Chapter 4
Nanoformulations and Plant Saline Stress Resistance

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4.1 Introduction

The word nano-formulations are a composite form from nanotechnology. The latter is a term which connotes synthesis or design of structural materials into a minutest scale ranging from 1 to 100 nanometers (Bhardwaj et al. 2019; Fabiyi et al. 2020; Kumar et al. 2024a; Mariyam et al. 2024). Nanomaterials (NMs) metamorphosed from the use of these structural materials and are practically smaller in size even than the given scale above. There are a number of specific attributes that comes along with the use of these NMs; these ranges from relatively limited surface area, increasing reactivity as a result of its unnatural surface structure, chemical composition, shape and assemblage. There is need to situate the importance of food in any country as appropriate in this context before exploring nano-formulations further. Food is widely accepted as a basic necessity of life because it is absolutely essential for the maintenance and reproduction of human life (Verma et al. 2024). It serves as

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a vital sustaining element to the health of an individual and its seen as the basic requirement of life before considering the other two basic needs of life (shelter and clothing) especially at the household level. It is in this light that food security becomes an important factor in considering the health of a nation. A projection was made on global population to increase to about 9.8 billion by the year 2050, while it is expected to increase to 11.2 billion by the year 2100 as indicated in Fig. 4.1 (United Nations 2015).

In order to meet the demands of the growing population, it is important to implement farming techniques that will facilitate increase in crop production, as well as protect the environment (Fabiyi et al. 2024a). Sustainable development goals 2 and 12 refer to zero hunger and responsible consumption and production, respectively. Good health, food security, nutrition and well-being are possible with good economic growth. This can be made feasible by achieving the goal of sustainable agriculture and food security. Food security can be sustained by good agricultural practices that will control biotic and abiotic factors like drought, salinity, floods, or deforestation in addition to application of fertilizers, pesticides and advanced technology that will promote food production (Fabiyi et al 2025). Food security encompasses economic and physical access to adequate, secure and nutritive food to meet the dietary needs and food preferences of citizens of a nation in order to secure an active and healthy life (FAO 2018; Jagadesh et al. 2024).

The Global Food Security Index (GFSI) is the relative measurement tool used in determining the level of food security status from one country to another based on the level of availability, affordability, qualitative and safety of food to the inhabitants of a country. It affords each country an opportunity to measure its status quo based on these indices that spells out the food security level and serves as a veritable international standard for measuring food security status of a nation. Data from various regions worldwide indicate that the number of food-insecure people in countries such as those in South America and many parts of Africa, including Liberia, Nigeria, Uganda, Somalia, Sudan, Malawi, Tanzania, and Zambia, increased

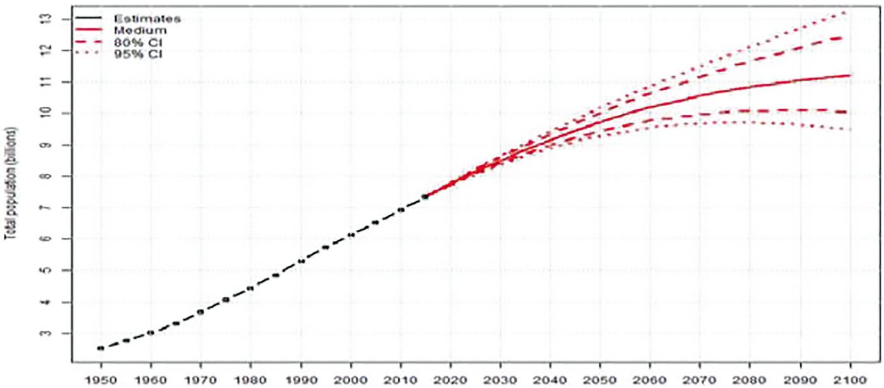

Fig. 4.1 Median variant projections of world population 2015–2100. (Source: https://en.wikipedia.org/wiki/Projections_of_population_growth#cite_note-UN-WPP-2015-4)

from an estimated 804 million in 2016 to nearly 821 million in 2017 (FAO 2018). When a country is not food secured, it manifests in diverse ways in forms like chronic food deprivation, inadequate access to healthy food, poor physiological adaptations due to food restrictions will and can eventually lead to all manner of health impairment like being underweight, overweight and obese. Available data showed that Africa constitute the major continent where a higher proportion of people are known to not being food secured. Data from the United Nations shows that the number of people suffering from hunger rose by about 38 million to 815 million (11%) of the world's population in 2016.

Report given by Squires and Glenn (2004) on the global impart of salinity, revealed about 30% of agricultural land becoming saline. According to the estimate of Bot et al. (2000), million hectares of land has been affected by soil salinity and has affected the economy to about twelve billion dollars per annum. According to FAO (2000), salinization occurs mostly in extremely dry soils and semi-tropical areas where irrigation is practiced with poor quality water. Developing and developed regions both experience soil salinity as shown in Fig. 4.2. Diverse strategies have been employed to mitigate its effect on crop production. Improper agricultural practices in dry regions lead to land deprivation through increasing concentration of salt.

Some countries that are affected by soil salinity includes: Bangladesh, where crop production is hindered as a result of climate change, poor irrigation water source and increasing excess soluble salts (Miah et al. 2020); Pakistan, affected by highly concentrated salt rates whereby the biological, chemical and physical properties of soils are affected (Syed et al. 2021); India, where a large portion of the land is under soil deprivation, salinity, water-logging, wind erosion and other environmental forces (Godfray et al. 2010; Kumar and Sharma 2020). Omar and Moussa (2016) reported that Egypt depends majorly on the water from Nile river; accounting for 93% of the country's conventional water resources. Application of shallow

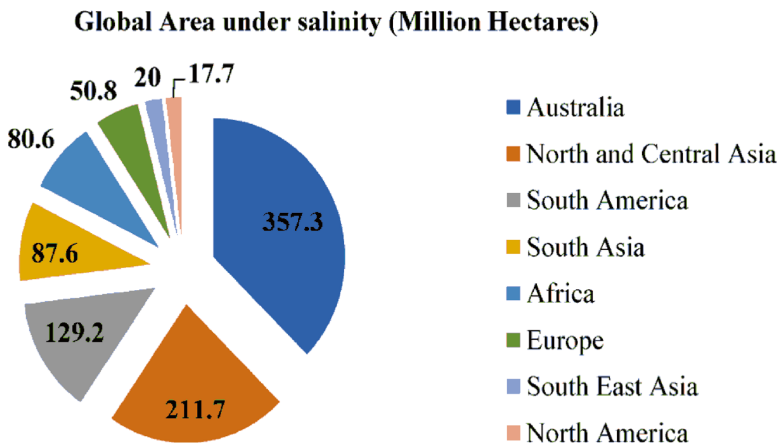

Fig. 4.2 Global distribution of salt-affected areas. (Source: Szabolcs 1993; Khan et al. 2011)

water, waste water and re-use of drainage water has been employed to fill the gap between water demand and water availability in Egypt.

Increasing deposits of salts in soil and water results in salinity, which limits plant growth and crop production (Zaki et al. 2011). This could either have occurred naturally or as a result of environmental activities, such as: improper irrigation management, temperature, sea level intrusion, excess irrigation, poor drainage, climate change and irregular rainfall. This is prevalent in desert areas or semi-arid areas. Some environmental factors that affect crop production include: light, temperature, availability of water and alkalinity.

4.2 Typical Abiotic Factors Affecting Plants

Typical abiotic stress types as reported by Safdar et al. (2019) include:

4.2.1 Drought

Insufficient moisture as a result of absence of rainfall, low water potential or low soil moisture content can result in drought. Consequently, there is a high rate of water loss from the aerial parts of the plant than water uptake from the roots. In order to save some water, plants close their stomata or the tiny pores on leaves. Symptoms that accompany drought stress includes: leaf scorching, yellowing of leaves, leaf rolling or wilting of plant leaves (Seleiman et al. 2021; Kumari et al. 2022).

4.2.2 Temperature

Plant functions can be affected by both high and low temperatures. While low temperatures can result in chilling injury, which affects cell structure and metabolic processes, high temperatures can cause heat stress, damaging proteins and membranes (Choudhary et al. 2025). Plants are constantly exposed to temperature changes throughout their lifecycle. As a result, there is needing to constantly adapt to various environmental changes. One of such changes is the global warming effect; whereby ocean and land temperatures are on the increase. This has been observed to affect the crop yields, over time.

4.2.3 Salinity

Presence of soluble ions in the soil, such as potassium, sulphate, sodium and chloride is known as salinity. Potassium and sulphate salts are considered to be more beneficiary to plants, while sodium and chloride ions are not measured as plant nutrients. Among the cations in the soil, an excess of sodium ions is referred to as sodicity (Qadir et al. 2007). Salinity can be brought about as a result of natural phenomenon, such as mineral weathering processes, water table quality or topography (Sverdrup and Warfvinge 1988). This is often referred to as primary salinization. Irrigation without proper drainage and water logging are referred to as secondary salinity. Consequently, salts are gradually accumulated in the soil, without being washed out, thereby mitigating growth of plant (Ayers and Westcot 1985). The effect of these salts in the soil by environmental and agricultural practices can upset the growth and development of plants negatively by affecting the availability of essential nutrients for plants as well as its water uptake. This results in ion toxicity, imbalance of nutrients as well as dehydration. Other abiotic factors include: Deposit of minerals, poor irrigation practices, effect of light, excess application of fertilizers, industrial wastes, deforestation, overgrazing.

4.2.4 Mineral Deposits

Natural activities such as weathering of rocks, mineral deposits, evaporation of water gradually accumulates salt deposits over a period of time, which adversely affects crop production.

4.2.5 Irrigation Practices

Too much irrigation and using low quality water can lead to increase in salt content in the soil. Poor drainage system can lead to accumulation of salts.

4.2.6 Light

Too little or too much light can be harmful. Low light levels can hinder photosynthesis, and high light levels can cause photo-inhibition, which is the damage of photosynthetic pigments by light energy.

4.2.7 *Excess Fertilizers*

Essential nutrients required for plant growth, such as potassium, nitrogen and phosphorus, are encapsulated in form of fertilizers. They enhance efficient nutrient uptake, strengthens plants against diseases and pests, thereby improving crop yield, when applied in proper quantity. Application of fertilizers in excess can result in too much deposits of salt, limits uptake of nutrients, cause toxicity of excess ions and environmental pollution.

4.2.8 *Industrial Wastes*

An accumulation of heavy metals, as a result of industrial effluents in the soil can harm cell membranes, interfere with plant growth, and disturb a number of metabolic processes.

4.2.9 *Deforestation*

This practice exposes the soil to adverse weather conditions particularly in arid areas; causing salt migration in upper and lower layers.

4.2.10 *Overgrazing*

Excessive overgrazing caused by animal husbandry in search of fodder has resulted in soil exposure and increasing salinization. As pasture diminishes, it often results in desertification.

4.3 Influence of Abiotic Factors on Plants Growth and Development

Plant growth is hindered in situation where there is deficiency of water supply due to minimization of extension of cell wall and turgor. The cell enlargement is more affected than cell division under this situation. In mild cases, an increase in respiration is observed, while in severe conditions, respiration decreases. Plants exposed to drought stress often undergo osmotic adjustment to adapt to these challenging conditions. The plant maintains rise in sugar content in roots compared to the shoots and experiences more growth in the former. Some of other effects of increasing temperature, such as inhibition of protein synthesis, changes in respiration and photosynthesis, cell mitigation. Low temperatures can affect crop growth by reducing nutrient uptake and minimizing metabolic processes. Heat stress is induced as a result of high temperature in plants, reduction of photosynthetic and metabolic processes, generation of ATP, electron transport rate and consequently, crop production (Wahid et al. 2007; Choudhary et al. 2024; Fabiyi and Ogundele 2025). In addition, the reproductive parts of a plant are affected resulting in minimized fruiting and yields (Prasad et al. 2008; Verma et al. 2020).

One of the effects of salinization is degradation of land, which eventually affects crop production and security of food. Consequently, global agricultural revenue is affected (Wichelns and Qadir 2014). The soil structure deteriorates as a result of sodification, thereby resulting in penetration of air in the soil as well as permeation of water. This leads to minimizing oxygen and water availability to plants (Stavi et al. 2021; Kumar et al. 2024b). There are two main effects of salinity on plants. First, the osmotic effect whereby, concentration of salt in the soil or water is higher than the concentration of salt inside the plant's cells. Consequently, a difference in osmotic pressure is created making it difficult for the plant to take up water from the soil. As a result, the plant experiences dehydration and wilting, leading to reduced growth and productivity. Secondly, there is ionic stress which occurs when high levels of salt in the soil or water lead to an excess accumulation of certain ions, such as sodium (Na^+) and chloride (Cl^-), inside the plant's cells. These ions can interfere with normal cellular processes, disrupt ion balance, and cause toxicity symptoms such as leaf burn, chlorosis, and necrosis. Ionic stress can also disrupt nutrient uptake and transport, leading to nutrient imbalances in the plant. Various crops react to salinity in diverse ways; while halophytes grow under saline conditions, glycophytes mostly exhibit reduction in growth and total yield. Secondary stress is induced as a result of ion toxicity and osmotic stress, resulting in diminished development in plants. Other effects include reduced photosynthetic activities arising from stomatal closure and continuous growth of oxidative species in plants (Hasanuzzaman and Fujita 2022).

4.4 Plant Response Mechanism

Plants make use of three main strategies in handling drought stress. These are: avoidance of stress, stress escape and stress tolerance. In avoiding stress, some plants make use of mechanisms that involves seasonal growth before commencement of the dry part of the year, reducing plant life cycle, self-reproduction, early flowering, etc. This has an implication of minimized growth period of plant and consequently plant productivity. In addition, reducing transpiration loss by stomatal closure, as well as high water intake from root system is also employed. Other plant mechanisms include: solute accumulation, antioxidant defence as well as osmotic adjustment among others. Plants respond to moderately high temperatures, by increasing growth of parts of plant, as well as make some changes like lengthening of the petiole, leaf hyponasty for monocots and dicot plants (Bawa et al. 2020; Rajput et al. 2021a). At the same time, plant organs development is influenced by increasing temperature. This is to protect the organs from the negative effects of the temperature rise (Zhu et al. 2021). For temperatures resulting from climate change, the flowering stage of the plant is enhanced (Zhao et al. 2020), while for male plants, sterility is inhibited. Opening of the stomata is observed for high temperatures. These morphological and physiological changes come along with cooling of the leaf parts (Kostaki et al. 2020). For high temperature changes, the process of light and photosynthesis is also affected, by minimizing the content of the chlorophyll (Mishra et al. 2021). To minimize the negative effects of excess temperature, Good irrigation practices, heat and cold-tolerant crops can be employed (Lobell et al. 2013).

Plants respond to saline stress in two ways. Firstly, cell expansion is inhibited and there is closure of stomata resulting in growth reduction, independent of ion concentration. Secondly, as the concentration of ions build up, the metabolic processes slow down leading to cell death. This is accompanied by series of molecular and physiological mechanisms such as: tissue tolerance, ionic tolerance and osmotic tolerance (Isayenkov and Maathuis 2019). Stomata closure reduces carbon accumulation. Transpiration is also limited so as to reduce loss of water. Chlorophyll content is reduced as a result of salinity stress; generally, limiting photosynthetic activities. To protect the over minimization of the photosynthetic electron chain, photorespiration has been adopted by plant. In addition, water cycle is another protective mechanism (Acosta-Motos et al. 2017).

Salt stress can affect the uptake of essential nutrients required by plants for growth and development, where sodium and chloride ions are in competition with phosphorus, nitrogen and potassium ions (Balasubramaniam et al. 2023). However, certain plants are known to be salt-tolerant; in such cases, growth in plants are not affected. Accumulation of osmolytes and compartmentalization of salts in vacuoles assist in mechanism for salt tolerance in plants (Acosta-Motos et al. 2017). Recent developments have introduced the application of NMs for better agricultural practices. Nanomaterials have relieved osmotic and ionic stress, enabled ROS detoxification, improved plant tolerance to salt stress by protecting photosynthesis in plants. Nanomaterials that have been employed include: zinc oxide, silicon oxide, titanium oxide, carbon quantum dot NPs (Li et al. 2022).

4.5 Brief Overview of the Current Challenges Faced in Crop Protection and Saline Stress

Low yield or reductions in cultivation of crops in agriculture have been triggered by a combination of biotic and abiotic factors. These factors range from environmental pollution, climatic variations, water and soil nutrients demands and agricultural land availability. Among these limiting factors is a hazardous indicator to crop growth and protection called saline stress which falls under environmental factors. This is also known as soil salinization. It literally connotes extreme accumulation of salts dissolved in the soil which inhibits growth and development of the plants (Safdar et al. 2019). High salt concentrations in the soil cause soil stress, leading to several negative outcomes, including reduced seed germination, inhibited seedling growth, and decreased water uptake by plant roots, this subsequently leads to retention of salts in plant tissues such that it becomes poisonous to the plant growth. Moreover, its impaired effect on seed germination arises from the osmotic built up at the external part of the seed which hinders absorption of water by the seed. Studies reviewed further shows that saline stress in plants also inhibits the process of photosynthesis in plant growth. The reduction in vegetative part of plants linked to high concentration of salts in plants was related to a significant delayed process of photosynthesis in these plants (Mandal 2019). However other studies revealed that this finding of salt concentration in plants linked with delayed photosynthesis process does not suffice for majority of other plant species (Safdar et al. 2019). The implication of saline stress on photosynthesis process in plants has been attributed to the specie of plant in view as well as salt concentration. This connotes that when there is low concentration of salts in the plants there is probability that the photosynthesis rate may be activated. Other limitations soil salinity brings encompasses weakening of cells metabolism, slowing down plant nutrition rate, osmotic stress, reduction in microbial activities thereby slowing down the rate of water and nutrient uptake in plants from the soil (Van den Burg et al. 2024).

Seeds need adequate water and nutrition in order to germinate. Seed germination requires enzymatic hydrolysis by α-amylase in order to break down the carbohydrate stored in the endosperm so as to release the energy required for the growth and development of the growing embryo (Weiss and Ori 2007). Presence of salinity reduces the uptake of quality water and nutrients (Munns et al. 2020). This is as a result of the osmotic pressure in the soil being reduced compared to the osmotic pressure in the seed. Consequently, the period of seed germination is prolonged. After germination, viability of the embryo is hindered due to the accumulation of excess chloride and sodium ions (El Sabagh et al. 2021).

Some ions are beneficial to plants, these ae: potassium, sulphate, nitrate ions. However, some are not referred to as nutritious. These are: chloride and sodium ions. Increasing concentration of such ions in soil solution lowers its osmotic pressure, thereby reducing the absorption of water from the soil. This results in osmotic stress, which hinders growth and crop yield. Also, absorption of sodium or chloride ions by the plant can lead to cytotoxicity, resulting in stunted growth of plant. High levels of sodium ions leads to competition of cations, whereby essential nutrients like magnesium, calcium ions may be unavailable; resulting in nutritional deficiencies (Atta et al. 2021).

Reactive oxygen species are primarily produced in cytosol, endoplasma, mitochondria, and chloroplasts. Water deficiency in addition to saline stress causes the oxygen species to have a damaging effect on plant organs. Earlier reports have shown damages done to crops like *Zea mays, Oryza sativa* and *Solanum lycopasicum* (Kaveh et al. 2011; Khodarahmpour et al. 2012; Rahman et al. 2016). Effect on

Crop Yield: Studies have shown how abiotic stress, especially, salinity can affect crop yield. Inadequate water uptake, reduced transpiration, stomatal closure, lower photosynthetic activities and oxidative damage due to salinity stress have contributed to a drop in crop production. The table below shows the extent to which salinity has affected several crop yield (Table 4.1).

4.5.1 An Obstacle to Plant Development

The amount of soluble salts in the soil, or soil salinity, is a significant environmental issue that affects agricultural productivity across a wide range of global regions. To ensure sustainable agricultural practices, it is essential to comprehend its causes, effects, and possible management solutions (Zhao et al. 2020; Kumar et al. 2024c). Salinity stress in plant is a condition whereby salts in the soil, such as carbonates, nitrates, chlorides, phosphates, sulphates, reach a concentration such that it becomes harmful to the growth and development of the plant. This is often accompanied by diverse alterations in the photosynthetic, biochemical, enzymatic and physiological activities of the plant resulting in delayed growths and reduced yield of the crop. Plants under salinity stress usually undergo limited water uptake, imbalance of nutrients, osmotic stress, ion toxicity, reactive oxygen species and hormonal imbalance (Wang et al. 2011; Kumar et al. 2020).

Irrigation salinity and dry land salinity are the main types of salinity. Irrigation salinity takes place as a result of accumulation of salts on the soil surface from rigorous irrigation practices with groundwater and leaching of irrigation water. Accumulation of concentrated salts on non-irrigated soil, is referred to as dry land salinity. Processes linked with dry land salinity includes: ground water movement, deep drainage and ground water discharge. Dry land salinity can be primary or secondary in classification: primary salinity occurs as a result of high concentration of salts in the soil or water, in arid or semi-arid regions, attributable to low rainfall and high temperature. Secondary salinity is as a result of activities such as: mining, industrial processes and irrigation (Atta et al. 2023). Methods through which salinity can be measured in soil or water include: Total dissolved solid measurement,

Table 4.1 Yield reduction due to salinity stress on different crops (Atta et al. 2023)

Crops	Yield loss (%)	Source
Maize (*Zea mays*)	50–60	Zorb et al. (2018)
Wheat (*Triticum aestivum*)	10–50	Yadav et al. (2020)
Sorghum (*Sorghum bicolor*)	15–50	Kenneth and Neeltje (2002)
Rice (*oryza sativa*)	30–50	Hoang et al. (2015)
Groundnut (*Arachis hypogaea*)	25–50	Zorb et al. (2018)
Barley (*Hordeum vulgare*)	10–60	Abd El-Monem et al. (2013)
Cotton (*Gossypium* spp.)	10–20	Zorb et al. (2018)

electrical conductivity measurement, chloride ion concentration measurement, sodium ion adsorption measurement, soil sampling and laboratory analysis.

Some of the causes of salinity in soil include: weathering of rocks that contain soluble salts is a natural process; tidal inundation near the coast; evaporitic processes that leave concentrated salts behind in arid areas; human endeavours; Using salted water for irrigation: Using salted water on a regular basis can cause the soil to become salted; Poor drainage: Salts can accumulate in the soil due to inadequate drainage, which prevents them from leaching (Singh et al. 2022). Some of the effects of salinity on soil include: Decreased water availability: Plant roots have harder time absorbing water from the soil because salt produces an osmotic pressure gradient. Plant growth is stunted and water stress results from this. Unbalanced nutrient intake: excessive salinity can interfere with plants' ability to absorb vital nutrients, resulting in deficits that hinder growth and development (Tanveer et al. 2020). Changes in soil composition: Salts can disrupt soil particles, leading to a loose soil structure, reduced water infiltration, and increased erosion. Decreased microbial activity: Excessive salinity can harm soil health and nutrient cycling by inhibiting the growth and activity of beneficial soil microorganisms (Ding et al. 2020). Some of the effects of saline stress on plant include**:** osmotic, oxidative, metabolic stresses and growth inhibition.

Plants that have trouble getting water and nutrients grow in an unnatural way. Stress induced by abiotic agents can cause hormonal alterations that favour survival over growth, which reduces the rate of cell division and elongation of shoots. Salt toxicity and water stress make it difficult for seeds to sprout. Salinity stress can also induce leaf injury. The browning and dying of leaf tips and margins can be caused by salt-induced tissue death. Overall crop yields are greatly decreased as a result of hampered plant growth and development (Zheng et al. 2023). Exposure of plants to high levels of salt, results in a number of disrupted physiological and biochemical processes resulting in reduced photosynthesis, nutrient imbalance, impaired growth, and oxidative damage. High concentration of ions in the soil affects the osmotic balance in the root of crops. Increasing absorption of sodium ions by plant cells causes a disruption in cell activities such as enzymatic activities, maintenance of the membrane potential as well as cell tugor (Yadav et al. 2020).

Abiotic factors like drought, temperature, salinity have adverse effect on plant crop productivity. However, increase in the oxygen reactive species in some plants, is as a result of salinity. Oxidative stress is observed when there is an imbalance between production of reactive oxygen species and its detoxification by mechanisms of antioxidants. This results in mutations of genetic parts of the plant like the proteins, RNA, DNA and finally, cell mutation (Mishra et al. 2023). Metabolic activities in plants are affected by abiotic factors. Some of these activities include: reduced photosynthesis, nutrient assimilation, respiration. Saline stress induces synthesis of abscisic acid in plants which results in stomata closure. Consequently, photosynthetic activity is hindered. Unbalanced nutrient uptake and translocation: Increase in uptake of ions can cause deficiencies or imbalances in nutrients that can hinder a plant's ability to grow and develop.

4.6 Nanomaterials and Their Potential in Plant Saline Stress Management

Application of nanotechnology to agriculture is a method employed for treatment and detection of plant diseases which fuel availability of plant nutrients thereby improving crop production, health and soil fertility. It has been established earlier that soil salinization could be as a result of a natural course or biological, physical and organic agricultural activities such as climatic variations. While on the other hand it could be due to unnatural courses such as poor irrigation practices, inadequate land clearing practices, poor drainage, erosion and upward movement of salts from the sub-soil to the surface soil. In time past, farmers have used several measures in reducing the fertility of agricultural land for optimum production by using crop rotation method, shifting cultivation, mixed cropping, these contemporary times, a lot of researches have been evolving towards the deployment of nanotechnology in developing improved materials, tools and devices that can control salty soils.

Application of nanotechnology in agriculture can be viewed as a new approach through which researchers can use in understanding and creating a new tool that can help in the identification and management of plant diseases. Nanomaterials could be classified into different categories: metals, metal oxides, metal sulfides, carbon, graphene oxides, lipids or polymers. Some examples of metals like Zn, C, Fe, Ag, Au, Ni, for metal oxides, i.e., Al_2O_3, CeO_2, MnO_2, TiO_2, Fe_2O_3, for metal sulphides, such as ZnS, CuS, AgS, FeS_2 (Sharma et al. 2019). Myriads of opportunities and possibilities are embedded in the use of NMs especially with regard to precision agriculture. It has scientific proofs of conserving resources and has more energy efficiency (Bhardwaj et al. 2019).

The roles of NMs in reducing plant saline stress cannot be overemphasized. These include bringing a geometric progression to agricultural production by improving soil fertility, ensuring adequate supply of nutrients to the plants and eliminating the osmotic imbalance causing soil salinization. When saline stress has been eliminated in a plant, there are other features within the plants that experiences radical transformation. These features include excellent germination of seeds, large growth of plant vegetative parts, healthy formation of the shoot and root regions of the plants, enhanced chlorophyll content, coloration and photosynthetic rate (Babaei et al. 2017). Farmers capacity is enhanced to improving the quality of agricultural products maximally in terms of reduction of farm input materials and resources (seed, water, fuel, etc). Significant attainment of the genetic potential of desired crop is speedily realized as this new phase of NMs usage is embraced. Soil health balance is much more pronounced as a result of reduced number of pesticides as it also aids reduction in over-dependence of agriculture in climatic variations. The importance of these unique materials in curbing saline stress reviewed in past studies include building defence systems of plants, helps in scaling up hormonal concentrations, ion homeostasis, gene expressions and antioxidants enzyme activities have been facilitated efficiently.

Plants treated with NMs exhibit fortification against various abiotic stresses and enhance improved photosynthetic activities, transpiration rate, stomatal conductance, water efficiency and proline content. Nanomaterials stimulate activities of antioxidant enzymes, accumulation of free amino acids, nutrients and osmolytes (Khan et al. 2017). Application of NPs to the leaves of plants has been shown to increase the amount of chlorophyll and photosynthetic responses. Previous studies show addition of zinc NPs to plant under salinity stress to exhibit improved photosynthetic activities as well as improved fluorescence activity (Cao et al. 2018).

4.6.1 Accumulation of Phenolic Compounds

Earlier studies reveal that addition of NPs to plants have contributed to an increase of phenolic compounds in plants. Experimental results show increase in phenolic and flavonoid metabolites particularly in the root of plants. Copper and zinc NPs exhibit similar properties by increasing glutathione, polyphenols, flavonoids and phenolic contents (Khan et al. 2020; Rajput et al. 2021a).

4.6.2 Improved Nutrient Uptake

Nutritional deficiencies in plant are one of the effects of salt stress, as a result of imbalance in nutrient uptake. Addition of NPs, such as silicon dioxide and copper has been observed to promote growth and balance of sodium/potassium ratio by increasing the amount of potassium in leaves (Rehman et al. 2024).

4.6.3 Strengthens Antioxidant Defence

Some NPs show certain characteristics similar to some antioxidant enzymes by removing oxidative species. Earlier studies reveal CAT–like attributes of cobalt and cerium NPs, while copper, iron and manganese show POD-like behaviour (Rico et al. 2015). The growth features of plants were enhanced as a result of the antioxidant activities.

4.6.4 Nanomaterials Mitigate Plants Saline Stress

Nanomaterials have emerged as promising agents in mitigating saline stress in plants, offering new avenues for enhancing plant growth and productivity in saline environments. There are several ways in which the saline stress in plants could be alleviated using NMs. Some of the few ways include:

4.6.5 Osmotic Adjustment

There are certain NMs that helps plants to maintain osmotic balance in saline conditions. They do it by modulating the levels of osmolytes, such as proline and glycine, betaine, which protect plants by stabilizing proteins and membranes. The growth of plant at earlier stages are usually affected to quite a significant level when water sustainability NPs are employed. It has also been established that NPs promote plant growth; and when higher doses of NPs are employed, this can impair a negative impact also on the plant (Verma et al. 2022).

4.6.6 Nutrient and Water Uptake

The efficiency of nutrient uptake in plants in saline conditions can be improved using NMs. The creation of NFs has the role of releasing nutrients in a controlled manner, making them more available to plants and this helps in mitigating the adverse effects of salt stress. Ahmad and Akhtar (2019) gave insight on the applications of different types of NMs in controlling salt stress in plants. It was shown that the NMs were able to enhance water uptake in plants, protected crops from invasion by diseases and pests and improved precision farming.

4.6.7 Antioxidant Defence System

Reactive oxidative species can accumulate in plants due to salinity stress. Nanomaterials with antioxidant properties like carbon based NPs or metal NPs can enhance the antioxidants defence mechanism in plants, by scavenging the oxidative species. Plant physiological function is maintained by reducing the oxidative damage by employing copper, iron, manganese and celenium NPs which act in similarity to antioxidant enzyme glutathione peroxidase, while iron celenium and cobalt NPs act similar to enzyme catalase (Yang et al. 2017; Khalid et al. 2022).

4.6.8 Ion Homeostasis

NMs can assist in maintaining ion homeostasis by enhancing the selectivity of ions, reducing the uptake of toxic ions, like Na^+, and improving the uptake of beneficial ions (like K^+), thus alleviating the ionic stress component of salinity. This results in increased osmotic potential within the plant. Tomato growth performance was enhanced as well as its sodium/potassium ratio, on foliar application of copper NPs. Likewise, the soya bean leaf seedling growth was enhanced on application of silicon dioxide NPs, by increasing concentration of potassium ion in the leaf (Khalid et al. 2022). Mushtaq et al. (2018) illustrated the application of SiO_2 NPs for both fresh and dried parts of tomato plant. They reported an increase in chlorophyll content, enhanced seed germination and improved proline accumulation. Laware and Raskar (2014) illustrated how the application of titanium oxide NPs in onions improved seedling growth and seed germination. It was also employed to induce the release of antioxidant enzymes. Another example of effect of NPs, cerium oxide on *Brassica napus* L was studied by Rossi et al. (2016). It was reported to have improved nutrient uptake, proline, the leaf pigment chlorophyll increased, as well as photosynthetic responses. In addition, Soliman et al. (2015) identified the effect of iron magnetic and zinc oxide NPs on Moringa plants. There was improvement in the macro and micro nutrients, enzymes, non-enzymes and antioxidant within the Moringa plant.

4.7 Transformations of Nanoparticles

Nanoparticles have various modifications in their interactions with environment. These modifications are of immense importance to their effectiveness on plants. Nanomaterials are synthesized at the nano scale using diverse techniques which could be biological, physical, or chemical in nature. These materials are characterized based on their sizes, shapes and surface areas. This will enable the effective determination of the efficiency of the NMs. Aggregation or dispersion of the NMs will depend on the amount of ions present and the pH of the water or soil. Presence of ions can bring about electrostatic repulsion or attraction of the NMs, while the organic substances can stabilize or destabilize the NMs. The coatings of NMs are carefully selected in order to enhance the effectiveness of NMs as well as their uptake. The coatings are modified based on factors like temperature and ions present in the soil (Alallam et al. 2023).

Chemical changes that take place in the environment can affect the impact of nanomaterials in the biological systems of plants. This is due to oxidation and reduction reactions that are likely to take place with metal NPs. Therefore, it is important that the NMs are designed to enhance their strength, reactivity and conductivity in its application (Staron et al. 2020). Interactions of NMs with the components in the soil such as organic matter, microbes and minerals can lead to alterations in the microflora of the soil and its fertility (Yang et al. 2017). The minute nature of NMs allows them to dissolve in soil water and then absorbed into the plant cells, through the root system. They get to the xylem by means of the cortex and the pericycle. This allows for interactions and modifications in the morphological and physiological activities of the plant (Burman and Kumar 2018). Chemical processes which initiate oxidative reactive species, reactions in plants, transportation, lipid peroxidation, guide the reactions of NMs in plants (Rehman et al. 2024). Nanomaterials move from one part of the plant to another.

4.8 Applications of Nanoparticles

Development of NMs in agriculture has given a promising outlook on the growth and development of crops (Fabiyi et al. 2021, 2023a, b). Recent studies reveal the effects of various NPs on plants. Silver NPs applied to wheat, tomato, carrot and rice enabled their growth and yield, zinc oxide, alumina and zinc enhanced germination and growth of cucumber, corn cabbage and lettuce. One of the essential micronutrients required for growth in plant is zinc. However, studies have shown that it protects the plant cells against oxidative species. Zinc has a biochemical role in the formation of chlorophyll and in the manufacture of indoleacetic acid from tryptophan (Fabiyi et al. 2018, 2024b; Ghidan and Al Antary 2020; Fabiyi 2021; Fabiyi and Olatunji 2022). Nano particles are efficient transport systems of agricultural inputs to the target sites. Silicon NPs transport fertilizers and pesticides to the desired site, as well as assist in water retention by acting as a nano-zeolite. It also acts as a nanosensor by detecting metals present in plants. Multi-walled carbon nanotubes, are employed in studying accumulation of pesticides in roots and shoots of plants.

Plants have always been seen to adjust to abiotic factors such as: drought, heat and salinity. Certain NPs have been employed in managing saline stress. For example, drought stress on wheat was minimized with the application of titanium NPs. Other NPs utilized in drought stress include: sodium and silicon silicate (Pei et al. 2010). According to Mohammadi et al., plant membrane disruption, ion leakage has been minimized by application of titanium oxide NPs. Other types of NPs that aid absorption of nutrients, growth of amino acids, proline, improve activity of antioxidant enzymes and enhance tolerance of plants against the severe environment, include nano silicon oxide and nano zinc oxide (Elsakhawy et al. 2018). Mesoporous silicon NPs can be applied to crops in various ways. It could be applied as a supplement to the soil, or in a powdered form to the nutrient solution where it would be absorbed by the roots or in a liquid form to the leafy parts of the crop which were taken up by epidermal cells or stomata. Suriyaprabha et al. (2014) earlier study showed that the soil application of silicon NPs was more effective than foliage application. Silicon NPs improved the germination of tomato with higher fresh and dry weight of seedlings (Roychoudhury 2020). Calcium borate NPs improved the growth of roots and shoots of lettuce. Fruit settings of strawberry was enhanced as a result of application of zinc oxide NPs. Titanium dioxide, silver NPs, multi-walled carbon nanotubes have enhanced growth of crops such as: soybean, cotton, barley, maize and spinach (Liu et al. 2021). Several types of NPs have been formulated to alleviate salinity stress in plants. Some of these NPs include: silica, chitosan, zinc, iron oxide, silver, copper oxide, titanium oxide NPs (Junedi et al. 2023).

4.9 Synthesis and Characterization of Nano Formulations for Plant Saline Stress

The introduction of nano-formulations has brought advancement in lowering the effects of saline stress on plants, as well as transferring nutrients in a targeted manner. Basically, nano materials can be synthesized physically, chemically or biologically (Dulta et al. 2020). The reduction of bulky materials into a nano scale is referred to as the physical method; while the chemical synthesis involves the application of chemical reactions in synthesizing NPs (Table 4.2).

4.9.1 Nano Agricultural Inputs

These are a novel class of agricultural materials that harness the power of nanotechnology with new functionalities to address modern agricultural challenges. These advanced materials combine the unique properties of NPs with targeted delivery systems to enhance plant growth, productivity, and resilience in a sustainable manner. Smart nano-agri inputs (SNAIs), provide more control and customization, enabling customized solutions based on unique crop needs and environmental conditions (Wang et al. 2020). Other benefits include: optimized photosynthesis, certain NPs, like metallic or carbon nanotubes, can act as light antennas, gathering solar radiation and focusing it on the pigments in plant cells that are engaged in photosynthetic reactions. Examples of Smart nano-agri inputs are as NFs, nanosensors and nanopesticides, and nano encapsulated biopesticides encasing natural biocontrol agents or targeted pesticides for controlled release and increased efficacy against particular pests and diseases (Fabiyi 2025). NFs consist of nano-sized materials having micro or macro nutrients like: nano-urea, nano-iron, nano-zeolite, nano-potash, nano-apartite (Chhipa 2017; Xin et al. 2020).

Macronutrients such as carbon, calcium, magnesium, phosphorus, potassium and nitrogen are encapsulated by various NMs. Studies have shown enhancement in

Table 4.2 Nanoparticles synthesized from the various method (Ealia and Saravanakumar 2017).

Category	Method	Nanoparticles
Bottom-up	Sol-gel	Carbon, metal and metal oxide based
	Spinning	Organic polymers
	Chemical Vapour Deposition (CVD)	Carbon and metal based
	Pyrolysis	Carbon and metal oxide based
	Biosynthesis	Organic polymers and metal based
Top-down	Mechanical milling	Metal, oxide and polymer based
	Nanolithography	Metal based
	Laser ablation	Carbon based and metal oxide based
	Sputtering	Metal based
	Thermal decomposition	Carbon and metal oxide based

absorption of fertilizers as well as reduced outflow of fertilizers. Chitosan NPs loaded with nitrogen, potassium and phosphorus have shown increase in absorption of the essential elements in coffee plant (Liu et al. 2021). Micronutrients such as: iron, zinc, copper, boron, manganese when enclosed in NPs, such as chitosan, copper, calcium, and zinc oxide NPs have enabled effective accessibility of micronutrients to plants. Micronutrients are involved in physiological and chemical processes in plants such as photosynthesis, enzyme activities. Nano encapsulated fertilizers are enhanced to resist degradation by evaporation, photolysis, microbial decomposition or weathering (Liu et al. 2021).

Nano-encapsulated nutrients provide a slow-release mechanism that improves nutrient use efficiency and minimizes leaching losses, particularly beneficial in saline soils. The nano fertilizers are employed by modifying the normal traditional fertilizer, or by extracting different vegetative or reproductive parts of the plant. Scientists have successfully introduced carbon nanotubes into plant photosynthesis's site, the chloroplast, and have seen an increase in electron flow and total photosynthetic activity as a result. Research is being conducted to determine whether it is possible to use NPs to directly supply chloroplasts with protective molecules or vital nutrients, thus improving their resilience and functionality (Elhefnawy and Elsheery 2023).

4.10 Challenges of Nanoformulations

Nanomaterials have been applied as a form of nano-remediation in agriculture, by enhancing ability of plants against abiotic stress, managing plant diseases, improving nutrient absorption, inhibiting loss of nutrients, waste water management. However, elevated concentrations of nanomaterials (NMs) can have adverse effects due to the generation of free radicals. The molecular mechanisms involved in the interactions between NPs and plant cells needs to be adequately studied. For instance, the influence of NPs involved in anti-oxidative activities in plants which enables plants to withstand any type of stress. This will enable the designing of specific NPs to meet specific targets (Rajput et al. 2021a, b). The current cost of producing and implementing NPs-based agricultural solutions on a large scale prevents their widespread adoption. For instance, treatment with silver or gold NPs is not economically reasonable (Rajput et al. 2021a, b).

Intake of vegetables and fruits encapsulated with NPs can result in ingestion of NPs into certain organs in the body such as blood, spleen, heart, liver or brain. Accessibility of NPs into the nucleus may result in damage to the DNA (Rajput et al. 2021b). Neural inflammation has been reported on exposure to ferric oxide NPs and titanium oxide NPs. In addition, further studies that enhances understanding of the interactions between NMs and plant cells and how it relates to biochemical pathways is necessary in order to identify which NPs will be most suitable under various conditions. Continuous application of NMs in crop sustainability can have effect on the public and environmental health, thereby creating the need for policies and regulations for use and sustainability. Careful consideration and risk assessment are required for the long-term consequences of introducing NPs into plant systems as well as any possible environmental effects of using them in agriculture.

4.11 Future Prospects of Nanoformulations

Encapsulating essential nutrients in NPs can promote uptake of nutrients in plants thereby enhancing crop growth, crop yield and improving plant ability to withstand salinity stress. NPs can protect nutrients from leaching and volatilization, increasing their availability to plants and reducing nutrient losses in the soil (Farooq et al. 2022). Sustainable soil management: Nanoformulations assist by mitigating the negative impacts of salinity stress on crop production and support long-term agricultural resilience in salt-affected regions. Nanoparticles can interact with soil components to enhance soil aggregation, water retention, and nutrient availability, thereby creating a conducive environment for plant growth in saline soils (Hussain et al. 2018).

Innovation in crop breeding: Development of salt-tolerant varieties through nanotechnology-based approaches can be driven through nano-formulations. Salt-tolerant crop varieties with improved yield potential and resilience to salinity stress, can be developed by integrating nanoformulations with modern breeding techniques, such as genome editing and marker-assisted selection. Nanoparticles can be used to deliver stress-responsive genes, proteins, and signalling molecules to plants, enabling the targeted manipulation of plant stress responses and enhancing salt tolerance in crops (Rajput et al. 2021a, b). There is need for practicable communication between researchers, industry and policy makers, to promote the production, development and deployment of nanoformulations for plant salinity on a large scale. The future of nanoformulations for plant salinity hinges on their successful commercialization and scalability in agricultural systems. By addressing regulatory, economic, and technical challenges, stakeholders can unlock the full potential of nanoformulations for sustainable agriculture and food production in saline environments.

4.12 Conclusions

Nanomaterials offer diverse mechanisms for managing plant saline stress, covering areas such as nutrient uptake enhancement; ROS scavenging, to gene expression modulation and water balance regulation. The unique properties available in NMs has enabled researchers and agronomists develop innovative strategies to enhance plant resilience to salinity stress and improve agricultural sustainability. Modern technologies such as geographic information systems (GIS), global positioning systems (GPS), satellite-based navigation systems, and remote sensing can be utilized to improve nutrient uptake and enhance productivity Further research into the long-term effects and environmental implications of NMs use in agriculture in cereals and other specific crops is essential to ensure the safe and effective application of nanotechnology in managing plant saline stress.

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