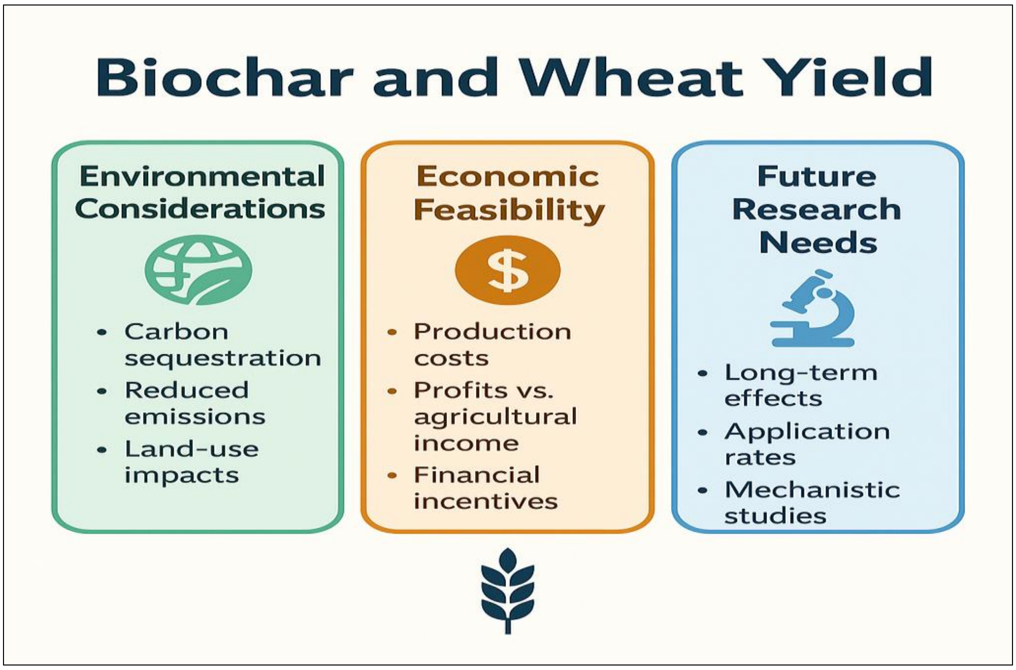

Fig 3: Changes in blood oxygenation and lactate concentration during a 4-hour period of exercise in four subjects

Conclusion

The idea that properly applied biochar increases wheat yield (8-20%) by improving soil fertility, water status, and stress resistance is supported by a substantial body of evidence from meta-analyses and field studies. Biochar must be made and used with evidence-based feedstocks, doses, and integration techniques in order to fully reap its benefits. Issues including cost, environmental effects, and long-term performance call for methodical research and policy backing. Biochar can only move from a specialized innovation to a widely used sustainable practice in wheat production with an integrated, standardized strategy.

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