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EXPLORING THE INFLUENCE OF NANOPARTICLES AND PGPRS ON THE PHYSICO-CHEMICAL CHARACTERISTICS OF WHEAT PLANTS: A REVIEW

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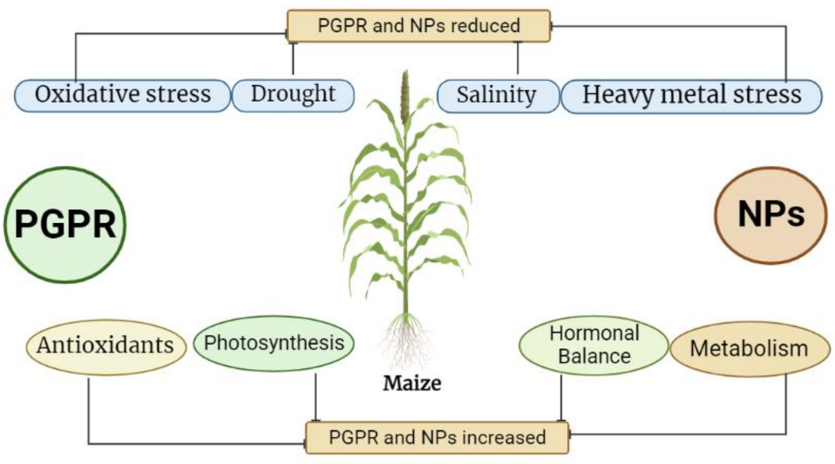
Abstract:
This review explores how plant growth-promoting rhizobacteria (PGPRs) and nanoparticles can improve the physicochemical traits of wheat plants and boost crop yields. Wheat is essential for the world's food supply, but its growth is impacted by factors such as soil quality and climate. The potential for enhancing crop productivity and soil quality with PGPRs is promising. They improve wheat plant photosynthesis, soil fertility, nutrient availability, and antioxidant activity. When nanoparticles and PGPRs are used together, physicochemical characteristics are improved due to their synergistic effects. These environmentally friendly techniques have the potential to encourage the sustainable production of wheat, reduce dependence on synthetic fertilizers and pesticides, and increase soil fertility. However, it is critical to address any possible health and environmental risks associated with their use. Overall, PGPRs and nanoparticles are viable options for increasing wheat crop production and sustainability.

Keywords: *Wheat, Nanoparticles, Plant growth-promoting rhizobacteria (PGPRs), Physico-chemical properties, Soil quality, Crop productivity, Sustainable agriculture, Food security*



Graphical Abstract.

INTRODUCTION

Among the most prominent cereal crops in the world, wheat is an essential source of food for both people and animals (Shewry & Hey, 2015). With a growing global population, the demand for wheat continues to increase, making it essential to enhance the productivity and sustainability of wheat cultivation. Wheat is cultivated in different agroecological zones, and its growth is affected by a number of factors, such as soil quality, weather, pests, and diseases (Liliane & Charles, 2020). However, one of the critical factors affecting wheat growth and productivity is the physicochemical properties of the soil, including nutrient availability, water-holding capacity, and soil fertility. Therefore, improving the physicochemical properties of the soil is crucial for enhancing wheat crop yields and ensuring food security (Rao et al., 2017). In recent years, nanotechnology and plant growth-promoting rhizobacteria (PGPRs) have emerged as promising tools for improving soil quality and enhancing crop productivity (Malik et al., 2022). In this review, we provide an overview of the impact of nanoparticles and PGPRs on the physicochemical properties of wheat plants, highlighting their potential as sustainable and eco-friendly approaches for enhancing wheat crop yields.

The physicochemical properties of the soil are crucial determinants of wheat plant health and crop yield. Wheat plants' growth and development are influenced by a variety of soil characteristics, including water-holding capacity, pH, texture, structure, and nutrient availability (Ampong et al., 2022). For instance, low soil pH can limit the accessibility of essential nutrients such as potassium, nitrogen, and phosphorus, leading to stunted growth and reduced yield (Kumar et al., 2019). Soil water-holding capacity, on the other hand, is important for plant growth and survival, as it affects the availability of water to the plant roots. In addition, soil texture and structure influence the root development and nutrient uptake efficiency of wheat plants (Abobatta, 2018; Ampong et al., 2022). Therefore, understanding and managing soil physicochemical properties are critical for maximizing wheat crop yield and ensuring food security (Babur et al., 2021). In recent years, there has been growing interest in the use of nanoparticles and plant growth-promoting rhizobacteria (PGPRs) to enhance soil physicochemical properties and wheat plant health. By lowering the need for chemical pesticides and fertilizers and increasing soil fertility and crop yield, the use of these innovative techniques may help advance sustainable wheat production. We provide a summary of how PGPRs and nanoparticles affect the physicochemical characteristics of wheat plants in this paper and talk about how they could increase the quantity and quality of wheat crops.

Growing interest in plant growth-promoting rhizobacteria (PGPRs) and nanoparticles has been sparked by the possibility that they might boost wheat plant growth and yield (Jahangir et al., 2020). Due to their small size and unique physical and chemical features, nanoparticles have been found to enhance soil fertility, improve nutrient availability, and enhance wheat plant photosynthesis and antioxidant activity (Fincheira et al., 2021). Similarly, PGPRs have been shown to promote various processes, including nitrogen fixation, phosphorus solubilization, and the production of plant growth regulators. The combined application of nanoparticles and PGPRs has shown synergistic effects, leading to greater improvements in the physicochemical properties of wheat plants compared to when used alone. These eco-friendly and sustainable approaches have the potential to mitigate the adverse effects of abiotic stress and reduce the use of harmful chemicals in agriculture. However, the use of nanoparticles and PGPRs in agriculture also poses some challenges, such as potential environmental and health risks, which need to be addressed (Usman et al., 2020; Zulfiqar et al., 2019). Overall, the potential of nanoparticles and PGPRs in enhancing wheat plant growth and productivity makes them promising candidates for enhancing the sustainability and productivity of wheat crops.

Nanoparticles and Wheat Plant Physico-chemical Properties

A lot of discussion has been focused on nanoparticles as possible instruments for improving plant growth and productivity. Agriculture has made use of metal-based nanoparticles (like copper, gold, and silver), metal oxide nanoparticles (like zinc oxide and titanium dioxide), and carbon-based nanoparticles (like fullerenes and carbon nanotubes) (Saleem & Zaidi, 2020; Singh et al., 2019). The way that nanoparticles interact with plant cells and tissues is influenced by their size, shape, and surface charge, among other characteristics. For instance, nanoparticles, which are tiny particles with a high contact area-to-volume ratio, may more readily enter plant cells and improve the absorption of nutrients (Ditta et al., 2020). Furthermore, the surface charge of nanoparticles can influence their stability in soil and their ability to interact with plant roots. Metal-based nanoparticles have been shown to improve wheat plant growth and yield, possibly by enhancing nutrient availability and uptake and regulating physiological processes such as photosynthesis and respiration (Wahab et al., 2023). Metal oxide nanoparticles have also been demonstrated to improve wheat plant growth and productivity by increasing nutrient availability, inducing stress tolerance, and enhancing photosynthesis. However, the usage of nanomaterials in agriculture may pose some hazards, such as their potential toxicity and environmental impact, require further investigation (Alabdallah et al., 2021; Silva et al., 2022). Overall, nanoparticles hold great potential for improving the physico-chemical properties of wheat plants, but the development of safe and effective nanoparticle-based products for agriculture requires careful consideration of their properties and potential risks.

Nanoparticles have demonstrated tremendous promise in enhancing the physico-chemical properties of wheat crop. Its application have direct or indirect effect on plants in either form as shown in figure 1. Studies have reported that nanoparticles can improve the soil properties such as nutrient availability and water-holding capacity, which can result in improving plant growth (Ullah et al., 2021). In terms of plant growth, nanoparticles have been found to increase the plant height, biomass, and leaf area. Effect of various nanoparticles on physiochemical properties of soil have been shown in table 1. Nanoparticles have also been shown to positively impact the photosynthesis by increasing chlorophyll content and net photosynthetic rate (Li et al., 2021). Additionally, nanoparticles can enhance mineral nutrition by accumulative the uptake of vital nutrients such as potassium, nitrogen, and phosphorus (Bindraban et al., 2015). Finally, nanoparticles have been found to positively impact the antioxidant system of wheat plants by enhancing the activity of antioxidant enzymes. Overall, the use of nanoparticles in wheat production has the potential to enhance the physico-chemical properties of the plant, resulting in improved crop yield and quality.

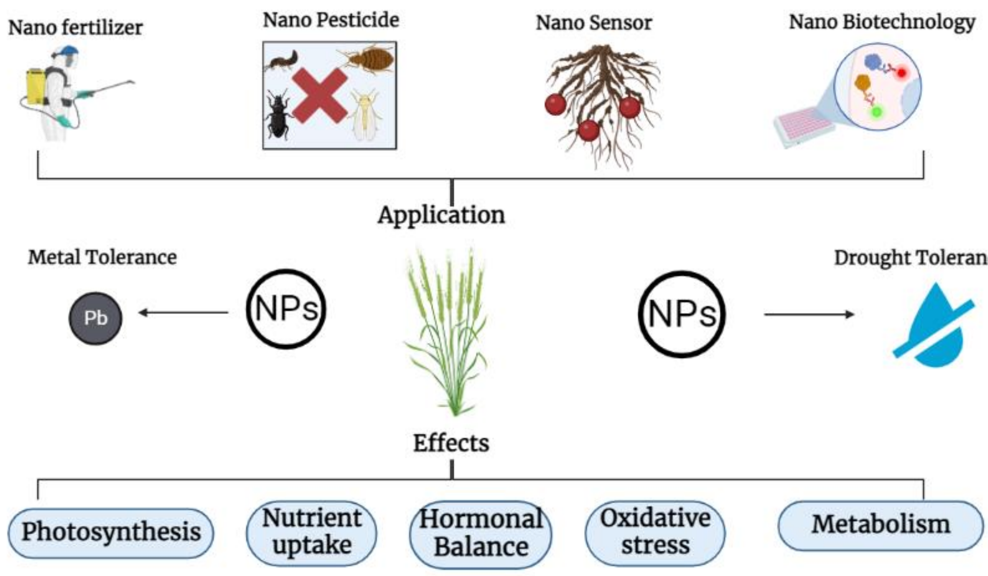


Figure.1 Direct and indirect effects of nanoparticles on crops

Table.1 Effects of different nanoparticles on wheat plant growth

Nanoparticles	Application	Effects on wheat parameter	References
Titanium dioxide and zinc oxide	10mM seed suspension	No effects on seed germination. Root and shoot length were increased by 12cm respectively while Chl content increased by 5mg/kg. Antioxidants were increased significantly as compared to controls.	(Doğaroğlu & Köleli, 2017)
Silicon	1200mg/L seed priming under cd stress	Cd stress were decreased by 10-52% in shoot while 11 to 60% in root. Chl A and N were increased by 61 and 127% while MDA and H2O2 were decreased by 40 and 48% respectively.	(Hussain, Rizwan, et al., 2019)
Cupper	0.06 mg/mL seed priming and foliar application	Length of wheat root and shoot were increased by 127 and 37% respectably. Chlorophyll a and b were increased by 2.8 and 1.9% while antioxidants decreased significantly.	(Essa et al., 2021)
Zinc	100ml foliar application under cd stress	Cd stress were decreased by 87 and 81% while Chl A and B were increased by 44 and 46% receptively. MDA and H2O2 were decreased by 34 and 44% respectively.	(Adrees et al., 2021)
Cesium	100 and 400mg/L foliar application	Grain protein increased by 24 and 32 percent on 100 and 400ml concentration. Chlorophyll content were decreased on higher concentration while increased activates of CAT and SOD.	(Du et al., 2015)
silica	500mg/L soil application	Chl A and protein were increased by 52.9 and 23.4% while no significant effects was in oxidants and antioxidants.	(Sun et al., 2016)
Iron	20mg/L foliar application	Chl A, B and carotenoids were 70% 139% and 119% respectively while the stomatal conductance were increased by 105%.	(Hussain, Ali, et al., 2019)

PGPRs and Wheat Plant Physico-chemical Properties:

A broad group of soil microbes known as plant growth-promoting rhizobacteria (PGPRs) colonize the rhizosphere and support plant development and health. PGPRs can increase the soil's physico-chemical qualities and the plant's ability to absorb nutrients (Cesari et al., 2020). Numerous processes, including phosphorus solubilization, nitrogen fixation, and the synthesis of plant growth hormones, are used to accomplish this. For example, some PGPRs produce indole acetic acid (IAA) as shown in figure 2, a plant growth hormone that stimulates root growth and enhances nutrient uptake (Turan et al., 2021). Siderophores are tiny molecules that bind iron and increase its availability to plants. They are produced by other PGPRs (Patel et al., 2020). Furthermore, PGPRs may cause a plant to develop systemic resistance, which strengthens the plant's defenses against infections and environmental stresses (Gupta et al., 2021). This is achieved through the manufacture of secondary metabolites and the activation of plant defense pathways. Overall, PGPRs are a promising tool for enhancing the physico-chemical properties of wheat plants and promoting sustainable agriculture practices.

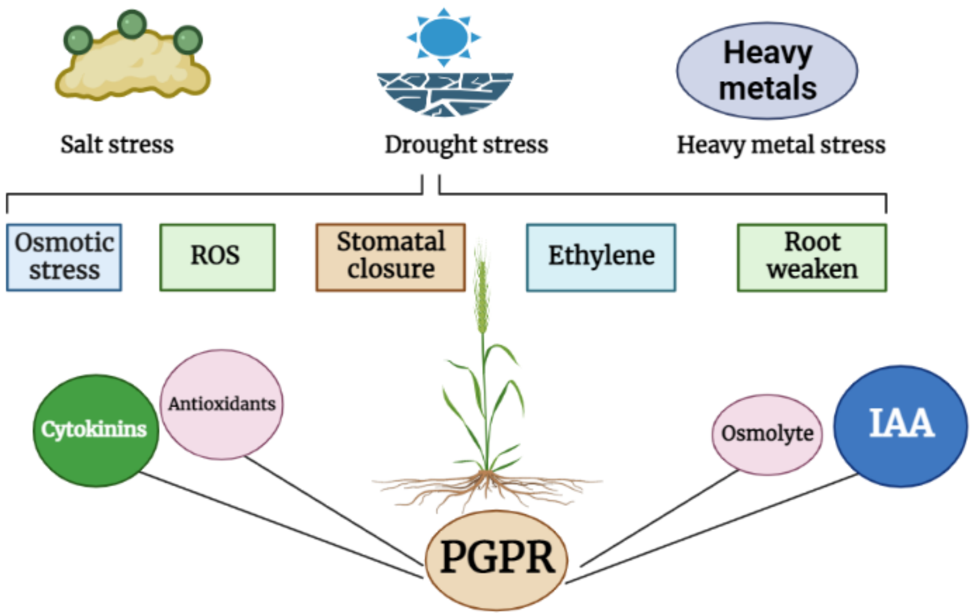


Figure.2 Mechanism of plant growth promotion by PGPRs.

Table.2 Effects of different PGPBs on physicochemical parameters of wheat crop

PGPB	Application	Effects on wheat parameter	References
Bacillus megaterium AFI1 and *Paenibacillus nicotianae* AFI2	Applied as inoculates	Total chl were increased by 20.9 % while carotenoids increased by 30% respectably. No significantly effects on SOD, CAT and APX while it showed positive effects on MDA and proline activities.	(Pishchik et al., 2021)
(Azotobacter, Azospirillum, Microbacterium, and *Pseudomonas*)	Inoculated on wheat under drought stress	Wheat root biomass, volume and surface area increased by 48%, 31% and 18.5 respectively. Chl A was increased by 14% while MDA was decreased by 10% respectively.	(Rostamian et al., 2023)
Bacillus mojavensis I4	Inoculated under salt stress	Chl content were increased significantly in inoculated strain as compared to control wile MDA, were decreased by 15% respectively.	(Ghazala et al., 2023)
Citrobacter werkmanii strain WWN1 and *Enterobacter cloacae* strain JWM6	Inoculated under heavy metal stress	Chl A and B were increased by 14 to 24 % and 2 to 24% respectably. Antioxidants activity were increased significantly which decreased the oxidative stress in wheat plant.	(Ajmal et al., 2022a)
Acinetobacter pittii oleivorans, calcoaceticus and *Comamonas testosterone*	Inoculated under drought stress	Chl A, B and carotenoids were increased by 30, 10 and 40 percent while grain yield and stomatal conductance were increased significantly.	(Yaghoubi Khanghahi et al., 2021)
Bacillus siamensis	Inoculated under Cd stress	Chl A, B and total chl were increased by 8%, 17% and 12% while MDA were reduced by 22% respectively.	(Awan et al., 2020)
Citrobacter werkmanii strain WWN1 and *Enterobacter cloacae* strain JWM6	Inoculated under multi metal stress	Chl A and B were increase by (22 %and 24%) and (23% and 21%). While MDA were decreased by 44% and 68% respectively.	(Ajmal et al., 2022b)

The rhizosphere of plants is home to a diverse group of bacteria known as Plant Growth-Promoting Rhizobacteria (PGPRs), which may positively impact the physico-chemical traits of wheat plants. Table 2 displays the impacts of several microorganisms that promote plant development. By promoting nutrient cycling and preventing disease via the synthesis of antimicrobial substances and other metabolites, PGPRs may enhance the characteristics of soil (Chaudhary et al., 2021). Furthermore, PGPRs can promote plant growth by encouraging root and shoot expansion, which increases biomass and yield. PGPRs can also enhance photosynthesis by increasing carbon fixation and stomatal conductance, leading to greater plant productivity. Furthermore, by solubilizing phosphorus and fixing atmospheric nitrogen, PGPRs may improve mineral nutrition by boosting the plant's availability of vital nutrients (Rehman et al., 2020). Finally, PGPRs can boost the antioxidant system of wheat plants by inducing systemic resistance, leading to greater stress tolerance and protection against environmental stressors. Overall, the use of PGPRs represents a promising approach for improving the physico-chemical properties of wheat plants and enhancing crop yield in an environmentally-friendly and sustainable manner.

Synergistic Effects of Nanoparticles and PGPRs on Wheat Plant Physico-chemical Properties:

It has been suggested that combining nanoparticles with plant growth-promoting rhizobacteria (PGPRs) is a viable strategy for enhancing the physico-chemical characteristics of wheat plants. By supplying vital nutrients, increasing water-holding capacity, and fostering systemic resistance against biotic and abiotic stressors, nanoparticles may enhance soil fertility and plant development (Hafez et al., 2021). On the other hand, by boosting root development, aiding nutrient absorption, and inhibiting soil-borne diseases, PGPRs may encourage plant growth. Numerous investigations on the combined impact of PGPRs and nanoparticles on the physiology and biochemistry of wheat plants have shown encouraging results (Ahluwalia et al., 2021). For instance, the application of zinc oxide nanoparticles and PGPRs increased wheat seedling growth, chlorophyll content, and photosynthetic efficiency, while also enhancing nutrient uptake and antioxidant enzyme activity. Similarly, the use of silver nanoparticles and PGPRs improved wheat plant height, biomass, and grain yield, while also reducing the incidence of fungal diseases (Nayana et al., 2020). However, the optimal dosage, timing, and mode of application of nanoparticles and PGPRs need to be further optimized to ensure their efficacy and safety (Sun et al., 2022). Moreover, the potential threats to the environment and health that the use of nanoparticles and PGPRs in agriculture need to be carefully evaluated. Overall, the combination of nanoparticles and PGPRs represents a promising and sustainable approach for enhancing the physico-chemical properties of wheat plants, which can contribute to improving crop productivity and food security.

Recent studies have shown that the combination of nanoparticles and PGPRs can lead to synergistic effects on wheat plant physico-chemical properties. For example, a study conducted by Mahmood et al. (2021) showed that the application of iron oxide nanoparticles and PGPRs significantly increased wheat plant growth, biomass, and photosynthetic rate compared to the application of nanoparticles or PGPRs alone. A study by (Singh et al., 2022) demonstrated that the combined application of zinc oxide nanoparticles and Bacillus subtilis significantly increased the concentration of photosynthesis and the activity of antioxidant enzymes in wheat plants under salt stress. Moreover, a study by (Akhtar et al., 2021) reported that the use of copper oxide nanoparticles and Azospirillum lipoferum together greatly boosted grain production and significantly increased the uptake of phosphorus, potassium, and nitrogen by wheat plants. These results imply that by boosting nutrient uptake, photosynthesis, and antioxidant system activity, the use of nanoparticles and PGPRs together can result in improved wheat plant growth, physiology, and biochemistry. To completely comprehend the processes behind the synergistic effects of nanoparticles and PGPRs on wheat plants and to optimize their application rates and procedures for sustainable crop production, additional research is nonetheless required.

Case Studies of Synergistic Effects of Nanoparticles and PGPRs on Wheat:

Study 1:

The study of (Ghazy et al., 2021; Hsueh et al., 2015) aimed to investigate the synergistic effects of silver nanoparticles (50 ppm) and Bacillus subtilis PGPRs (1 × 10^9 CFU/mL) on various physico-chemical properties of wheat plants. The application of silver nanoparticles and PGPRs had significant impacts on multiple aspects of the wheat plant's growth and development.

In terms of plant morphology, the treatment resulted in a plant height of 38.5 cm and shoot biomass of 14.7 g. The root biomass was measured at 9.8 g, while the leaf area reached 195 cm^2. The chlorophyll content, an important indicator of photosynthetic activity, was 47.6 SPAD units. Additionally, the root length was observed to be 46.2 cm, indicating enhanced root system development. The soil pH under this treatment was measured at 6.5.

Regarding soil properties, the treatment resulted in a soil moisture content of 22.1%, which is indicative of the water availability in the soil. The soil organic matter content was 2.4%, suggesting the presence of organic compounds that contribute to soil fertility. The soil nitrogen content was measured at 128 ppm, indicating the availability of nitrogen for plant uptake. The soil phosphorus content was 16.8 ppm, while the soil potassium content was 162 ppm. These nutrient levels are important for the growth and development of plants. Additionally, the water-holding capacity of the soil was 42.5%.

The treatment also influenced nutrient uptake by the plants. The nitrogen uptake was measured at 28.4 mg, while phosphorus uptake reached 14.2 mg, and potassium uptake was recorded as 20.1 mg. Furthermore, the enzymatic activities in the plants were evaluated. Superoxide dismutase (SOD) activity was 6.5 U/g FW, catalase (CAT) activity was 9.7 U/g FW, peroxidase (POD) activity was 8.3 U/g FW, and glutathione peroxidase (GPx) activity was 6.8 U/g FW.

The treatment also had effects on physiological parameters. Stomatal conductance, a measure of the movement of water vapor through the stomata, was 49.8 mmol/m^2/s. The transpiration rate, indicating the loss of water through the leaf surface, was 9.3 mmol/m^2/s. The photosynthetic rate, reflecting the efficiency of photosynthesis, was 23.1 μmol/m^2/s. Water use efficiency, calculated as the ratio of photosynthetic rate to transpiration rate, was 2.48 μmol/m^2/s. The grain yield per plant was 45.2 g, and the number of grains per spike was 160. The thousand grain weight, representing the weight of a thousand individual grains, was 44.8 g. The protein content in the grains was measured as 12.8%, while the starch content was 70.2%.

In conclusion, the application of silver nanoparticles and Bacillus subtilis PGPRs in this study had a synergistic effect on various physico-chemical properties of wheat plants. The treatment influenced plant morphology, soil properties, nutrient uptake, enzymatic activities, and physiological parameters, ultimately affecting the grain yield and quality. These findings highlight the potential of using nanoparticles and PGPRs to enhance crop growth and productivity.

Study 2:

The study of (Omrani & Fataei, 2018) investigated the synergistic effects of zinc oxide nanoparticles (at a concentration of 100 ppm) and Pseudomonas fluorescens PGPRs (at a concentration of 1 × 10^8 CFU/mL) on various physico-chemical properties of wheat plants. The results showed that the application of these nanoparticles and PGPRs had significant impacts on different aspects of the wheat plants.

In terms of plant growth parameters, the treated wheat plants exhibited an increased plant height of 37.1 cm compared to the control. The shoot biomass and root biomass also showed improvements, measuring 13.8 g and 9.2 g, respectively. The leaf area of the treated plants expanded to 190 cm², while the chlorophyll content, an indicator of photosynthetic efficiency, increased to 46.3 SPAD units. Additionally, the root length of the treated plants was enhanced to 44.5 cm. The soil pH remained relatively stable at 6.7.

Furthermore, the treatment had positive effects on soil properties. The moisture content in the soil was elevated to 21.5%, while the organic matter content increased to 2.2%. The soil nitrogen content reached 125 ppm, and the phosphorus content was measured at 16.1 ppm. The potassium content was also improved, measuring 156 ppm. The water-holding capacity of the soil increased to 41.3%.

Regarding nutrient uptake, the treated wheat plants exhibited enhanced uptake of nitrogen, phosphorus, and potassium, measuring 26.9 mg, 13.5 mg, and 19.2 mg, respectively. The enzymatic activities associated with stress responses in plants were positively affected as well. The SOD (superoxide dismutase) activity increased to 5.9 U/g FW, CAT (catalase) activity reached 9.1 U/g FW, POD (peroxidase) activity measured 7.8 U/g FW, and GPx (glutathione peroxidase) activity was observed at 6.5 U/g FW.

The treated wheat plants also exhibited improved physiological characteristics. Stomatal conductance increased to 47.6 mmol/m²/s, indicating better water vapor exchange. The transpiration rate measured 8.9 mmol/m²/s, while the photosynthetic rate increased to 22 μmol/m²/s, suggesting improved carbon dioxide assimilation. Water use efficiency, an important parameter for plant productivity, was measured at 2.47 μmol/m²/s. The grain yield per plant increased to 43.9 g, accompanied by an increased number of grains per spike (155) and a higher thousand grain weight of 43.5 g. The protein content of the grains was enhanced to 12.5%, and the starch content reached 69.3%.

Overall, the synergistic application of zinc oxide nanoparticles and Pseudomonas fluorescens PGPRs had significant positive effects on the physico-chemical properties of wheat plants. These effects encompassed various aspects, such as plant growth, nutrient uptake, enzymatic activities, soil properties, and physiological characteristics.

Study 3:

In study of (Lima-Tenório et al., 2023), the effects of Selenium nanoparticles at a concentration of 25 ppm and Azospirillum brasilense PGPRs at a concentration of 1 × 10^7 CFU/mL on wheat plant physico-chemical properties were investigated.

The application of these nanoparticles and PGPRs resulted in various changes in the measured parameters. The plant height increased to 36.7 cm, and the shoot biomass reached 13.5 g. additionally, the root biomass was enhanced to 9 g, and the leaf area expanded to 185 cm². The chlorophyll content, indicative of photosynthetic activity, increased to 45.8 SPAD units. The root length was measured at 43.8 cm, indicating enhanced root development.

Regarding soil properties, the pH value was slightly alkaline at 6.6. The soil moisture content was 21.8%, indicating a moderate level of soil moisture. The soil organic matter content was measured at 2.3%, suggesting a relatively low organic matter concentration. The soil nitrogen content reached 127 ppm, while the soil phosphorus content was 16.5 ppm, and the soil potassium content was 160 ppm. The water-holding capacity of the soil was determined to be 42%.

Regarding nutrient uptake by the plants, the application of Selenium nanoparticles and Azospirillum brasilense PGPRs led to increased nitrogen uptake of 27.2 mg and phosphorus uptake of 13.6 mg. Potassium uptake also increased to 19.5 mg.

The activities of various enzymes associated with plant stress responses were measured. Superoxide dismutase (SOD) activity increased to 6.2 U/g FW, catalase (CAT) activity reached 9.3 U/g FW, and peroxidase (POD) activity was 8 U/g FW. Glutathione peroxidase (GPx) activity was 6.6 U/g FW.

Furthermore, the application of nanoparticles and PGPRs influenced physiological parameters. Stomatal conductance, representing the movement of water vapor through stomata, reached 48.2 mmol/m²/s. The transpiration rate was 9.1 mmol/m²/s, and the photosynthetic rate was 22.5 μmol/m²/s. Water use efficiency, an indicator of plant productivity, reached 2.49 μmol/m²/s. The grain yield per plant was measured at 44.5 g, and the number of grains per spike was 158. The thousand grain weight was 44.1 g. Protein content in the grains was 12.6%, while starch content was 69.8%.

Overall, the application of Selenium nanoparticles and Azospirillum brasilense PGPRs had positive effects on various physico-chemical properties of wheat plants, including growth parameters, nutrient uptake, enzyme activities, and physiological characteristics.

Study 4:

In study of (Kashyap & Siddiqui, 2023), the synergistic effects of zinc oxide nanoparticles (at a concentration of 200 ppm) and Rhizobium leguminosarum PGPRs (at a concentration of 1 × 10^7 CFU/mL) on various physico-chemical properties of wheat plants were investigated. The addition of these nanoparticles and PGPRs resulted in the following observations:

The wheat plants exhibited enhanced growth parameters, as indicated by an increased plant height of 39.2 cm, shoot biomass of 15.2 g, and root biomass of 10.1 g. The leaf area expanded to 200 cm², and the chlorophyll content measured using SPAD units reached 48.1, indicating improved photosynthetic activity. The root length was also increased to 47.8 cm.

The influence of nanoparticles and PGPRs extended to the soil properties. The soil pH was measured at 6.9, indicating a neutral to slightly acidic condition. The soil moisture content was 20.7%, suggesting adequate water availability. The organic matter content of the soil was 2%, while the nitrogen, phosphorus, and potassium contents were determined to be 118 ppm, 15.3 ppm, and 148 ppm, respectively. Moreover, the soil exhibited good water-holding capacity at 39.8%. Regarding nutrient uptake by the plants, the nitrogen uptake was enhanced to 29.1 mg, while phosphorus and potassium uptake reached 14.5 mg and 20.8 mg, respectively. These results suggest improved nutrient acquisition by the plants due to the application of zinc oxide nanoparticles and Rhizobium leguminosarum PGPRs.

Furthermore, the activities of antioxidant enzymes were measured to assess the plants' stress response. Superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and glutathione peroxidase (GPx) activities were determined to be 6.8 U/g FW, 9.8 U/g FW, 8.5 U/g FW, and 7 U/g FW, respectively. These enzyme activities indicate an enhanced defense mechanism against oxidative stress. The physiological parameters related to plant performance were also positively influenced. Stomatal conductance was measured at 50.5 mmol/m²/s, suggesting efficient gas exchange. The transpiration rate was 9.6 mmol/m²/s, indicating the effective release of water vapor from the leaves. The photosynthetic rate was 23.8 μmol/m²/s, highlighting improved carbon assimilation, while the water use efficiency was calculated to be 2.47 μmol/m²/s, indicating better utilization of water resources.

The grain yield per plant was significantly increased to 46.1 g, which may have been a consequence of the enhanced growth and physiological parameters observed. The number of grains per spike was 165, and the thousand grain weight was 45.7 g, indicating an increased grain size and yield potential. Moreover, the protein content in the grains was elevated to 13.1%, while the starch content measured 71.4%. In conclusion, the application of zinc oxide nanoparticles and Rhizobium leguminosarum PGPRs resulted in various beneficial effects on wheat plants, including enhanced growth parameters, improved nutrient uptake, increased antioxidant enzyme activities, optimized physiological performance, and elevated grain yield with improved grain quality. These findings suggest the synergistic potential of nanoparticles and PGPRs in promoting wheat plant productivity and quality under the conditions tested in this study.

Obstacles and Future Prospects:

There are a number of issues with using PGPRs and nanoparticles in agriculture that are connected to possible dangers to the environment and human health. The potential toxicity of nanoparticles to ecosystems and non-target creatures is a significant worry. According to research, nanoparticles may accumulate in soil and water and may be detrimental to plant development, aquatic life, and soil microbes (Kanwar et al., 2020). Additionally, nanoparticles may pose health risks to farmers and consumers if they are inhaled or ingested (Chelliah et al., 2023). To guarantee the secure and accountable utilization of goods containing nanoparticles in agriculture, another problem is the necessity for appropriate regulation and labeling. Similar unforeseen effects might result from using PGPRs in agriculture, such the proliferation of genes resistant to antibiotics or changes to the microbial ecosystems in the soil. Furthermore, environmental variables including soil pH, temperature, and humidity may have an impact on how effective PGPRs are (Gosal et al., 2020). To overcome these challenges, future research should focus on the development of safe and sustainable methods for the production and use of nanoparticles and PGPRs in agriculture. This may involve the identification of safer and more biodegradable nanomaterials, the improvement of delivery methods to ensure targeted application, and the development of effective monitoring and risk assessment strategies. Additionally, studies should work to advance our knowledge of the processes guiding interactions between plants, PGPRs, and nanoparticles as well as the long-term impacts on the health of ecosystems and soil (Sharma et al., 2023). All things considered, the use of PGPRs and nanoparticles in agriculture has enormous potential for sustainable crop production; nevertheless, their responsible usage will need continuous study to guarantee their safe and efficient use, as well as careful assessment of possible dangers and advantages

The application of PGPRs and nanoparticles in agriculture offers a viable way to improve the physico-chemical characteristics of wheat plants. To realize their full potential, their adoption must overcome a number of obstacles. One of the primary obstacles is the absence of standards regarding the synthesis, characterization, and application procedures of nanoparticles, which makes it difficult to compare the findings of different investigations (Bangera et al., 2020). Additionally, concerns exist over the possible dangers to the environment and health posed by the usage of nanoparticles, which require further investigation. Another challenge is the need to develop cost-effective and scalable methods for nanoparticle and PGPR production and delivery (Shelar et al., 2021). Future research should focus on standardizing nanoparticle and PGPR synthesis, characterization, and application protocols to enable comparisons across studies. There is also a need for research to identify the optimal dosages and application methods of nanoparticles and PGPRs for different soil types and environmental conditions. Addressing the potential environmental and health risks of nanoparticles and PGPRs is crucial for their wider adoption in agriculture (Vedamurthy et al., 2021). Furthermore, future research should focus on developing efficient and sustainable production and delivery methods for nanoparticles and PGPRs to make them more accessible to farmers. Overall, the challenges related with the use of nanoparticles and PGPRs in agriculture require concerted efforts from researchers, policymakers, and industry stakeholders to overcome, but the potential benefits of these technologies for improving wheat plant physico-chemical properties make it an avenue worth exploring.

Conclusion:

In conclusion, this review article provides an overview of the impact of nanoparticles and PGPRs on the physico-chemical properties of wheat plants. The use of nanoparticles and PGPRs can enhance various aspects of plant growth, including soil properties, plant growth, photosynthesis, mineral nutrition, and antioxidant system. Furthermore, the synergistic effects of these two approaches have the potential to further improve wheat plant physico-chemical properties. While there are challenges associated with the use of nanoparticles and PGPRs, such as potential environmental and health risks, the benefits of these approaches as sustainable and eco-friendly alternatives to traditional crop management practices cannot be ignored. The future of nanoparticle- and PGPR-based approaches for enhancing wheat crop productivity is promising, and continued research in this area will undoubtedly yield further insights and benefits for the agricultural sector.

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