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REVIEW ARTICLE

# Role of nano fertilizers on improving drought tolerance of maize

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## Abstract

Maize is a versatile crop that is primarily used as human food and animal feed. It is also a fundamental raw material utilized in various industrial products owing to its nutritional value. One of the most harmful abiotic stresses in maize cultivation is drought. A water shortage caused by drought limits crop development and yield because there is less available moisture. Water shortage stress causes restricted stomatal opening, enhanced photorespiration and accelerated photoreduction of oxygen in the chloroplast. Eventually, this causes oxidative damage in maize owing to ROS accumulation. Plants respond to drought stress by producing the phytohormone abscisic acid, closing their stomata, changing gene expression and preserving their osmotic balance. Nano micro fertilizers are a phenomenal tool for drought tolerance when combined with deficit soil moisture in maize. When it is paired with deficit soil moisture, nano micro fertilizers are an incredible weapon for drought tolerance under changing climatic conditions. It aids in keeping maize's green characteristics. The greater advantages of using nano micro fertilizers in maize are retention of chlorophyll, regulation of stomatal openings, the activities of antioxidant enzymes, the proliferation of roots and higher grain filling, which resulted in higher productivity. The development of stay-green character and drought resistance in maize is positively influenced by nano micro fertilizer with suitable form and dose. Under drought conditions, nanomicronutrients play a critical role in controlling physiological processes, reducing oxidative stress and preserving cellular homeostasis. Additionally, every micronutrient acts differently and produces a different physiological response related to drought tolerance.

## Keywords

drought; grain; maize; nano; resistance; stay green; stress

## Introduction

Maize is a versatile crop primarily used as human food and animal feed and as a raw material utilized in various industrial products owing to its nutritional value (1). It can be consumed in various forms, such as whole corn, corn meal, corn flour and corn grits. A wide range of foods like tortillas, bread, breakfast cereals, snacks and porridge are made from maize (2). It is also used as animal feed, providing a crucial source of nutrients and energy for aquaculture, poultry and cattle. In addition, maize has several industrial applications. One well-known example is maize processing to extract starch from fermentation, which is then used to produce ethanol for fuel. Moreover, starch, high-fructose corn syrup and other sweeteners can be produced from maize (3). The vast majority of the globe's maize-growing areas are found in temperate climates. Three-quarters of the world's production comes from the United States, China, Brazil and Mexico. India accounts for 2% of global corn production, with 5% of the acreage. Different nations use maize in different ways. The primary uses of maize in the industrialized countries of the globe, comprising the USA, EU, Canada and other nations, are raw material for the extractive and fertilizer industries as well as for direct animal feeding. Maize is used in developing nations in a variety of ways. Maize is mainly consumed for food in Latin America and Africa, although it is also used for animal feed in Asia. In the real world, it's a basic staple food and a major component of many people's diets in many countries (4).

### *Impact of early drought stress on maize*

The occurrence of drought during the flowering and reproductive phases is highly sensitive and causes much damage to productivity. Drought stress reduces crop normal growth and development and limits yield by lowering carbon absorption, stomatal conductance and cell turgor (5, 6). Drought stress primarily causes decreased tissue water content, which reduces membrane stability; it also causes loss of green leaf area, carbon uptake and partitioning, which reduces growth, biomass, and yields. Similarly, membranes are severely affected by temperature extremes, which reduce membrane stability, reduce carbon absorption, increase respiration and decrease floret fertility are the results of high-temperature stress, which also reduce seed output, size and number. While higher membrane stability, greater gamete viability and reproductive success leading to higher seed number, canopy temperature depression, favourable respiration and early flowering are the key traits associated with high temperature (HT) stress, stay green (chlorophyll content), limited transpiration, higher reproductive success and root architecture are the key traits associated with drought tolerance (7).

The intensity of drought stress is identified by the time. Plants that exhibit symptoms of leaf rolling early in the morning are under more stress as compared to plants that begin rolling their leaves later in the day. It also depends on the crop growth stages and occurrence of drought stress during vegetative growth, which results in shorter plant height and generates fewer leaves. Poor nodal root growth in maize under drought stress conditions affects water uptake from the soil turgidity, and plants stay erect. Maize is believed to be less resistant to drought than sorghum (8). Drought stress can significantly affect the germination and shoot length of maize seedlings. The fact that different maize hybrids may exhibit varying degrees of drought tolerance highlights the need for further research in this area (9).

Early drought in maize inhibits plant population per unit area and ultimately affects crop productivity. The critical periods such as seed germination and seedling establishment are particularly susceptible to water stress (9, 10). Water availability is crucial for encouraging shoot elongation, root growth and germination, all of which contribute to the development of a consistent crop stand.

Elevated osmotic potential may hinder seed hydration, affecting germination and early development (11, 12). To sum up, maize is more vulnerable to drought stress than sorghum and when osmotic potential increases, there is a noticeable decrease in the germination response. To ensure sustainable crop production, it is essential to understand the mechanisms underlying maize's resistance to drought and implement mitigation measures to reduce the detrimental effects of drought stress on seed germination and early growth. The productivity and resilience of maize crops under varying degrees of water stress greatly depend on certain factors, like anthesis-silking time sequence. The synchronization between the male (anthesis) and female (silking) flowering stages of maize plants is referred to as anthesis-silking synchrony. Appropriate pollination and kernel development rely on the ideal timing of anthesis and silking. It is crucial to maintain this synchronization during drought stress to ensure proper pollination and kernel set, which in turn affects grain yield drastically. Under drought stress, ASI has a high frequency and a strong correlation with grain yield (12, 13). Another important trait is the number of kernels per cob. The quantity of kernels per ear is a crucial factor that affects the potential yield of maize. Reduced kernel number per ear can result from the effects of drought stress on kernel set and development. In water-limited regions, it is helpful to breed for a greater kernel number during a drought, which can aid in increasing yield stability and productivity. In maize, maturity is defined as the time it takes for the crop to achieve physiological maturity, which is the point at which the kernels are dry and fully formed (12).

### *Terminal drought impact on maize productivity*

One of the most important components for better crop development and production is soil water (14, 15). At the silking stage of the maize plant, soil water stress may lead to a 50% reduction in grain yield (15, 16). At critical stages of crop growth, skipping a single irrigation could result in a 40% reduction in maize production (15, 17). Short-term droughts, sometimes known as flash droughts, start quickly and are frequently accompanied by strong dry winds with high temperatures that cause the soil to rapidly lose its moisture at a crucial point in the growing season (15, 18). Flash droughts are more likely to happen in the growing season when there is a high evaporative demand (15).

The flash drought affected soil water, evapotranspiration, and gross primary productivity (19, 20). Therefore, it is imperative to monitor flash droughts during critical crop growth stages by using both short- and long-term drought indices. Flash droughts can severely impact plants, especially grain crops like maize, by rapidly depleting soil moisture during important growing stages. The study confirms that the one-month Standardized Precipitation Evapotranspiration Index (SPEI) and Standardized Precipitation Index (SPI) are useful tools for detecting flash droughts. These indices accurately matched the decrease in soil water content and were reliable in identifying the onset of the flash drought. To comprehend the effects of drought on crops, it's crucial to understand the relationship between soil water and agroecological parameters such as evapotranspiration and gross primary productivity during different growth stages. The study underscores the importance of normalized drought indices, such as SPI and SPEI, for tracking flash droughts and assessing the severity of droughts (20).

The effect of drought on crop output indicates a substantial danger of yield loss in the event of extreme drought; projected yield losses for maize harvests will be 50.66%. Moreover, yield loss risk dynamics and drought data indicated that a one-unit drop in the Standardized Precipitation Evapotranspiration Index (SPEI) value would result in a 14.2% decline in maize yield. In general, an irregular extended period below the typical water supply can be used to characterise drought. The main cause of droughts is a dramatic reduction in the amount of moisture available owing to insufficient rainfall. Though production technology has its benefits, 60% of yield variability is caused mainly by climate factors, which have a significant influence on crop output trends (21).

### *Importance of Nano micro fertilizers*

Atomic or molecular aggregates having at least one dimension between 1 and 100 nm that differ from the bulk material in a variety of physico-chemical ways are known as nanoparticles (NPs) (22-24). NPs can be made from a range of bulk materials, and their size, shape, and chemical makeup all affect how they work (25). The quantity of particles per unit weight of applied fertilizer rises with decreasing particle size. Also, a fertilizer with smaller particles has a higher specific surface area, which should help fertilizers that are not very soluble in water dissolve more readily (26). The most popular way to supplement nutrients using chemical and organic fertilizers is through soil application. The length of time the fertilizer will remain in the soil, the texture and salinity of the soil, plant sensitivity to salt, the amount of salt in the amendment and its pH all need to be considered when selecting this type of fertilizer delivery. Foliar nutrition involves spraying liquid fertilizers directly onto leaves. Typically, it is employed in the trace element supply chain. Compared to soil application, where iron, manganese and copper get adsorbed on soil particles and are therefore less available to the root system, uptake of these elements may be more efficient with this strategy (27). The plant parts like stomata and leaf epidermal cells play a crucial role in nutrient intake. Applying fertilizers by foliar spray can have agronomic benefits when using nanofertilizers (28).

According to a study conducted (29) utilizing nano-micro fertilizers resulted in a significant increase in plant height, ear weight, number of grains/rows, number of grains/ear, and weight (g) of 100 grains. The highest mean values of these traits were recorded when a combination of nano-Fe + Zn + Mn was applied topically.

Low food nutrition content and poor productivity are mainly attributed to yield-limiting elements such as zinc, iron, manganese, and copper. As soluble salts for crop uptake, they are frequently applied along with N, P and K fertilizers at low rates (<5 $mgL^{-3}$). These composite fertilizers' micro fertilizers often supply adequate nutrition with minimal environmental danger (28). On the other hand, the administered micro fertilizers may become less available to the plants. Following the addition of micro fertilizers to soils, the trace elements either interact with the organo-mineral matrix of the soil and clay colloids to produce chemical precipitates, or they react quickly to render the nutrients inaccessible for synchronized plant uptake throughout crop growth. As a result, the crop's micronutrient usage efficiency (MUE) is very low (less than 5%) and leaching causes its loss in regions with heavy rains. Providing micro fertilizers through micro fertilizer-containing nanoparticles may enhance plant development. They are utilizing nano fertilizers as intelligent delivery systems that can enhance fertilizer formulation by reducing nutrient loss and increasing cellular uptake in plants. These nano fertilizers are considered smart delivery systems because of their large surface area, sorption capacity, and controlled-release kinetics to specific spots (28, 30).

It was reported that the effects of several nanoparticles, including $TiO_2$, $Al_2O_3$, carbon nanotubes, zinc, zinc oxide, alumina, aluminium iron, copper, silver and silicon, on root elongation, seed germination and other plant factors (31). However, the results of the study have been inconsistent because different nanoparticles are found to have different effects on plant growth. For instance, when maize seeds were treated with zinc oxide nanoparticles, their germination rate, seedling vigor and plant growth were enhanced (32). Similarly, nanoscale micro fertilizers ZnO and $\gamma$-$Fe_2O_3$ created through a green synthesis approach using *Ulva lactuca*, an edible sea green alga, were found to be appropriate and *in vitro*, nano-priming tests showed that applying these nano-micro fertilizers resulted in a significant improvement in seed germination and seedling parameters. Furthermore, applying nanomaterials, such as iron oxide, carbon nanoparticles, silver nanoparticles and zinc oxide nanoparticles, had a significant effect on yield characteristics in a variety of crops, including rice and maize.

### *Effect of nano micro fertilizers in retaining greenness (chlorophyll content) in maize*

Iron (Fe) takes up the forms of $Fe^{2+}$ and $Fe^{3+}$ in roots. In plant tissue, the range of Fe sufficiency is 50–250 mg/L. It helps ribonucleic acid synthesis, activates several enzymes and enhances photosystem function (33, 34). Porphyrin molecules, including heme protein, leghaemoglobin, cytochrome and Fe-S protein, are structurally composed of iron. These materials participate in respiration and photosynthesis's oxidation-reduction processes. The biosynthesis of chlorophyll is accelerated by Fe. It is a component of nitrogenase, an enzyme that N-fixing microbes need to fix N. Application of iron nanoparticles significantly increased the chlorophyll content in maize. This increase in chlorophyll content leads to improvements in various plant growth indices such as height, biomass, leaf area and green pigment. Administering iron micro fertilizer formulations in nanoscale forms can stimulate the synthesis of chlorophyll and improve the physiological mechanisms involved in photosynthesis. The study highlights that by adding the right amounts of nano-iron micro fertilizers to plants, their chlorophyll content and general leaf health can be increased, making them greener and more vibrant. Iron micro fertilizers promote the production of chlorophyll and other biochemical reactions, enhancing plant growth and productivity (34, 35).

According to one report, after entering the plant cell, zinc oxide (ZnO) nanoparticles in the nutritional solution enhanced the growth of maize seedlings (36). As a cation ($Zn^{2+}$) and a part of both artificial and natural organic complexes, zinc is taken up by roots. In plants, its content varies from 25 to 150 mg/L. Tryptophan, a building block of several proteins and a substance required for the synthesis of growth hormones (auxins) such as gibberellic acid and indoleacetic acid, is synthesized with zinc. It is a part of metabolic processes and enzyme systems. It is required for the synthesis of carbohydrates and chlorophyll.

Melatonin synthesis, antioxidant enzyme activity, and metabolism were altered by Nano-ZnO, which enhanced drought resistance in maize (37). Nano-ZnO particles with an average size of 37.7 ± 15.5 nm, which had a roughly spheroidal to oblong shape. The hydrodynamic size of the nanoparticles was around 300 nm, and they had an absorption peak of 376 nm. Nano-ZnO treatment led to a considerable up-regulation of antioxidant enzymes such as Cu/Zn SOD, Fe/Mn-SOD, APX and CAT in drought-stressed maize plants. The up-regulation of antioxidant enzymes improved drought tolerance and decreased oxidative damage. Treating maize with nano-ZnO greatly improved tryptophan metabolic pathways under drought stress. Increased levels of tryptophan and tryptamine, precursors to auxins and melatonin, have been linked to enhanced resistance to drought by mitigating oxidative damage and controlling osmotic equilibrium (38, 39). This could have a significant impact on increasing crop output in agriculture by improving plant stress tolerance and reducing the detrimental effects of drought on crop output (39). It was found that those treated with ZnO-N had a more significant impact on improving relative water content (RWC) and electrolyte conductivity (EC) in comparison to those treated with $ZnSO_4$ (40).

Additionally, application of $ZnSO_4$ at 10 and 20 mg/L resulted in higher levels of chlorophyll content in drought-stressed plants. Whereas, plants treated with ZnO-N at 20 mg/L had significantly higher soluble sugar content under drought-stress conditions. Furthermore, plants treated with ZnO-N showed the highest proline content, which is an indicator of greater drought resistance (40, 41). Conversely, plants treated with $ZnSO_4$ had higher protein contents, with the highest concentration at 10 mg/L. Under drought stress circumstances, the application of ZnO-N treatment plants produced the highest activities of the enzymes superoxide dismutase (SOD), polyphenol oxidase (PPO) and guaiacol peroxidase (GPO) (40, 42).

$Cu^{2+}$ is absorbed by plants both independently and as part of artificial or natural organic complexes. Plant tissue typically has a Cu content of 5–20 mg/L. Plants need lignin, a component of their cell walls, to provide the strength and stiffness of their walls and to help them stand upright. Cu is present in several enzymes crucial to the formation of lignin, including diamine oxidase and polyphenol oxidase. Cu is a component of the cytochrome oxidase enzyme, which facilitates the transfer of electrons during respiration, which is significant for the metabolism of fats and carbohydrates. In addition to fatty acid desaturation, hydroxylation and elongation, plant cytochrome b5 (CB5) proteins serve as electron carriers in the synthesis of specialised metabolites such as flavonoids, phenolic esters and heteropolymer lignin. Additionally, it has been discovered that plant CB5s interact with various non-catalytic proteins, including sugar transporters, cell death inhibitors and ethylene signalling regulators. These interactions suggest that plant CB5s play a variety of regulatory roles in coordinating various metabolic and cellular processes, most likely concerning the redox status and/or availability of carbon within the cell (43).

Nano-Cu priming can help maize plants become more drought-tolerant by preserving leaf water status, chlorophyll, carotenoid levels and anthocyanin accumulation. This ultimately helps improve growth balance and the plant's response to drought stress by preserving photosynthesis and defense systems. In addition, nano-Cu priming can enhance the activities of 2 important antioxidant enzymes, superoxide dismutase (SOD) and ascorbate peroxidase (APX). These enzymes play a crucial role in detoxifying reactive oxygen species (ROS), reducing oxidative damage and enhancing plant resilience in drought-stressed plants. Furthermore, the application of nano-Cu can support the preservation of photosynthetic efficiency, which is essential for plant respiration and the metabolism of proteins and carbohydrates (44-49). This leads to increased production and growth. Moreover, copper nanoparticles can help control plant defence systems linked to drought tolerance by preserving water status, boosting pigments involved in photosynthesis and promoting ROS detoxification through enzymatic and non-enzymatic antioxidants. These processes work together to support higher plant productivity when drought stress is present (49).

Plants need manganese as a micronutrient because it plays a crucial role in several physiological functions such as photosynthesis, enzyme activity and antioxidant defence mechanisms. The water-splitting complex of photosystem II, which is essential for the light-dependent processes of photosynthesis, involves manganese. A deficiency of manganese can affect plant growth and development, leading to reduced photosynthetic efficiency and increased vulnerability to environmental stressors like drought. Studies have shown that adequate manganese levels in plants can promote photosynthetic activity and antioxidant defense systems, thereby improving their resistance to drought stress (34).

Reports are on the performance of composite formulations of zinc, boron and copper nanoparticles and their salts in alleviating drought stress (40). They found that applying micro fertilizer formulations to the soil was more effective than applying them topically in mitigating the effects of drought stress. The micro fertilizer formulations were able to increase grain production by an average of 36% and shoot growth by 33% under drought circumstances. The formulations were also able to boost nutrient uptake, increasing shoot N by 28%, K by 19%, Zn by 10.80%, B by 74% and Cu by 95.4% on average under drought stress.

### *Role of nanoparticles in stomatal regulation*

Plants rely on stomatal control to exchange gases and maintain water relations (36). Stomata are small pores on the leaves that regulate the exchange of gases like carbon dioxide and oxygen, as well as water vapor. To ensure proper stomatal functioning, several nano micronutrients such as zinc (Zn), silicon (Si), and titanium (Ti) play vital roles. Zinc is an essential micro fertilizer that regulates stomatal function. When zinc is deficient in plants, it can lead to compromised stomatal function, which can affect plant transpiration and water intake. Therefore, it is crucial to provide proper zinc feeding to maintain stomatal conductance and general plant water status. Silicon is another nano micro fertilizer that impacts plant stress. It has been found that silicon plays a crucial role in tomato seed germination and seedling development. It also helps in improving plant resistance to stress and influences stomatal control.

Titanium (Ti) is yet another nano micro fertilizer that regulates the stomatal function, and titanium dioxide nanoparticles have greatly improved plant water status and nutrient uptake during the occurrence of drought (49). $TiO_2$ nanoparticles also improved plant anthocyanin levels, relative water content, and antioxidant activity, which enhanced stomatal control. In summary, nano micro fertilizers such as zinc, silicon and titanium play a crucial role in stomatal control and they affect plant water relations, gas exchange and overall drought resistance. These nutrients can be applied as nanoparticles to improve crop resilience and productivity in water-limited environments (50).

### *Effect of nanoparticles on root growth*

Plants require essential micronutrients in small amounts for their growth and development. These micronutrients are referred to as nano microfertilizers. Iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), molybdenum (Mo), boron (B), and chlorine (Cl) are some of the elements that make up these micro fertilizers. Researchers have been exploring the use of nanotechnology in agriculture to enhance the effectiveness and distribution of microfertilizers in plants. Microfertilizer formulations at the nanoscale can increase the availability and uptake of nutrients by plant roots, leading to improved growth and production (51). In an experiment conducted (31) applications of $\gamma$-$Fe_2O_3$ and ZnO nanoparticles were found to positively impact maize seedling parameters, root biomass and germination. In particular, when 500 mg/L of $\gamma$-$Fe_2O_3$ nanoparticles were applied to maize seedlings, their parameters improved considerably in comparison to control and other concentrations at the beginning. In a similar vein, the ZnO nanoparticle efficacy trial demonstrated that 500 mg/L of ZnO nanoparticles outperformed other concentrations in maize, yielding noteworthy benefits. According to a study under various circumstances, the administration of quaternary ammonium imino fullerenes (IFQA) significantly impacted the root length of maize seedlings (52). As compared to the water-treated control group, IFQA treatment resulted in a statistically significant increase in root length under normal circumstances. In comparison to polyethylene glycol (PEG) therapy alone, the combination of PEG and IFQA caused a significant increase in root length when subjected to osmotic stress (PEG treatment). PEG treatment is one of the treatments that exhibits characteristics similar to drought stress and causes osmotic stress, which lowers the plant's water potential (53). When IFQA had been added, the root length of *Arabidopsis* seedlings was considerably longer than in the control group. Among all treatment groups, the elongation zones of roots treated with IFQA showed the longest length, suggesting that IFQA promotes root growth.

### *Effect of Nano micro fertilizers on ROS Activity*

Low concentrations of ROS serve as signalling molecules to control plant protective stress responses, such as ABA-induced $Ca_2$ channel activation, stomatal closure and induction of defence gene expression. Excess ROS can cause oxidative damage to cells during abiotic stresses (54-57).

Nano-sized nutrients have been shown to regulate ROS (Reactive Oxygen Species) levels in plants and preserve ROS homeostasis. They work by increasing the activities of antioxidant enzymes and reducing oxidative stress. Nano-sized nutrients, such as nano-selenium and nano-zinc oxide, have exhibited antioxidant qualities by reducing ROS accumulation and lipid peroxidation in plants under stress. Furthermore, applying nano-sized iron oxide particles to plants has been demonstrated to enhance their antioxidant defence system, thereby improving stress tolerance and reducing damage from ROS. In addition, research has shown that nanosized silicon can alter the expression of genes associated with enzymes that scavenge ROS, thereby enhancing a plant's resistance to oxidative stress (57).

### *Effect of nano micronutrients in grain yield*

The use of nanomaterial nano chitin can significantly improve the production and quality of winter wheat grain. By applying nano chitin to the soil at a certain concentration, the number of spikes and grains per spike increased, resulting in a higher yield of 2 distinct wheat varieties (58, 59). Interestingly, the grain weight remained unchanged. The study also highlighted the positive impact of nano chitin on plant nitrogen and potassium accumulation, which led to an improvement in the nutritional quality of the wheat. This included an increase in protein, iron and zinc contents (59).

According to one report, the use of nano-CuO has been found to have a beneficial effect on maize grain yield

(60). It was also revealed that CuO nanoparticles (NPs) have desirable chemical and physical characteristics, such as outstanding stability, large surface areas, appropriate redox potential, great electrochemical activity and super-thermal conductivity (60, 61). Under normal conditions, maize plants treated with nano-CuO produced a significantly higher average seed-dried weight per plant compared to those treated with water. Additionally, under drought conditions, plants treated with nano-CuO showed a much higher average yield per plant and a greater number of seeds than those treated with water. Furthermore, the application of copper nanoparticles assisted in enhancing drought tolerance in maize. Under drought stress, the production of maize grain increased due to the augmentation of drought tolerance brought about by nano-CuO priming. The use of nano-CuO helped maintain the relative leaf water status and levels of carotenoid and chlorophyll, as well as increasing anthocyanin contents in maize. Hence, nano-CuO priming could mitigate the adverse impact of drought on maize yield and thus could be a promising solution for sustaining grain yield during drought.

Nano iron at 300 mg $L^{-1}$ as foliar nutrition was superior in recording all yield-attributing characters such as ear length, number of rows, number of grains per row, number of grains in the ear, weight of 500 grains and total grain yield of 7.13 ton $ha^{-1}$ (62).

The most effective treatments to improve the quality parameters in maize were Au-NP-bioSi (gold nanoparticles anchored to meso-biosilica) and ZnO-NPs (nanoparticles) as against conventional micronutrients. The application of ZnO-NPs (nanoparticles) increased grain calcium content and decreased iron content, whereas, the lowest grain calcium and iron content were observed under Au-NP-bioSi (63).

### Influence of Nano micro fertilizers on Chlorophyll Content

Nano nutrients are micronutrients that have been engineered to be more efficiently absorbed and bioavailable than traditional micronutrients. They have the potential to significantly improve plant growth and development, including the synthesis of chlorophyll. Recent studies have investigated the impact of nanomaterials, such as titanium dioxide nanoparticles ($nTiO_2$), on the amount of chlorophyll in microalgae. These studies have shown that the combination of phosphorus and $nTiO_2$ can have a binary effect that greatly affects the amounts of chlorophyll in microalgae, with total chlorophyll content and chlorophyll a/b increasing dramatically in response to the combined exposure (64). However, the amount of chlorophyll can be affected by many factors, including the type of nanomaterial, its concentration, the length of exposure and the type of plant. Research has shown that nanomaterials can have both positive and negative effects on the chlorophyll concentration of a variety of plant species (65).

### Effect of Nano micro fertilizers on Starch Synthesis

Nano micronutrients can regulate various plant metabolic pathways, including those involved in the production of starch (Table 1). By modifying the expression of genes and the activity of enzymes involved in starch biosynthesis, nano micro fertilizers like zinc, and copper may be able to increase the amount of starch produced in plant tissues. Moreover, nano micro fertilizers can boost the activity of antioxidant enzymes in plants, which is crucial for sustaining regular metabolic processes such as starch synthesis (66). By doing so, they can help protect plant cells from oxidative damage (39).

**Table 1.** List of functions performed by various nano micro fertilizers (34, 67, 69)

| Sl. No. | Functions | Nano micro fertilizers |
|---|---|---|
| 1 | Retain greenness | Fe, Zn, Cu, Mn |
| 2 | Stomatal regulation | Zn, Si, Ti, (Zn + B + Cu) |
| 3 | Enhance root growth | Fe, Zn |
| 4 | Decrease ROS activity | Se, Zn, Fe, Si, Mn, Cu |
| 5 | Increase grain yield | Cu |
| 6 | Increase chlorophyll content | Ti, Fe |
| 7 | Enhance starch synthesis | Zn, Cu |

### Effect of nano micronutrient on maize physiological parameters

Improvement in the yield-attributing characteristics and yield of maize was ascertained by treating with ZnONPs (68). Foliar application of ZnONPs had increased chlorophyll content , which improved the photosynthetic efficiency of maize, which in turn was specifically linked to an increase in soluble protein content; thereby, higher productivity was recorded under ZnONPs (70).

The osmotic potential of cell cytoplasm, which is considered critical for plant survival under stress conditions, has resulted in increased proline content (71). Proline accumulation has been supported as a stress tolerance selection criterion (72). Fe nanoparticles at an optimum concentration of 54 μ mol/g resulted in a decreased concentration of leaf proline content in maize. While changing the nanoparticles to sub-optimal concentration, increased leaf proline content indicates that plant stress decreases at the optimal dose of nanoparticles, and lower proline content in the leaf is an indicator of plants under low stress (34).

Reports revealed that, foliar application of nano micronutrient consortia (IQ COMBI), which consisted of 8% Fe, 1.5% Zn and 1.5% Mn, stimulated enzymatic activity that facilitates the synthesis of chlorophyll, which resulted in higher SPAD value of 56.3 as compared to control SPAD value of 45.3 (water spray) under drought stress condition (73).

### Spraying techniques

#### Conventional method for foliar Spray of nanoparticles

At the three- to four-leaf stage, L-Tryptophan (L-TRP) and Salicylic Acid (SA) were applied topically to maize plants using varying SA concentrations (100, 150, 200 ppm) and L-TRP concentrations (5, 10, 15 ppm) via traditional foliar spray procedures. This ensured that the chemicals were evenly administered on the plant leaves, providing uni-

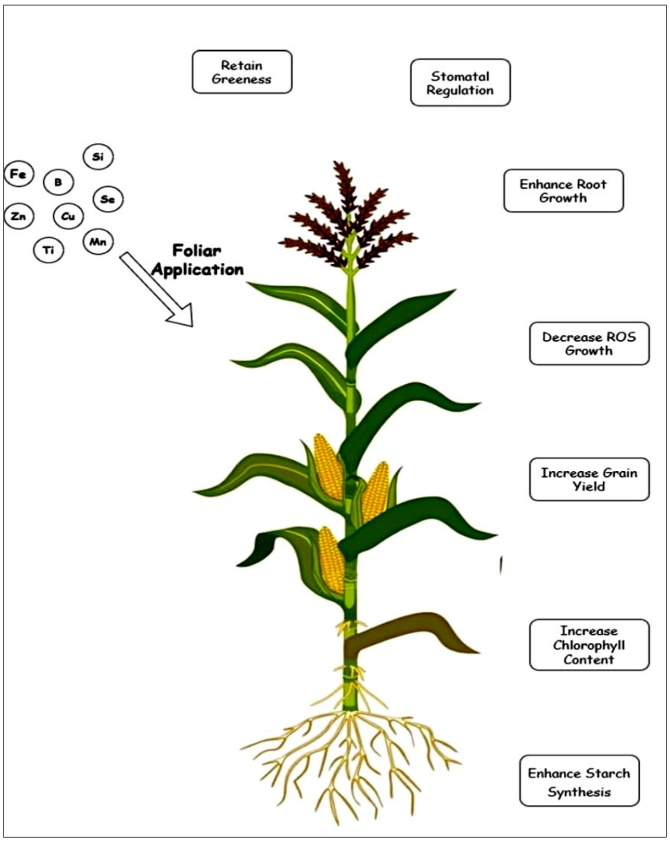

**Fig.1.**Schematic diagram of functions of nano microfertilizers when applied to maize leaves.

form treatment throughout the trial units. The study's findings showed that foliar application of SA and L-TRP using this traditional spray technique improved the relative water content, leaf membrane stability index, chlorophyll content and potassium content of plants under drought stress. These positive results suggest that the traditional foliar spray technique was effective in providing nutrients to the plants (74).

## Use of drone for foliar Spray of nanoparticles

Studies are on the foliar spray of nano fertilizers through drones is an effective way to deliver nutrients to crops with less input compared to traditional knapsack sprayers (75). Drones use less spray fluid and fertilizers but still produce comparable or better outcomes. This suggests a more economical use of resources. Using fuel-operated drones equipped with atomizer nozzles to apply TNAU Maize maxim resulted in improved biometric characteristics and yield parameters. This includes plant height, leaf area index, dry matter accumulation, cob yield and number of grains per cob. Compared to manual sprayers, the use of drones for nutrient administration led to better crop development and greater yields.

An unmanned aerial vehicle (UAV) can sufficiently deliver long-range connections with or without payloads and survey a region of several km in a short period. UAVs have a wide range of shapes and remarkable capabilities and their aerodynamic designs are very different from one another. The speed and weight-carrying capacity of various UAVs differ. Therefore, it's critical to comprehend which UAV is best suited for intricate operations and agricultural surveillance. Using a UAV consistently is an easy, quick and economical substitute for agricultural drudgery (76).

Using a UAV for agricultural tasks in a reliable manner is an easy, quick and economical substitute. Inclement weather can also make it functional. UAVs can monitor crops more accurately, consistently and economically. They can also provide higher-quality, constantly updated data that can be used to identify inefficient or wasteful farming techniques and provide insight into agricultural improvement. Moreover, multispectral images of crops taken by UAVs can be analysed to track changes in form and maturity. UAVs can be a beneficial tool for agronomists and producers alike. It makes sense to fit infrared cameras on UAVs to glean additional information from the imagery and it paves the way for aiding in accurately defining the quantity of chlorophyll present in the crops (77).

## Cost economics of nano micronutrients

Experimental plot fertilized with 50% recommended dose of Zn and 100% N-P-K coupled with 2 foliar sprays of Nano-Zn at 4 mL $L^{-1}$ at 25 and 50 DAS, resulted in higher grain and stover yield of maize which reflected in realizing higher gross returns (Rs.134200 $ha^{-1}$), net returns (77100 $ha^{-1}$) and benefit-cost (B:C) ratio of 2.35 (78).

Nano ZnO at 800 ppm as seed treatment for 30 minutes followed by foliar application at 600 ppm at 30 DAS recorded a significantly higher cost of cultivation (Rs. 52344 $ha^{-1}$) owing to the higher dose and cost of nano ZnO. Whereas, a lower cost of cultivation was incurred towards foliar application of $ZnSO_4$ at 0.5% (Rs.29265 $ha^{-1}$). In contrast to this, higher gross and net returns were observed in seed treatment with 800 ppm of nano ZnO for 30 min and foliar application of nano ZnO at 500 ppm (Rs. 133636 $ha^{-1}$ and Rs.84777 $ha^{-1}$ respectively) due to higher kernel yield (79).

## Conclusion

Maize is a multifaceted crop that is highly susceptible to drought and it is impacted by both early and terminal dryness. Occurrence of drought during the critical stages particularly during the silking and tasseling stages is extremely harmful and has an impact on pollen viability, filling efficiency, number of kernels per pod, and anthesis silking interval (ASI). Thus, it is imperative to mitigate these anomalies in places susceptible to drought. Micronutrients are the primary determinant of parameters such as yield, chlorophyll content, ROS activity, root growth and biomass because they function as an enzyme's component and a physiological event's promoter. Therefore, it is vital to apply these micronutrients in the form of nanoparticles in the ideal amounts, as soil application alone cannot sufficiently meet their needs. Because of its clever application method, broad surface area and sorption capacity, and controlled-release kinetics to specified locations, nano micronutrient is superior to micronutrient spray. This review paper explains the application of nanotechnology in agriculture. In specific, the best approach for nutrient management is discussed and also potential ways to formulate designer fertilizer are discussed.

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## Authors' contributions

All the authors gone through the manuscript and approved the final manuscript. SV collected the literature, drafted and conceived the manuscript on nano particles and its effect on maize. PK framing, designing, conceptualization of content, reviewed critically and overall proofread and guided as chairman of the advisory committee. VM helped in collecting the literature and proof reading pertinent to agronomical parameters. MD special thanks for providing inputs on physiological parameters and correcting the manuscript. ST assisted in collection of literature and proofreading of soil related parameters.

## Compliance with ethical standards

**Conflict of interest**: The writers admitted not any conflicts of interest.

**Ethical issues**: None

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