Review

Evaluated Nano Fertilizer on Wheat Crops Under Salinity Stress

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Abstract

Wheat is a staple food and is consumed by more than 36% of the world's population as a protein and carbohydrate source globally. Nano-fertilizers represent a breakthrough in agricultural technology, offering promising opportunities to enhance crop productivity and mitigate negative environmental impacts. Utilizing nanoparticles to deliver essential nutrients to plants can improve nutrient use efficiency, as they can provide a more targeted and controlled release of nutrients compared to conventional fertilizers. Wheat, as one of the world's most important staple crops, plays a vital role in global food security. However, wheat cultivation often faces various challenges, one of which is salt stress. Salinity is a major environmental stress factor affecting the growth, development, and productivity of crops worldwide, including wheat. It impacts the physiology and biochemistry of plants, leading to nutrient imbalances, osmotic stress, and ion toxicity, which collectively reduce crop yield. Over the last decade, researchers have started to investigate the potential of nano-fertilizers in enhancing the resilience of wheat and other crops under salt stress conditions. Studies have demonstrated that certain nano-fertilizers can improve plant tolerance to salinity stress by enhancing nutrient availability, promoting water retention, and modulating the plant's physiological responses to stress. This review summarizes the information that is currently available on the usage of NFs worldwide, showing their promise for sustaining crop output in an environmentally benign way. It also highlights the encouraging results of using nano-fertilizers' impact on wheat under salt stress and the optimal strategies for their application.

Keywords: Nano-fertilizer, wheat, salt stress

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Introduction

Wheat (*Triticum aestivum* L.) is a cereal that belongs to the Poaceae (Gramineae) family, which originated from subtropical areas, and it contains 13% protein, 11% gluten, and 69% carbohydrate. It has a high nutrient content, and a variety of products made from wheat serve as a staple food for a third of the population worldwide. Also, wheat is the second-largest grain worldwide based on cultivated area and total production volume. The global production volume of wheat came to

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over 778 million metric tons in the marketing year 2021/22. This was an increase of about four million tons compared to the previous year (Glauber, 2023).

Salinity stress negatively affects the growth and development of wheat, leading to diminished grain yield and quality. Wheat constitutes a pivotal position for ensuring food and nutritional security; however, rapidly rising soil and water salinity pose a serious threat to its production globally. Wheat plants utilize a range of physiological, biochemical, and molecular mechanisms to adapt to salinity stress at the cell, tissue, as well as whole plant levels to optimize growth and yield by offsetting the adverse effects of a saline environment. Recently, various adaptation and management strategies have been developed to reduce the deleterious effects of salinity stress and maximize the production and nutritional quality of wheat (El Sabagh et al., 2021).

The background of fertilizers can be traced back to traditional practices such as the use of manure, compost, and crop residues to enrich the soil. However, with the development of agricultural practices, the demand for higher crop yields necessitated the development of synthetic fertilizers. In the early 20th century, the Haber-Bosch process revolutionized fertilizer production by enabling the synthesis of ammonia from atmospheric nitrogen, leading to the large-scale production of nitrogen-based fertilizers (Lassaletta et al., 2020).

Fertilizers are substances or mixtures that contain essential nutrients required by plants for their growth and development, such as N, P, K, Fe, Zn, and Cu. Inadequate nutrient availability in the soil can limit plant growth and lead to nutrient deficiencies, lower crop yields, and poor produce quality (Pote et al., 2022).

Moreover, fertilizers have played a pivotal role in the development of sustainable agricultural practices. With proper nutrient management, farmers can reduce nutrient loss, reduce environmental pollution, and make better use of resources. This is particularly important in areas where soil nutrient depletion and degradation pose significant challenges to agricultural productivity (Wang et al., 2022).

In recent years, there has been a growing interest in exploring new methods of fertilization, such as the use of nanotechnology in the development of nano fertilizers. Nano fertilizers are nanomaterials designed to enhance nutrient uptake, improve nutrient use efficiency, and reduce environmental impacts. These developments show promise for addressing the limitations of conventional fertilizers and promoting sustainable agricultural practices (Khalil et al., 2022; Mathur et al., 2022).

Objectives of the review article

One of the objectives of the review is to look at the impact of nano-fertilizers on wheat subjected to salt stress. The objectives could potentially be along these lines:

1. Assess the impact of salt stress on wheat growth and productivity: This involves evaluating the direct effect of salt stress on wheat plants. This can include studying parameters like germination rate, growth rate, biomass production, and grain yield under conditions of varying salinity (Dadshani et al., 2019).
2. Examine the effect of nano-fertilizers on wheat under salt stress: Here, after applying different concentrations or types of nano-fertilizers to wheat under salt stress, monitor their effects. Specific parameters to measure might include changes in plant growth, biomass, and yield, as well as any changes in the plant's physiological response to salt stress (Dimkpa and Bindraban, 2017)
3. Determine the optimal type and concentration of nano-fertilizer for maximizing wheat yield under salt stress: Based on the experimental results, it may be possible to suggest an optimal type and dosage of nano-fertilizer to apply to wheat under salt stress in order to maximize yield (Dutta and Bera, 2021).
4. Elucidate the mechanism of action of nano-fertilizers in wheat under salt stress: This could involve more in-depth

investigations into how nano-fertilizers affect the physiological or molecular responses of wheat plants to salt stress, potentially using techniques like gene expression analysis or metabolic profiling (Arif et al., 2020).

Problem Statement

Climate change and the rapid increase in population are pragmatically posing a serious threat to the world's agronomic food security (Francini and Sebastiani, 2019). Salt stress has become a great concern in areas covering approximately 1125 million hectares around the world; of which 76 million hectares are affected solely by anthropogenic activities, resulting in the loss of 1.5 million hectares of arable land per year due to solidification and salinization (Hossain, 2019). The paramount anthropic pursuits encompassing excessive irrigation practices, soil topographic perturbation, overuse of fertilizers, and impoverished drainage systems account for this spread of salinity stress (Romano-Armada et al., 2020).

Salt stress has altered physiological responses such as disruption of plasma membrane integrity, excessive reactive oxygen species (ROS) production, reduced photosynthetic efficiency, decreased aperture size of stomata, and insufficient accessibility of antioxidant enzymes (Muchate et al., 2016). Moreover, the accumulation of ROS results in oxidative bursts in cellular compartments, affecting their components such as proteins, DNA, and lipids (Tanveer and Ahmed, 2020). Additionally, the higher accumulation of sodium (Na^+) and chloride (Cl^-) ions in plants causes ionic stress and leads to disturbances in uptake, distribution, availability of essential elements, and impairment in selectivity and integrity of cellular membranes (Thor, 2019). However, the tolerance mechanism of salinity-stressed plants manifests traits such as the exclusion of excessive salt ions, changes in membrane permeability to regulate ionic uptake, synthesis and accumulation of compatible metabolites or osmolytes such as proline, promoting ionic homeostasis, and hormonal regulation including abscisic acid (ABA), which governs salt tolerance in plants (Banik and Bhattacharjee, 2020; Saad et al., 2019).

Wheat Crops Under Salinity Stress

Soil salinity is the second major factor responsible for land degradation after soil erosion, causing a decline in agricultural economic outputs for over 10,000 years (Shahid et al., 2014). Poor salinity management can cause soil solidification in farming soils, where Na binds to negatively charged clay, causing clay swelling and dispersal, subsequently decreasing crop yield. Higher levels of salinity affect 1.5 million hectares of land globally every year, and hence about 50% of cultivable land could be deteriorated by the middle of the 21st century. During salinity, the effects on most plants are apparent in the early stages, especially during seedling establishment, as it is the most responsive and critical stage and is reported to be strongly associated with successful germination and seedling development. Various factors hamper crop yield under salinity stress, but osmotic stress, ionic imbalance, and oxidative stress are the major ones (Fig. I). In brief, osmotic stress leads to an increased accumulation of salts in cell sap and tissues, which become observable as leaf burn and wilting. Thus, this ionic imbalance causes a disequilibrium of nutrients that declines germination, and adversely affects subsequent metabolic processes (Usman et al., 2020).

Salinity is the most adversely affecting factor on the productivity and quality of wheat by altering the physiological as well as biochemical activities in plants. The generation of ROS due to Na+ toxicity, which damages biomolecules (e.g., lipids, proteins, and nucleic acids) at the cellular level and alters redox homeostasis, is a common phenomenon under salt stress (Kundu et al., 2018). However, salt-impacted soils are difficult to remediate due to the circumstances outlined by Arzani and Ashraf (2016).

Ionic Imbalance and Ionic Toxicity:

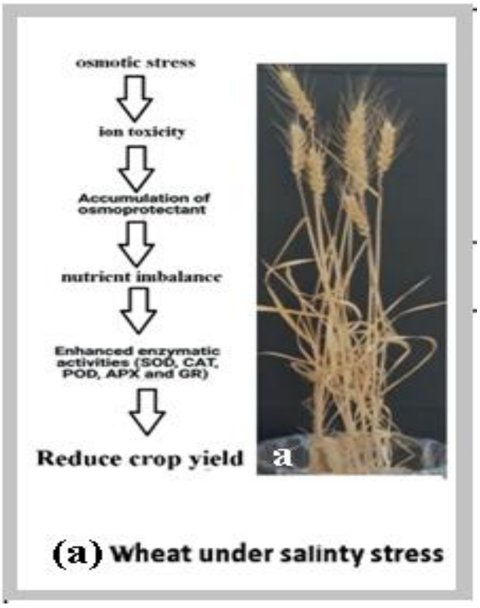

Fig. I. Wheat crops under salinity stress

In soils, Na$^+$ and Cl$^-$ ions are extremely mobile. Additionally, this can be a costly and short-term solution for ongoing issues. Moreover, the dynamic nature of soil salinity is influenced by numerous factors such as soil pH, density, and water levels, as well as geographic elements like elevation and slope. Furthermore, agricultural practices, such as irrigation and fertilization, and climate elements, such as temperature and precipitation, can also contribute to the spatial variation in soil salinity. According to some researches, these complex interactions result in the perplexing and volatile phenomenon of soil salinity(Otlewska et al., 2020). Under salinity, Na$^+$ is the primary toxic ion imposing both osmotic stress and ionic toxicity (Munns and Tester, 2008). Salinity inhibits seed germination by either exerting osmotic stress that thwarts water uptake or causes ionic toxicity. These consequences collectively inhibit cell division and expansion, as well as modulate the activity of some key enzymes, ultimately reducing the seed reserve utilization (El-Hendawy et al., 2019). Salinity adversely affects the growth and yield of crop plants by decreasing the availability of soil moisture, and due to the toxic effects of sodium and chloride ions at high concentrations to the plant (Munns and Tester, 2008). Thus, it can be said that salinity negatively affects the process of germination by altering the normal germination mechanism, resulting in reduced growth and development, ultimately declining the economic yield. However, salinity severely disturbs ionic harmony as excessive salt ions (e.g., Na$^+$, Cl$^-$, Mg^{+2}, and SO$_4^{-2}$) accumulation alters the composition of the soil solution. Excessive accumulation of the Na$^+$ cation disturbs the uptake of many cationic nutrients such as K$^+$ (Al-Shamma and Al-Shahwany, 2014; Wakeel et al., 2011) or Ca^{+2} (Gardner, 2016), resulting in nutrient imbalance. For instance, excessive Na$^+$ induces Ca^{+2} deficiency, appearing as lesions on aerial plant parts, along with a reduction in leaf blade dry weight (Maas and Grieve, 1990). Furthermore, Na$^+$ induces K$^+$ uptake reduction, leading to declined shoot growth. In contrast, Cl$^-$ presence in excessive concentrations leads to impairment of nutrient uptake by disturbing anion uptake (Geilfus, 2018a; b). The uptake and anion-anion interactions are antagonistic as the Cl$^-$ concentration multiplies many folds in the soil solution under NaCl salt stress. It has been established that Cl$^-$ is highly mobile in the soil, and negatively charged kaolin and clay minerals significantly repel Cl$^-$, leading to its accumulation in the soil macro-pores and soil solution (Thomas and Swoboda, 1970). On the other hand, cations, including Na+, get absorbed in very minute concentrations by the negatively charged soil surface under the soil environment (Borggaard, 1984). Moreover, antagonism has been reported among Cl$^-$ and nitrate (NO$_3^-$) when external Cl$^-$ concentrations become higher (Abdelgadir et al., 2005), which causes a reduction in the growth and yield of wheat (Hu and Schmidhalter, 1998). However, this has not been the same for corn crops (Hütsch et al., 2016). Interestingly, severe competition for anion-anion uptake has also been described for Cl$^-$ and phosphate (PO$_4^{-3}$). In addition to cereals, such competition has also been reported for tomatoes as well as rose plants (Massa et al., 2009). Under NaCl salinity, it seems that Cl$^-$ tends to hinder the growth and development of crops by inducing a deficiency of phosphorus and sulphur by inhibiting PO$_4^{-3}$ and SO$_4^{-2}$ uptake. However, generalizable conclusions cannot be drawn from the published research and relevant findings. For concise conclusiveness, it becomes pertinent to distinguish between Cl$^-$ and counter-cations' effects under a saline environment. There is a dire need to perform further experiments regarding the behaviour of membrane-impermeable counter-cations of a specific salt(Pannwitz et al., 2021). Besides, the underlying molecular mechanism of nutrient-nutrient antagonistic uptake remains unclear. However, one possible explanation can be attributed to antagonistic competition for a binding site at transport proteins of salt ions. Another explanation could be the leaking of Cl^- from protein pores, which quantitatively displaces PO_4^{-3} or SO_4^{-2}, leading to a sharp decline in their uptake. Both of the above scenarios rely on transmembrane pores and physicochemical attributes such as charge and size. For instance, the hydrated Cl^- ion radius is similar to SO_4^{-2}. It seems that under salinity stress, glycophytic crops did not develop mechanisms to exclude Na^+ and Cl^- uptake during the breeding and evolution process, which hampered the development of adaptive mechanisms at the transporter site for differentiating between requisite nutrients and undesired salt ions(Kataria and Verma, 2018). Thus, it might be inferred that a two-pronged strategy encompassing a reduction in the uptake of salt ions and their replacement in the soil is needed (EL Sabagh et al., 2021).

Wheat phenological developments under salinity stress

Salinity also negatively affects wheat phenological developments such as leaf number, leaf expansion rate, and root/shoot ratio (El-Hendawy et al., 2005), and biomass production (Sorour et al., 2019). The saline environment disturbs plant water relations, including relative water content, leaf water potential, water uptake, transpiration rate, water retention, and water use efficiency (Nishida et al., 2009).

Salinity adversely affects the growth and yield of crop plants by accelerating all phenological phases of wheat (Grieve et al., 1994), reducing the number of fertile tillers (Abbas et al., 2013), decreasing the number of spikelets per spike (Frank et al., 1987), kernel weight ((Abbas et al., 2013), and affects grain yield adversely (Sorour et al., 2019). For instance, yield losses up to 45% have been recorded in salt-stressed wheat (Ali et al., 2009). Hasan et al. (2015) observed that saline stress (15 dSm^{-1}) significantly decreases grains per spike, 1,000-grain weight, and seed yield in tolerant and sensitive wheat cultivars.

Furthermore, the oxidative stress exerted via accelerated ROS generation induces lipid peroxidation and disrupts nucleic acids, which ultimately decreases the consistency and overall yield of the affected seed (Kumari and Kaur, 2020; Rajabi Dehnavi et al., 2020).

The Reproductive Stage of Wheat Growth and Yield under Salinity Stress

Several earlier studies illustrated that the reproductive phase of any crop is the most sensitive stage to abiotic stresses, including salinity (Ehtaiwesh and Rashed, 2020), and causes massive yield penalties in important crops, including wheat (Kalhoro et al., 2016).

There have been significant achievements pertaining to boosting wheat yield over the decades. However, the demand for higher quality grain has also increased with the improvement in human lifestyle (Park et al., 2009). Plant variety, in conjunction with the prevalent environment, has also been reported to determine wheat quality to a certain extent (Sairam et al., 2002). Previously, most researchers focused on the impacts of salinity on wheat grain yield (Zheng et al., 2009).

Salt stress caused the acceleration of shoot apex development but decreased the number of spikelet primordia and also resulted in early terminal spikelet stage and anthesis. It has been inferred that salinity levels, especially beyond 150mM of NaCl, significantly reduced the grain yield, whereby grain quality deterioration remained significant at 100mM (Farooq and Azam, 2006). Likewise**,** the use of 200mM NaCl stress at pre-anthesis and post-anthesis stage caused a reduction in aboveground biomass, ears $plant^{-1}$, ear weight, number of grains $plant^{-1}$, C, N, and C/N ratio in grains, and carbon use efficiency at both stages, although the reductions were higher due to the imposition of stress at both stages as compared to a single stage (Eroğlu et al., 2020). Similarly, yield component traits such as spike length, spike weight, filled spikelets plant^{-1}, total spikelets plant^{-1}, and test weight were reduced to 8%, 3%, 37%, 20%, and 10%, respectively, under stress conditions, and resulted in a 16% low total grain weight plant^{-1} (Tareq et al., 2011). Further, losses of grain weight under saline stress occur due to pollen sterility, the less production of assimilates, and reduced partitioning toward economic parts (grains) of plants. Likewise, the study on 151 synthetic wheat-breeding lines suggested that salt stress **is** associated with Na^+ toxicity, which reduced the total kernel weight and starch content by 20% and 6%, respectively (Dadshani et al., 2019).

Similarly, Nadeem et al. (2020) reported that salinity negatively influenced the yield (grain length, test weight, and grain yield), nutritional quality traits (moisture, fat, ash, fiber, and gluten content), and mineral nutrient content (K, Ca, Fe, P, Zn, and Mg) in wheat crop. Therefore, it can be concluded that salinity stress is a major factor limiting yield and yield quality traits, and it affects the reproductive phase severely by altering ion homeostasis, water status, and assimilate partitioning. Consequently, from these findings, salinity stress is a major factor limiting yield and grain quality traits, and it affects the reproductive phase severely by altering ionic homeostasis, water status, and assimilate partitioning (Arshad et al., 2020)

Finally, the effect of salt stress on wheat can be mentioned as

1. Reduce seed utilization metabolism by affecting enzymes such as α-amylase, protease, and lipase; reduce cell division and expansion by affecting water uptake, avert seedling, increase germination time, reduce seedling vigor by affecting root and shoot growth.
2. Morphological traits: Reduce plant height, leaf number, leaf area, leaf expansion, plant fresh and dry weight, vascular tissue thickness, photosynthesis rate, nutrient uptake, and transport.
3. Yield and quality attributes: Affect pollen growth and pollination, causing pollen sterility; reduce spike length, spike number, and spikelet number, grain per spike, number of grains, grain size, and test weight. Reduce protein, amino acids, gluten, ash, carbohydrate, and micronutrients.
4. Physiological and biochemical processes: Alters nutrient transporters, ion homeostasis, osmolyte accumulation, disrupt photosynthetic machinery, transpiration rate, antioxidant enzymes, reduce relative water content, membrane stability, assimilate partitioning, and phytohormone imbalance.
5. Root system architecture and activity: Reduce root length, root volume, number of root hairs, deep root weight, root exudates, root length density, and number of lateral roots.
6. Root activity: Hammer ion exchange capacity, water use efficiency, nutrient use efficiency, root microbial interaction, root microbial activity, root respiration, root hydraulic conductivity, and efficient root transporters.

Nanotechnology in Agriculture

Nanotechnology, the science and engineering of manipulating matter at the nanoscale level (usually between 1 and 100 nanometers), has emerged as a promising field with diverse applications in various industries, including agriculture. The application of nanotechnology in agriculture, often referred to as "nanotechnology in agriculture" or "agricultural nanotechnology," involves the use of nanoscale materials and devices to address agricultural challenges and improve crop production (Pramanik et al., 2020).

Nanotechnology offers many unique properties and advantages that make it particularly suitable for agricultural applications. These properties include a high surface-to-volume ratio, increased reactivity, unique optical and electrical properties, and the ability to modify materials at the atomic and molecular level. These properties open up new possibilities for developing innovative solutions to enhance plant growth, nutrient utilization, pest control, and soil health (Roy and Hossain, 2024).

One of the main areas where nanotechnology is being applied in agriculture is the development of nano-fertilizers. Nano-fertilizers are nano-sized particles or nano-structured materials designed to deliver nutrients to plants more efficiently and precisely compared to conventional fertilizers. These nano formulations can improve plant nutrient uptake, enhance nutrient use efficiency, and reduce nutrient loss through leaching or volatilization. Nanofertilizers can also provide a controlled release of nutrients, allowing prolonged nutrient availability and reducing fertilizer application frequency(Subramanian et al., 2015).

In addition to nano-fertilizers, nanotechnology is being explored for various other agricultural applications. For example, nanosensors can be used to monitor soil moisture, nutrient levels, and pest infestations in real time, enabling farmers to make timely and accurate decisions regarding irrigation and pest management(Bharti et al., 2024). Nanomaterials can also be used to develop smart delivery systems for pesticides, herbicides, and plant growth regulators, ensuring targeted and controlled release to minimize environmental impacts (Deshmukh et al., 2023).

Nanotechnology has the potential to revolutionize precision farming practices(Anjum et al., 2018). By integrating nano sensors, communication technologies, and data analytics, farmers can collect and analyze vast amounts of data related to soil conditions, weather patterns, and crop growth, allowing for accurate and optimized resource management. This can improve crop yields, reduce resource waste, and minimize environmental impacts (Debnath and Das, 2020).

In the last couple of decades, nanotechnology has been widely used in agriculture for the development of biosensors, food additives, plant growth regulators, and nano pesticides (Heikal and Abdel-Aziz, 2020). It is expected that in the coming decade, the applicability of this technology will further increase due to its low production cost and less toxicity at low dosages, which might lead to a slow release of plant nutrients, efficient availability of water to plant roots, better soil quality by removal of soil contaminants, and enhancement in crop productivity (Abdel-Aziz and Rizwan, 2019).

The effects of nanoparticles have been reported so far in the agricultural discipline, focusing on enhancing seed germination (Kim et al., 2018), plant growth, and photosynthetic rate (Wang et al., 2020; Khalil et al., 2022). Silver nanoparticles (AgNPs) have remarkably superior behavior over existing nanoparticles (Chouhan, 2018), because of their unique physicochemical properties imparting antimicrobial and antioxidant attributes (Yousaf et al., 2020). Furthermore, the non-toxicity and chemical stability at ambient conditions of AgNPs regard them as the ‘biocompatible precursors’ for inducing the specific traits responsible for the overall development in plants (Castro-González et al., 2019). This may happen due to better penetrability of AgNPs into the seed pores (Azura et al., 2017), which increases the water uptake efficiency, resulting in coleoptile elongation and proper seedlings establishment; resulting in a notable acceleration in the germination rate of seedlings of wheat. Furthermore, the enhanced germination percentage has also accelerated the vigorous growth of stems, fresh weight, and root length at the germination stage (Almutairi, 2016). The seed primed with AgNPs showed reduced Na^+ ions translocation from roots to shoots, resulting in increased biomass, photosynthetic pigments, and endogenous proline concentration, but a decrease in H_2O_2 and MDA contents under salt-stressed conditions (Mohamed et al., 2017). The results are in agreement with (Fig. II) (Abou-Zeid and Ismail, 2018; Hojjat and Kamyab, 2017).

In addition to the germination parameters, other criteria including the elevation in ROS levels, lipid peroxidation, and stress-induced injuries were analyzed by detecting the hallmark traits such as H_2O_2 and Thiobarbituric acid reactive substances (TBARS), respectively(Gianella, 2021). An effective deterioration in these stressful attributes under the influence of AgNPs was clearly demarcated in the results for AgNPs supplemented wheat during salinity, which was in contradiction to NaCl treated plants. This may result from the activation of the scavenging systems in the modulation of the defense system via the ascorbate-glutathione

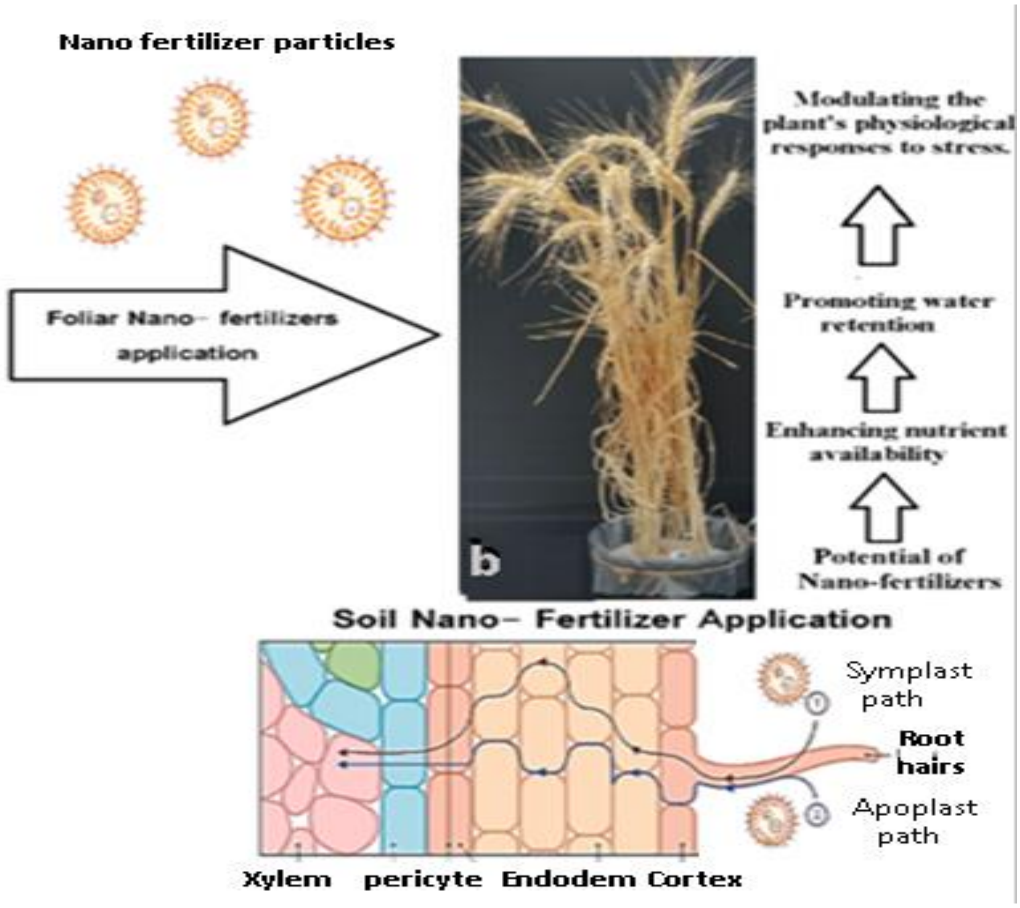

Fig. II. Nano fertilizer on wheat crops under salinity stress

cycle-mediated (Noctor and Foyer, 1998), thereby inhibiting lipid peroxidation and formation of their byproducts (TBARS), modulating the K$^+$ exuvial inactivation of hydroxyl radical-activated K$^+$ outwardly rectifying channels (Demidchik et al., 2010). Biogenic nanoparticles have been shown to influence antioxidant responses mediating oxidative stress and plant growth (Zaeem et al., 2020). The biochemical-stress markers such as enzymatic and non-enzymatic antioxidants escalated with high intensity in response to salt stress under NaCl. Enzymatic antioxidants such as SOD, APX, GR, and GPX act as the first line of defense in stress-induced responses, while the non-enzymatic antioxidant entities such as AsA and GSH are mainly regarded as the buffering system of the plant cells (Hasanuzzaman et al., 2019).

Salinity tolerance is a complex trait, which involves plant-specific traits, including physiological mechanisms such as osmotic tolerance, exclusion of toxic ions, and tissue tolerance. Osmotic tolerance involves the adjustments in plants by the production of osmoprotectants such as proline, uptake of K$^+$, and translocation of K$^+$ in shoots, as well as exclusion of toxic levels of Na$^+$ in roots and shoots (Almeida et al., 2017). The ability to maintain K$^+$ ions during salinity stress is a requirement for salt-tolerant plants (Ismail and Horie, 2017). It has been shown that K$^+$ levels decrease in salt-stressed plants, despite the higher accumulation of Na$^+$. The uptake of crucial K$^+$ ions is antagonistic to excessive Na$^+$ and Cl$^-$ ions in wheat during salinity. In the presence of AgNPs, treatment resulted in a reduced level of both Na**+** and Cl$^-$ and an increased level of K$^+$ ions in leaves as well as in roots. This happens perhaps due to the high K^+/Na^+ ratio in plant tissues, a reduction in Na^+ induced K^+ efflux from the root and leaf, resulting in high intracellular K^+ retention and/or reduction in K^+ efflux (Janicka-Russak and Kabała, 2014).

Furthermore, proline concentration significantly increased under NaCl treatment, corresponding to glutamic acid activation and inhibition of proline oxidation via the action of Proline Oxidase (POX) to other soluble compounds such as Pyrroline-5-carboxylate (P5C) (Holmström and Finkel, 2014). Proline also adjusts the osmotic balance of cells, acts as a source of energy for the recovering tissues, alleviates the concentration of cytosolic acids, mediates apoptotic pathways in response to ROS accumulation, and can lead to cell-cycle arrest or autophagy. Therefore, the AgNPs-mediated enhanced proline content, along with up-regulation of the activity of GK, and repressed activity of POX, supports the outcomes of the study (Jawad et al., 2015).

Wheat seed priming with AgNPs at low doses increased shoot and root fresh weight while reducing total soluble sugars and proline contents under salt-stressed conditions (Mohamed et al., 2017). The application of nanoparticles in plants under oxidative stress conditions develops a strong defense system in plants by upregulating enzymatic activities (Husen and Siddiqi, 2014; Khalil et al., 2022). However, the effectiveness of NPs depends upon their dose and type. It has been reported that NPs have the potential to enhance crop growth, quality, and productivity under salt-stressed conditions (Taran et al., 2017). Previously, it has been demonstrated that AgNPs contribute to promising applications in agriculture, especially in the near future because seed priming with AgNPs increases the growth and improves the physiology of crop plants under abiotic stresses (Aziz et al., 2019).

The Characteristics of Nanofertilizers

Nanofertilizers can be defined as nano-sized materials or nano formulations specifically designed to deliver nutrients to plants in a controlled and targeted manner. These nanomaterials display unique physicochemical properties and characteristics that distinguish them from conventional fertilizers (Dimkpa and Bindraban, 2017).

The main characteristics of nanofertilizers include

1. Nano-sized particles: Nanoparticles consist of particles or structures with dimensions typically ranging from 1 to 100 nanometers. The nano size provides a large surface area to volume ratio, which enhances the interaction of the nanofertilizer with plant roots and soil (Yadav et al., 2023b).
2. Controlled release of nutrients: One of the main advantages of Nano fertilizers is their ability to release nutrients gradually and in a controlled manner. This controlled release mechanism helps ensure that nutrients are available to plants over a prolonged period, reducing fertilizer application frequency and minimizing nutrient loss (Zulfiqar et al., 2019).
3. Enhanced Nutrient Absorption: The small particle size and unique surface properties of nan fertilizers facilitate enhanced nutrient uptake by plant roots. The nanoscale dimensions allow for better root system penetration and efficient nutrient uptake, increasing nutrient utilization efficiency and reducing wastage (Wang et al., 2016).
4. Nutrient protection: Nano fertilizers can provide protection for the nutrients they carry. By encapsulating nutrients within nanostructures or coatings, Nano fertilizers can protect them from environmental factors, such as moisture, pH fluctuations, and microbial activity. This protection ensures that nutrients are preserved and available for plant uptake (Kumar et al., 2021).
5. Tailor-made nutrient composition: Nano fertilizers offer the possibility to tailor the composition of nutrients to the specific needs of different crops. This flexibility allows for customized formulations that address specific nutrient deficiencies and

promote optimal plant growth and development (Yadav et al., 2023b).

6. Compatibility with other agricultural inputs: Nano fertilizers can be compatible with other agricultural inputs, such as pesticides or herbicides, enabling the development of integrated smart delivery systems. This alignment allows for the targeted and coordinated release of multiple inputs, improving the efficiency and effectiveness of agricultural practices (Usman et al., 2020).

It is important to note that nanofertilizers remain an area of active research, and there are ongoing discussions and evaluations regarding their efficacy, safety, and potential environmental impacts. While their unique properties hold promise for improving nutrient management and agricultural sustainability, comprehensive assessments and risk evaluations are necessary to ensure safe and responsible use (Sharma et al., 2022).

Conclusion

1. Nanofertilizers have emerged as a promising technology in agriculture, offering several potential benefits for sustainable crop production. Through their unique properties and targeted nutrient delivery, nanofertilizers have the potential to enhance nutrient use efficiency, reduce environmental impact, and improve crop yield. This paper explored various aspects of nanofertilizers, including their definition, properties, methods of synthesis, mechanisms of action, environmental impacts, applications, and challenges (Nair et al., 2010).
2. Nanofertilizers offer several advantages over conventional fertilizers. Their nanostructured nature allows nutrient release to be controlled, resulting in improved nutrient availability to plants and reduced nutrient losses to the environment. The enhanced efficiency of nanofertilizers can contribute to lower fertilizer application rates and lower risks of nutrient run-off and associated water pollution. Moreover, nanofertilizers can be tailored to specific crop requirements, addressing nutrient deficiencies and improving nutrient uptake (Abou Seeda et al., 2024).
3. However, the adoption of nanofertilizers also comes with some challenges and considerations. Production costs, standardization, regulatory compliance, potential environmental risks, and social acceptance are among the key factors that need to be addressed in order to be successfully implemented. Collaboration between researchers, industry partners, policymakers, and farmers is critical to overcoming these barriers and ensuring the responsible and sustainable use of nanofertilizers (Dadshani et al., 2019).
4. Potential synergies between nanofertilizers and other agricultural technologies enhance their effectiveness and contribute to sustainable farming practices. By integrating nanofertilizers with precision farming, controlled release systems, soil amendments, biocides, smart irrigation systems, genetic engineering, and renewable energy technologies, farmers can improve nutrient management, enhance crop health, and reduce the environmental impact of agricultural practices (Adetuyi et al., 2024).
5. As the field of nanotechnology continues to advance, further research and development are necessary to explore the full potential of nanofertilizers. Long-term studies are needed to evaluate their environmental fate, effects on soil health, and interactions with soil microorganisms. In addition, efforts should focus on standardization, regulatory frameworks, and educational initiatives to promote the safe and responsible use of nanofertilizers (Yadav et al., 2023a).
6. In conclusion, nanofertilizers have the potential to revolutionize agricultural practices by improving nutrient management, enhancing crop yields, and reducing environmental impact. Despite the challenges ahead, with continued

research, technological advances, and collaborative efforts, nanofertilizers can pave the way for a more sustainable and efficient agricultural sector, contributing to global food security and environmental sustainability (Kumari and Kaur, 2020).

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