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Vikas
Maharishi Markandeshwar (Deemed to be University), Mullana-Ambala, Haryana, India

Ishwar Singh
Maharishi Markandeshwar (Deemed to be University), Mullana-Ambala, Haryana, India

Sanjeev Kumar
Maharishi Markandeshwar (Deemed to be University), Mullana-Ambala, Haryana, India

Kunjan
Maharishi Markandeshwar (Deemed to be University), Mullana-Ambala, Haryana, India

Corresponding Author:
Vikas
Maharishi Markandeshwar (Deemed to be University), Mullana-Ambala, Haryana, India

Influence of sustainable crop production, vermicompost, and *Azotobacter* in wheat (*Triticum aestivum* L.)

Vikas, Ishwar Singh, Sanjeev Kumar and Kunjan

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Abstract
Wheat (*Triticum aestivum* L.), one of the world's most significant staple food crops, is frequently referred to as the "King of Cereals." It covers around 214.79 million hectares and produces nearly 735.17 million tonnes each year, serving as an important source of carbohydrates, proteins, minerals, and vitamins. However, modern wheat farming faces challenges such as unsustainable crop management, overdependence on chemical fertilisers, and environmental degradation. Traditional practices have led to reduced soil fertility, poor nutrient uptake, and stagnant yields. The potential of Natural farming and the application is biofertilizers are investigated in this study, particularly *Azotobacter* and vermicompost, as sustainable alternatives to minimise reliance on chemical-intensive cultivation. Organic agriculture supports ecological balance and soil rejuvenation by enhancing nutrient cycling, encouraging biodiversity, and reducing environmental harm. *Azotobacter*, a free-living nitrogen-fixing bacterium, promotes seed germination, plant height, tiller production, and grain yield. When combined with vermicompost or farmyard manure, *Azotobacter* further enhances physiological functions, nutrient absorption, and overall productivity. Vermicompost, farmyard manure, and biofertilizers are exemplification of organic inputs can greatly improve plant growth, nutrient cycling, and soil health. Vermicompost enhances soil texture, promotes water retention, boosts microbial activity, and enriches the soil with macro and micronutrients. An integrated nutrient management system that includes recommended fertiliser levels, *Azotobacter* inoculation, and vermicompost application has shown significant improvement in wheat yield, grain quality, and soil fertility. Both *Azotobacter* and vermicompost significantly enhance root colonisation and nutrient uptake, resulting in better yield and protein content. The study emphasises the significance of using sustainable techniques to boost the long-term productivity and ecological resilience of wheat-growing systems. Research confirms that integrated organic management achieves results similar to or better than conventional methods while safeguarding environmental and economic sustainability. Promoting the use of biofertilizers and organic manures offers a practical solution for building resilient wheat production systems that ensure food security and environmental well-being.

Keywords: Wheat, organic farming, vermicompost, *Azotobacter*, yields

Introduction
Wheat (*Triticum aestivum* L.), which originated in Southwest Asia, is recognized as among the major food crops and is often called the “King of Cereals” (Parewa *et al*., 2019) [57]. As the most important cereal crop globally, wheat is a principal source of carbohydrates and also provides significant amounts of protein, minerals, and vitamins. Wheat is the main cereal consumed worldwide (Kizilgeci *et al*., 2021) [37], and its cultivation occurs in nearly every part of the world. Global wheat production was predicted to be close to 790 million metric tonnes for the 2023-2024 cropping season, grown on about 216 million hectares with an average productivity of 3.65 tonnes per hectare (FAO, 2024). India produced 114 million metric tonnes of wheat on 31.3 million hectares, or 3.64 tonnes per hectare on average (Ministry of Agriculture and Farmers Welfare, 2024) [46]. With a productivity level of 4.42 tonnes per hectare, production in Haryana was measured at 11.06 metric tonnes per million from an area of 2.5 million hectares (Anonymous 2024) [7] With roughly 12% protein, 1.72% fat, 69.60% carbs, and 27.20% minerals, wheat grains are nutritious (BARI.,2016). Recent research has largely examined the movement of heavy metals within the wheat grain system (Ahmad *et al*., 2019; Sharma *et al*., 2018) [2, 69], but less attention has been given to how these metals migrate in various parts of the

crop. The fat content in wheat grains is measured using the Soxhlet extraction technique (GB5009.6-2016). Inefficient crop management, improper fertilizer use, poor nutrient extraction, and water shortages directly impact wheat yields (Zhang *et al.*, 2017) [82]. India ranks seventh in terms of organic arable land and is the world's top producer of organic products. Since 2016, the state of Sikkim in India has been fully certified for organic production (Aulakh and Ravisankar, 2017) [12].

Sustainable Crop Production and Organic Farming's Role

After the Brundtland Report (1987) defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs," the concept of sustainable agriculture gained traction. Thirty distinct sustainable farming methods in India were discovered by (Gupta *et al.*,2021) [30]. According to APEDA 2020-21, India ranked first in terms of organic producers and ninth in terms of organic agricultural land in 2020 (Willer & Sahota, 2020) [77]. The overall certified organic producing area under NPOP was 4,339,184.93 hectares as of March 31, 2021. Organic farming production strategy that maintains the health of soils, ecosystems, and people, according to the International Federation of Organic Agriculture Movements (IFOAM). Soil regions around the globe can significantly help mitigate future climate change effects on maintaining soil health and advancing sustainable farming (Oroian *et al.*, 2017; Broberg *et al.*, 2017) [55, 18]. A declining response to agricultural inputs has become a primary challenge for the sustainability of wheat-based systems (Desai *et al.*, 2015) [22]. Organic farming provides lasting environmental and societal benefits as a sustainable management system (Basavalingaiah *et al.*, 2022) [15]. Ongoing cropping without adequate restorative measures can jeopardize agricultural sustainability (Gopinath *et al.*, 2022; Rajanna *et al.*, 2022) [29, 62]. Adding FYM (Farm Yard Manure) and nitrogen fertilizers increases a crop’s biological yield and harvest index (Singh *et al.*, 2018; Arif *et al.*, 2016) [72, 9]. According to IFOAM (2015) [33] and Lampkin, organic farming is an agricultural approach that prioritises social, environmental, and economic sustainability, animal welfare, minimising reliance on external inputs, optimising the use of local, renewable resources, managing agroecosystems, and making up for internalised external costs. Limiting the use of fertilisers, herbicides, insecticides, and other external inputs is a key component of organic agriculture (WHO, 2015). Cow urine is used in organic farming to prepare growth enhancers and bio-pesticides, improving soil fertility and managing various pests and diseases. The biochemical composition of plants increases with cow urine application (Pradhan *et al.*, 2018) [60]. The individual and combined use of organic manures has raised bread wheat productivity (Ali *et al.*, 2020) [6]. Sustainable agriculture avoids using chemicals, synthetic substances, pesticides, and growth hormones to produce food of high nutritional value and adequate quantity (Onkar *et al.*, 2019) [54]. Organic amendments such as compost, vermicompost, poultry manure, and farmyard manure are effective at mobilizing nutrients and enhancing crop productivity. Organic matter supports a vast population of beneficial soil organisms essential for plant health (Kumar *et al.*, 2015) [38]. The principles of health, ecology, fairness, and care are fundamental to the development and growth of organic agriculture. Organic farming methods stem from traditional techniques refined over thousands of years in villages and farming communities (Singh *et al.*, 2019) [73]. Despite many governmental efforts to encourage organic farming, only about 2% of India’s net sown area is under organic cultivation. In India, there are about two million certified organic farmers, but many uncertified growers lack documentation. (Gupta *et al.*, 2021) [30]. Additionally, the organic produce market is now expanding rapidly both in India and globally. Organic agriculture holistically promotes consumer health, improves ecological well-being, and contributes to economic growth by generating income. According to Willer and Lernoud (2019) [78], India is presently the world's top producer of organic products. In light of this, promoting organic farming in India has the potential to build a future that is economically, ecologically, and nutritionally sound. Press mud application has also been shown to increase yields in crops like wheat (Sheoran *et al.*, 2017; Chattha *et al.*, 2019) [71, 19] and sugarcane (Nawaz *et al.*, 2017) [48]. A healthy environment, economic viability, and social and economic fairness are the main goals of sustainable agriculture. Vermiwash implementation is a useful strategy for achieving these goals and maintaining agricultural systems (Nayak *et al.*, 2019) [49]. There are significant benefits to using organic manure and biofertilizers in terms of dry matter production, grain yield, and grain nutrient content. (Broberg, 2017; Arshad *et al.*, 2018) [18, 10]. Traditional soil management methods reduce both organic matter and biological activity, disrupting vital ecosystem functions (de Jesus Souza *et al.*, 2019). Manure application improves the soil's physical characteristics, boosts nutrient uptake (Li and Marschner, 2019) [43], and boosts crop productivity by promoting sustainability (AlAmin *et al.*, 2017) [5]. Biofertilizers offer diverse benefits in sustainable agriculture (Barman *et al.*, 2017) [14]. These products have been shown to improve plant yield and growth by 10% to 40% (Batista *et al.*, 2018) [16].

***Azotobacter*'s Impact on Wheat Yield and Growth Factors**

Azotobacter has a positive effect on crop growth rate (CGR) and enhances seed germination. Essam and associates (2016). The free-living *Azotobacter* and *Azospirillum* genera fix atmospheric nitrogen in cereal crops without the need for symbiosis. Vitamins like riboflavin and thiamine can be produced by *Azotobacter* (Revillas *et al.*,2021) [65]. *Azotobacter* chroococcum inoculation significantly increased plant growth in comparison to the control, according to another study (Perdomo *et al.*, 2021). In crop production, *Azotobacter* chroococcum has demonstrated its significance in enhancing soil fertility and plant nutrition (Kurrey *et al.*, 2018) [41]. *Azotobacter* actively colonised the roots of wheat crops, offering the plants good protection. (Akram *et al.*, 2016) [4]. Vermiwash contains nitrogen-fixing bacteria such as *Azotobacter*, *Agrobacterium,* Rhizobium, and some PSB, according to a microbiological investigation (Kauri *et al.*, 2015) [36]. According to Verma *et al.*,2014) [76], the maximum grain yield of wheat was obtained by applying the recommended quantity of fertilisers + vermicompost @ 5.0 t ha^{-1} + *Azotobacter* and PSB as seed treatment. This was followed by RDF + vermicompost @ 5.0 t ha^{-1} + *Azotobacter* & PSB as seed treatment. Similar findings were obtained by (Raki *et al.*, 2019) [63], (Ahmad *et al.*,2022) [3], and (Gedefa *et al.*,2022) [27]. Fertilization is one of the key driving forces in agriculture and plays an important role in crop grain yield formation (Mon *et al.*,2016-Gai *et al.*,2019) [47, 26], and farmers in general apply a high dose of chemical fertilizers during wheat production to harvest high grain yields (Niu *et al.*,2013; Ashraf *et al.*, 2019) [51, 11]. Plant height, number of tillers/plants, number of spikes/plants, spike length, number of grains/spikes, grain yield (kg/ha), and straw yield (kg/ha) were all significantly higher in plants inoculated with seed treatment, particularly PSB in liquid form, according to the effects of *Azotobacter* inoculation (Me Carty *et al*., 2017). Seed yield (1687 kg ha^{-1}), oil content (41.5%), and oil production (703.5 kg ha^{-1}) all showed noticeably higher values following *Azotobacter* seed inoculation (Kumar *et al*., 2023) [39]. When coupled with farmyard waste and inorganic fertiliser (NPK), *Azotobacter* can be utilised as a biofertilizer to increase production (Mahato *et al*., 2018) [44]. The findings showed that *Azotobacter* seed inoculation considerably improved plant height and yield characteristics compared to no inoculation. With *Azotobacter* inoculation, wheat grain and straw yields rose from 4.89 to 5.14 t ha^{-1} and from 6.88 to 7.23 t ha^{-1}, respectively. *Azotobacter* inoculation also produced similar findings for grain protein content (12.95 to 13.22%) and protein yield (632.7 to 678.0 kg ha^{-1}). The uptake of phosphorus by wheat grain and straw was unaffected by *Azotobacter* (Jaga *et al*., 2017) [34]. Grain yield, straw yield, test weight, number of grains per ear, and number of spikelets per ear were all strongly impacted by *Azotobacter* and Mycorrhiza (Darjee *et al*., 2024) [20]. When *Azotobacter* was used, the grain yield rose (Nongthombam *et al*., 2021) [52]. Plant height was considerably boosted by *Azotobacter* seed inoculation. In contrast to the mean values of 28.21 cm, 74.51 cm, and 80.94 cm $plant^{-1}$ in inoculation at 40 DAS, 80 DAS, and harvest stage, *Azotobacter* displayed the highest values of 30.42 cm, 76.45 cm, and 82.63 cm $plant^{-1}$ (Yadav *et al*., 2023) [80].

Vermicompost's Impact on Wheat Yield and Growth Factors

The experiment's findings demonstrated that applying 50% RDF + 50% N through vermicompost increased the yield of grain and straw. Treatment T_6 (50% RDF + 50% N through vermicompost) had the highest plant height, number of grains/spikes, test weight, and protein content. According to the results, treatment T_7 (75% RDF + 25% N through vermicompost) had the highest harvest index (42.97%) (Ahmad *et al*.,2022) [3]. The combined EM (5377 kg ha ^{1} or 2176 kg acre 1) and vermicompost (5324 kg ha ^{1} or 2155 kg acre $^{-1}$) produced more grain (Bezabeh *et al*., 2022) [17]. The maximum mean grain (4587.2 kg/ha) and straw yield (6648.5 kg/ha) were reported under 50% VC at sowing + 50% VC at tillering (V3), which was comparable to V4 and much greater than the control and basal treatment (V2). (Aechra and others, 2022) [1]. In comparison to other integrated treatments, *Azotobacter* and vermicompost @ 5 t ha^{-1} (T_5) produced noticeably better tillers per m^2 (490.29), productive tillers per m^2 (271.24), spike length (9.67), grain per spike (45.79), grain weight per spike (2.45), and test weight (43.93). T_4 (RDF + *Azotobacter* + Vermicompost @ 4.0 t ha^{-1}). Vermicompost has phytohormones, micronutrients, macronutrients, and microorganisms that are vital to plant growth. (Kumar *et al*. 2017) [40]. Earthworm rearing is growing in importance on a global scale as a means of turning organic waste into beneficial nutrients (Hussain *et al*. 2018) [32]. Field crops can benefit greatly from the use of vermicompost (Nurhidayati *et al*.,2018) [53]. Vermicompost can improve the characteristics of the soil, increasing crop growth and yield (Pezeshkpour *et al*., 2014) [59]. As compared to conventional compost. Vermicompost is the microbial composting of organic wastes through earthworms' activity to form organic fertilizer, which contains a higher level of organic matter, organic carbon, total and available N, P, K, and micronutrients, microbial and enzyme activities (Pandey *et al*.,2017 and Verma *et al*.,2017) [56, 75]. Increments in growth values might be owing to the increased availability of all essential nutrients due to application of organic manures such as farmyard manure, vermicompost along with three sprays of vermiwash (Ranva *et al*.2022) [64] This enhances the rhizosphere surrounding the root system's ability to hold water and increases the availability of macro and micro components, both of which promote plant growth (Radwan *et al*., 2021) [61]. Additionally noted that phosphorus-solubilizing bacteria and vermicompost at a rate of 5 tonnes ha^{-1} improved wheat yield and yield characteristics (Kumar *et al*. 2017) [40]. Vermicompost application has a positive impact on soil enzyme activity, microbial population, and pH (Yasmin *et al*., 2021) [81]. Vermiwash is becoming a significant potential tool (Nayak and Yadav, 2019) [49]. It is a valuable source of plant nutrients in organic agriculture since it is high in dissolved nutrients and amino acids (Dongare and Gawas, 2021) [23]. In the field, vermicomposting has demonstrated enormous effects on crop development. Additionally, the pathogenic content of the vermireactor feed is decreased during the vermicomposting process (Huang *et al*., 2020) [31]. An alternate approach to plant growth is to use vermicompost and vermiwash. By employing vermiwash and vermicompost in a medium composed of paddy husks and white sand, plants can be grown hydroponically without the need for soil to provide nutrients. This reduces the amount of space needed to grow crops (Jaikishun *et al*. 2018) [35]. Vermiwash is used as both a liquid spray and a liquid biofertilizer (Shafique *et al*., 2021) [68]. Vermicompost application enhances soil aeration, water retention, and plant nutrient availability (Gill *et al*. 2019) [28]. Application of vermicompost considerably decreases bulk density and particle density and enhances the water-holding capacity due to increased soil aggregation (Sheikh and Dwivedi 2018) [70]. Vermicompost's positive impact on nutrient availability was the reason for the increase in grain and straw yield following its treatment (Patidar *et al*. 2019) [58].

Conclusion

Wheat (*Triticum aestivum* L.) remains a critical global staple crop, appreciated for its great nutritional value and environmental tolerance. Challenges such as imbalanced fertilization, inefficient crop management, and environmental constraints continue to affect wheat productivity. Organic farming, supported by applying farmyard manure, vermicompost, and biofertilizers like *Azotobacter*, provides a sustainable substitute that improves crop output, soil health, and nutrient availability. These eco-friendly inputs not only enhance soil fertility and structure but also improve plant growth parameters, yield attributes, and grain quality. *Azotobacter* contributes significantly by improving nitrogen fixation, while vermicompost improves soil structure, increases beneficial microbial activity, and enriches the soil with vital nutrients. It also promotes seed germination and enhances plant development metrics. The integrated use of organic amendments alongside conventional fertilizers results in improved wheat growth, yield, and quality, supporting both environmental and economic sustainability. To promote ecological sustainability and food security, there is a pressing need to adopt integrated organic farming approaches, backed by farmer training, policy support, and increased market accessibility. Encouraging such practices can help build a nutritionally secure, environmentally sound, and economically viable agricultural future.

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