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# Climate Change, Food Security, and Nanobiology: Significance of Nanoparticles in Mitigating Drought Stress in Food Crops

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# Abstract

Globally, among the many undesirable impacts of climate change is drought. Drought is one of the major environmental stress factors resulting in monumental loss in agricultural yields and productivity, which, hitherto, poses a significant threat to food security. Nanotechnology has emerged as a potent and creative alternative to mitigating abiotic stresses, including drought. This systematic narrative review highlights the application of nanoparticles (NPs) in agriculture and assesses their impact on plant health and productivity under drought conditions through an in-depth literature review (analysis) of previous studies obtained from reputable databases using appropriate keywords and search terms. Relevant inclusion and exclusion criteria were used to narrow down the literature to the most accurate studies for the review. This study underscores the significance of food crops and evaluates the efficacy of nanoparticles in mitigating the effects of drought stress on food crops. The ecological impacts, mechanisms of action and possible toxicity elicited by nanoparticle applications in agriculture were also discussed. Overall, the review provided practical recommendations to maximise the potential of nanoparticles in mitigating the effects of drought stress in food crops to promote food security.


# 1 Introduction

Drought a consequence of climate change is one of the major challenges contributing to global poverty increase through food insecurity. Climate change is regarded as the most hazardous natural disaster that negatively impacts agricultural output (Praveen and Sharma, 2019; Roy *et al.*, 2025). The last few decades indicates that increased anthropogenic activities have modified the composition of the global atmosphere, resulting to substantial changes in the climate on a global scale (Malhi et al., 2021). The beginning and duration of the growing seaons are both influenced by climate change (Fiwa et al., 2014; Zhao et al., 2015) and the duration and magnitude of heat and water stress in agricultural production systems (Lobell et al., 2015; Schauberger et al., 2017; Aryal et al., 2020). Climate change is now impacting every country and continent, affecting livelihoods and disrupting national economies, costing people, communities, and countries dearly. Despite the different approaches at mitigating the effect of climate change, drought impacts on water and food security are not often continuously monitored or even included in drought monitoring and early warning systems (DEWSs) (Bhattacharya, 2019; Kchouk et al., 2022).

Owing to its huge size and sensitivity to climatic conditions, agriculture is regarded as the most vulnerable sector to climatic change, and the attendant economic impacts remain massive and unquantifiable (Malhi et al., 2021). The changes in climatic events such as temperature and rainfall significantly affect the yield of crops. Climatic variability is attributed to almost 60% of yield variability, and thus a critical factor influencing food production and the income of farmers (Ray et al., 2015; Matiu et al., 2017, Aryal et al., 2020). The increase in population has raised the demand for food, leading to unprecedented use of agrochemicals, exploitation of water resources etc., which has resulted in intense agricultural practices. This has exacerbated the problem through pollution of natural resources and the release of greenhouse gases (GHGs) due to intensive agricultural activities. The forests are now a reservoir for the ever increasing amount of $CO_2$ but the natural carbon cycle is now out of balance, because of accelerated deforestation, mostly for industrialization and farming. This has led to higher carbon footprints and an irregular climate pattern with various negative impacts that have serious implications on agricultural productivity (Arora, 2019).

Drought and dersertification is one of the major direct consequences of climate change, even though it is a natural phenomenon, it has recently been exacerbated by the increasing climate variability. The primary cause of drought

stress in plants is lack of water, albeit irrigation. Consequence of drought stress is seen in excessive soil salinity, severe evapotranspiration rates, or a limited water supply to the roots of the plant (Kim et al., 2022; Madouh and Quoreshi, 2023). When drought stress is caused by certain factors, including excessive soil salinity, flooding, and low soil temperature, it is termed "physiological drought". In this scenario, there is enough water needed by plants in the soil but plants are unable to absorb it (Rahman and Hasegawa, 2012). When plants experience water deficit for a long period, the problem becomes apparent and it significantly impact plants' physiology, morphology, and production ability (Wahab et al. 2022; Yasmeen *et al.*, 2022).

Agriculture has steadily improved over time due to a multitude of technological advancements, including breeding of hybrid varieties, use of synthetic herbicides, and fertilizers. Researchers studying agriculture are now beginning to grasp how important it is for agricultural expansion to leverage innovative ideas like nanotechnology in order to address global concerns like food insecurity and climate change. Although, there have been studies on the application of nanotechnology in agriculture for over 50 years, its significance has not been this apparent until recently (Mukhopadhyay 2014; Tang et al., 2023; Rasool et al., 2024).

Nanobiology, which involves the application of nanoparticles or nanomaterials, has emerged to be employed in agriculture for various applications including mitigation of plant stress and preventing pre- and post-harvest losses (Ramya et al., 2025; Shinga et al., 2025; Zaman et al. 2025). Nanoparticles (NPs) are particles with at least one dimension smaller than 100 nm. NPs have attracted a lot of scientific attention due to their rapidly expanding usage in a wide range of disciplines (Altammar, 2023). Many NPs have garnered special attention recently due to their percieved non-threatening applications in the agricultural sector (Šebesta et al., 2021; Kaningini et al., 2022; Balusamy et al., 2023; Santás-Miguel et al., 2023; Kumari et al., 2024; Bouhadi et al., 2025). Plant growth and development are positively impacted by nanoparticles (NPs); however, the benefits can vary based on the crop's origin, size, concentration, application timing, and so on (Rubilar et al., 2013; Alabdallah et al., 2021).

# 1.1 Nanoparticles synthesis approaches

Various methods are used to synthesise nanoparticles, each specifically designed to provide the desired nanoparticles for a certain application. Samuel et al. (2022) classify these methods into two primary classes based on their modes of operation: top-down and bottom-up syntheses (Fig. 2).

**Bottom-up Approach**

this entails using both chemical and physical forces to mobilize the fundamental building blocks of nanoparticles into complicated structures. This bottom-up strategy is applied to the biological environment, where chemical force was used by nature to create all of the necessary structural components for life. The most popular bottom-up methods for synthesizing nanoparticles include spinning, sol-gel, chemical vapour deposition (CVD), pyrolysis, and biosynthesis (Das and Pradhan 2022).

**Top-bottom Approach**

as its name implies, this destructive method involves reducing bulk materials to the size of nanoparticles. There are two categories for this method of creating nanoparticles

1. (a) Physical method of synthesis: this includes procedures such as physical vapour condensation, high energy ball milling, inert gas condensation, sputtering, laser ablation or pulse laser ablation, flame spray pyrolysis,

laser pyrolysis, electrospraying methods, and so on.
2. (b) Chemical methods of synthesis: sol-gel, micro-emulsion, hydrothermal synthesis, polyol synthesis, chemical vapour deposition, and plasma accelerated chemical vapour deposition are among the frequently used chemical techniques.

In order to contribute to sustainable food production under climatic stressor, this review assesses the mitigating potential of nanoparticles against drought, and evaluate its significance as an innovative tool to improve drought tolerance in plants, with focus on food crops. It evaluates evidence on the mechanisms by which these NPs improve plants resilience as seen in improved antioxidant activities, improved water use efficiency, and expression of stress responsive genes. The focus is on aligning eco-friendly and scalable methods to match nanobiotechnology applications with global food security objectives.

## 2 Review methodology

This review adopted a systematic narrative approach to synthesise evidence documenting the role of nanoparticles in ameliorating drought stress in food crops. Overview of literature searches conducted in Web of Science, Scopus, Google Scholar and PubMed predominantly between January 2010 to March 2025 (to encapsulate major advances dedicated to agricultural nanobiology). Boolean operators were used to combine search terms including “nanoparticles”, “nanobiology”, “drought stress”, “abiotic stress mitigation”, ”food crops”, ”climate change”, ”water stress” and “agricultural nanotechnology”. The reference lists of relevant articles were screened for additional studies.

Original research articles and reviews that underwent peer review were included if they;

1. evaluated application of nanoparticles in agriculture and especially in food crops,
2. specifically addressed water-deficit stress or drought, and
3. documented results pertaining to physiology, biochemistry, growth, or yield.

Excluded were studies that lacked experimental data, were solely focused on non-plant systems, or had non-agricultural application. After exclusion of duplicates, titles and abstracts were screened for relevance, followed by full-text assessment. Data extracted included nanoparticle type, synthesis approach, crop species, application method, concentration range, experimental scale (laboratory, greenhouse, or field), and reported effects under drought stress.

Inclusion criteria consisted of peer-reviewed publications written in English, focusing on the interactions and use of nanoparticles in plant systems or functioning with plants that reported biological or non-biological effects relevant to phenotypic, physiological, biochemical or molecular responses under drought (or abiotic) stressors in crop and model species; exclusion criteria comprised articles that were not peer-reviewed publications, provided insufficient methodological details and quantitative data based upon experimental evidence followed by only nanoparticle synthesis studies without biological relevance towards applicability to crops, including associated agricultural systems (Fig. 3).

## 3 Climate change and its implication on food security

Food production globally is largely dependent on human, technological, and natural elements. The natural element involves climatic variables such as rainfall, relative humidity, and temperature. The technological element involves

modern mechnisation, application of novel approaches such as nanotechnology,etc. It is the dynamic interactions among these elements that result in agricultural systems that underpin food security. The sustainable growth of agriculture globally is increasingly threatened by climate change, which has created a global problem (Idumah et al., 2016).

The agriculture sector is very vulnerable to climate change because its activities are directly dependent on climatic conditions. The impacts of climate change on agriculture, however, vary by crop and country (Agovino et al., 2019). Some areas could benefit from the action of some components of climate change e.g. cold regions with rising temperatures or “carbon fertilization effects” (Stokes and Howden, 2010; Agovino et al., 2019); other countries could suffer significant adverse effects (e.g. water stress, increase in the variability of yield, reduced crop yields etc.). The impacts in different countries may be a mix of different types of impacts that can further lead to vulnerabilities (Füssel, 2007; Agovino et al., 2019).

More than other constraints on agricultural systems, climate change is likely to become a major threat to food securiy over the next few decades, as estimated by IPCC (2007) and BNRCC (2008). Climatic changes are expected to create a major shift in food production due to increase in temperatures and rainfall in some places and decrease in others, while, coastal flooding will reduce the size of available land viable for agriculture (Odjugo 2008; Idumah et al., 2016). Climate change will adversely affect food security in all its dimensions (food availability, food access, food utilization and food system stability) through its effects on agriculture. While food security will be affected through other channels, for instance, by extreme weather events that reduce urban dwellers’ incomes and thus access to food (El Bilali et al., 2020).

The demand for agricultural products is estimated to increase by around 50% by 2030 as the global population increases, which will require a shift toward sustainable intensification of food systems (Garnett et al., 2013). Climate change will have an influence on local food systems, as small agricultural communities frequently rely on locals and their own production, as well as the global food equation for both supply and demand. This will result in additional pressure on the global food system. Therefore, progress toward a world free of hunger may be slowed down or even reversed by climate change (Wheeler and Von Braun, 2013). The reality of the impact of climate change on agricultural development, with several projections for the future which necessitate proactive measures have been shown in a number of studies (Ahmed, 2020; Arora, 2019; Dawson et al., 2016; El Bilali et al., 2020).

# 4 Impacts of drought on crop physiology and productivity

Since droughts are a major form of climatic extreme that results in losses in food production and consequent increases in food prices, they have drawn constant attention (Esper et al., 2017; FAO 2012; Kim *et al.*, 2019). A study based on historical records shows that droughts slowed food production globally by 10% in the period 1964–2007 (Lesk et al. 2016). Although the potential impacts of climate change on food production are now clearly in the spotlight, the link between climate change and other food security components like access, availability and stability, and utilisation have not yet been explored in detail. This might result in under-estimating the impacts of climate change on food security, for instance, through factors such as price increases and malnutrition (Hasegawa et al., 2018).

Besides the duration of water shortages, the timing of the drought during the plant ontogenic phase is important for ensuring a crop optimal yield (Dietz et al., 2021). Water deficit during the germination and establishment of seedlings delays or prevents germination, photosynthesis and seedling growth, whereas during at the early

growing stage, it reduces vegetative and generative yields. Consequently, there are less robust (established) plants. During vegetative growth, plants undergo altered shape and often, secondary chemicals are also stored during periods of drought (Farooq et al., 2009; Olowolaju et al., 2023; Adejumo et al., 2025). Most damages (such as flower or ovary abortion) resulting from drought at reproductive phases are irreversible and will therefore have a far greater impact on yield than compared to occurrence of drought at the vegetative phases (Mahalingam and Bregitzer 2019).

Agricultural drought adversely affects crop production by reducing leaf size, stem elongation and root proliferation, disturbing plant water and nutrient relations, and inhibiting water-use efficiency (Kang et al., 2022; Sun et al., 2024). The effect of drought on yield losses is devastating and could result in total crop loss especially during extreme drought conditions (Mutava et al., 2011; Begna 2020). Drought stress can lead to a high risk of crop loss or failure in most areas where crop production is mainly rain-fed (Begna, 2020). The effect of heat and drought can help to reduce the life cycle of crop, total carbon assimilation and grain filling period (Awasthi et al. 2014). In addition, this stress combination causes some yield components to suffer, such as reduced harvest index (HI), reduced seed number and reduced single seed size (Sehgal et al. 2017; Cohen et al., 2021).

Plant performance at various stages of development can be limited by drought events. Water deficit can reduce the rate of germination and development of young plants (Yigit et al., 2016). Drought essentially affects the water relations of plants as they grow, which can seriously disrupt the entire plant metabolism (at the physiological, biochemical, and molecular levels), depending on the intensity and duration of the stress (Osakabe et al., 2014; Sharma *et al*, 2020). One of the main effects of water shortage conditions is reduced photosynthetic activity and, therefore, decreased yields in plants (Vurayai et al., 2011; Kapoor et al., 2020). The direct or indirect oxidative stress that arise in plants during drought conditions is one of the key drivers behind plant responses .It affects cell membranes, alters membrane integrity and leads to physiological and biochemical changes that produce high metabolic disorders which in turn alter plant productivity (Sharma et al., 2019; Kapoor et al., 2020).

Incorporating socioeconomic metrics such as annual soil moisture deficits and grain production into a quantitative harvest vulnerability index, Simelton et al. (2012) reported that rice, wheat, and maize production in middle-income countries (MIC) was most sensitive to drought due to socioeconomic influence over harvest losses to meteorological events. However, harvests made in countries that invested more in agriculture were less susceptible to drought (Guo et al., 2021; Kolapo and Sieber, 2025; Pret et al., 2025). Simelton et al. (2012) also found that there were significant regional differences in determinants of maize crop drought susceptibility; rice and wheat crops were quite consistent.

## 5 Projections: climate scenarios, drought trends, vulnerable regions, and staple crops at risk.

Climate change can influence agricultural output significantly when it alters regional or global climate patterns. Green House Gases (GHGs) emitted due to enhanced anthropogenic activities such as industrialization and urbanization, deforestation, agriculture and degrading land-use patterns which in turn increases the pace of climate change. Climate change is further accelerated by rising temperatures, altered rainfall patterns and rising levels of carbon dioxide ($CO_2$) in the atmosphere (Bibi and Rahman, 2023; Farah et al., 2025). According to a report of Intergovernmental Panel on Climate Change (IPCC) published in 2018, industrialization has caused roughly 1.0 $^0$C degrees of warming. Estimates suggest that continued human activity could increase global temperatures by 1.5 $^0$C by 2052 (IPCC, 2018; Chandra et al., 2021). Rising global temperatures and extreme weather events are

seen by recent meteorological data as significant and distinct trends of global climate change. These events are specified as constant periods of heat causing drought and a protracted absence of precipitation. Climate forecasts show these problems will persist and may exacerbate in most of the world (Dietz et al., 2021).

The global climate models unanimously agree that higher concentrations of greenhouse gasses will result in an increase in global average temperature, which will increase the atmosphere's evaporative demand, although some limitations and uncertainties have been linked to some of the forecasting models (Wild, 2020; Vicente-Serrano et al., 2022). This trend is projected to last beyond 21st century (Lu et al., 2019). From an ecological perspective, increased $CO_2$ would promote photosynthetic carbon uptake, improve respiration, boost nitrogen use efficiency in $C_3$ plants, and ultimately raise net primary production from an ecological perspective Leakey et al. (2009). This viewpoint might be misleading as climate change include not only changes of atmospheric $CO_2$ concentrations but also involve other climatic variabilities such as temperature and precipitation of which their extreme elevation/shortage levels are expected to increase occurrences of severe environmental conditions such as flood and drought in many regions of the world (Seneviratne et al., 2021; IPCC, 2022), with its anticipated effects on crop production, hydrologic balances, input supplies and other components of agricultural systems (IPCC, 2022).

Generally, increased respiration rates, decreased seed development time and ultimately lower biomass accumulation and quality of the crop, especially in cereals and forage crops, are associated with elevated temperatures levels. In arid and semi-arid regions, however, higher precipitation could increase soil moisture availability and possibly alleviate water-related problems, while lower precipitation could, on the other hand, aggravate them (Lu et al., 2019). Hence, the future drought scenarios and its impacts on global water use for agriculture should not be assessed based on rising atmospheric $CO_2$ levels alone, but should also consider other meteorological factors for a better accuracy and reliability of the future drought scenarios (Lu et al., 2019).

Based on the EM-DAT international disaster database managed by the Centre for Research on the Epidemiology of Disasters (CRED), drought is a significant proportion of natural disasters in the world and causes significant economic losses in the tune of billions of USD per year globally (Song and Park, 2020). Additional historical assessments of droughts throughout the late 20th and early 21st century also indicate an increase in the frequency and severity of droughts globally (Sheffield et al., 2012). Furthermore, droughts have become more frequent, intense and widespread since the 1970s onwards and widespread droughts have been reported in many regions of Africa, Europe, Australia, South America and Asia (Burke *et al*., 2006; Mishra and Singh, 2010).

The occurrence of droughts in certain areas of South Africa in 2023/2024 partly attributed to what is popularly termed “El Niño event”, which had notable impact in various sectors, including agriculture and water resources (Orimoloye, 2022). Due to the prolonged drought spell experienced in several provinces, including the Free State, the National Disaster Management Centre (NDMC) declared the drought a disaster, and mobilised national resources to assist those affected, especially the farming communities (Tembile, 2021). Moreover, South Africa still faces high levels of water insecurity due to increasing water demand as a result of population growth, poor planning and management of water resources, lack of investment in water storage and repeated droughts over the past decades.

North Darfur, Sudan, which lies on the edge of the Sahara Desert, is also reportedly prone to droughts due to chronic lack of precipitation and high summer temperatures (Mohmmed et al., 2018). Good drought risk management and prevention of land degradation depends on the ability to recognize the characteristics of a drought. This conclusion was reached when drought indices including Standardized Precipitation Index (SPI),

Vegetation Condition Index (VCI) and Soil Moisture Content Index (SMCI), and a Combined Drought Index (CDI) were used in spatiotemporal drought analysis of North Darfur State from 2004 to 2013. Furthermore, both biophysical and socio-economic indicators were used to assess drought vulnerability and major drought components, in an integrated risk assessment framework. The results showed that in North Darfur, the drought situation was chronic throughout the study period, with the worst being in the years 2007–2011. The northern part of the region was determined to be the area of high vulnerability because of crop diversity, land degradation, frequent occurrence of drought and poverty incidence (Mohmmed et al., 2018).

Epule et al. (2017) reported that climate projections for Sub Saharan Africa show an increased in the frequency and intensity of drought events that will have a consequence on maize productivity. At the national scale, cassava was found to be the most sensitive crop and maize the least sensitive crop of six major crops assessed for their sensitivity to variations in the growing season rainfall in Uganda at the national and in the southwestern region of Uganda. However, at the regional scale millet was the most vulnerable and sweet potatoes the least (Epule et al., 2017). In addition, Epule and New (2019) showed that the vulnerability of the crop at both spatial scales increased with increasing exposure and sensitivity, and decreased with increasing adaptive capacity.

Fraser et al. (2013) integrated projections of drought exposure with adaptive capacity under future climate scenarios for the 2050s and 2080s, using 1990–2005 as the reference baseline. Their analysis, based on global hydrological models, indicated substantial reductions in soil moisture across numerous regions. Similarly, Rosenzweig et al. (2014) identified major agricultural vulnerability hotspots, including the southeastern United States, South America, the northeastern Mediterranean, and parts of Central Asia for wheat production, and South America, Sub-Saharan Africa, and the northeastern Mediterranean for maize. Collectively, these findings demonstrate that semi-arid and marginal agricultural zones across South and Southeast Asia are particularly susceptible to the adverse impacts of climate change.

Fitton et al. (2019) estimated that approximately 11% of current croplands and 10% of grasslands could have significantly less available moisture, which could reduce productivity; and that Africa, the Middle East, China, Europe and Asia are the areas most vulnerable. Similarly, Wu et al. (2017) estimated agricultural drought vulnerability in 18 global climatic regions and found significant spatial differences. They found the highest vulnerability levels in Australia (over half highly vulnerable or very highly vulnerable), the Tibetan Plateau (over 50% highly vulnerable or very highly vulnerable), with Western North America and Eastern Africa having over 50% vulnerability index. On the other hand, Southeast Asia, East Asia, Northern Europe and the Amazon region had comparatively low levels of vulnerability with Southeast Asia accounting for just 8.75% of its area in the high to very high vulnerability range.

The study on the spatiotemporal evolution of agricultural vulnerability to droughts and floods on a global scale between 2003 and 2019 recoded low level of vulnerability and stated that both the reduction in floods/drought exposure and the increase in adaptability are driving this decrease in agricultural vulnerability, while an increase in adaptability is beneficial to offset the adverse impacts of agricultural disasters (Cheng et al., 2024). This study indientified the Northern parts of the United States, the northeast part of China, and the border between Russia and Kazakhstan to be vulnerable to drought and flooding (Cheng et al., 2024).

Socio-economic drought risk was evaluated under climate change scenarios using the product of hazard, exposure and vulnerability at a base period (2016–2035) and two future periods (2046–2065) for general circulation models (GCMs), demographic data, GDP data, water resources data and land cover data. The highest risk for population is

estimated to occur between 2046 and 2065, with east and south Asia, the eastern USA, and the coastal regions of South America at greater risk (Liu and Chen, 2021). The study found that the climate change induced socioeconomic hazards from drought will increase, and that approximately 70% of the global risk is in the top 10 countries (Liu and Chen, 2021).

## 7 Efficacy of nanoparticles in mitigating effects of drought stress in food crops: empirical evidences

Food crops have long been vital to human survival as they provide the body with essential nutrients and energy. The need for food crops is growing in the modern world, and as a result, we must protect the crops from biotic and abiotic stressors in order to maintain the balance between the food supply and human demand (Gautam and Kumar, 2020). Nanotechnology, has recently emerged as a practical and creative alternative to conventional means of combating environmental stressors including drought, hence, has a huge potential of contributing significantly to global food security.

A comprehensive review of the literature on the effectiveness of nanoparticles in the mitigation of drought stress reveals promising results across various studies (Table 1). $TiO_2$-NPs, for instance were found to be highly effective in some food crops, including maize (khalilvand et al., 2019; Karvar et al., 2022), wheat (Faraji and Sephiri, 2019; Faraji and Sephiri, 2020; Mustafa et al., 2021), barley (Janmohammadi et al., 2016), lentil (Kolenčík et al., 2022) and chick-pea (Ghorbani et al., 2021) among others, leading to drought tolerance indices such as improved antioxidant activities, enhanced photosynthetic and carotenoid content, improved yield and biomass amongst others. ZnO-NPs has also shown impressive efficacy in mitigating drought stress in several food crops, including rice (Kheyri and Abbasalipour, 2020; Elshayb et al., 2022; Waqas Mazhar et al., 2022), maize (Sun *et al.*, 2021; Fatima et al., 2023), eggplant (Semida et al., 2021), soybean (Sedghi et al., 2021), cucumber (Ghani et al., 2022), and tomatoes (El-Zohri et al., 2021) among others. Induced osmotic adjustment, enhancement of water and nutrient uptakes, modulation of water use, and increased accumulation of protective antioxidants are among the mechanisms ascribed to their effectiveness.

$SiO_2$-NPs also gave similar promising results under drought conditions when applied on maize (Hafez et al., 2021; Sharf-Eldin et al., 2023), ginger (Zhu et al., 2024), sorghum (Al-Zandi, 2019), wheat (Raza et al., 2023), barley (Hellala et al., 2020), banana (Mahmoud et al., 2020), and rice (Elshayb et al., 2021) to mention a few. $Fe_2O_3$ is another oxide of metal nanoparticles with promising results across several food crops such as garden pea (Bidabadi et al., 2023), maize (Eliaspour et al., 2020), wheat (Noor et al., 2022), soybean (Farajollahi et al., 2023), rice (Darmaningtyas and Sakya, 2023), and sorghum (Ndou et al., 2023). All the plants showed significant improvement on the evaluated indices upon nanoparticles-mediated intervention under drought conditions.

Metallic nanoparticles notably, Si-NPs, Se-NPs, Ag-NPs, and Cu-NPs have also shown great potential in ameliorating drought stress in various food crops, including barley (Ghorbanpour et al., 2020; Siddiqui et al., 2021), faba bean (Desoky et al., 2021), wheat (Ikram et al., 2020; Sardari et al., 2022), marigold, tomato (Haghighi et al., 2013), millet (Mokari and Abedinpour, 2020), coriander (Afshari et al., 2023), eggplant (Alabdallah et al., 2021), lettuce (Akhoundnejad et al., 2022b), maize (Van Nguyen et al., 2022), chickpea (Rani et al., 2024) among others. Chitosan, a polymeric nanoparticle has also demonstrated great potential in enhancing growth, yield, physiological and other related attributes in plants under water deficit conditions in various important food crops such as soybean (Methela et al., 2023), barley (Behboudi, et al., 2018b), tomato (Mohamed and Abdel-Hakeem, 2023), wheat (Behboudi et al., 2019) etc.

Other notable nanoparticle efficacy studies reviewed include CaO-NPs on canola (Mazhar et al., 2022) and alfalfa (Yazicilar et al., 2024), Fe-NPs on barley (Zahedi and Alipour, 2018), $B_2O_3$-NPs on pea (Sutulienė et al., 2023b), $MoO_3$-NPs on pea (Sutulienė et al., 2023a), Mn-NPs on barley (Zahedi and Alipour, 2018), Zn-NPs on turnip (Li et al., 2023) and rice (Alhasan et al., 2021), and fullerenol-NPs on sugarbeets (Borišev et al., 2016) among others. These results underscore the potentials of nanoparticles in improving crop resilience to drought, which is crucial for sustainable agriculture in the face of climate change.

Table 1
Efficacy of Nanoparticles in Mitigating Effects of Drought Stress in Different Food Crops

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| $TiO_2$-NP | Wheat | - Up to 18% and 47% increase in shoot and root respectively.<br>- Up to 70% increase in chlorophylls a and b accumulations<br>- Up to 53% increase in sugar content<br>- Up to 52% increment in peroxidase synthesis<br>- Up to 51% increase in grain weight | - induces osmotic adjustment in plants<br>- enhances antioxidant enzyme production<br>- enhances nutrients and water uptakes | (Mustafa et al., 2021) |
| | Wheat | - significantly promoted seed germination<br>- significantly enhanced growth and physiological indices | - induction of oxidation-reduction reactions during germination by the superoxide ion radical<br>- enlargement of root pores or creation of new ones, resulting into improved water and nutrient uptake by the roots | (Faraji and Sepehri, 2019) |
| | Flax | - improved morphological and physiological attributes<br>- enhance chlorophyll and carotenoid contents<br>- lowered MDA and $H_2O_2$ levels | - not stated | (Aghdam et al., 2016) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | Maize | - increased the antioxidant activity of leaf SOD, APX, and CAT by 17%, 10%, and 24%, respectively.<br>- increased proline content by up to 17%<br>- enhanced grain yield<br>- showed adverse effects at a concentration of 100 $mg/L^{-1}$ | - not stated | (Karvar et al., 2022) |
| | Maize | - improves yield parameters<br>- improved antioxidant enzyme activities | - not stated | (khalilvand et al., 2019) |
| | Mung bean | - improve grain yield up to 6.6%<br>- improved morphological growth indices | - not stated | (Makarian et al., 2017) |
| | Grass Pea | - enhanced growth, biomass and germination indices. | - stimulation of plant metabolic activities<br>- improved water and nutrient uptake | (Hojjat, 2020) |
| | Chickpea | - improves chlorophyll index<br>- improves the osmotic potential<br>– 10% increase in dry weight | - not stated | (Ghorbani et al., 2021) |
| | Dragon's head | - improves antioxidant activities<br>- improves phytochemical content accumulation | - increases the accumulation of protective antioxidants | (Shoarian et al., 2020) |
| | Wheat | - Enhances transpiration, stomatal conductance, relative water content and other physiological parameters<br>- enhances chlorophyll and carotenoid pigment accumulation | - not stated | (Faraji and Sepehri, 2020) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | | - improves yield and biomass indices<br><br>significantly reduced hydrogen peroxide ($H_2O_2$) and malondialdehyde (MDA) contents | | |
| | Barley | - improve straw and grain yield by 8%<br><br>– 10% improvement in grain numbers per spike | - enhancement of photo-assimilates supply<br><br>- improves the photosynthetic complexes and nitrogen metabolism | (Janmohammadi et al., 2016) |
| | Barley | - Up to 57% improvement in germinability<br><br>- Up to 8% improvement in dependence on germination energy<br><br>– 31% and 21% increase in root and coleoptile length, respectively | - increase mitotic activity as a result of auxin (heteroauxin) synthesis at the root tip | (Nagdalian et al., 2023) |
| | Wheat | - significant increase in morphological growth parameters<br><br>- negative effect on growth parameters at high concentration | - maintenance of plant-water relation and stimulation of organogenesis | (Ikram et al., 2020) |
| Se-NPs | Pomegranate | - improves photosynthetic pigments, phenolic content and osmolytes accumulation<br><br>- improves physiological growth indices<br><br>- improves fruit's physical and chemical parameters | - enhances the activity of antioxidant enzymes | (Zahedi et al., 2021) |
| | Wheat | - improved growth indices<br><br>- stimulate secondary metabolite accumulation and non-enzymatic antioxidant activities. | - detoxification of ROS and decrease lipid peroxidation of the membrane. | (Sardari et al., 2022) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | Barley | – 87% increase in root length<br>- Improve percentage germination | - enhanced mitotic activities | (Siddiqui et al., 2021) |
| $CeO_2$-NPs | Rice | - $CeO_2$ modified the nutritional value of rice<br>- may negatively impact food quality over time | - accumulation of Ce content in the grain | (Rico et al., 2013) |
| | Sorghum | - significantly improved the photosynthetic rate (19%) and tissue water content (18%)<br>- increase catalase, peroxidase and hydrogen peroxide activities by 53%, 45% and 74%, respectively<br>- improve seed set and individual seed mass by 24% and 27%, respectively. | - stomatal regulation and osmolyte build-up. | (Djanaguiraman et al., 2024) |
| | Sorghum | - enhanced photosynthetic indices<br>- improved grain yield | - inhibition of oxidative damage | (Djanaguiraman et al., 2018) |
| ZnO-NPs | Sorghum | - enhanced plant development and yield<br>- enhanced levels of zinc, potassium, and nitrogen in plants during drought stress | - enhanced acquisition of certain nutrients<br>- lowering of IAA and stimulation of ABA production | (Dimkpa et al., 2019) |
| | Rice | - enhanced growth and yield indices | - enhancement of the osmotic regulation | (Elshayb et al., 2022) |
| | Coriander | - improved the photosynthetic activity and chlorophyll content<br>- enhanced secondary metabolites accumulation<br>- alteration in stomatal ultrastructures | - enhancement of stomatal attributes | (Ahmed et al., 2023) |
| | Rice | - significantly improved yield and Zn uptakes | - not stated | (Kheyri and Abbasalipour, 2020) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | Coriander | - significantly improved agronomic attributes<br>- | - enhanced activities of antioxidant enzymes | (Khan et al., 2021) |
| | Wheat | - obvious but statistically insignificant increase in growth parameters<br>- enhanced biomass parameters and photosynthetic pigments. | - amelioration of total phenols and antioxidant enzyme activities | (Kausar et al., 2023) |
| | Tomato | - significantly increased growth and biomass parameters<br>- enhanced activities of antioxidant enzymes | - efficient scavenging of reactive oxygen species | (El-Zohri et al., 2021) |
| | Millet | - improved physiological properties of various grain nutritional parameters<br>- improved morphological growth and yield parameters | - Stimulation of enzymatic activities | (Kolenčík et al., 2019) |
| | Rice | – 53% reduction in MDA contents<br>- significantly increased plant biomass<br>- increased SOD, CAT, and POD activities by 11%, 13%, and 38%, respectively | - stimulation of enzymatic activities<br>- nanoparticle-mediated membrane recovery<br>- increased biosynthesis of nutrients uptake responsive enzymes | (Waqas Mazhar et al., 2022) |
| | Eggplant | - increased the yield and growth indices by 22.6% and 12.2%, respectively.<br>- increased photosynthetic efficiency, membrane stability index, and relative water content. | - improved nutrient acquisition | (Semida et al., 2021) |
| | Millet | - no significant effect on most measured traits, including plant height and grain yield | - not stated | (Davoody et al., 2013) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | Maize | - enhanced the phosphoglucoisomerase, cytoplasmic invertase, and UDP-glucose pyrophosphorylase activities by 17.8%, 391.5%, and 126%, respectively.<br><br>- improved photosynthetic activities. | - modulation of water use and carbohydrate metabolism | (Sun *et al.*, 2021) |
| | Maize | - improved morpho-physiological and biochemical parameters.<br><br>- improved yield parameters | - not stated | (Fatima et al., 2023) |
| | Cucumber | - improve photosynthetic and photosystem II activities. | - modulation of the antioxidant defence system and osmolyte accumulation | (Ghani et al., 2022) |
| | Soybean | - improved germination rate | - boost antioxidant enzyme activities | (Sedghi et al., 2021) |
| | Lentil | - improves yield and biomass parameters<br><br>- improves physiological growth indices | - improvement in nutrients (nitrogen) assimilation | (Kolenčík et al., 2022) |
| | Bean | - minimization of ROS in leaves<br><br>- improves chlorophyll pigment accumulation | - maintains cell turgor pressure and regulates homeostasis. | (Babanli et al., 2024) |
| $SiO_2$-NPs | Sorghum | - improved germination percentage<br><br>- enhanced growth parameters | - enhanced imbibition | (Al-Zandi, 2019) |
| | Wheat | – 12.54 and 84.04% increase in leaf greenness (SPAD) and relative water content<br><br>- up to 17.81% increase in yield | - enhances the endogenous level of cytokinin<br><br>- induces proline accumulation | (Behboudi, et al., 2018a) |
| | Barley | - improve growth and yield parameters<br><br>- improve protein content | - not stated | (Hellala et al., 2020) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | Wheat | - enhancements by 12–42%, 14–54%, 5–49%, 5–41%, 17–62%, and 21–64% were observed in the spike length, grains per spike, 1000 grain weight, plant height, grain yield, and biological yield, respectively. | - improve cytokinin endogenously and chlorophyll ultrastructure<br><br>- Si deposition in the apoplast and cuticle thickens the cell wall, which reduces transpiration rate, shields the plant from stress, and improves nutrition flow through the xylem opening. | (Raza et al., 2023) |
| | Shallot | - significant in the fresh and dry weight of tubers and their quantity. | Improved efficiency of photosynthesis in the presence of water stress and reduced peroxidation of membrane lipids | (Rahmawati and Wulandari, 2024) |
| | Ginger | - significantly enhanced relative water content (up to 63% increase), chlorophyll concentrations, and photosynthesis (up to 72.7% increase).<br><br>- increased leaf osmotic potential (up to 35.1% ) and leaf water potential (up to 3.6%) | - inhibition of oxidative damage<br><br>- increase leaf water potential by maintaining stomatal openings | (Zhu et al., 2024) |
| | Rice | - significantly improved growth, yield and photosynthetic parameters<br><br>- increased proline accumulation and antioxidant enzyme activities<br><br>- had no ameliorating effects on treatments exposed to drought regimes of 6 days and more. | - homeostasis remobilization and reduction of water loss by concentration on the surface of the shoot parts | (Elshayb et al., 2021) |
| | Maize | - improved growth indices<br><br>- increased levels of osmolyte accumulation, | - increased antioxidant enzyme activity and reduced oxidative damage | (Sharf-Eldin et al., 2023) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | | photosynthetic pigments | | |
| | Wheat | - enhanced growth and yield attributes of wheat | - facilitate water uptake and transportation in plant | (Akhtar et al., 2021) |
| | Banana | - improve shoot growth parameters<br><br>- improve chlorophyll content and mitigate electrolyte leakages | - deposition of Si in the cuticle and apoplast increases the thickness of the cell wall and thus reduces the transpiration rate<br><br>- induce $K^+$ uptake, modulate $Na^+$ levels. | (Mahmoud et al., 2020) |
| | Maize | - improved morphological growth indices<br><br>- enhanced physiological parameters and antioxidant enzyme activities.<br><br>- improved yield traits and productivity<br><br>- enhanced nutrient uptakes | - enhancement of the soil's physicochemical properties and enzymatic activity (dehydrogenase and alkaline phosphatase).<br><br>- stimulation of nutrients binding in plant tissues, and by enhancing their translocation into shoots | (Hafez et al., 2021) |
| | Hawthorn | - positive effects on biochemical and physiological indices<br><br>- positive effects on growth and biomass parameters. | - not stated | (Ashkavand et al., 2015) |
| Fe-NPs | Barley | - Improve vegetative growth and yield | - not stated | (Zahedi and Alipour, 2018) |
| Mn-NPs | Barley | - Improved vegetative growth and yield | - not stated | (Zahedi and Alipour, 2018 |
| Chitosan<br><br>(Polymeric NPs) | Barley | - increase leaf area, shoot height and relative water content<br><br>- increase photosynthetic pigment accumulation<br><br>- increased proline, catalase and superoxide dismutase content | - enhances the endogenous level of cytokinin<br><br>- increases antioxidants and enzyme activities<br><br>- regulation of osmotic pressure inside cells and | (Behboudi, et al., 2018b) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | | - improved grain protein and yield components<br><br>- improved biomass and harvest index | prevention of dangerous free radicals build-up | |
| | Wheat | -improved leaf area (LA), relative water content (RWC), chlorophyll content, photosynthesis rate<br><br>- improved catalase (CAT) and superoxide dismutase (SOD) activities<br><br>- improved biomass and yield parameters | - modify cell osmotic pressure to enhance water and vital nutrient availability and uptake<br><br>- reduction of the build-up of<br><br>harmful free radicals | (Behboudi et al., 2019) |
| | Soybeans | - significantly improves morphological growth parameters<br><br>- lowers electrolyte leakage<br><br>- boosts proline content and catalase and peroxidase activities. | - boosting of cellular enzymatic activity<br><br>- enhancement of pro-metabolism genes and suppression of pro-catabolism gene expressions | (Methela et al., 2023) |
| | Tomato | - significant up-regulation in the expression of all tested genes under drought conditions | - gene expression modulation | (Mohamed and Abdel-Hakeem, 2023) |
| | White lupin | - improves growth, yield and quality of lupin<br><br>- improves photosynthetic pigments and phytochemical content accumulation. | - CS-NPS enhances the nitrogen metabolism and photosynthetic complexes by functioning as an efficient photocatalyst | (Bakhoum et al., 2022) |
| Si-NPs | Barley | - significant increase in shoot and root biomass<br><br>- up to 17.1% and 24.1% in total chlorophyll and carotenoid | - modification of the membrane stability indices, metabolite profile, and plant osmolyte<br><br>- alters the morpho-physiological and antioxidative characteristics of plants and stimulates the | (Ghorbanpour et al., 2020) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | | | creation of certain metabolites | |
| | Maize | - enhanced growth and photosynthetic parameters<br><br>- inhibits the production of superoxide radicals, $H_2O_2$ and MDA | - osmotic regulation | (Xu *et al.*, 2022) |
| | Faba Beans | - enhanced agronomic traits<br><br>- improved physiological and biochemical parameters | - alleviate overproduction of ROS and improve defence systems | (Desoky et al., 2021) |
| | Green pea | - increased RWC and specific leaf area (SLA) by 29%<br><br>- decrease root/shoot ratio by 4% | - improvement in antioxidant enzyme activities | (Sutulienė et al., 2021) |
| | Millet | - significantly increased grain yield, harvest indices and water productivity | - not stated | (Mokari and Abedinpour, 2020) |
| | Coriander | - increases in chlorophyll content, total soluble sugar, and antioxidant enzyme activities.<br><br>- enhanced secondary metabolites accumulation | - reactive oxygen species scavenging activities | (Afshari et al., 2023) |
| | Marigold | - significantly enhanced germination rate, germination index and time to germination<br><br>- enhanced vigor and dry weight | - not stated | (Saeedeh et al., 2021) |
| | Tomato | - improved germination rate by 32% compared to control<br><br>- at high concentrations (2mM), Si-NP had negative effects | - not stated | (Haghighi et al., 2013) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| Ag-NPs | Lentil | - improve germination rate and germination percentage<br>- improve shoot and root length. | - not stated | (Hojjat and Ganjali, 2016) |
| | Tomato | - improve morphological and physiological growth indices<br>- improve yield and fruit quality | - regulates osmotic water potentials and ensures water balance | (Akhoundnejad et al., 2022a) |
| | Eggplant | - limited proline accumulation, decreased $H_2O_2$, and lower MDA concentration<br>- improve growth and yield attributes. | - upregulation of antioxidant enzymes | (Alabdallah et al., 2021) |
| | Lettuce | - glutathione S-transferase activity decreased (at a concentration of 100 mg $L^{-1}$) but vice versa at lower concentrations<br>- enhanced total flavonoids and phenolic content<br>- no significant effect on water use efficiency | - not stated | (Akhoundnejad et al., 2022b) |
| | Boysenberry | - improves morphological and physiological growth parameters<br>- increases antioxidant activities of SOD and catalase enzyme<br>- reduces malondialdehyde (MDA) levels | - blockage of ethylene signals<br>- improves water and nutrients uptakes | (Şener and Sayğı, 2023) |
| $Fe_2O_3$-NPs | Sorghum | - increased fresh weight (56%), dry weight (34%), total chlorophyll (104%), chla (160%), and chlb (1936%) of plants as well as their height (70%). | - reduction of ROS formation and osmolyte accumulation<br>- prevention of biomolecule degradation | (Ndou et al., 2023) |
| | Grape | - improved chlorophyll content and | - promotion of antioxidant | (Bidabadi et al., 2023) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | | fluorescence | protection by reduction of MDA and $H_2O_2$ generation. | |
| | Soybean | - boosted yield and seed quality<br>- improved yield and physiological parameters | - enhancement of photosynthetic activities | (Farajollahi et al., 2023) |
| | Rice | - enhanced nutrient uptake, antioxidant enzyme concentrations, photosynthetic efficiency, biomass, and reduced reactive oxygen species. | - not stated | (Ahmed et al., 2021) |
| | Rice | - significantly reduced membrane damage | - Fe involvement in protein biosynthesis | (Darmaningtyas and Sakya, 2023) |
| | Wheat | - increased photosynthetic pigments, proline, reduced lipid peroxidation<br>- increased concentrations of ascorbate peroxidase (44.6%), proline (127%), superoxide dismutase (115%), and peroxidase (43.8%).<br>- enhanced photosynthetic pigments | - not stated | (Noor et al., 2022) |
| | Maize | - no significant improvement in measured traits of chlorophyll content, biomass and yield parameters. | - not stated | (Eliaspour et al., 2020) |
| | Garden Pea | - shoot length and number of leaves increased by 38% and 24%<br>- reduced levels of MDA and $H_2O_2$ in the water-stressed plants by 35% and 52%, respectively<br>- enhanced the levels of the antioxidant enzymes catalase (CAT) and | - maintenance and balancing of cellular osmotic pressure | (Mazhar et al., 2023) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | | superoxide dismutase (SOD) by 38% and 13%, respectively. | | |
| Se-NPs<br>$TiO_2$-NPs<br>Si-NPs | Mango | - All three NPs improve growth parameters, fruit yield, fruit set percentages, fruits' physical and chemical characteristics and nutritional status.<br>- Titanium gave the best result, followed by Selenium across different concentrations. | - increased nitrogen assimilation, thereby boosting amino acids and protein production<br>- Si-NPs enhance the uptake and transport of water and nutrients<br>- Ti-NPs enhance macro- and micro-nutrients acquisition. | (Almutairi et al., 2023) |
| $MoO_3$-NPs | Pea | - improves morphological and yield parameters<br>- significantly activated antioxidant enzymes and increased total phenolic compounds. | - increases the accumulation of protective antioxidants | (Sutulienė et al., 2023a) |
| | Maize | - enhanced photosynthetic and carotenoid contents<br>- improved grain yield | - enhancement of ROS scavenging activities | (Van Nguyen et al., 2022) |
| Cu-NPs | Chickpea | - significantly enhanced germination percentage<br>- boosts proline accumulation and lessens ROS accumulations. | - improved energy status of the mitochondria and elevated protein synthesis<br>- penetration of Cu-NPs into the cell walls, thereby assisting in the formation of new pores and enhancing imbibition. | (Rani et al., 2024) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | Oat | - improved train quality and yield parameters<br><br>- Co-NP improved germination percentage by 4%, while Co-NP had no significant effect.<br><br>- the combination of both NPs yielded the best results. | - not stated | (Nazarova, 2020) |
| | Wheat | - increase in superoxide dismutase (SOD) activities by 22%<br><br>- decreased the amount of thiobarbituric acid reactive substance (TBARS) build-up<br><br>- raised the RWC of leaves and stabilized the amount of pigments used in photosynthetic processes. | - possible involvement of nanoparticles in enzymatic reactions of plant metabolism | (Taran et al., 2017) |
| Fe-CTs NPS | Peppermint | - significant increase in vegetative yield<br><br>- increase proline accumulation<br><br>- increased chlorophyll fluorescence | - limiting of evapotranspiration rate | (Giglou et al., 2022) |
| Kinetin-capped ZnO-NPs (K-ZnO) | Mung beans | - improves morphological (growth), physiological and biochemical parameters | - upregulation of osmolytes and the antioxidant defence system | (Ajmal et al., 2023) |
| $Fe_2O_3$-NPs<br><br>CuO-NPs<br><br>CoO-NPs &<br><br>$ZnO_2$-NPs | Soybean | - significantly improved relative water content drought tolerance indices.<br><br>- $Fe_2O_3$-NP was found to be most effective among the tested NPs in increasing drought tolerance traits | - induce drought-related gene expressions<br><br>- stimulation of antioxidative enzyme activities. | (Linh et al., 2020) |
| $B_2O_3$-NPs | Pea | - improves morphological traits<br><br>- reduces the accumulation of MDA and $H_2O_2$. | - increases nitrogen fixation and antioxidant production | (Sutulienė et al., 2023b) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| CaO-NPs | Canola | - enhanced germination rate<br><br>- enhanced total chlorophyll by 28.9% and the number of leaves by 16%.<br><br>- increased yield, 100 seed weights, number of seeds per pod, number of pods per branch, and number of seeds per pod by 29.99%, 73.076%, 35.13%, and 35.18%, respectively.<br><br>- improved level of antioxidant enzyme | - CaO-NPs mediated ROS production<br><br>- accelerated starch<br><br>metabolism<br><br>- the expression of the aquaporin gene, which promotes water absorption, is mediated by nanoparticles. | (Mazhar et al., 2022) |
| | Alfalfa | - Significantly improved physiological, biochemical and biomass indices. | - alterations in ROS levels and metabolic processes | (Yazicilar et al., 2024) |
| Si-NPs<br><br>Zn-NPs &<br><br>Ze-NPs | Coriander | - water use efficiency, photosynthetic rate, chlorophyll fluorescence, and photosystem-II efficiency were all noticeably higher in leaves.<br><br>- significantly enhanced growth and biomass attributes. | - enhancement of water use efficiency, and nutrient accumulation and phytohormones<br><br>- improved water and nutrient uptakes. | (Mahmoud et al., 2023) |
| Cu-NPs<br><br>Fe-NPs &<br><br>Co-NPs | Maize | - improved photosynthetic content<br><br>- improved growth and productivity of maize<br><br>- Fe-NP had the strongest effect at the early growth stage.<br><br>- Cu-NP yielded the best results | - not stated | (Hoang et al., 2019) |
| PNS (Potassium nano-silica) | Maize | - enhanced nutrient uptake<br><br>- had no significant impact on the seed's absorption of certain nutrients, including P, Ca, Na, and Cu, or the shoot's absorption of Ca and Na. | - improvement in the level of absorption of certain nutrients | (Aqaei et al., 2020) |
| Urea doped-$Ca_3(PO_4)_2$-NPs | Millet | - significantly enhanced growth and biomass indices.<br><br>- enhanced plant defence enzymes, including proline (35.4%), superoxide dismutase | - enzymatic regulation | (Mishra et al., 2023) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | | (47.7%), guaiacol peroxidase (30.2%), and ascorbate peroxidase (70%), as well as an enhanced pigment system (chlorophyll). | | |
| Ti-NPs & Si-NPs | Cumin | - enhanced biochemical attributes | - not stated | (Salajegheh et al., 2020) |
| Zn-NPs | Rice | - increased root dry weight, biomass, number of leaves, number of tillers, and plant height to 6%, 33%, 23%, 28%, and 34%, respectively. | - not stated | (Alhasan et al., 2021) |
| | Turnip | - Zn-NPs led to a significant increase in plant height, biomass, antioxidant defence system, root/turnip length, and turnip diameter.<br><br>- improved chlorophyll contents | - enhancement of the levels of total free amino acids and total soluble sugar<br><br>- upregulation of antioxidants | (Li et al., 2023) |
| Fe-Si-NPs | Triticale | - enhanced chlorophyll fluorescence components<br><br>- significantly improved physiological components | - not stated | (Aghaei et al., 2022) |
| Fullerenol-NPs (FNP) | Sugar beets | - majorly, FNP had no significant effect on the measures of growth and yield attributes. | - intracellular binding of water, creating an additional water reserve | (Borišev et al., 2016) |
| Fullerene C-nanotube, & Graphene (Carbon based NPs) | Chilli Pepper | - graphene enhanced the number of flowers per plant, while other CNMs had no significant effect on plant performances.<br><br>- a 1000 mg/L concentration of carbon nanotubes significantly increased stomatal conductance and the rate of photosynthesis. | - not stated | (Ahmadi et al., 2024) |
| $Fe_3O_4$-NPs ZnO-NPs | Potato | - both significantly enhanced growth and biochemical parameters<br><br>- ZnO-NP was more effective than Fe3O4 in most growth and biochemical parameters | - enhanced reactive oxygen species scavenging activities | (Sallam et al., 2022) |
| ZnO-NPs & $SiO_2$-NPs | Potato | - improved leaf gas exchange attributes, LRWC, and proline content<br><br>- significantly enhanced chlorophyll and carotenoid content | - increased Rubisco enzyme activity by ZnO-NP | (Al-Selwey et al., 2023) |

| Nanoparticle (NPs) | Food Crop | Efficacy (Key Findings) | Stated Mechanism of Actions | References |
|---|---|---|---|---|
| | | - boosted yield traits and harvest index<br>- ZnO-NP yielded better results | | |
| $SiO_2$-NPs<br>Se-NPs &<br>Se/$SiO_2$-NPs | Strawberry | - all three treatments improved growth, biomass and yield attributes and chlorophyll content<br>- all treatments enhanced physiological and biochemical attributes<br>- Se/$SiO_2$-NP yielded the best results | - stimulation of ethylene production in fruits during drought stress<br>- reduction of oxidative damage by scavenging ROS | (Zahedi *et al.*, 2020) |
| Se-NPs & Si-NPs | Rice | - reduced reactive oxygen species production<br>- significantly enhanced growth, yield and quality traits<br>- the combination of both NPs yielded the best results | - increased osmoprotectant synthesis and increased antioxidant enzyme activity | (Ghouri et al., 2022) |
| ZnO-NPs &<br>$SiO_2$-NPs | Potato | - significantly enhanced yield and quality parameters except for tuber dry weight. | - raising of melatonin levels in response to dryness because they can scavenge free radicals. | (Seleiman et al., 2023) |

# 8. Mechanisms of actions of nanoparticles in mitigating drought stress in food crops

The mechanisms of action by which nanoparticles (NPs) mitigates drought stress in food crop plants are complex, with interconnections that is focused mainly on inducing the physiological, biochemical and genetic resistance to the plant under drought stress conditions. Conceptually, these mechanisms can be broadly grouped into activation of antioxidant systems, regulation of osmotic and water status, enhancement of metabolic processes and nutrient uptake and genetic or hormonal modulation.

The primary attributed mechanism is the up-regulation of antioxidant defense in food crops. Under drought conditions, plants usually undergo oxidative stress, which is caused by reactive oxygen species (ROS). But NP treatment boosts the formation of antioxidant enzymes and other antioxidants. For instance, $TiO_2$-NPs promote the production of antioxidant enzymes (Mustafa et al., 2021) and ZnO-NPs are known for the effective scavenging of reactive oxygen species (El Zohri *et al.*, 2021). Likewise, $Fe_2O_3$-NPs decrease ROS production (Ndou et al., 2023), and malondialdehyde (MDA) and $H_2O_2$ production to protect membranes (Bidabadi et al., 2023). Other mechanisms include increasing melatonin for free radical scavenging (Seleiman et al., 2023) and inhibiting electrolyte leakage to maintain membrane integrity (Mahmoud et al., 2020).

NPs also help food crops under drought stress conditions by maintaining osmotic potential and water status to to maintain essential physiological functions. These include certain mechanisms of plant osmotic adjustment (Mustafa et al., 2021), and inducing osmolytes such as proline and total soluble sugars (Zahedi et al., 2021; Shoarian et al., 2020). Mechanically, this maintains the water status of plants (Ikram et al., 2020), helps sustain cell turgor pressure to maintain homeostasis (Babanli et al., 2024) and enhances the binding of water to cells, forming an additional water reserve (Borišev et al., 2016). In particular, $SiO_2$-NPs deposit Si in the cell wall and thickens it, thus decreasing transpiration (Raza et al., 2023). In the root, NPs enhance water absorption by widening root pores or generating new pores (Faraji and Sepehri, 2019) and by modulating the expression of aquaporin gene (Mazhar et al., 2022).

Furthermore, the application of NPs mitigates the effects of drought stress by improving overall metabolic and biochemical processes, and nutrient uptake. NPs are reported to increase the overall metabolic activity of plants (Hojjat, 2020), as well as to increase the rate of specific processes, such as starch metabolism (Mazhar et al., 2022). One crucial mechanism is the enhancement of photosynthetic efficiency through photosystem complexes and photosynthetic induction (Janmohammadi et al., 2016; Ahmed et al., 2023). NPs also improve the uptake of nutrients (Mustafa et al., 2021), enhance nitrogen assimilation, and hence amino acid and protein synthesis (Almutairi et al., 2023). Silica ($SiO_2$) nanoparticles have been observed to keep stomatal pores open to boost leaf water potential in ginger (Zhu et al., 2024), while carbon-based NPs such as carbon nanotubes can lead to increased stomatal conductance (Ahmadi et al., 2024).

Finally, the above mechanisms include genetic and hormonal regulation. Particular nanoparticles work by modulating enzyme and gene expression involved in drought tolerance. These mechanisms include the production of auxins (heteroauxin) to boost mitotic index at the root tip (Nagdalian et al., 2023), the endogenous inducement of cytokinin (Behboudi et al., 2018a), and modulation of carbohydrate metabolism (Sun *et al.*, 2021). Genetic responses are stated as a critical mechanism including the regulation of genes associated with biochemical or genetic mechanisms of tolerance (Faraji and Sepehri, 2019; Ahmed et al., 2021). Some empirical studies of reference in the above table cite certain mechanisms such as the modulation of gene expression (Mohamed and Abdel-Hakeem, 2023), enhancing pro-metabolism genes, while down-regulating pro-catabolism gene expressions (Methela et al., 2023), and increased expression of drought-related genes to enhance plant tolerance (Linh et al., 2020).

# 9 Current challenges and safety concerns

The complex nature of nanoparticles is one of the fundamental issues in assessing their ecological impact. Indeed, nearly every one of their basic characteristics and actions is challenging to evaluate and research. Nonetheless, a lot of advancement has been made in the last recent years. This challenge of the complex nature of nanoparticles,though both boundary states have been comparatively well characterized for a significant amount of time, nanomaterials can exist in a wide range of shapes and sizes between the molecular and bulk states (Bernhardt et al., 2010).

One of the best perspectives on dissecting the ecological impacts of nanoparticles is based on their mode of synthesis. While nanoparticles can either be naturally occurring or synthesized via different means, nanoparticles application in agriculture and other fields of study are mainly synthesized. Chemical, physical, biological, and mechanical processes can all be used to create nanoparticles, and each synthesis method has pros and cons of its own. Based on the mode of synthesis, biologically synthesized nanoparticles have widely been accepted by the

vast majority of studies (Patra and Baek 2014; Wahab et al., 2023) as the best alternative, and particularly in terms of eco-friendliness compared to other methods chemical methods.

Even though nanoparticles synthesized by other means can also be effective in their various applications, nevertheless, biologically synthesized, in particular, phyto-synthesized nanoparticles appear more advantageous, which are attributed but not limited to the following; low toxic (hazardous waste) generation (Chen et al., 2022), cost-effectiveness (Yew *et al.*, 2022), energy efficiency (Vejan et al., 2021), scalability and adaptability (Ikram et al., 2021), usage of renewable plant resources (Akintelu *et al.*, 2021), time efficiency (Taghavizadeh yazdi et al., 2019), safety consideration (Hadinejad, et al., 2021), and quality control (Samari et al., 2019).

Shafiq et al. (2021), Rónavári *et al.*(2021), and Aswathi et al., (2023). Phyto-synthesized nanoparticles as more eco-friendly over those synthesized via other means due to their relatively simpler and safer methodology involving the use of plant extracts (Shafiq et al., 2021; Rónavári *et al.*2021; Aswathi et al., 2023). In a similar vein Aththanayaka et al., 2022 and Khan et al., 2022 cited lower toxic bye-product and environmentally friendly process while Chinnathambi et al., (2023) ascribed safer choice of phyto-synthesized nanoparticles to adaptation to various applications and Qadeer et al., 2023 cited broadness in the scope of application (e.g. medicine and bioremediation etc.). These are all predicated on methodological techniques that are safe and straightforward, as well as their implications for sustainability and real-world applications.

From the standpoint of a single nanoparticle, its toxicity might vary depending on a number of variables, such as its size, shape, and characteristics. Higher concentrations of NPs can have detrimental effects on food nutritional value (Rico et al., 2013), seed germination (Haghighi et al., 2013), growth (Ikram et al., 2020), yield and antioxidant enzyme activity (Karvar et al., 2022). Nanoparticles can also affect plant growth by decreasing chlorophyll synthesis, photosynthetic performance, and antioxidant activities (Wang et al., 2018). Compared to conventional bulk materials, nanoparticles (NPs) reach biological systems 15–20 times faster because of their small size (Khan et al., 2021). NPs are absorbed by soil systems and negatively affect native nematodes, fungi, and bacteria (Handy and Shaw, 2007; Khan et al., 2021). Studies have shown that NP-mediated toxicity in plants, algae, and other microbes is associated with oxidative stress and physical injury caused by ROS generation (Hou et al., 2018).

Human health may be at risk from several metal nanoparticles (NPs) utilized in various industries, such as iron, silver, platinum, and gold, as well as metal oxide NPs like $Fe_3O_4$, ZnO, and $TiO_2$. When these NPs come into contact with cells, they can cause damage to membranes, DNA, and proteins (Hsin et al., 2008). These NPs can penetrate the bloodstream and important organs, where they can have a highly harmful effect (Hsin et al., 2008). When absorbed by the roots, NPs penetrate the root cortex and cell wall epidermis before moving to the upper part of the plant, where they have the potential to be highly hazardous if not regulated (Rajput et al., 2018). Because NPs produce ROS, they are also cytotoxic and genotoxic to mammals in addition to plants (Khan et al., 2015). Similarly, NPs alter the growth of amphibian plants, PS-II efficiency, and photosynthetic colour structure in aquatic environments (Jacobasch et al., 2014). Ecotoxicity of different classes of nanoparticles, including carbon-based nanoparticles, metal and oxides of metal nanoparticles, etc., have been discussed (Rana and Kalaichelvan, 2013).

## 10 Future perspective and research gaps

There are still a number of important knowledge gaps despite growing evidence on nanoparticles' potential to improve food crops' resistance to drought. The translation of nanoparticle-based interventions to actual agroecosystems is hampered by the majority of studies conducted to date being limited to laboratory or

greenhouse conditions with little multi-season and field-scale validation (Cao et al., 2025). There is also a significant variation in the type, concentration, synthesis pathway, and application technique of nanoparticles, highlighting the necessity of standardized experimental and reporting frameworks to facilitate cross-study comparability.

As of now, little is known about the long-term environmental fate and persistence of nanoparticles in soil–plant systems, particularly under repeated applications and changing soil physicochemical conditions. This raises questions about trophic transfer, microbial communities, and soil health (Tourinho et al., 2012; Kah et al., 2018). Furthermore, physiological reactions like increased antioxidant activity are widely known, there are still few molecular and omics-level insights into nanoparticle-mediated drought tolerance, which call for further research using transcriptomic and metabolomic techniques.

Significantly, little research evaluates the accumulation of nanoparticles in edible plant tissues, resulting in significant gaps in our knowledge of possible food chain and human health consequences (Parisi et al., 2015). In addition, research is disproportionately focused on temperate regions and controlled environments, with little attention to drought-prone, food-insecure regions like South Asia and sub-Saharan Africa.

Therefore, in order to support the responsible integration of nanobiology into agricultural systems that are both climate resilient and food secure, future research should prioritize field validation, biosafety assessment, molecular mechanistic studies, and life-cycle and economic analyses.

# 11 Conclusion and recommendation

In conclusion, nanobiology offers a powerful and innovative approach to fortifying global food systems against climatic variability, particularly drought. By strategically focusing future research majorly on field validation, deeper mechanistic insights and understanding, and robust biosafety evluation, the enormous potential of nanoparticles can be responsibly maximized to secure sustainable crop production and advance global food security objectives. Extensive studies are recommended on nanoparticle-crop relationships to ensure effective maximisation to match best-fit nanoparticles for different food crop plants with more attention focused on emerging biodegradable plant elicitors such as chitosan biopolymers. More studies are also recommended to determine optimal dosages and concentration levels, optimal application method for on-field treatment and priming duration for seed treatments.

# Declarations

**Authors contribution**

**Adejumo:** Conceptualization, Literature Search, Review famework, Writing (Original Draft).
**Raimi:** Methodology, Resources, Validation, Review and Editing.
**Sakpere:** Supervision, Resources, Review and Editing, Final Approval of Manuscript.

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**Data availability**

No datasets were generated or analysed during the current study.

**Ethics approval and consent to participate**

Ethical approval was not required.

**Ethical approval**

Not required

**Consent for publication**

All authors are in agreement to submit this manuscript to 'Discover Plants' for publication.

**Declaration of competing interest**

We have no competing interest to declare

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# References

1. Adejumo MA, Olowolaju ED, Okunlola GO, Akinyemi DS. Symptom expression and severity indices of *Solanum lycopersicum* L. and *Solanum melongena* L. at different growth stages under water deficit. Discov Plants. 2025;2(1):171. https://doi.org/10.1007/s44372-025-00254-9.
2. Afshari M, Pazoki A, Sadeghipour O. Biochemical changes of coriander (*Coriandrum sativum* L.) plants under drought stress and foliar application of salicylic acid and silicon nanoparticles. J Med Plants By-Prod. 2023;12(3):197–207. https://doi.org/10.22092/jmpb.2022.356434.1417.
3. Aghaei F, Seyed Sharifi R, Farzaneh S. The effect of some nanoparticles and biofertilizers on chlorophyll fluorescence components and some physiological traits of Triticale(*Triticosecale Wittmack*) at different irrigation levels. Iran J Plant Biol. 2022;14(3):13–40. https://doi.org/10.22108/IJPB.2023.137496.1320.
4. Aghdam MTB, Mohammadi H, Ghorbanpour M. Effects of nanoparticulate anatase titanium dioxide on physiological and biochemical performance of *Linum usitatissimum* (Linaceae) under well-watered and drought stress conditions. Brazilian J Bot. 2016;39(1):139–46. https://doi.org/10.1007/s40415-015-0227-x.
5. Agovino M, Casaccia M, Ciommi M, Ferrara M, Marchesano K. Agriculture, climate change and sustainability: The case of EU-28. Ecol. Indic. 2019;105:525–43. https://doi.org/10.1016/j.ecolind.2018.04.064.
6. Ahmadi SZ, Zahedi B, Ghorbanpour M, Mumivand H. Comparative morpho-physiological and biochemical responses of *Capsicum annuum* L. plants to multi-walled carbon nanotubes, fullerene C60 and graphene nanoplatelets exposure under water deficit stress. BMC Plant Biol. 2024;24(1):116. https://doi.org/10.1186/s12870-024-04798-y.
7. Ahmed S, Khan MT, Abbasi A, Haq IU, Hina A, Mohiuddin M, Tariq MAUR, Afzal MZ, Zaman QU, Ng AWM. Characterizing stomatal attributes and photosynthetic induction in relation to biochemical changes in *Coriandrum sativum* L. by foliar-applied zinc oxide nanoparticles under drought conditions. Front Plant Sci. 2023;13:2022. https://doi.org/10.3389/fpls.2022.1079283.
8. Ahmed SM. Impacts of drought, food security policy and climate change on performance of irrigation schemes in Sub-saharan Africa: The case of Sudan. Agric Water Manag. 2020;232:106064.

https://doi.org/10.1016/j.agwat.2020.106064.

9. Ahmed T, Noman M, Manzoor N, Shahid M, Abdullah M, Ali L, Wang G, Hashem A, Al-Arjani ABF, Alqarawi AA. Nanoparticle-based amelioration of drought stress and cadmium toxicity in rice via triggering the stress responsive genetic mechanisms and nutrient acquisition. Ecotoxicol Environ Saf. 2021;209:111829. https://doi.org/10.1016/j.ecoenv.2020.111829.
10. Ajmal M, Ullah R, Muhammad Z, Khan MN, Kakar HA, Kaplan A, Okla MK, Saleh IA, Kamal A, Abdullah A. Kinetin capped zinc oxide nanoparticles improve plant growth and ameliorate resistivity to polyethylene glycol (PEG)-induced drought stress in *Vigna radiata* (L.) R. Wilczek (Mung Bean). Molecules. 2023;28(13):5059. https://doi.org/10.3390/molecules28135059.
11. Akhoundnejad Y, Karakaş Ö, Daşgan H, Sevgin N, Gundogdu G, Temur B. Effects of silver nanoparticles (Ag-NPs) on physiological and biochemical properties of tomato plants under drought stress. MKU J Agric Sci. 2022;28(3):522–35. https://doi.org/10.37908/mkutbd.1266767.
12. Akhoundnejad Y, Karakas O, Demirci O. Response of lettuce to silver nanoparticles under drought conditions. J Sci Technol Trans Sci. 2022;46(1):111–20. https://doi.org/10.1007/s40995-021-01241-x.
13. Akhtar N, Ilyas N, Hayat R, Yasmin H, Noureldeen A, Ahmad P. Synergistic effects of plant growth promoting rhizobacteria and silicon dioxide nano-particles for amelioration of drought stress in wheat. Plant Physiol Biochem. 2021;166:160–76. https://doi.org/10.1016/j.plaphy.2021.05.039.
14. Akintelu SA, Folorunso AS. A review on green synthesis of zinc oxide nanoparticles using plant extracts and its biomedical applications. BioNanoScience. 2020;10(4):848–63. https://doi.org/10.1007/s12668-020-00774-6.
15. Alabdallah NM, Hasan M, Salih AM, Roushdy SS, Al-Shammari AS, Alsanie SI, El-Zaidy M. Silver nanoparticles improve growth and protect against oxidative damage in eggplant seedlings under drought stress. Plant Soil Environ. 2021;67(11). https://doi.org/10.17221/323/2021-PSE.
16. Alhasan FM, Sakya AT, Rahayu M. Improving growth performance of rice cultivars IR64 and Mentik Wangi in drought stress with applying nano Zn. IOP Conf. Ser. Earth Environ Sci. 2021;824(1):012047. https://doi.org/10.1088/1755-1315/824/1/012047.
17. Almutairi KF, Górnik K, Awad RM, Ayoub A, Abada HS, Mosa WF. Influence of selenium, titanium, and silicon nanoparticles on the growth, yield, and fruit quality of mango under drought conditions. Horticulturae. 2023;9(11):1231. https://doi.org/10.3390/horticulturae9111231.
18. Al-Selwey WA, Alsadon AA, Ibrahim AA, Labis JP, Seleiman MF. Effects of zinc oxide and silicon dioxide nanoparticles on physiological, yield, and water use efficiency traits of potato grown under water deficit. Plants. 2023;12(1):218. https://doi.org/10.3390/plants12010218.
19. Altammar KA. A review on nanoparticles: characteristics, synthesis, applications, and challenges. Front Microbiolol. 2023;14:1155622. https://doi.org/10.3389/fmicb.2023.1155622.
20. Al-Zandi A. Influence of silica nanoparticles on germination and early seedling growth of *Sorghum bicolor* L. under water stress. Int J Bot Stud. 2019;4(5):45–9.
21. Aqaei P, Weisany W, Diyanat M, Razmi J, Struik PC. Response of maize (*Zea mays* L.) to potassium nano-silica application under drought stress. J Plant Nutr. 2020;43(9):1205–16. https://doi.org/10.1080/01904167.2020.1727508.
22. Arora NK. Impact of climate change on agriculture production and its sustainable solutions. Environ Sustain. 2(2):95–6. https://doi.org/10.1007/s42398-019-00078-w

23. Aryal JP, Sapkota TB, Khurana R, Khatri-Chhetri A, Rahut DB, Jat ML. Climate change and agriculture in South Asia: adaptation options in smallholder production systems: JP Aryal. Environ Dev Sustain. 2020;22(6):5045–75. https://doi.org/10.1007/s10668-019-00414-4.
24. Ashkavand P, Tabari M, Zarafshar M, Tomásková I, Struve D. Effect of $SiO_2$ nanoparticles on drought resistance in hawthorn seedlings. Res Pap. 2015;76(4). https://doi.org/10.1515-frp-2015-0034.
25. Aswathi V, Meera S, Maria CA, Nidhin M. Green synthesis of nanoparticles from biodegradable waste extracts and their applications: A critical review. Nanotechnol Environ Eng. 2023;8:377–97. https://doi.org/10.1007/s41204-022-00276-8.
26. Aththanayaka S, Thiripuranatha G, Ekanayake S. Emerging advances in biomimetic synthesis of nanocomposites and potential applications. Mater Today Sustain. 2022;20:100206. https://doi.org/10.1016/j.mtsust.2022.100206.
27. Awasthi R, Kaushal N, Vadez V, Turner NC, Berger J, Siddique KH, Nayyar H. Individual and combined effects of transient drought and heat stress on carbon assimilation and seed filling in chickpea. Funct Plant Biol. 2014;41(11):1148–67. https://doi.org/10.1071/FP13340.
28. Babanli S, Ahmadov I, Khalilov R. Effect of nano zinc oxide on the chlorophyll content of bean plants under drought stress. Adv Bio Earth Sci. 2024;9:40–52. https://doi.org/10.62476/abes9s40.
29. Bakhoum G, Sadak M, Tawfic M. Chitosan and chitosan nanoparticle effect on growth, productivity and some biochemical aspects of *Lupinus termis* L plant under drought conditions. Egypt J Chem. 2022;65(5):537–49. https://doi.org/10.21608/EJCHEM.2021.97832.4563.
30. Balusamy SR, Josh AS, Perumalsamy H, Mijakovic I, Sing P. Advancing sustainable agriculture: a critical review of smart and eco-friendly nanomaterial applications. J Nanobiotechnol. 2023;21(1):72. https://doi.org/10.1186/s12951-023-02135-3.
31. Begna T. Effects of drought stress on crop production and productivity. Int J Res Stud Agric Sci. 2020;6(9):34–43. https://doi.org/10.20431/2454-6224.0609005.
32. Behboudi F, Tahmasebi SZ, Zaman KM, Modares SAM, Sorooshzadeh A. Improving growth and yield of wheat under drought stress via application of $SiO_2$ nanoparticles. J Agric Sci Tech. 2018;20(7):1479–92. https://sid.ir/paper/62757/en.
33. Behboudi F, Tahmasebi Sarvestani Z, Kassaee MZ, Modares Sanavi SAM, Sorooshzadeh A, Ahmadi SB. Evaluation of chitosan nanoparticles effects on yield and yield components of barley (*Hordeum vulgare* L.) under late season drought stress. J Water Environ Nanotechnol. 2018;3(1):22–39. https://doi.org/10.22090/jwent.2018.01.003.
34. Behboudi F, Tahmasebi-Sarvestani Z, Kassaee MZ, Modarres-Sanavy SAM, Sorooshzadeh A, Mokhtassi-Bidgoli A. Evaluation of chitosan nanoparticles effects with two application methods on wheat under drought stress. J ant Nutr. 2019;42(13):1439–51. https://doi.org/10.1080/01904167.2019.1617308.
35. Bernhardt ES, Colman BP, Hochella MF, Cardinale BJ, Nisbet RM, Richardson CJ, Yin L. An ecological perspective on nanomaterial impacts in the environment. J Environ Qual. 2010;39(6):1954–65. https://doi.org/10.2134/jeq2009.0479.
36. Bhattacharya A. Global climate change and its impact on agriculture. Changing climate and resource use efficiency in plants. 2019;1:1–50. https://doi.org/10.1016/B978-0-12-816209-5.00001-5
37. Bibi F, Rahman A. An overview of climate change impacts on agriculture and their mitigation strategies. Agriculture. 2023;13(8):1508. https://doi.org/10.3390/agriculture13081508.

38. Bidabadi SS, Sabbatini P, VanderWeide J. Iron oxide ($Fe_2O_3$) nanoparticles alleviate PEG-simulated drought stress in grape (*Vitis vinifera* L.) plants by regulating leaf antioxidants. Sci Hortic. 2023;312:111847. https://doi.org/10.1016/j.scienta.2023.111847.
39. Borišev M, Borišev I, Župunski M, Arsenov D, Pajević S, Ćurčić Ž, Vasin J, Djordjevic A. Drought impact is alleviated in sugar beets (*Beta vulgaris* L.) by foliar application of fullerenol nanoparticles. PLoS ONE. 2016;11(11):e0166248. https://doi.org/10.1371/journal.pone.0166248.
40. Bouhadi M, Javed Q, Jakubus M, Elkouali MH, Fougrach H, Ansar A, Ban SG, Ban D, Heath D, Černe M. Nanoparticles for sustainable agriculture: assessment of benefits and risks. Agronomy. 2025;15(5):1131. https://doi.org/10.3390/agronomy15051131.
41. Braga PCS, Martins JPR, Bonomo R, Borges RM, Silva JVG, Falqueto AR. Differential response of photosystem II and I photochemistry in leaves of two Crambe abyssinica Hochst lineages submitted to water deficit. Photosynthetica. 2020;58(5). https://doi.org/10.32615/ps.2020.065.
42. Building National Response to Climate Change BNRCC. (2008) www.nigeriaclimatechange.org. Accessed 3rd August, 2025.
43. Cao Y, Turk K, Bibi N, Ghafoor A, Ahmed N, Azmat M, Ahmed R, Ghani MI, Ahanger MA. Nanoparticles as catalysts of agricultural revolution: enhancing crop tolerance to abiotic stress: a review. Front Plant Sci. 2025;15:1510482. https://doi.org/10.3389/fpls.2024.1510482.
44. Chandra P, Wunnava A, Verma P, Chandra A, Sharma RK. Strategies to mitigate the adverse effect of drought stress on crop plants—influences of soil bacteria: a review. Pedosphere. 2021;31(3):496–509. https://doi.org/10.1016/S1002-0160(20)60092-3.
45. Chen W, Li X, Cheng H, Xia W. Chitosan-based selenium composites as potent Se supplements: Synthesis, beneficial health effects, and applications in food and agriculture. Trends Food Sci Technol. 2022;129:339–52. https://doi.org/10.1016/j.tifs.2022.10.008.
46. Cheng W, Li Y, Zuo W, Du G, Stanny M. Spatio-temporal detection of agricultural disaster vulnerability in the world and implications for developing climate-resilient agriculture. Sci Total Environ. 2024;928:172412. https://doi.org/10.1016/j.scitotenv.2024.172412.
47. Chinnathambi A, Alharbi SA, Lavarti R, Jhanani G, On-Uma R, Jutamas K, Anupong W. Larvicidal and pupicidal activity of phyto-synthesized zinc oxide nanoparticles against dengue vector aedes aegypti. Environ Res. 2023;216:114574. https://doi.org/10.1016/j.envres.2022.114574.
48. Cohen I, Zandalinas SI, Huck C, Fritschi FB, Mittler R. Meta-analysis of drought and heat stress combination impact on crop yield and yield components. Physiol Plant. 2021;171(1):66–76. https://doi.org/10.1111/ppl.13203.
49. Darmaningtyas RF, Sakya AT. Application of nano Fe on the growth of rice under drought stress. IOP Conf Ser Earth Environ Sci. 2023;1165(1):012034. https://doi.org/10.1088/1755-1315/1165/1/012034.
50. Das R, Pradhan A. An introduction to different methods of nanoparticles synthesis. In: Arakha M, Pradhan AK, Jha S, editors. Bio-Nano Interface. Singapore: Springer; 2022. https://doi.org/10.1007/978-981-16-2516-9_2.
51. Davoody N, Seghatoleslami MJ, Mousavi S, Nasrabad AA. Foxtail millet responses to bulk and nano zinc oxcide particles in water stress conditions. Annu Res Rev Biol. 2013;3(4):959–73. http://publish7promo.com/id/eprint/3156.
52. Dawson TP, Perryman AH, Osborne TM. Modelling impacts of climate change on global food security. Clim Change. 2016;134(3):429–40. https://doi.org/10.1007/s10584-014-1277-y.

53. Desoky ESM, Mansour E, El-Sobky ESE, Abdul-Hamid MI, Taha TF, Elakkad HA, Arnaout SM, Eid RS, El-Tarabily KA, Yasin MA. Physio-biochemical and agronomic responses of faba beans to exogenously applied nano-silicon under drought stress conditions. Front Plant Sci. 2021;12:637783. https://doi.org/10.3389/fpls.2021.637783.
54. Dietz KJ, Zörb C, Geilfus CM. Drought and crop yield. Plant Biol. 2021;23(6):881–93. https://doi.org/10.1111/plb.13304.
55. Dimkpa CO, Singh U, Bindraban PS, Elmer WH, Gardea-Torresdey JL, White JC. Zinc oxide nanoparticles alleviate drought-induced alterations in sorghum performance, nutrient acquisition, and grain fortification. Sci Total Environ. 2019;688:926–34. https://doi.org/10.1016/j.scitotenv.2019.06.392.
56. Disasa KN, Yan H, Zhang J, Wang G, Zhang C, Zhang D, Wang B, Hao B. Comprehensive review of drought characteristics and intensification under climate change: implications for agriculture and water resources. J Hydrol. 2025;134571. https://doi.org/10.1016/j.jhydrol.2025.134571.
57. Djanaguiraman M, KS VB, Raghu R, Jeyakumar P. Sorghum drought tolerance is enhanced by cerium oxide nanoparticles via stomatal regulation and osmolyte accumulation. Plant Physiol Biochem. 2024;212:108733. https://doi.org/10.1016/j.plaphy.2024.108733.
58. Djanaguiraman M, Nair R, Giraldo JP, Prasad PVV. Cerium oxide nanoparticles decrease drought-induced oxidative damage in sorghum leading to higher photosynthesis and grain yield. ACS Omega. 2018;3(10):14406–16. https://doi.org/10.1021/acsomega.8b01894.
59. El Bilali H, Bassole IHN, Dambo L, Berjan S. Climate change and food security. Agric For or Agric For /. Poljopr šumar. 2020;66(3). https://doi.org/10.17707/AgricultForest.66.3.16.
60. Eliaspour S, Seyed Sharifi R, Shirkhani A, Farzaneh S. Effects of biofertilizers and iron nano-oxide on maize yield and physiological properties under optimal irrigation and drought stress conditions. Food Sci Nut. 2020;8(11):5985–98. https://doi.org/10.1002/fsn3.1884.
61. Elshayb OM, Nada AM, Ibrahim HM, Amin HE, Atta AM. Application of silica nanoparticles for improving growth, yield, and enzymatic antioxidant for the hybrid rice ehr1 growing under water regime conditions. Materials. 2021;14(5):1150. https://doi.org/10.3390/ma14051150.
62. Elshayb OM, Nada AM, Sadek AH, Ismail SH, Shami A, Alharbi BM, Alhammad BA, Seleiman MF. The integrative effects of biochar and ZnO nanoparticles for enhancing rice productivity and water use efficiency under irrigation deficit conditions. Plants. 2022;11(11):1416. https://doi.org/10.3390/plants11111416.
63. El-Zohri M, Al-Wadaani NA, Bafeel SO. Foliar sprayed green zinc oxide nanoparticles mitigate drought-induced oxidative stress in tomato. Plants. 2021;10(11):2400. https://doi.org/10.3390/plants10112400.
64. Epule TE, New MG. Vulnerability of crop yields to variations in growing season precipitation in Uganda. SN Appl Sci. 2019;1(8):899. https://doi.org/10.1007/s42452-019-0912-7.
65. Epule TE, Ford JD, Lwasa S. Projections of maize yield vulnerability to droughts and adaptation options in Uganda. Land use policy. 2017;65:154–63. https://doi.org/10.1016/j.landusepol.2017.04.013.
66. Esper J, Büntgen U, Denzer S, Krusic PJ, Luterbacher J, Schäfer R, Schreg R, Werner J. Environmental drivers of historical grain price variations in Europe. Clim Res. 2017;72(1):39–52. https://www.jstor.org/stable/26394295.
67. Farah AA, Mohamed MA, Musse OSH, Nor BA. The multifaceted impact of climate change on agricultural productivity: A systematic literature review of SCOPUS-indexed studies (2015–2024). Discov Sustain. 2025;6(1):397. https://doi.org/10.1007/s43621-025-01229-2.

68. Faraji J, Sepehri A. Ameliorative effects of $TiO_2$ nanoparticles and sodium nitroprusside on seed germination and seedling growth of wheat under PEG-stimulated drought stress. J Seed Sci. 2019;41:309–17. https://doi.org/10.1590/2317-1545v41n3213139.
69. Faraji J, Sepehri A. Exogenous nitric oxide improves the protective effects of $TiO_2$ nanoparticles on growth, antioxidant system, and photosynthetic performance of wheat seedlings under drought stress. J Soil Sci Plant Nutr. 2020;20(2):703–14. https://doi.org/10.1007/s42729-019-00158-0.
70. Farajollahi Z, Eisvand HR, Nazarian-Firouzabadi F, Nasrollahi AH. Nano-Fe nutrition improves soybean physiological characteristics, yield, root features and water productivity in different planting dates under drought stress conditions. Ind Crops Prod. 2023;198:116698. https://doi.org/10.1016/j.indcrop.2023.116698.
71. Farooq M, Wahid A, Kobayashi NSMA, Fujita DBSA, Basra SM. Plant drought stress: effects, mechanisms and management. Sustainable agriculture. Dordrecht: Springer Netherlands; 2009.
72. Fatima A, Safdar N, Ain N, Yasmin A, Chaudhry GS. Abscisic acid-loaded zno nanoparticles as drought tolerance inducers in *Zea mays* L. with physiological and biochemical attributes. J Plant Growth Regul. 2023;42(11):7280–93. https://doi.org/10.1007/s00344-023-11016-w.
73. Fitton N, Alexander P, Arnell N, Bajzelj B, Calvin K, Doelman J, Gerber JS, Havlik P, Hasegawa T, Herrero M, Krisztin T. The vulnerabilities of agricultural land and food production to future water scarcity. Glob Environ Change. 2019;58:101944. https://doi.org/10.1016/j.gloenvcha.2019.101944.
74. Fiwa L, Vanuytrecht E, Wiyo KA, Raes D. Effect of rainfall variability on the length of the crop growing period over the past three decades in central Malawi. Clim Res. 2014;62:45–58. https://doi.org/10.3354/cr01263.
75. Food and Agriculture Organization of the United Nations (FAO). Coping with Water Scarcity: An Action Framework for Agriculture and Food Scarcity. FAO Water Rep. 2012;38:79. http://www.fao.org/3/i3015e/i3015e.pdf.
76. Fraser ED, Simelton E, Termansen M, Gosling SN, South A. Vulnerability hotspots: Integrating socio-economic and hydrological models to identify where cereal production may decline in the future due to climate change induced drought. Agric Meteorol. 2013;170:195–205. https://doi.org/10.1016/j.agrformet.2012.04.008.
77. Füssel HM. Adaptation planning for climate change: concepts, assessment approaches, and key lessons. Sustain Sci. 2007;2(2):265–75. https://doi.org/10.1007/s11625-007-0032-y.
78. Garnett T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer P, Burlingame B, Dawkins M, Dolan L, Fraser D, Herrero M. Sustainable intensification in agriculture: premises and policies. Science. 2013;341(6141):33–4. https://doi.org/10.1126/science.1234485.
79. Gautam AK, Kumar S. Techniques for the detection, identification, and diagnosis of agricultural pathogens and diseases. In Natural remedies for pest, disease and weed control. Acad Press. 2020;135–42. https://doi.org/10.1016/B978-0-12-819304-4.00012-9.
80. Ghani MI, Saleem S, Rather SA, Rehmani MS, Alamri S, Rajput VD, Kalaji HM, Saleem N, Sial TA, Liu M. Foliar application of zinc oxide nanoparticles: An effective strategy to mitigate drought stress in cucumber seedling by modulating antioxidant defense system and osmolytes accumulation. Chemosphere. 2022;289:133202. https://doi.org/10.1016/j.chemosphere.2021.133202.
81. Ghorbani R, Movafeghi A, Gangeali A, Nabati J. Effects of $TiO_2$ nanoparticles on morphological characteristics of chickpea (*Cicer arietinum* L.) under drought stress. Env Stresses Crop Sci. 2021;14(1):85–98. https://doi.org/10.22077/escs.2020.2485.1654.

82. Ghorbanpour M, Mohammadi H, Kariman K. Nanosilicon-based recovery of barley (*Hordeum vulgare*) plants subjected to drought stress. Environ Sci Nano. 2020;7(2):443–61. https://doi.org/10.1039/C9EN00973F.
83. Ghouri F, Ali Z, Naeem M, Ul-Allah S, Babar M, Baloch FS, Chattah WS, Shahid MQ. Effects of silicon and selenium in alleviation of drought stress in rice. Silicon. 2022;14(10):5453–61. https://doi.org/10.1007/s12633-021-01277-z.
84. Giglou MT, Giglou RH, Esmaeilpour B, Azarmi R, Padash A, Falakian M, Lajayer HM. A new method in mitigation of drought stress by chitosan-coated iron oxide nanoparticles and growth stimulant in peppermint. Ind Crops Prod. 2022;187:115286. https://doi.org/10.1016/j.indcrop.2022.115286.
85. Guo H, Chen J, Pan C. Assessment on agricultural drought vulnerability and spatial heterogeneity study in China. Int J Environ Res Public Health. 2021;18(9):4449. https://doi.org/10.3390/ijerph18094449.
86. Hadinejad F, Jahanshahi M, Morad H. Microwave-assisted and ultrasonic phyto-synthesis of copper nanoparticles: A comparison study. Nano Biomed Eng. 2021;13:6–19. https://doi.org/10.5101/nbe.v13i1.p6-19.
87. Hafez EM, Osman HS, Gowayed SM, Okasha SA, Omara AED, Sami R, Abd El-Monem AM, Abd El-Razek UA. Minimizing the adversely impacts of water deficit and soil salinity on maize growth and productivity in response to the application of plant growth-promoting rhizobacteria and silica nanoparticles. Agronomy. 2021;11(4):676. https://doi.org/10.3390/agronomy11040676.
88. Haghighi M, Da Silva JT, Mozafarian M, Afifipour Z. Can Si and nano-Si alleviate the effect of drought stress induced by PEG in seed germination and seedling growth of tomato? Minerva Biotecnol. 2013;25(1):17–22.
89. Handy RD, Shaw BJ. Toxic effects of nanoparticles and nanomaterials: implications for public health, risk assessment and the public perception of nanotechnology. Health Risk Soc. 2007;9(2):125–44. https://doi.org/10.1080/13698570701306807.
90. Hasegawa T, Fujimori S, Havlík P, Valin H, Bodirsky BL, Doelman JC, Fellmann T, Kyle P, Koopman JF, Lotze-Campen H, Mason-D'Croz D. Risk of increased food insecurity under stringent global climate change mitigation policy. Nat Clim Change. 2018;8(8):699–703. https://doi.org/10.1038/s41558-018-0230-x.
91. Hashem AH, Saied E, Amin BH, Alotibi FO, Al-Askar AA, Arishi AA, Elbahnasawy MA. Antifungal activity of biosynthesized silver nanoparticles (AgNPs) against aspergilli causing aspergillosis: Ultrastructure Study. J Funct Biomater. 2022;13(4):242. https://dio.org/10.3390/jfb13040242.
92. Hellala F, Amerb AK, El-Sayeda S, El-Azab K. Mitigation the negative effect of water stress on barley by nano silica application. Plant Arch. 2020;20:3224–31.
93. Hoang SA, Nguyen LQ, Nguyen NH, Tran CQ, Nguyen DV, Le NT, Ha CV, Vu QN, Phan CM. Metal nanoparticles as effective promoters for Maize production. Sci Rep. 2019;9(1):13925. https://doi.org/10.1038/s41598-019-50265-2.
94. Hojjat SS. Effects of $TiO_2$ nanoparticles on germination and growth characteristics of grass pea (*Lathyrus sativus* L.) seed under drought stress. Nanotechnologies Russ. 2020;15(2):204–11. https://doi.org/10.1134/S199507802002010X.
95. Hojjat SS, Ganjali A. The effect of silver nanoparticle on lentil seed germination under drought stress. Int J Farm Allied Sci. 2016;5(3):208–12.
96. Hou J, Wu Y, Li X, Wei B, Li S, Wang X. Toxic effects of different types of zinc oxide nanoparticles on algae, plants, invertebrates, vertebrates and microorganisms. Chemosphere. 2018;193:852–60. https://doi.org/10.1016/j.chemosphere.2017.11.077.

97. Hsin YH, Chen CF, Huang S, Shih TS, Lai PS, Chueh PJ. The apoptotic effect of nanosilver is mediated by a ROS-and JNK-dependent mechanism involving the mitochondrial pathway in NIH3T3 cells. Toxicol Lett. 2008;179(3):130–9. https://doi.org/10.1016/j.toxlet.2008.04.015.
98. Idumah FO, Mangodo C, Ighodaro UB, Owombo PT. Climate change and food production in Nigeria: implication for food security in Nigeria. J Agric Sci. 2016;8(2):74–83.
99. Ikram M, Javed B, Raja NI, Mashwani ZUR. Biomedical potential of plant-based selenium nanoparticles: a comprehensive review on therapeutic and mechanistic aspects. Int J Nanomed. 2021;249–68. https://doi.org/10.2147/IJN.S295053.
100. Ikram M, Raja NI, Javed B, Mashwani ZR, Hussain M, Hussain M, Ehsan M, Rafique N, Malik K, Sultana T, Akram A. Foliar applications of bio-fabricated selenium nanoparticles to improve the growth of wheat plants under drought stress. Green Process Synth. 2020;9(1):706–14. https://doi.org/10.1515/gps-2020-0067.
101. Intergovernmental Panel on Climate Change (IPCC). Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2023.
102. Intergovernmental Panel on Climate Change (IPCC). Climate change the physical science basis. In Agu fall meeting abstracts (Vol. 2007, U43D-01); 2007.
103. Intergovernmental Panel on Climate Change (IPCC). Special report on the impacts of global warming of 1.5 0C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. Sustainable Development, and Efforts to Eradicate Poverty. 2018:32.
104. Jacobasch C, Völker C, Giebner S, Völker J, Alsenz H, Potouridis T. Long-term effects of nanoscaled titanium dioxide on the cladoceran Daphnia magna over six generations. Environ Pollut. 2014;186:180–6. https://doi.org/10.1016/j.envpol.2013.12.008.
105. Janmohammadi M, Amanzadeh T, Sabaghnia N, Dashti S. Impact of foliar application of nano micronutrient fertilizers and titanium dioxide nanoparticles on the growth and yield components of barley under supplemental irrigation. Acta Agric Slov. 2016;107(2):265–76. https://doi.org/10.14720/aas.2016.107.2.01.
106. Kah M, Kookana RS, Gogos A, Bucheli TD. A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. Nat Nanotechnol. 2018;13(8):677–84. https://doi.org/10.1038/s41565-018-0131-1.
107. Kang J, Peng Y, Xu W. Crop root responses to drought stress: molecular mechanisms, nutrient regulations, and interactions with microorganisms in the rhizosphere. Int J Mol Sci. 2022;23(16):9310. https://doi.org/10.3390/ijms23169310.
108. Kaningini AG, Nelwamondo AM, Azizi S, Maaza M, Mohale KC. Metal nanoparticles in agriculture: A review of possible use. Coatings. 2022;12(10):1586. https://doi.org/10.3390/coatings12101586.
109. Kapoor D, Bhardwaj S, Landi M, Sharma A, Ramakrishnan M, Sharma A. The impact of drought in plant metabolism: How to exploit tolerance mechanisms to increase crop production. Appl Sci. 2020;10(16):5692. https://doi.org/10.3390/app10165692.
110. Karvar M, Azari A, Rahimi A, Maddah-Hosseini S, Ahmadi-Lahijani MJ. Titanium dioxide nanoparticles ($TiO_2$-NPs) enhance drought tolerance and grain yield of sweet corn (*Zea mays* L.) under deficit irrigation regimes. Acta Physiol Plant. 2022;44(2):14. https://doi.org/10.1007/s11738-021-03349-4.

111. Kausar A, Hussain S, Javed T, Zafar S, Anwar S, Hussain S, Zahra N, Saqib M. Zinc oxide nanoparticles as potential marks for enhancing drought stress tolerance in wheat seedlings. J Plant Biochem Physiol. 2023;195:341–50. https://doi.org/10.1016/j.plaphy.2023.01.014.
112. Kchouk S, Melsen LA, Walker DW, Van Oel PR. A geography of drought indices: mismatch between indicators of drought and its impacts on water and food securities. Nat Hazards Earth Syst Sci. 2022;22(2):323–44. https://doi.org/10.5194/nhess-22-323-2022.
113. Khalilvand BE, Yarnia M, Ghasemi A. Effect of foliar application of titanium dioxide nanoparticles on maize yield and some antioxidant enzymes of sweet maize (*Zea mays* var saccharata) under water deficit tension conditions. Crop Physiol. 2019;43:105–18. https://www.sid.ir/paper/365467/en.
114. Khan F, Shariq M, Asif M, Siddiqui MA, Malan P, Ahmad F. Green nanotechnology: plant-mediated nanoparticle synthesis and application. Nanomaterials. 2022;12(4):673. https://doi.org/10.3390/nano12040673.
115. Khan M, Naqvi AH, Ahmad M. Comparative study of the cytotoxic and genotoxic potentials of zinc oxide and titanium dioxide nanoparticles. Toxicol Rep. 2015;2765774. https://doi.org/10.1016/j.toxrep.2015.02.004.
116. Khan MT, Ahmed S, Shah AA, Noor Shah A, Tanveer M, El-Sheikh MA, Siddiqui MH. Influence of zinc oxide nanoparticles to regulate the antioxidants enzymes, some osmolytes and agronomic attributes in *Coriandrum sativum* L. grown under water stress. Agronomy. 2021;11(10):2004. https://doi.org/10.3390/agronomy11102004.
117. Kheyri N, Abbasalipour M. Effect of foliar application of ZnO nanoparticles on yield components, yield and Zn efficiency indices in rice under water stress. Env Stresses Crop Sci. 2020;13(4):1203–18. https://doi.org/10.22077/escs.2020.2298.1591.
118. Kim G, Ryu H, Sung J. Hormonal crosstalk and root suberization for drought stress tolerance in plants. Biomolecules. 2022;12(6):811. https://doi.org/10.3390/biom12060811.
119. Kim W, Iizumi T, Nishimori M. Global patterns of crop production losses associated with droughts from 1983 to 2009. J Appl Meteorol Climatol 58(6), 1233–44. https://doi.org/10.1175/JAMC-D-18-0174.1
120. Kolapo A, Sieber S. From vulnerability to viability: Climate-Smart agriculture as drivers of productivity and food security in Nigerian maize-based farming households. Environ Chall. 2025;101268. https://doi.org/10.1016/j.envc.2025.101268.
121. Kolenčík M, Ernst D, Komár M, Urík M, Šebesta M, Dobročka E, Černỳ I, Illa R, Kanike R, Qian Y. Effect of foliar spray application of zinc oxide nanoparticles on quantitative, nutritional, and physiological parameters of foxtail millet (*Setaria italica* L.) under field conditions. Nanomaterials. 2019;9(11):1559. https://dio.org/10.3390/nano9111559.
122. Kolenčík M, Ernst D, Komár M, Urík M, Šebesta M, Ďurišová L, Bujdoš M, Černỳ I, Chlpík J, Juriga M. Effects of foliar application of ZnO nanoparticles on lentil production, stress level and nutritional seed quality under field conditions. Nanomaterials. 2022;12(3):310. https://dio.org/10.3390/nano12030310.
123. Kumari A, Gupta AK, Sharma S, Jadon VS, Sharma V, Chun SC, Sivanesan I. Nanoparticles as a tool for alleviating plant stress: mechanisms, implications, and challenges. Plants. 2024;13(11):1528. https://doi.org/10.3390/plants13111528.
124. Leakey AD, Ainsworth EA, Bernacchi CJ, Rogers A, Long SP, Ort DR. Elevated $CO_2$ effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. J Exp Bot. 2009;60(10):2859–76. https://doi.org/10.1093/jxb/erp096.

125. Lesk C, Rowhani P, Ramankutty N. Influence of extreme weather disasters on global crop production. Nature. 2016;529(7584):84–7. https://doi.org/10.1038/nature16467.
126. Li J, Zafar S, Javaid A, Perveen S, Hasnain Z, Ihtisham M, Abbas A, Usman M, El-Sappah AH, Abbas M. Zinc nanoparticles (ZnNPs): High-fidelity amelioration in Turnip (*Brassica rapa* L.) production under drought stress. Sustainability. 2023;15(8):6512. https://doi.org/10.3390/su15086512.
127. Linh TM, Mai NC, Hoe PT, Lien LQ, Ban NK, Hien LTT, Chau NH, Van NT. Metal-based nanoparticles enhance drought tolerance in soybean. J Nanomater. 2020;1–13. https://doi.org/10.1155/2020/4056563.
128. Liu Y, Chen J. Future global socioeconomic risk to droughts based on estimates of hazard, exposure, and vulnerability in a changing climate. Sci Total Environ. 2021;751:142159. https://doi.org/10.1016/j.scitotenv.2020.142159.
129. Lobell DB, Hammer GL, Chenu K, Zheng B, McLean G, Chapman SC. The shifting influence of drought and heat stress for crops in northeast Australia. Glob Chang Biol. 2015;21(11):4115–27. https://doi.org/10.1111/gcb.13022.
130. Lu Y, Cai H, Jiang T, Sun S, Wang Y, Zhao J, Yu X, Sun J. Assessment of global drought propensity and its impacts on agricultural water use in future climate scenarios. Agric Meteorol. 2019;278:107623. https://doi.org/10.1016/j.agrformet.2019.107623.
131. Madouh TA, Quoreshi AM. The function of arbuscular mycorrhizal fungi associated with drought stress resistance in native plants of arid desert ecosystems: A review. Diversity. 2023;15(3):391. https://doi.org/10.3390/d15030391.
132. Mahalingam R, Bregitzer P. Impact on physiology and malting quality of barley exposed to heat, drought and their combination during different growth stages under controlled environment. Physiol Plant. 2019;165(2):277–89. https://doi.org/10.1111/ppl.12841.
133. Mahmoud AWM, Rashad HM, Esmail SE, Alsamadany H, Abdeldaym EA. Application of silicon, zinc, and zeolite nanoparticles - a tool to enhance drought stress tolerance in coriander plants for better growth performance and productivity. Plants. 2023;12(15):2838. https://doi.org/10.3390/plants12152838.
134. Mahmoud LM, Dutt M, Shalan AM, El-Kady ME, El-Boray MS, Shabana YM, Grosser JW. Silicon nanoparticles mitigate oxidative stress of in vitro-derived banana (*Musa acuminata* 'Grand Nain') under simulated water deficit or salinity stress. S Afr J Bot. 2020;132:155–63. https://doi.org/10.1016/j.sajb.2020.04.027.
135. Makarian H, Shojaei H, Damavandi A, Nasiri Dehsorkhi A, Akhyani A. The effect of foliar application of Zinc oxide in common and nanoparticles forms on some growth and quality traits of Mungbean (*Vigna radiata* L.) under drought stress conditions. Iran J Pulses Res. 2017;8(2):166–80. https://doi.org/10.22067/IJPR.V8I2.51644.
136. Malhi GS, Kaur M, Kaushik P. Impact of climate change on agriculture and its mitigation strategies: A review. Sustainability. 2021;13(3):1318. https://doi.org/10.3390/su13031318.
137. Matiu M, Ankerst DP, Menzel A. Interactions between temperature and drought in global and regional crop yield variability during 1961–2014. PLoS ONE. 2017;12(5):e0178339. https://doi.org/10.1371/journal.pone.0178339.
138. Mazhar MW, Ishtiaq M, Maqbool M, Akram R. Seed priming with Calcium oxide nanoparticles improves germination, biomass, antioxidant defense and yield traits of canola plants under drought stress. S Afr J Bot. 2022;151:889–99. https://doi.org/10.1016/j.sajb.2022.11.017.

139. Mazhar MW, Ishtiaq M, Maqbool M, Ullah F, Sayed SR, Mahmoud EA. Seed priming with iron oxide nanoparticles improves yield and antioxidant status of garden pea (*Pisum sativum* L.) grown under drought stress. S Afr J Bot. 2023;162:577–87. https://doi.org/10.3390/agronomy14061141.
140. Methela NJ, Pande A, Islam MS, Rahim W, Hussain A, Lee DS, Mun BG, Maria Joseph Raj NP, Kim SJ, Kim Y, Yun BW. Chitosan-GSNO nanoparticles: A positive modulator of drought stress tolerance in soybean. BMC Plant Biol. 2023;23(1):639. https://doi.org/10.1186/s12870-023-04640-x.
141. Mishra D, Chitara MK, Upadhayay VK, Singh JP, Chaturvedi P. Plant growth promoting potential of urea doped calcium phosphate nanoparticles in finger millet (*Eleusine coracana* (L.) Gaertn.) under drought stress. Front Plant Sci. 2023;14:1137002. https://doi.org/10.3389/fpls.2023.1137002.
142. Mohamed NG, Abdel-Hakeem MA. Chitosan nanoparticles enhance drought tolerance in tomatoes (*Solanum lycopersicum* L.) via gene expression modulation. Plant Gene. 2023;34:100406. https://doi.org/10.1016/j.plgene.2023.100406.
143. Mohmmed A, Zhang K, Kabenge M, Keesstra S, Cerdà A, Reuben M, Elbashier MM, Dalson T, Ali AA. Analysis of drought and vulnerability in the North Darfur region of Sudan. Land Degrad Dev. 2018;29(12):4424–38. https://doi.org/10.1002/ldr.3180.
144. Mokari M, Abedinpour M. Investigating the effect of spraying silica nanoparticles in increasing the drought resistance of millet seedlings in Kashmar weather conditions. Iran J Soil Water Res. 2020;51(9):2307–22. https://doi.org/10.22059/ijswr.2020.302497.668606.
145. Mukhopadhyay SS. Nanotechnology in agriculture: prospects and constraints. Nanotechnol Sci Appl. 2014;7:63–71. https://doi.org/10.2147/NSA.S39409.
146. Mustafa H, Ilyas N, Akhtar N, Raja NI, Zainab T, Shah T, Ahmad A, Ahmad P. Biosynthesis and characterization of titanium dioxide nanoparticles and its effects along with calcium phosphate on physicochemical attributes of wheat under drought stress. Ecotoxicol Environ Saf. 2021;223:112519. https://doi.org/10.1016/j.ecoenv.2021.112519.
147. Mutava RN, Prasad PVV, Tuinstra MR, Kofoid KD, Yu J. Characterization of sorghum genotypes for traits related to drought tolerance. Field Crops Res. 2011;123(1):10–8. https://doi.org/10.1016/j.fcr.2011.04.006.
148. Nagdalian AA, Blinov AV, Siddiqui SA, Gvozdenko AA, Golik AB, Maglakelidze DG, Rzhepakovsky IV, Kukharuk MY, Piskov SI, Rebezov MB. Effect of selenium nanoparticles on biological and morphofunctional parameters of barley seeds (*Hordéum vulgáre* L). Sci Rep. 2023;13(1):6453. https://doi.org/10.1038/s41598-023-33581-6.
149. Nazarova AA. Morpho-physiological and productive indicators of oat under the influence of nanopowders of cobalt and copper trace elements. E3S Web Conf. 2020;222:02016. https://doi.org/10.1051/e3sconf/202022202016
150. Ndou N, Rakgotho T, Nkuna M, Doumbia IZ, Mulaudzi T, Ajayi RF. Green synthesis of iron oxide (Hematite) nanoparticles and their influence on sorghum bicolor growth under drought stress. Plants. 2023;12(7):1425. https://doi.org/10.3390/plants12071425.
151. Noor R, Yasmin H, Ilyas N, Nosheen A, Hassan MN, Mumtaz S, Khan N, Ahmad A, Ahmad P. Comparative analysis of iron oxide nanoparticles synthesized from ginger (*Zingiber officinale*) and cumin seeds (*Cuminum cyminum*) to induce resistance in wheat against drought stress. Chemosphere. 2022;292:133201. https://doi.org/10.1016/j.chemosphere.2021.133201.
152. Olowolaju ED, Adejumo MA, Popoola KM, Okunlola GO. Susceptibility of Solanum melongena L/Solanaceae to drought at different growth stages. MEJS. 2023;15(2):216–34. https://doi.org/10.4314/mejs.v15i2.5.

153. Orimoloye IR. Agricultural drought and its potential impacts: enabling decision-support for food security in vulnerable regions. Front Sustain Food Syst. 2022;6:838824. https://doi.org/10.3389/fsufs.2022.838824.
154. Osakabe Y, Osakabe K, Shinozaki K, Tran LSP. Response of plants to water stress. Front Plant Sci. 2014;5:86. https://doi.org/10.3389/fpls.2014.00086.
155. Parisi C, Vigani M, Rodríguez-Cerezo E. Agricultural nanotechnologies: what are the current possibilities? Nano Today. 2015;10(2):124–7. https://doi.org/10.1016/j.nantod.2014.09.009.
156. Patra JK, Baek KH. Green nanobiotechnology: factors affecting synthesis and characterization techniques. J Nanomat. 2014;2014(1):417305. https://doi.org/10.1155/2014/417305.
157. Praveen B, Sharma P. A review of literature on climate change and its impacts on agriculture productivity. J Public Aff. 2019;19(4):e1960. https://doi.org/10.1002/pa.1960.
158. Pret V, Falconnier GN, Affholder F, Corbeels M, Chikowo R, Descheemaeker K. Farm resilience to climatic risk: A review. Agron Sustain Dev. 2025;45(1):10. https://doi.org/10.1007/s13593-024-00998-w.
159. Qadeer K, Al-Hinai A, Chuah LF, Sial NR, Al-Muhtaseb AH, Al Abri R, Qyyum MA, Lee M. Methanol production and purification via membrane-based technology: Recent advancements, challenges, and the way forward. Chemosphere. 2023;335:139007. https://doi.org/10.1016/j.chemosphere.2023.139007.
160. Rahman IM, Hasegawa H, editors. Water stress. BoD–Books on Demand; 2012.
161. Rahmawati N, Wulandari N. Foliar application of $SiO_2$ nanoparticles to increase shallot production under water stress as an effort to mitigate climate change. IOP Conference Series: Earth Environ Sci. 2024;1302(1):012031. https://doi.org/10.1088/1755-1315/1302/1/012031
162. Rajput VD, Minkina TM, Behal A, Sushkova SN, Mandzhieva S, Singh R. Effects of zinc-oxide nanoparticles on soil, plants, animals and soil organisms: a review. Environ Nanotech Monit Manage. 2018;9:76–84. https://doi.org/10.1016/j.enmm.2017.12.006.
163. Ramya S, Auxcilia J, Paital B, Sharmila DJS, Vethamoni PI, Venugopal S, Indra N, Subramanian KS, Sahoo DK. Application of nanotechnology in fruit crops—from synthesis to sustainable packaging. PeerJ. 2025;13:e19603. https://doi.org/10.7717/peerj.19603.
164. Rana S, Kalaichelvan PT. Ecotoxicity of nanoparticles. Int Sch Res Notices. 2013;2013(1):574648. https://doi.org/10.1155/2013/574648.
165. Rani S, Kumar P, Dahiya P, Gupta A, Arora K, Dang AS, Suneja P. Effect of biopriming and nanopriming on physio-biochemical characteristics of *Cicer arietinum* L. under drought stress. Plant Stress. 2024;12:100466. https://doi.org/10.1016/j.stress.2024.100466.
166. Rasool A, Tariq M, Asif M, Shah GM, Fatima R, Majeed M, Aziz R, Khan J, Hussain K, Ozodbek A. Nanotechnology for improved crop resilience in challenging environments. InHarnessing nanoomics and nanozymes for sustainable agriculture. IGI Global Scientific Publishing; 2024. https://doi.org/10.4018/979-8-3693-1890-4.ch008
167. Ray DK, Gerber JS, MacDonald GK, West PC. Climate variation explains a third of global crop yield variability. Nat Commun. 2015;6(1):5989. https://doi.org/10.1038/ncomms6989.
168. Raza MAS, Zulfiqar B, Iqbal R, Muzamil MN, Aslam MU, Muhammad F, Amin J, Aslam HMU, Ibrahim MA, Uzair M. Morpho-physiological and biochemical response of wheat to various treatments of silicon nano-particles under drought stress conditions. Sci Rep. 2023;13(1):2700. https://doi.org/10.1038/s41598-023-29784-6.
169. Rico CM, Morales MI, Barrios AC, McCreary R, Hong J, Lee WY, Nunez J, Peralta-Videa JR, Gardea-Torresdey JL. Effect of cerium oxide nanoparticles on the quality of rice (*Oryza sativa* L.) grains. J Agric Food Chem.

2013;61(47):11278–85. https://doi.org/10.1021/jf404046v.

170. Rónavári A, Igaz N, Adamecz DI, Szerencsés B, Molnar C, Kónya Z, Pfeiffer I, Kiricsi M. Green silver and gold nanoparticles: biological synthesis approaches and potentials for biomedical applications. Molecules. 2021;26:844. https://doi.org/10.3390/molecules26040844.
171. Rosenzweig C, Elliott J, Deryng D, Ruane AC, Müller C, Arneth A, Boote KJ, Folberth C, Glotter M, Khabarov N, Neumann K. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc Natl Acad Sci USA. 2014;111(9):3268–73. https://doi.org/10.1073/pnas.1222463110.
172. Roy D, Korir YC, Gillespie SA, Hossain MS. Social-ecological systems approach in drought-food insecurity nexus research. npj Sustain Agric. 20253(1):26. https://doi.org/10.1038/s44264-025-00070-4
173. Rubilar O, Rai M, Tortella G, Diez MC, Seabra AB, Durán N. Biogenic nanoparticles: copper, copper oxides, copper sulphides, complex copper nanostructures and their applications. Biotechnol Lett. 2013;35:1365–75. https://doi.org/10.1007/s10529-013-1239-x.
174. Saeedeh R, Mehrnaz H, Mansour G. Silicon-nanoparticle mediated changes in seed germination and vigor index of marigold (*Calendula officinalis* L.) compared to silicate under PEG-induced drought stress. Gesunde Pflanz. 2021;73(4):575–89. https://doi.org/10.1007/s10343-021-00579-x.
175. Salajegheh M, Yavarzadeh M, Payandeh A, Akbarian MM. Effects of titanium and silicon nanoparticles on antioxidant enzymes activity and some biochemical properties of *Cuminum cyminum* L. under drought stress. Banat's J Biotechnol. 2020;11(21):19–25. https://doi.org/10.7904/2068-4738. –XI(21)–19.
176. Sallam AR, Mahdi AA, Farroh KY. Improving drought stress tolerance in potato *Solanum tuberosum* L. using magnetite and zinc oxide nanoparticles. Plant Cell Biotechnol Mol Biol. 2022;23:1–16. https://doi.org/10.56557/PCBMB/2022/v23i37-387886.
177. Samari F, Baluchi L, Salehipoor H, Yousefinejad S. Controllable phyto-synthesis of cupric oxide nanoparticles by aqueous extract of Capparis spinosa (caper) leaves and application in iron sensing. Microchem J. 2019;150:104158. https://doi.org/10.1016/j.microc.2019.104158.
178. Samuel MS, Ravikumar M, John JA, Selvarajan E, Patel H, Chander PS, Soundarya J, Vuppala S, Balaji R, Chandrasekar N. A review on green synthesis of nanoparticles and their diverse biomedical and environmental applications. Catalysts. 2022;12:459. https://doi.org/10.3390/catal12050459.
179. Santás-Miguel V, Arias-Estévez M, Rodríguez-Seijo A, Arenas-Lago D. Use of metal nanoparticles in agriculture. A review on the effects on plant germination. Environ Pollut. 2023;334:122222. https://doi.org/10.1016/j.envpol.2023.122222.
180. Sardari M, Rezayian M, Niknam V. Comparative Study for the Effect of Selenium and Nano-Selenium on Wheat Plants Grown under Drought Stress. Russian J Plant Physiol. 2022;69(6):127. https://doi.org/10.1134/S102144372206022X.
181. Schauberger B, Archontoulis S, Arneth A, Balkovic J, Ciais P, Deryng D, Elliott J, Folberth C, Khabarov N, Müller C, Pugh TA. Consistent negative response of US crops to high temperatures in observations and crop models. Nat Commun. 2017;8(1):13931. https://doi.org/10.1038/ncomms13931.
182. Šebesta M, Kolenčík M, Sunil BR, Illa R, Mosnáček J, Ingle AP, Urík M. Field application of ZnO and TiO2 nanoparticles on agricultural plants. Agronomy. 2021;11(11):2281. https://doi.org/10.3390/agronomy11112281.
183. Sedghi M, Sheikhnavaz Jahed P, Gholi-Tolouie S. Zinc oxide nano particles alleviate drought stress effects on soybean antioxidant system during germination. Iran J Plant Physiol. 2021;11(4):3769–78.

https://doi.org/10.30495/ijpp.2021.684985.

184. Sehgal A, Sita K, Kumar J, Kumar S, Singh S, Siddique KH, Nayyar H. Effects of drought, heat and their interaction on the growth, yield and photosynthetic function of lentil (Lens culinaris Medikus) genotypes varying in heat and drought sensitivity. Front Plant Sci. 2017;8:1776. https://doi.org/10.3389/fpls.2017.01776.
185. Seleiman MF, Al-Selwey WA, Ibrahim AA, Shady M, Alsadon AA. Foliar applications of ZnO and $SiO_2$ nanoparticles mitigate water deficit and enhance potato yield and quality traits. Agronomy. 2023;13(2):466. https://doi.org/10.3390/agronomy13020466.
186. Semida WM, Abdelkhalik A, Mohamed GF, Abd El-Mageed TA, Abd El-Mageed SA, Rady MM, Ali EF. Foliar application of zinc oxide nanoparticles promotes drought stress tolerance in eggplant (*Solanum melongena* L). Plants. 2021;10(2):421. https://doi.org/10.3390/plants10020421.
187. Şener S, Sayğı H. The role of silver nanoparticles in response of in vitro boysenberry plants to drought stress. Horticulturae. 2023;9(11):1177. https://doi.org/10.3390/horticulturae9111177.
188. Seneviratne SI, Zhang X, Adnan M, Badi W, Dereczynski C, Luca AD, Ghosh S, Iskandar I, Kossin J, Lewis S, Otto F. Weather and climate extreme events in a changing climate. Climate change 2021: The physical science basis: Working group I contribution to the sixth assessment report of the intergovernmental panel on climate change. 2021;1513–1766.
189. Shafiq T, Uzair M, Iqbal MJ, Zafar M, Hussain SJ, Shah SAA. Green synthesis of metallic nanoparticles and their potential in bio-medical applications. Nano Biomed Eng. 2021;13:191–206. https://doi.org/10.5101/nbe.v13i2.p191-206.
190. Sharf-Eldin AA, Alwutayd KM, El-Yazied AA, El-Beltagi HS, Alharbi BM, Eisa MA, Alqurashi M, Sharaf M, Al-Harbi NA, Al-Qahtani S. Response of maize seedlings to silicon dioxide nanoparticles ($SiO_2$NPs) under drought stress. Plants. 2023;12(14):2592. https://doi.org/10.3390/plants12142592.
191. Sharma A, Goyal MK. Assessment of drought trend and variability in India using wavelet transform. Hydrol Sci J. 2020;65(9):1539–54. https://doi.org/10.1080/02626667.2020.1754422.
192. Sharma D, Kanchi S, Bisetty K. Biogenic synthesis of nanoparticles: a review. Arab J Chem. 2019;12(8):3576–600.
193. Sheffield J, Wood EF, Roderick ML. Little change in global drought over the past 60 years. Nature. 2012;491(7424):435–8. https://doi.org/10.1038/nature11575.
194. Shinga MH, Silue Y, Fawole OA. Recent advancements and trends in postharvest application of edible coatings on bananas: a comprehensive review. Plants. 2025;14(4):581. https://doi.org/10.3390/plants14040581.
195. Shoarian N, Jamei R, Pasban Eslam B, Salehi Lisar SY. Titanium dioxide nanoparticles increase resistance of *L. iberica* to drought stress due to increased accumulation of protective antioxidants. Iran J Plant Physiol. 2020;10(4):3343–54. https://doi.org/10.30495/ijpp.2020.1901976.1233.
196. Siddiqui SA, Blinov AV, Serov AV, Gvozdenko AA, Kravtsov AA, Nagdalian AA, Raffa VV, Maglakelidze DG, Blinova AA, Kobina AV. Effect of selenium nanoparticles on germination of *Hordéum Vulgáre* barley seeds. Coatings. 2021;11(7):862. https://doi.org/10.3390/coatings11070862.
197. Simelton E, Fraser ED, Termansen M, Benton TG, Gosling SN, South A, Arnell NW, Challinor AJ, Dougill AJ, Forster PM. The socioeconomics of food crop production and climate change vulnerability: a global scale quantitative analysis of how grain crops are sensitive to drought. Food Secur. 2012;4(2):163–79. https://doi.org/10.1007/s12571-012-0173-4.

198. Singh P, Garg A, Pandit S, Mokkapati V, Mijakovic I. Antimicrobial effects of biogenic nanoparticles. Nanomaterials. 2018;8:1009. https://doi.org/10.3390/nano8121009.

199. Song Y, Park M. Assessment of quantitative standards for mega-drought using data on drought damages. Sustainability. 2020;12(9):3598. https://doi.org/10.3390/su12093598.

200. Sorori S, Asgharzadeh A, Marjani A, Samadi-Kazemi M. Assessment of biochemical and physiological responses of several grape varieties under water deficit stress. Not Bot Horti Agrobot Cluj-Na. 2024;52(2):13427–13427. https://doi.org/10.15835/nbha52213427.

201. Stokes C, Howden M, editors. Adapting agriculture to climate change: preparing Australian agriculture, forestry and fisheries for the future. CSIRO publishing; 2010.

202. Sun L, Song F, Guo J, Zhu X, Liu S, Liu F. Nano-ZnO induced drought tolerance is associated with melatonin synthesis and metabolism in maize. Int J Mol Sci. 2020;21:782. https://doi.org/10.3390/ijms21030782.

203. Sun M, Li X, Xu H, Wang K, Anniwaer N, Hong S. Drought thresholds that impact vegetation reveal the divergent responses of vegetation growth to drought across China. Glob Change Biol. 2024;30(1):e16998. https://doi.org/10.1111/gcb.16998.

204. Sutulienė R, Brazaitytė A, Małek S, Jasik M, Samuolienė G. Biochemical responses of pea plants to drought stress and in the presence of molybdenum trioxide nanoparticles. Plant Soil. 2023a;492(1):381–97. https://doi.org/10.1007/s11104-023-06179-0.

205. Sutulienė R, Brazaitytė A, Małek S, Jasik M, Samuolienė G. Response of oxidative stress and antioxidant system in pea plants exposed to drought and boron nanoparticles. Antioxidants. 2023b;12(2):528. https://doi.org/10.3390/antiox12020528.

206. Sutulienė R, Ragelienė L, Samuolienė G, Brazaitytė A, Urbutis M, Miliauskienė J. The response of antioxidant system of drought-stressed green pea (*Pisum sativum* L.) affected by watering and foliar spray with silica nanoparticles. Horticulturae. 2021;8(1):35. https://doi.org/10.3390/horticulturae8010035.

207. Taghavizadeh Yazdi ME, Modarres M, Amiri MS, Darroudi M. Phyto-synthesis of silver nanoparticles using aerial extract of *Salvia leriifolia* Benth and evaluation of their antibacterial and photo-catalytic properties. Res Chem Intermed. 2019;45:1105–16. https://doi.org/10.1007/s11164-018-3666-8.

208. Tang Y, Zhao W, Zhu G, Tan Z, Huang L, Zhang P, Gao L, Rui Y. Nano-pesticides and fertilizers: Solutions for global food security. Nanomaterials. 2023;14(1):90. https://doi.org/10.3390/nano14010090.

209. Taran N, Storozhenko V, Svietlova N, Batsmanova L, Shvartau V, Kovalenko M. Effect of zinc and copper nanoparticles on drought resistance of wheat seedlings. Nanoscale Res Lett. 2017;12(1):60. https://doi.org/10.1186/s11671-017-1839-9.

210. Tembile S, South, Africa. Worst in 100 years-drought in all three cape provinces declared a national disaster; 2021.

211. Tourinho PS, Van Gestel CA, Lofts S, Svendsen C, Soares AM, Loureiro S. Metal-based nanoparticles in soil: Fate, behavior, and effects on soil invertebrates. Environ Toxicol Chem. 2012;31(8):1679–92. https://doi.org/10.1002/etc.1880.

212. Van Nguyen D, Nguyen HM, Le NT, Nguyen KH, Nguyen HT, Le HM, Nguyen AT, Dinh NTT, Hoang SA, Van Ha C. Copper nanoparticle application enhances plant growth and grain yield in maize under drought stress conditions. J Plant Growth Regul. 2022;41(1):364–75. https://doi.org/10.1007/s00344-021-10301-w.

213. Vejan P, Khadiran T, Abdullah R, Ahmad N. Controlled release fertilizer: A review on developments, applications and potential in agriculture. J Control Release. 2021;339:321–34.

https://doi.org/10.1016/j.jconrel.2021.10.003.

214. Vicente-Serrano SM, Peña-Angulo D, Beguería S, Domínguez-Castro F, Tomás-Burguera M, Noguera I, Gimeno-Sotelo L, El Kenawy A. Global drought trends and future projections. Phil Trans R Soc A: Math Phys Eng Sci. 2022;380(2238). https://doi.org/10.1098/rsta.2021.0285.

215. Vurayai R, Emongor V, Moseki B. Effect of water stress imposed at different growth and development stages on morphological traits and yield of bambara groundnuts (*Vigna Subterranea* L. Verdc). Am J Plant Physiol. 2011;6(1):17–27. https://doi.org/10.3923/ajpp.2011.17.27.

216. Wahab A, Abdi G, Saleem MH, Ali B, Ullah S, Shah W, Marc RA. Plants' physio-biochemical and phyto-hormonal responses to alleviate the adverse effects of drought stress: a comprehensive review. Plants. 2022;11(13):1620. https://doi.org/10.3390/plants11131620.

217. Wahab A, Batool F, Muhammad M, Zaman W, Mikhlef RM, Naeem M. Current knowledge, research progress, and future prospects of phyto-synthesized nanoparticles interactions with food crops under induced drought stress. Sustainability. 2023;15(20):14792. https://doi.org/10.3390/su152014792.

218. Wang XP, Li QQ, Pei ZM, Wang SC. Effects of zinc oxide nanoparticles on the growth, photosynthetic traits, and antioxidative enzymes in tomato plants. Biol Plant. 2018;62(4):801–8. https://doi.org/10.1007/s10535-018-0813-4.

219. Waqas Mazhar M, Ishtiaq M, Hussain I, Parveen A, Hayat Bhatti K, Azeem M, Thind S, Ajaib M, Maqbool M, Sardar T. Seed nano-priming with zinc oxide nanoparticles in rice mitigates drought and enhances agronomic profile. PLoS ONE. 2022;17(3):e0264967. https://doi.org/10.1371/journal.pone.0264967.

220. Wheeler T, Von Braun J. Climate change impacts on global food security. Science. 2013;341(6145):508–13. https://doi.org/10.1126/science.1239402.

221. Wild M. The global energy balance as represented in CMIP6 climate models. Clim Dyn. 2020;55(3):553–77. https://doi.org/10.1007/s00382-020-05282-7.

222. Wu J, Geng G, Zhou H, Liu J, Wang Q, Yang J. Global vulnerability to agricultural drought and its spatial characteristics. Sci China Earth Sci. 2017;60(5):910–20. https://doi.org/10.1007/s11430-016-9018-2.

223. Yasmeen S, Wahab A, Saleem MH, Ali B, Qureshi KA, Jaremko M. Melatonin as a foliar application and adaptation in lentil (*Lens culinaris* Medik.) crops under drought stress. Sustainability. 2020;14:16345. https://doi.org/10.3390/su142416345.

224. Yazicilar B, Nadaroğlu H, Alayli A, Nadar M, GedìKlì S, BezìRğanoğlu İ. Mitigation of drought stress effects on alfalfa (*Medicago sativa* L.) callus through CaO nanoparticles and graphene oxide in tissue culture conditions. Plant Cell Tissue Organ Cult. 2024;157(3):54. https://doi.org/10.1007/s11240-024-02776-8.

225. Yew YP, Shameli K, Miyake M, Khairudin NB, Mohamad SE, Naiki T, Lee KX. Green biosynthesis of superparamagnetic magnetite $Fe_3O_4$ nanoparticles and biomedical applications in targeted anticancer drug delivery system: A review. Arab J Chem. 2020;13:2287–308. https://doi.org/10.1016/j.arabjc.2018.04.013.

226. Yigit N, Sevik H, Cetin M, Kaya N. Determination of the effect of drought stress on the seed germination in some plant species. Water stress plants. 2016;43:62. https://doi.org/10.5772/63197.

227. Zahedi H, Alipour A. Effect of spraying of iron and manganese nano chelated on yield and yield component of barley (*Hordeum vulgare* L.) under water deficit stress at different growth stages. ESCS. 2018;11(4):847–61. https://doi.org/10.22077/escs.2018.890.1176.

228. Zahedi SM, Hosseini MS, Daneshvar Hakimi Meybodi N, Peijnenburg W. Mitigation of the effect of drought on growth and yield of pomegranates by foliar spraying of different sizes of selenium nanoparticles. J Sci Food

Agric. 2021;101(12):5202–13. https://doi.org/10.1002/jsfa.11167.
229. Zaman W, Ayaz A, Park S. Nanomaterials in agriculture: a pathway to enhanced plant growth and abiotic stress resistance. Plants. 2025;14(5):716.
230. Zhang Y, Liu N, Wang W, Sun J, Zhu L. Photosynthesis and related metabolic mechanism of promoted rice (*Oryza sativa* l.) growth by $TiO_2$ nanoparticles. Front Environ Sci Engin. 2020;14:1–12. https://doi.org/10.1007/s11783-020-1282-5.
231. Zhao Y, Ducharne A, Sultan B, Braconnot P, Vautard R. Estimating heat stress from climate-based indicators: present-day biases and future spreads in the CMIP5 global climate model ensemble. Environ Res Lett. 2015;10(8):084013. https://doi.org/10.1088/1748-9326/10/8/084013.
232. Zhu Y, Xi K, Ma H, Yang P, Wang Y, Li H, Liu Y. Exogenous silica nanoparticles improve drought tolerance in ginger by modulating the water relationship. Environ Sci Nano. 2024;11(3):1259–70. https://doi.org/10.1039/D3EN00903C.

## Figures

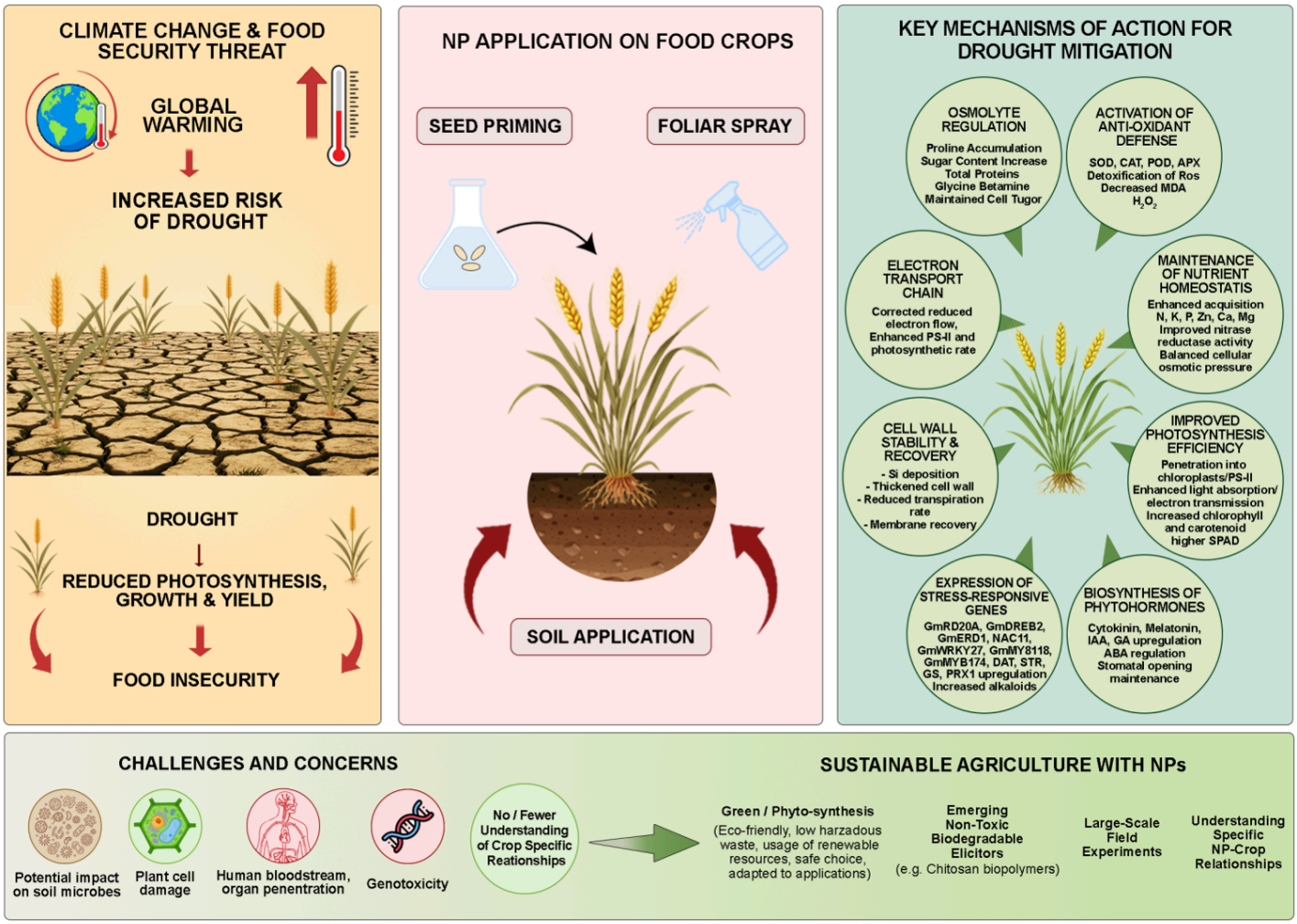



**Figure 1**

Graphical Abstract

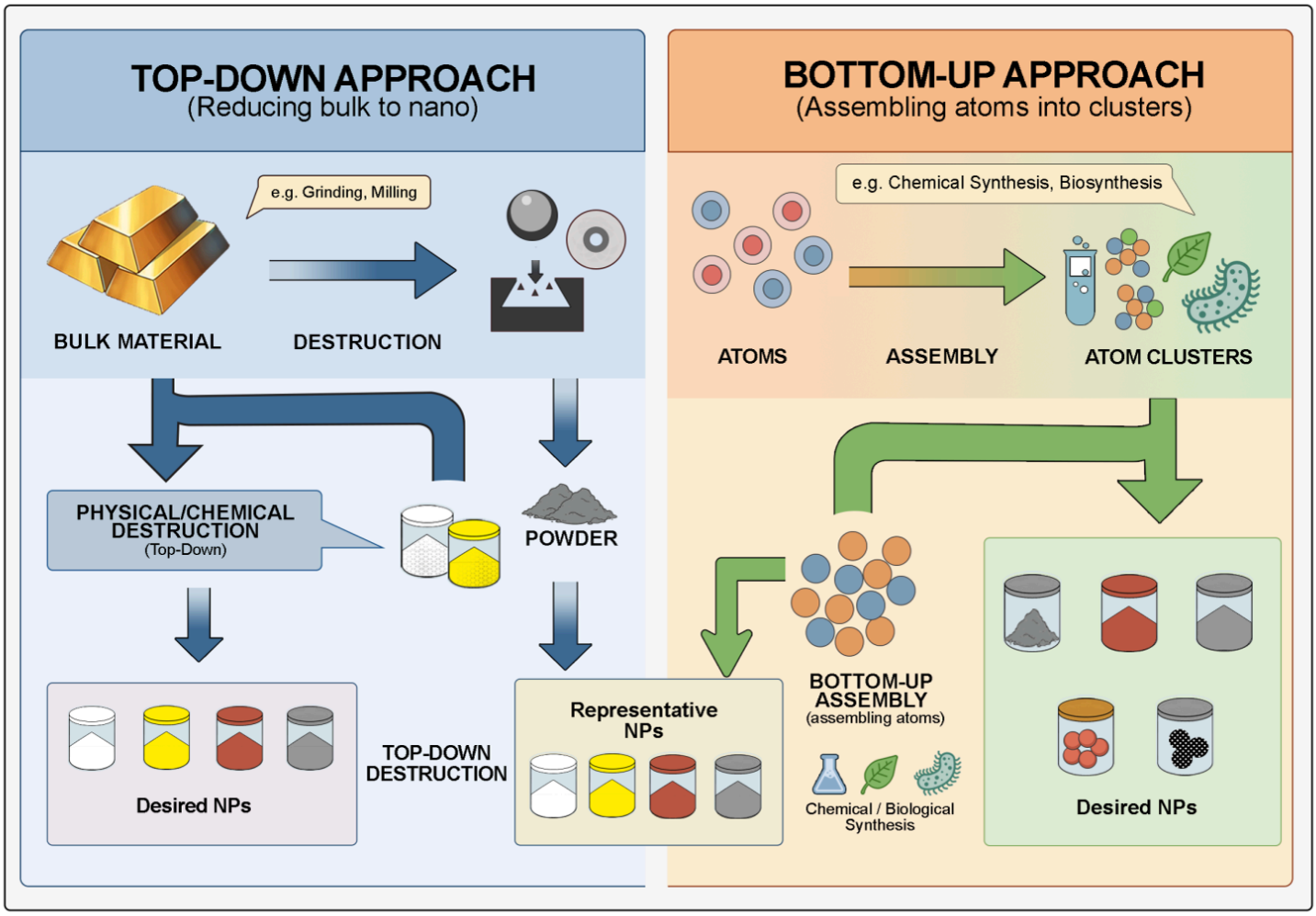



**Figure 2**

Nanoparticle Synthesis Approaches

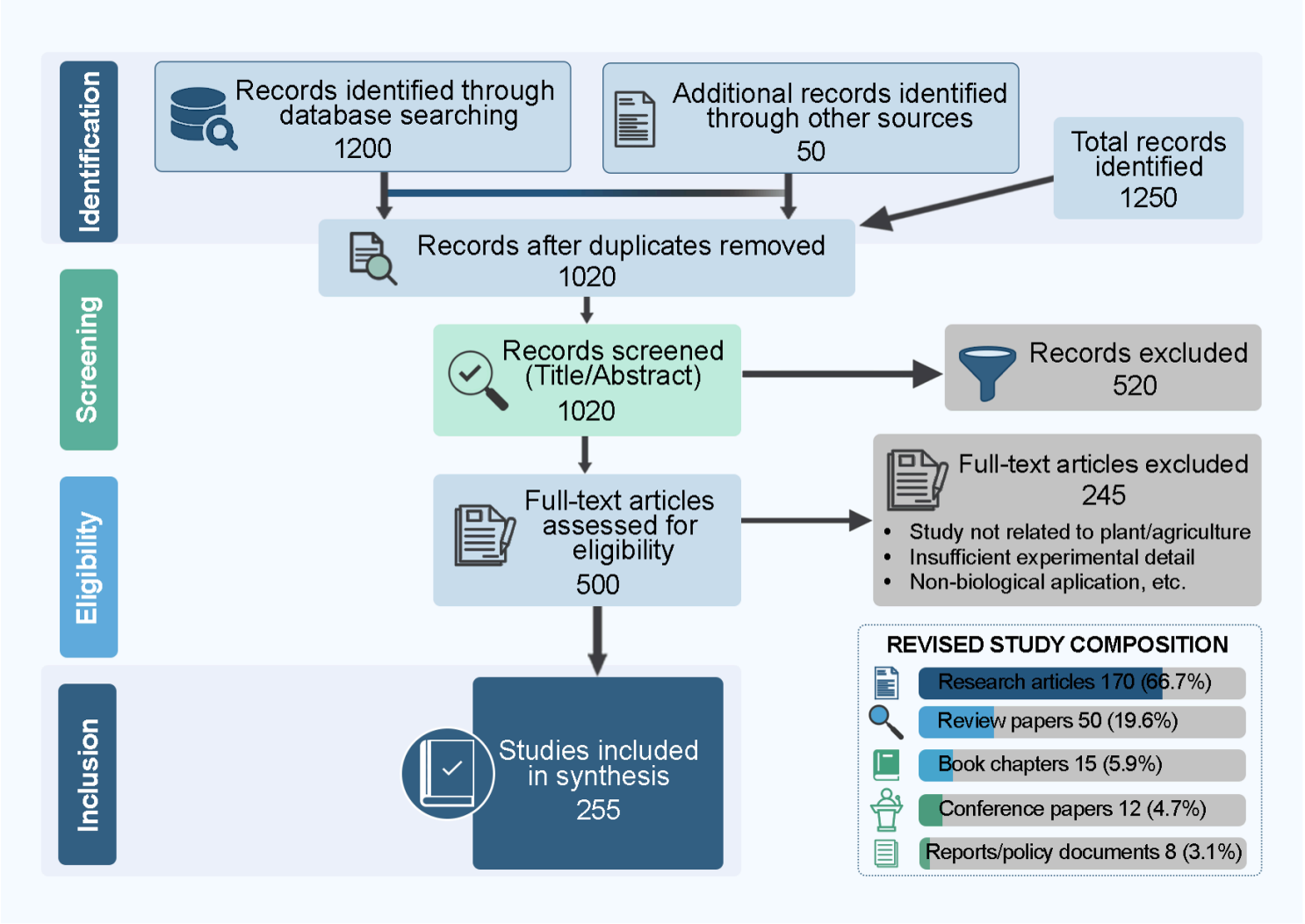



**Figure 3**

Review Methodology Flow Diagram