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Effect of various management practices on growth and yield in black wheat (*Triticum aestivum* L.)

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Abstract
Enhancing black wheat (*Triticum aestivum* L.) productivity requires a holistic approach integrating high-quality seed selection, advanced seed treatments and balanced nutrient management. Vigorous seeds ensure optimal plant stands and resilience against abiotic and biotic stresses, while seedling vigor depends on biochemical and physiological attributes such as enzyme activity and reserve metabolites. Seed treatments with micronutrients, fungicides, insecticides and polymers improve germination and early growth without compromising emergence. Fungicides like fludioxonil, carbendazim and thiram effectively control seed-borne pathogens, whereas imidacloprid reduces pest damage during early development. Among innovative techniques, ozone seed treatment has emerged as an eco-friendly alternative that reduces microbial load without toxic residues, aligning with sustainable agricultural practices. Addressing seed dormancy through pre-germination treatments—such as soaking in cold or warm water—can substantially increase germination rates and establishment, particularly under suboptimal conditions. Furthermore, integrated nutrient management (INM), combining manures, fertilizers and biofertilizers enhances nutrient efficiency, soil fertility and yield sustainability. Nitrogen remains one of the most critical macronutrient, while phosphorus solubilizing bacteria, balanced potassium application and micronutrients like zinc, boron and sulphur significantly improve nutrient uptake, grain quality and stress tolerance. The inclusion of nano-fertilizers and organic amendments further promotes nutrient availability while reducing environmental impact. Overall, optimizing seed quality, dormancy management and nutrient integration represents a sustainable method to improve profitability, yield and resilience of black wheat cultivation, supporting both food security and agricultural sustainability in the context of a changing climate.

Keywords: anthocyanin, wheat, nutritional security, micronutrients, macronutrients

Introduction

Wheat (*Triticum aestivum* L.) stands as one of the most important cereal crop worldwide and constitutes as a principal food source for a substantial proportion of the global population (Sahu *et al*., 2020) [70]. It contributes approximately 40% of the total dietary energy and about 20% of the protein intake of the world's inhabitants (Kumar *et al*., 2015) [39]. During the 2023–24 cropping season, global wheat production was estimated at nearly 790 million metric tons, cultivated across nearly 216 million hectares, having an average productivity of 3.65 tons per hectare. In India, wheat production reached 114 million metric tons from 31.3 million hectares, corresponding to a mean yield of 3.64 tons per hectare (Ministry of agriculture and farmers Welfare, 2024) [53]. Throughout Haryana, production was recorded at 11.06 metric tons per million from an area of 2.5 million hectares, attaining a productivity level of 4.42 tons per hectare (CEIC, 2024) [7]. Wheat accounts for nearly 36% of India's total food grain output, underscoring a key role in maintaining both food and nutritional security at the national level. Across the world, the primary contributors to wheat production include China, India, the U.S., Russia, Canada and Mexico (Zahan *et al*., 2021) [96]. Black wheat has emerged as a nutritionally enriched cereal crop, attracting global attention due to its unique biochemical composition and potential health benefits (Dhua *et al*., 2021) [14]. Its dark pigmentation is primarily attributed to high concentrations of anthocyanins—flavonoid compounds with potent antioxidant activity—accompanied by elevated total phenolic content dominated by ferulic acid (Sharma *et al*., 2020; Dhua *et al*., 2021) [76, 14]. Beyond its enhanced antioxidant capacity, black wheat contains higher levels of dietary fiber, protein, vitamins, minerals, zinc and iron compared to conventional varieties, thereby classifying it as a double-biofortified crop (Sharma *et al*., 2018; Garg, 2021; Padhy *et al*., 2024) [77, 23, 60]. Anthocyanins additionally confer protection to amino acids and proteins against oxidative and thermal degradation, thereby enhancing biomolecular stability (Joshi *et al*., 2025) [33]. In India, the variety 'NABI MG' was developed at the National Agri-Food Biotechnology Institute (NABI), Mohali, through crossing Japanese germplasm (EC866732) with PBW621 (Kapoor and Thakur, 2022) [34], whereas in China, 'Black 76' was produced via hybridization of blue–purple and purple hexaploid wheat lines (Miraan Mallick and Sayan Sau, 2021) [49]. Regular wheat is widely cultivated and processed into various food products, with a well-established production system yielding 48.6 bushels per acre in the US in 2023 (US Department Anonymous, 2024) [87]. Similarly, black wheat is also versatile, used in nutritious breakfast porridge, fiber-rich chapati, healthy pasta and traditional sweets like halwa and laddoos (Ghosh *et al*., 2025) [26]. However, white wheat consumption is linked to intolerances such as celiac disease and allergies (Biswal *et al*., 2022) [5]. Efforts in conventional wheat focus on sustaining yield and quality, reducing agrochemical inputs and developing cultivars for diverse uses including biofuels and enhanced nutrition (Yadav *et al*., 2020; Biswal *et al*., 2022) [93, 5]. In contrast, black wheat, although richer in health promoting compounds and associated with benefits such as aiding heart disease, constipation, colon cancer, diabetes, intestinal infections, anemia, tissue regeneration, body development and cholesterol reduction (Gautam and Kumar, 2022) [24, 36], faces agronomic challenges and lacks comprehensive research on its long-term health impacts, limiting its large-scale adoption (Salim and Raza, 2020) [72]. Black wheat (*Triticum aestivum* L.) has recently gained prominence as a biofortified and nutritionally superior cereal due to its high anthocyanin, protein and micronutrient content. Despite its growing recognition as a functional food with potential health benefits, its large-scale cultivation remains limited because of several agronomic, physiological and management-related constraints. The lack of comprehensive information on optimized production practices—particularly concerning seed quality, seed treatments, dormancy management and integrated nutrient management—has hindered its wider adoption and productivity improvement. Previous studies have largely focused on the biochemical composition and nutritional advantages of black wheat, with limited emphasis on the holistic integration of agronomic and physiological management strategies required to enhance yield and sustainability. Moreover, there is a growing need to align black wheat production practices with eco-friendly and resource-efficient approaches, such as ozone seed treatment, biofertilizers and nano-fertilizers, in response to global calls for sustainable agriculture and reduced chemical dependency. Therefore, this review is needed to compile, analyse and synthesize current research findings related to seed vigour, treatment technologies, dormancy management and integrated nutrient management practices in black wheat. It aims to provide a scientific basis for developing sustainable production protocols that enhance productivity, profitability and nutritional quality while supporting food and nutritional security under changing climatic conditions.

Effects of Different Management Strategies on Growth and Yield in Wheat

Effects of Seed Treatment

Cereal yield losses often result from poor seed germination due to environmental factors and dormancy (Omokhua *et al*., 2015) [59]. Pre-germination treatments like soaking seeds in cold or hot water improved germination rates to 84% and 78.5%, respectively, compared to 30% in untreated seeds (Cheboi *et al*., 2019) [9]. High-quality, vigorous seeds are essential for achieving optimal plant populations and producing seedlings capable of overcoming early biotic and abiotic stresses) (Jacob *et al*., 2016) [31] Seedling dry matter, a key indicator of physiological vigor, depends on growth regulators, reserve metabolites, and enzyme activities (Geetha and Bhaskharan, 2020) [25]. Seed treatments using micronutrients, polymers, fungicides, insecticides, or their combinations generally do not reduce emergence and may improve seedling stands, although they do not always influence wheat grain yield (Freiberg *et al*., 2017) [21]. Managing seed-borne diseases is critical for maintaining seed quality and achieving high yields (Hozzein *et al*., 2019) [29]. Fungal diseases cause 15–50% of crop losses (Różewicz *et al*., 2021) [68] and increasing fungicide resistance underscores the need for sustainable alternatives such as innovative seed treatments (Fisher *et al*., 2018) [19]. Pre-sowing seed treatments enhance resistance, increase grain yield and improve plant density particularly under dry conditions (Sekmen Cetinel *et al*., 2021) [74]. Fungicides like fludioxonil, carbendazim and thiram provide protection for seeds from fungal diseases and support improved germination while insecticides like imidacloprid help lower pest activity during early seedling growth (Zhou *et al*., 2019; Oliveira *et al*., 2021; Penido *et al*., 2021; Li *et al*., 2022; Dimant *et al*., 2023) [99, 58, 63, 42, 5]. The combined use of fungicides further enhances seedling survival and helps maintain yield stability under suboptimal conditions (Santos *et al*., 2023) [73]. Chemical seed applications have been found to boost both fertility and productivity in crops as demonstrated by the System for Wheat Intensification which integrates optimal seed treatments with seed rate adjustments and advanced planting methods (Mengesha *et al*., 2022; Singh *et al*., 2024) [52, 79]. Among the newly developing sustainable technologies, ozone seed treatment offers promising benefits. It effectively reduces microorganisms such as bacteria, fungi and viruses without causing injury to seeds or plants, as it quickly breaks down into non-toxic oxygen and ensures that no detrimental residues persist (Guo and Wang 2017; Çetinkaya *et al*., 2022) [27, 8]. Additionally, ozone promotes seed germination and acts as an environmentally friendly, cost-effective "green" technology that reduces chemical pesticide use and environmental pollution (Pandiselvam *et al*., 2019; Sivaranjani *et al*., 2021) [61, 84]. This approach aligns with EU agricultural policies aimed at reducing chemical inputs and supporting sustainable practices.

Effect of Integrated Nutrient Management

Integrated nutrient management, combining manures with chemical fertilizers, is essential for healthy wheat production and agricultural sustainability (Sachan *et al*., 2017) [69]. This is especially relevant in rice-wheat systems, a dominant cropping pattern in India and south eastern Rajasthan (Sharma *et al*., 2019) [78]. The integrated application of FYM and NPK enhances nutrient availability, photosynthesis and growth (Borse *et al*., 2019; Kumar and Pareek, 2022) [6, 40], while foliar spraying of the water-soluble NPK formulation (19:19:19) improves dry matter, plant height and yield components by promoting rapid nutrient uptake and leaf expansion (Nitharwal *et al*., 2022) [56]. RDF with FYM increases grain, straw and biological yields by improving soil nutrient retention and moisture availability (Borse *et al*., 2019; Sharma *et al*., 2021) [6, 75]. Wheat after rice responds well to increased NPK rates, with 125–150% RDF and

FYM providing the best yields and economic returns; foliar NPK sprays enhance these effects (Dhaker *et al*., 2022; Singh *et al*., 2024) [13, 81]. Incorporating biofertilizers like *Azotobacter* with FYM and chemical fertilizers improves nutrient use efficiency, soil health and yield sustainability (Tiwari *et al*., 2023) [86].

Effect of Nitrogen (N)

Nitrogen (N) is a fundamental nutrient in crop production and is crucial for supporting the food requirements of the world's increasing population (Maaz *et al*., 2021) [48]. Approximately 70 percent of the applied nitrogen accumulates in the kernels, while the remaining 30% is distributed to the culms (Panhwar *et al*., 2019) [62]. The response to nitrogen fertilization is affected by multiple soil characteristics, such as texture, pH, organic matter content, and both available and total soil nitrogen (Keikha *et al*., 2023) [35]. Climatic factors like temperature, rainfall, and climatic zone also critically affect crop response to nitrogen $_0$fertilization (Liu *et al*., 2019 Wang *et al* 2023) [44, 89]. Furthermore, agronomic practices, including water management, soil tillage, and the type, timing and rate of nitrogen application— $_9$ significantly impact nitrogen use efficiency and crop performance (Hu *et al*., 2023; Wang *et al*., 2023b) [30, 91]. Given the challenges of a growing global population and limited water resources, wheat production faces the dual pressures of improving grain yield and quality while enhancing $_9$ water productivity (Wang *et al*., 2018c; Wang *et al*., 2022; Yao *et al*., 2023) [92, 90, 94]. In this context, nitrogen addition remains a crucial management strategy to increase wheat production, water use efficiency, and grain protein levels (Maaz *et al*., 2021; Mayor *et al*., 2023) [48, 51].

Effect of Phosphorous (P)

Phosphorus (P) is an essential nutrient but often limits crop productivity due to soil deficiency (Luo *et al*., 2017; Johnston and Poulton, 2019) [47, 32]. In semiarid maize systems, prolonged no-till farming increases soil organic matter and soluble P, reducing fixation (Anil *et al*., 2022) [3]. Conservation-based agriculture using residue retention and field-specific nutrient management improves available P, nutrient uptake efficiency and profitability while lowering environmental impact (Haokip *et al*., 2020; Rawal *et al*., 2022) [28, 65]. However, reduced tillage may reduce residue retention and labile P availability (Margenot *et al*., 2017) [50]. Though nitrogen and potassium are well studied, Management of phosphorus in conservation agriculture wheat systems remains underexplored (Kumawat *et al*., 2018) [41]. Phosphorus-solubilizing bacteria and banded fertilizer application enhance availability and plant uptake of phosphorus (Bijarniya *et al*., 2020; Salim *et al*., 2023) [4, 71]. Biofertilizers mobilize soil-bound P, promoting nutrient cycling and reducing fertilizer needs (Yuan *et al*., 2016; Nunes *et al*., 2022) [95, 57]. However, P recovery efficiency declines at high application rates (Kumar *et al*., 2022; Kumar *et al*., 2023b) [40, 38]. Integrating microbiota-based P management with no-till practices and residue retention provides a sustainable approach to improve wheat yield in semi-arid regions (Kumar *et al*., 2023 A) [37]. This improved cycling of nutrients facilitates better phosphorus absorption by plants, notably when chemical fertilizer is applied in reduced amounts (Luo *et al*., 2017; Ven *et al*., 2019) [47, 88].

Effects of Potassium (K)

Potassium plays a vital role in wheat growth and quality, enhancing water use efficiency, photosynthesis and disease resistance. After harvest, about 75% of potassium in straw is recycled back into the soil (Panhwar *et al*., 2019) [62]. It is a key enzyme activator as it regulates various processes, promotes the translocation of assimilates within plants, maintains ionic equilibrium, contributes to carbohydrate and protein synthesis and cellular development (Erel *et al*., 2015) [16]. Nevertheless, the practice of unbalanced fertilizer application has become prevalent in many developing regions, resulting in nutrient imbalances, diminished crop yields and decline in soil quality (Singh *et al*., 2021) [80]. Potassium (K) fertilization contributes to nitrogen metabolism regulation by stimulating the enzymes involved in nitrogen assimilation, which in turn enhances nitrogen absorption and utilization efficiency in plants (Zahoor *et al*., 2017) [97]. Applying 100 kg K_2O/ha boosts nitrogen, phosphorus and potassium absorption in grain and straw, improving overall growth and yield (Singh *et al*., 2025) [82].

Effect of Micronutrients

Secondary macronutrients calcium, magnesium, and sulphur though needed in smaller amounts, are vital for wheat growth, contributing to protein synthesis, cell structure and chlorophyll formation. Similarly, micronutrients such as manganese, boron, iron and zinc are crucial for optimal crop development; deficiencies or imbalances impair growth and yield (Panhwar *et al*., 2019) [62]. Low micronutrient levels in wheat grains, especially in regions like China, limit their role in human nutrition, contributing to micronutrient deficiencies in populations (Rehman *et al*., 2020; Chu *et al*., 2022) [66, 11]. Organic fertilizer substitution (OFS) enhances soil fertility and crop yields by promoting nutrient availability and organic matter. It can increase micronutrient content in wheat; for example, 25–50% substitution raised grain zinc by up to 67% compared to chemical fertilizers (Zhang *et al*., 2021) [98]. However, some studies report negligible effects of organic fertilizer substitution on micronutrient content and excessive use may reduce yields due to slow nutrient release, causing nutrient deficiencies at crucial developmental stages (Adekiya *et al*., 2020; Lu *et al*., 2022; Liu *et al*., 2023; Mohant *et al*., 2024) [1, 46, 45,]. The bioavailability of soil micronutrients is a critical indicator of agro-ecosystem health and predicts wheat grain nutrient density and human nutritional security more accurately than total micronutrient content alone (Liu *et al*., 2017; Chu *et al*., 2024) [43, 10] as Micronutrients present in organic fertilizers also influence the micronutrient composition of crops (Provolo *et al*., 2018) [64]. Boron enhances wheat growth significantly; application at 0.3kg/ha and foliar spray at 60 days after sowing increased plant height, leaf area, grain number, spike length and grain yield by up to 35% (Farhan *et al*., 2021) [18]. Higher rates (2 kg/ha) improve harvest index and physiological efficiency (Galindo *et al*., 2018) [22]. Zinc is crucial for enzyme function, nitrogen metabolism and redox reactions, with deficiency common in cereals (Singh *et al*., 2017) [83]. Nano-fertilizers like ZnCNP have improved grain zinc content and fertilizer efficiency (Dapkekar *et al*., 2018) [12]. Combining Zn and S with recommended fertilizers boosts plant growth by enhancing nutrient uptake and cell division, while foliar sprays help mitigate soil nutrient limitations (Reena *et al*., 2018; Tiwari *et al*., 2021) [85]. Manganese seed priming increase grain yield in certain cultivars, though foliar Mn application may reduce yield in others (Ullah *et al*., 2017) [2]. Soil Mn supplementation alongside organic manures and phosphate fertilizers enhances Mn availability and uptake (Narender *et al*., 2018) [55].

Conclusion

These various management practices significantly influence wheat growth and yield, with seed treatment and integrated nutrient management being particularly crucial. Seed treatments improve seedling vigour and disease resistance, enhancing early crop establishment and yield stability, while sustainable options like ozone treatment offer environmentally friendly alternatives. Integrated nutrient management, combining organic and chemical fertilizers along with bio-fertilizers, optimizes nutrient availability, improves soil health and boosts wheat 4productivity. Balanced application of micronutrients (Zn, B, Mn) and macronutrients (N, P, K) is necessary for enhancing crop yield grain quality. These practices, when tailored effectively, can substantially improve black wheat cultivation, addressing both agronomic challenges and nutritional goals. Continued research on these integrated approaches is vital for advancing sustainable black wheat production systems.

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