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## Drought Stress Under a Nano-Farming Approach: A Review

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ONGOING climate change is leading to more extreme weather, which affects agriculture in various ways. In semi-arid regions of the world, and even some humid areas, drought stress is becoming more frequent. Prolonged drought periods lead to severe damages to cultivated plants, which impacts water and food resources. This review investigates how drought stress impacts plants and how management practices can be utilized to reduce the negative effects. Special attention is given to nano-farming where application of nanomaterials may ameliorate drought stress by increasing enzymatic antioxidants and decreasing generation of reactive oxygen species (ROS). Despite the promising results of nano-farming we conclude that further research is required, particularly to investigate potential negative effects, for example on nano-toxicity where particles can enter groundwater or into the food chain. Finally, drought stress is a complexed problem that affects all living organisms. A quick fix is not possible, but humankind needs to collaborate and work for a better future for all.

**Keywords**: Global warming, Food crisis, Nano technology, Poverty, Water crisis, Water deficit.

### 1. Introduction

Drought can be defined as "*drier than normal conditions due to a deficiency of precipitation over an extended period of time, a season or more, leading to a water shortage*" as reported by the National Oceanic and Atmospheric Administration (NOAA 2023). Drought can come as a result of shifts in weather systems. This can be in the monsoon, in other weather patterns caused by global warming, or by random or seasonal variations and rainfall anomalies (Seleiman et al. 2021). Drought can be classified into meteorological, hydrological, agricultural, ecological, or socioeconomical drought depending on the cause of the water deficits (Kresic 2009).

Drought stresses plants including their production systems. This creates great pressure on global resources, which are already stressed by a steadily increasing population, ongoing climate change (Ahluwalia et al. 2021), soil salinity, and air, water, and soil pollution (Zandalinas and Mittler 2022).

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Drought is an abiotic stress which severely aggravates other stresses like pathogen attack, salinity, and heat, which cause damage to cultivated plants and reduces agricultural productivity (Fadiji et al. 2022). Drought also is one of the most common, intense, and frequent extreme weather events besides heatwaves and floods, with events that differ from region to region and from one year to another (Rajanna et al. 2023). Severe drought events have increased globally in recent years. Due to changes in rainfall patterns, the frequency of droughts has led to water scarcity, especially in arid and semi-arid regions of the world. Several recent publications have shed light on drought stress. It is important to investigate drought from different points of view to understand the mechanisms of stress and what can be done to minimize negative effects. This includes research into projections of future drought trends (Vicente-Serrano et al. 2023), drought stress on crops (Fadiji et al. 2022) and forests (Konings et al. 2021), plant propagation under drought stress (Zhang et al. 2022), application of bio-irrigation to mitigate drought (Rajanna et al. 2023), how drought impacts water quality (Qiu et al. 2023), microbial resistance to drought (Allison 2023), and plant-soil feedback mechanisms under drought (de Vries et al. 2023).

Nano-farming is the application of nanomaterials to crop production, including seed germination by nano-priming, fertilization with nanofertilizers, protecting plants from pathogens with nanopesticides, and enhancing crop quality with nanomaterials (El-Ramady et al. 2023). Several studies have investigated applications and issues in nano-farming, such as vegetable production (Abdalla et al. 2022), nanotoxicity issues (Behl et al. 2022), nano-farming to improve crop production (El-Ramady et al. 2023; Haris et al. 2023), and nitrogen cycling under nanomanagement (Wang et al. 2023).

This review focuses on the impact of drought stress on plants and production systems. The main aims are to: 1) better understand the mechanisms behind drought stress in plants; 2) provide a set of management practices that reduce the negative effects of drought on plant production; 3) explore drought at a system level, including how it affects water and food resources; and finally, 4) examine if nano-farming could reduce the impact of drought. Drought stress affects not only plants but also animals, microorganisms, and the total environment. A broad perspective will therefore be applied in this review.

## 2. Impacts on plants and farming systems

Drought leads to morphological and physiological changes in plants, which includes reduced photosynthesis, reduced transpiration, reduced root and shoot growth, osmotic adjustments, increased reactive oxygen species (ROS) production, and enhanced plant senescence (Nadeem et al. 2019; Ilyas et al. 2021; Fadiji et al. 2022; Ahluwalia et al. 2021). Drought stress damage is increased when accompanied by other stresses, like salinity stress (Angon et al. 2023) or heat stress (Yang et al. 2022a; Sharma et al. 2023). Many studies have highlighted how combined drought and salinity stress increase negative effects on plants through impacts on photosynthesis, growth, ionic balance, and oxidative balance (Angon et al. 2022; Kumar et al. 2023).

Many strategies can be applied to mitigate drought stress. These include seed priming (Ishtiaq et al. 2023), the ability of metal-based nanoparticles to mitigate drought stress (Rasheed et al. 2022), use of drought resistant plant varieties (Yu et al. 2022), use of mulch or film farming (Han et al. 2023), application of beneficial microbes (Chieb and Gachomo 2023), super-absorbent hydrogels (Saha et al. 2020), fertilizers like potassium (Fang et al. 2023), selenium (Ishtiaq et al. 2023), and silicon (Anitha et al. 2023), as well as biochar (Alotaibi et al. 2023). The mechanisms resulting from these strategies may directly and/or indirectly benefit or induce systemic tolerance. System tolerance can be achieved by improving certain biological processes in the plant, such as stimulating the antioxidant system, enhancing the root and shoot systems, increasing photosynthesis rates, and improving the production of carotenoids. The effects can also be due to phosphate solubilization, ACC-deaminase and phytohormones production, nitrogen fixation, and siderophore and exopolysaccharides production (Ahluwalia et al. 2021).

Drought affects cultivated plants by reducing photosynthesis, growth, and biomass production, while at the same time increasing protein degradation and oxidative chloroplast damage in plants (Ahmad et al. 2022; Kumar et al. 2023). Qiu et al. (2023) reported that agricultural and hydrological droughts can increase water pollution issues and agricultural drought is the type of drought most impacted by climate change. A summary of drought causes, types, and effects on plants is given in **Figure 1**.

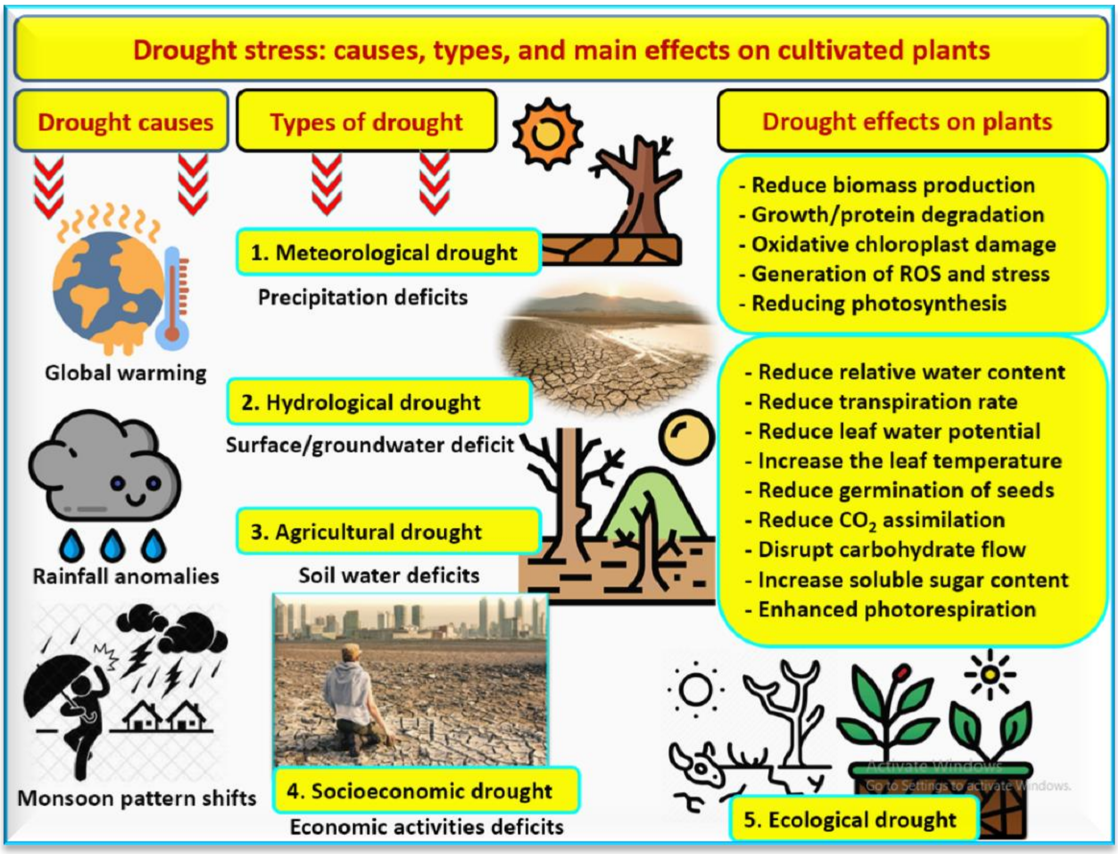


**Fig. 1. Drought causes, types, and its effects on cultivated plants.**

There are several farming systems, including arable or crop farming, agro-livestock farming, bio-farming, cropping-agroforestry farming, microalgae or seaweed farming, integrated mixed farming, integrated livestock forestry, climate-smart agriculture, smart or precision farming, and enhanced smart farming (**Figure 2**) (El-Ramady et al. 2023). Each of these can face drought threats, causing significant decreases in productivity, but the susceptibility differs from one system to another. Drought-related losses in crop productivity might be lower under organic compared to conventional farming due to higher soil organic carbon content and more abundant plant symbionts in organic cropping systems, which potentially contribute to improved soil water retention and aggregation (Banerjee et al. 2019; Büchi et al. 2022; Schärer et al. 2022; Hura et al. 2023; Liu et al. 2023; Wittwer et al. 2023). Drought related grain yield reduction when comparing organic farming and conservation tillage practices was 34, 23 and 17% lower in the organic system for maize, pea-barley, and winter wheat, respectively (Wittwer et al. 2023).

Several studies have been published on the impacts of drought stress under different farming systems in many regions, such as rainfed farming in Afghanistan (Aliyar et al. 2022), agroforestry and goat system in India (Palsaniya et al. 2023), wet crop farming in Indonesia (Irawan et al. 2023), rice farming in Vietnam (van Aalst et al. 2023), semi-arid farming in Zimbabwe (Mupepi and Matsa 2023), organic farming and conventional farming in Switzerland (Wittwer et al. 2023; Gavín-Centol et al. 2023), cowpea farming in Portugal (Moreira et al. 2023), agricultural drought in northeast Italy (Sofia et al. 2023) and southern China (Pan et al. 2023), and meteorological droughts in China (Zhang et al. 2023). Drought stress has been found to reduce invertebrate feeding activity in soils under conventional agriculture, which is associated with mesofauna and their vertical migration, and which decreased with soil depth (Gavín-Centol et al. 2023).

## 3. Agricultural management practices

It is necessary to manage during a drought to minimize damage to cultivated plants, farm animals, and the entire agroecosystem. According to previous studies there are three levels of agro-practices that can be applied, which can be termed individual, combined, and multiple agro-practices (**Table 1**).

Management options to address drought range from plant breeding and selection to molecular or genomic perspectives, grafting, pruning, flower/fruits thinning, bio-irrigation, mulching, and net shading (**Figure 3**), and they can be applied at different stages of crop development from seeding to maturation (Liu et al. 2023). Agro-practices and drought stress combine to cause direct and/or indirect impacts on cultivated plants, e.g., by reducing the formation of reactive oxygen species (ROS) and boosting stress antioxidant enzymes and protein expression for mitigation of drought stress (Malko et al. 2022). Depending on plant growth stages, many agro-chemicals can be applied as treatments to reduce the negative effects of drought (Devin et al. 2023). Applied silicate solubilizing bacteria and potassium silicate supported the growth of sugarcane under drought conditions (Anitha et al. 2023), and grafting can enhance drought resistance in fruit and vegetable crops (Yang et al. 2022b).

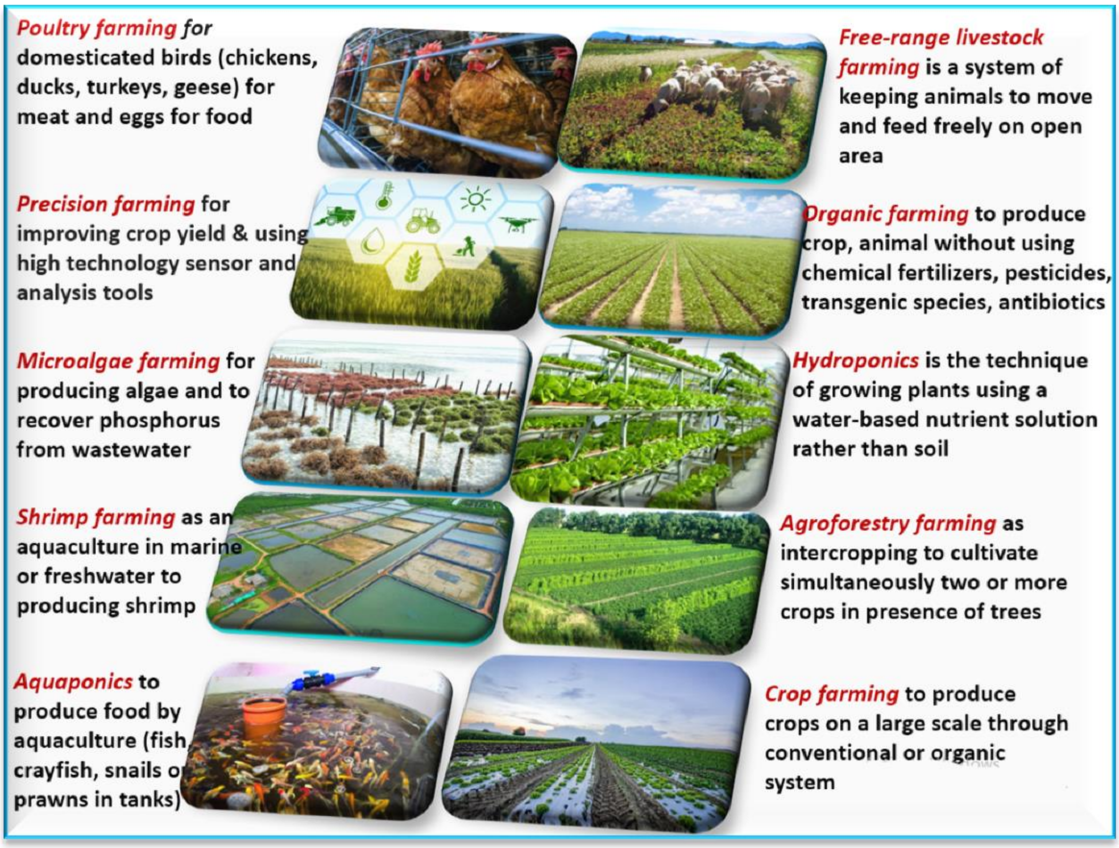


**Fig. 2. Some common farming systems.**

There is great concern that drought is and will continue to increase in severity, duration, and frequency given the ongoing changes in climate and documented increases in extreme climatic events (Wilhite 2019). Integrated drought management (IDM) should be moved from reactive to proactive forms. Here, the 3-pillars of integrated drought management good serve as a guideline. They are: (1) monitoring and early warning systems; (2) vulnerability and impact assessment; and (3) mitigation, preparedness, and response actions (Wilhite 2019). Many recent reports on IDM focus on related-topics such as ecological drought (Sadiqi et al. 2022) and assessing drought vulnerability for water resources management, e.g., in Central India (Thomas et al. 2022), Bangladesh (Islam et al. 2023), and Iran (Jalili et al. 2023). Some studies have focused on multiple uncertainties (Wang et al. 2023a), hydro-systems and cities (de Assis Souza Filho et al. 2023), or food (Alves et al. 2023), This IDM approach can involve application of materials for mitigation of drought such as addition of nutrients including silicon (Si), potassium nitrate ($KNO_3^-$) (Alam et al. 2023), methyl jasmonate and potassium (Beigi et al. (2023), or biochar and methyl jasmonate (Nasiri et al. 2023).

**Table 1: Management of crop production under drought using different agro-practices.**

| Agro-practices | Cultivated crop/Setting | Main effects | Reference |
|---|---|---|---|
| **I. Individual agro-practices** | | | |
| Grafting | Fruit and vegetable crops | Grafting supports morphological, physiological and molecular changes in roots, stems, and leaves and activates osmoregulation, reduces transpiration, enhances antioxidants, and regulates phytohormones | Yang et al. (2022b) |
| Canopy architecture | Multiple crops | Dwarf cultivars are needed for smaller leaf size to reduce transpiration and improve energy savings | Devin et al. (2023) |
| Canopy architecture | *Prunus yedoensis* seedlings | Canopy structural changes-controlled canopy-level solar induced chlorophyll fluorescence reduction during drought | Hwang et al. (2023) |
| Net shading and mulching | *Camellia oleifera* trees | Ecological mat mulching improved yield of *C. oleifera* by maintaining soil water potential and temperature | Ye et al. (2021) |
| Deficit irrigation for water savings | *Festuca arundinacea* | The proper deficit irrigation may improve water conservation by promoting transpiration rate, root activity, and biomass yield | Peng et al. (2022) |
| Rainwater harvesting tools | Cultivated area of Kumari River basin in India | Identifying suitable sites for rainwater harvesting using check dams, earthen dams, percolation tanks, farm ponds, and gulley plug sites to mitigate drought effects | Bera and Mukhopadhyay (2023) |
| Seed priming | Soybean (*Glycine max* L. Merr.) seeds | Seed priming with α-naphthaleneacetic acid regulated germination and seedling by increasing triacylglycerol mobilization, antioxidant capacity, and sucrose transport under drought conditions | Xing et al. (2023) |
| Fertilizers (e.g., K, Se, Si, etc.) | Sesame (*Sesamum indicum* L.) | Potassium fertilizers improved drought stress alleviation by increasing salicylic acid, regulation of phytohormones (ABA acid JA) and photosynthesis | Fang et al. (2023) |
| Fertilization | Tomato (*Solanum lycopersicum* L.) | Se promoted photosynthetic efficiency, alleviated drought-induced oxidative stress, and increased the endogenous salicylic acid levels | Fan et al. (2022) |
| Fertilization | Maize (*Zea mays* L.) | Exogenous Si alleviated drought by improving photosynthetic enzymes, the stomatal size and stomatal aperture, inhibited superoxide free radicals and increased antioxidant enzymes activities | Xu et al. (2022) |
| **II. Combined agro-practices** | | | |
| Melatonin + 24 -epibrassinolide | Pea (*Pisum sativum* L.) | Applying both improved photosynthesis, proline accumulation, and antioxidant enzymes under combined drought and salt stress | Yusuf et al. (2024) |
| Microbes and selenium | *Camelina sativa* L. | *Rhizophagus intraradices* inoculant and Se-priming improved morphological, bio-physiological properties, and production of plants under water stress | Nazim et al. (2023) |
| Abscisic acid and Selenium | Tomato (*Solanum lycopersicum* L.) | Foliar spraying of abscisic acid and Se enhanced the vegetative growth of plants under water deficit conditions by protecting then from oxidative stress | Ramasamy et al. (2022) |
| Salicylic acid (SA) and silicon | *Scrophularia striata* L. | Foliar application of Si and SA increased phenyl-alanine ammonialyase activity, polyphenol and proline contents under water stress | Shohani et al. (2023) |
| Si + arbuscular mycorrhiza fungi (AMF) | Rice (*Oryza sativa* L.) | Combined use of Si fertilization with AMF application can mitigate salinity and drought stress as AMF hyphae/spores accumulate Si in rice roots | Etesami et al. (2022) |
| $K_2SiO_3$ + silicate solubilizing bacteria | Sugarcane (*Saccharum* spp.) | Improved uptake of Si and NPK along with enhanced plant growth and quality parameters compared to the control under drought conditions | Anitha et al. (2023) |
| Brassinosteroids and timber waste biochar | Wheat (*Triticum aestivum* L.) | Combined application enhanced drought tolerance by increasing photosynthetic pigments, antioxidants, Ca, P, and K content in plants under drought stress | Lalarukh et al. (2022) |
| **III. Multiple agro-practices** | | | |
| Multiple agro-chemicals | Wheat (*Triticum aestivum* L.) | Applying a combination of agro-chemicals and methods of treatment as an effective treatment approach for drought stress depend on growth stages | Malko et al. (2022) |

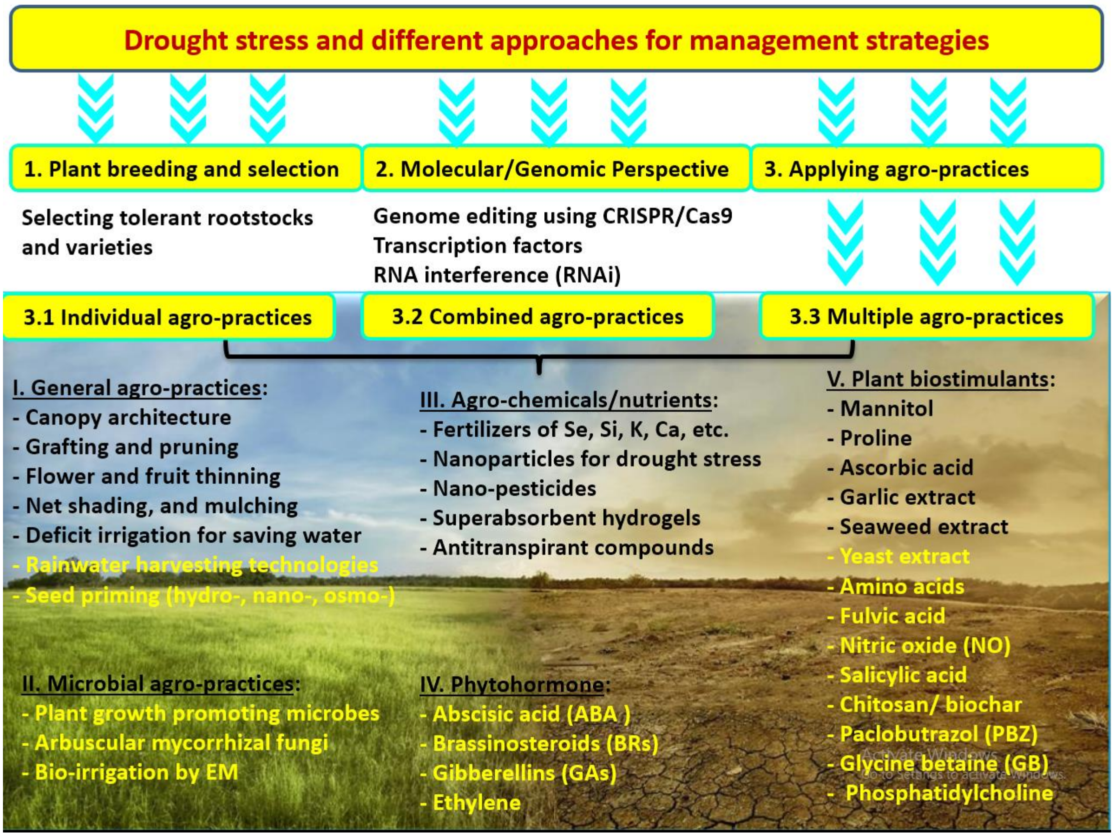


**Fig. 3. Different levels of agro-practices for drought management.**
Abbreviations: Effective Microorganisms (EM)

**4. Drought stress and water resources**

Climate change has many key indicators, including a higher average global temperature, alterations in rainfall patterns, rising sea levels, ice loss at Earth's poles, and more frequent and severe droughts, hurricanes, floods, wildfires, and heatwaves (**Figure 4**). As a part of the carbon, nitrogen, and water cycles, changes that influence our climate also influence soils and vice versa (Brevik, 2012).

There are complex interactions between cultivated plants and water that have been studied under drought conditions (Arab et al. 2023; Guarnizo et al. 2023). Plant water relations that might be disrupted by droughts due to water deficit include root hydraulic conductance, root sap flow rate, leaf water potential, turgor pressure, and water use efficiency. These plant water disturbances may reduce hydraulic conductance in both stomata and roots, lowering water potential of the environment due to stomatal closure during water deficit (Guarnizo et al. 2023). Thus, a global water shortage would become a serious eco-problem facing all humankind. This is especially true under the ongoing global climate changes, which have increased concerns about drought as a key factor restricting the development of agricultural production worldwide (Yang et al. 2021).

Several mechanisms are initiated in plants when they are exposed to drought (Khan et al. 2018; Yang et al. 2021; Angon et al. 2023; Riyazuddin et al. 2023; Wang et al. 2023b). The main mechanisms include changes in the internal structure and external morphology of leaves, roots, and stems, and activation of drought-induced proteins, osmotic regulation, and the reactive oxygen scavenging system (**Figure 4**). Morphological mechanisms include reducing leaf stomatal density and/or conductivity, increasing the epidermal wax layers, increasing thickness of the leaf cuticle, and lowering levels of lignin in the leaves. Physiological mechanisms include reducing photosynthetic rate and Ribulose-1,5-bisphosphate (RuBP) content, increasing osmotic regulation through $K^+$, $Na^+$, $H^+$, and organic substances (glycine betaine and polyamines, proline, and trehalose, mannitol, fructan, and others), increasing drought-induced proteins (e.g., dehydrin and aquaporin), preventing degradation of chlorophyll in leaves, and decreasing electron transfer rate or photoinhibition (Yang et al. 2021).

Drought has serious impacts on water resources which has led to numerous studies focused on integrated approaches for water resource management under drought (Alhama et al. 2020; Alam et al. 2023; Wang et al. 2023b). This approach to manage water resources under drought has been employed in many regions such as Southern Algeria (Zegait et al. 2023), Saudi Arabia (Abd El-Hamid and Alshehri 2023), Eastern India (Biswas et al. 2023), Italy (Rossi and Peres 2023), North America (Asif et al. 2023), Sweden (Teutschbein et al. 2023), and Iran (Khani et al. 2023).

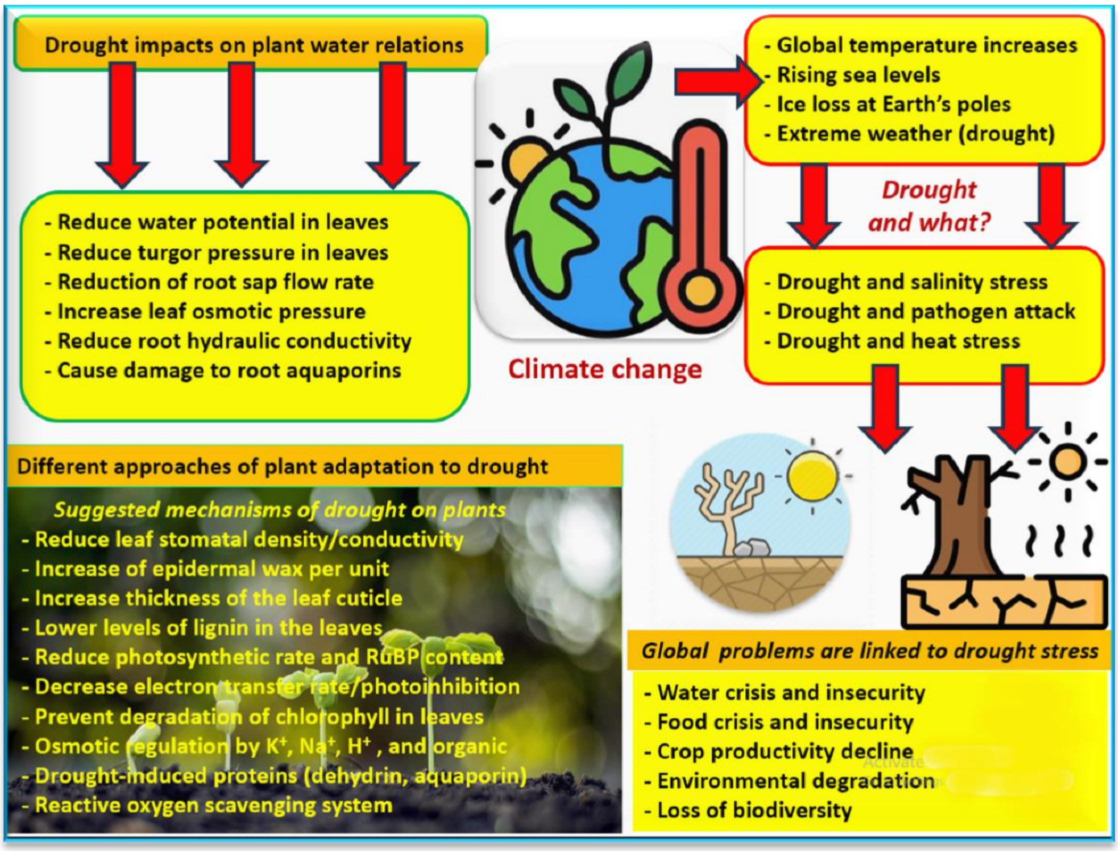


**Fig. 4. Climate change can induce drought, which may be accompanied with salinity or heat stress. There are a variety of impacts of drought, and many plant adaptations to drought are common**

## 5. Drought stress and food resources

Food resources can be defined as *"natural or artificially produced materials which are used as food to derive metabolic energy*". These include plant and animal sources.

Global problems linked to food resources under drought include poverty, undernourishment, famine, malnutrition, hunger, acute food insecurity, food-deficit, and global food scarcity (**Figure 5**). Global food security is strongly linked to the relationship between the impacts of drought impacts and agricultural production (Krishnamurthy R et al. 2022). With increasing food demand due to population growth, food production needs to roughly double by the 2050s (Leng and Hall 2019). Drought is an extreme weather phenomenon that is one of the main climatic constraints to crop productivity. Drought forces crops to close their stomata to limit evaporative water loss, thus reducing carbon uptake for photosynthesis and decreasing yields. It is estimated that a loss of 1820 million Mg of cereal crops (rice, maize, and wheat) has occurred globally during the past four decades due to droughts (Leng and Hall 2019). The impact of drought stress on crop productivity (food) and food security can be found in the literature (Fadiji et al. 2022; Roy et al. 2022; Yang et al. 2023). Integrated management of drought risks has been discussed by Alves et al. (2023) while agricultural drought has been investigated by studies in several countries and regions, e.g., China (Pan et al. 2023), Southeast Asia (Ha et al. 2023), India (Bhukya et al. 2023), and Iran (Kheyruri et al. 2023).

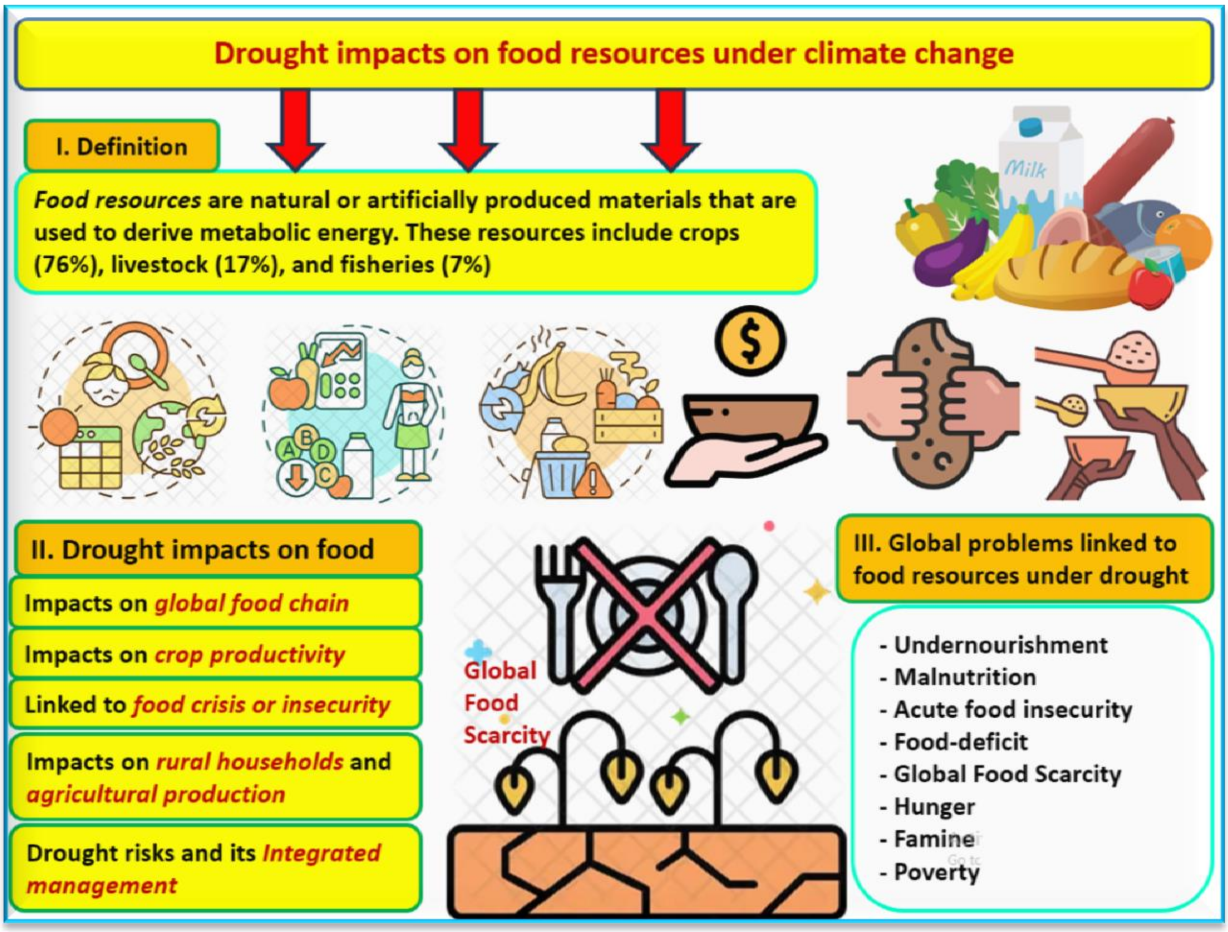


**Fig. 5. Common impacts of droughts on food resources under climate change.**

As previously mentioned, drought causes serious food security concerns. Investigation of these concerns have included drought resilience in a multi-level food supply chain in the UK (Vicario et al. 2023), agricultural vulnerability to drought in China's agro-pastoral ecology (Li et al. 2023), breeding plants to be tolerant to drought stress with a focus on rhizosphere properties (Cheraghi et al. 2023), and evaluation of the impact of complex drought patterns on global yield loss for major crops (Santini et al. 2022). Loss of crop productivity due to drought stress has been investigated using many approaches such as APSIM crop models in northeast China (Wang et al. 2022), analyzing spatiotemporal crop yield loss in Nepal (Dahal et al. 2023), crop simulation, risk curves, and risk maps in Huaibei Plain, China (Wei et al. 2022), using crop growth stages in the Huaibei Plain, China (Wei et al. 2023), and analysis of economic losses of crop production in Pakistan (Rahman et al. 2023).

**6. Nano-farming approach under drought**

Nanotechnology has penetrated nearly all fields of agriculture, including cropping, animal, and fish systems. Several nanomaterials have been utilized to mitigate stressful conditions, including drought stress. Such material includes nanofertilizers, nano-encapsulated plant growth regulators, nano-based biostimulants, nanopesticides, and nanosensors (**Figure 6)**. These nanomaterials (NMs) are often viewed as being eco-friendly and low-cost remedies. They have high surface to volume ratios and possess unique physicochemical properties that regulate plant protective responses through synergistic actions, which can include regulating phytohormone signaling and modulating the gene expression of phytohormones involved in plant growth under stress (El-Ramady et al. 2023). The application of NMs in agriculture has two important dimensions. The first is the positive side of the applied NMs, which may lead to improved performance in crop, animal, and fish units. The second is the negative side, which may lead to unwanted effects that result in pollution and nano-toxicity.

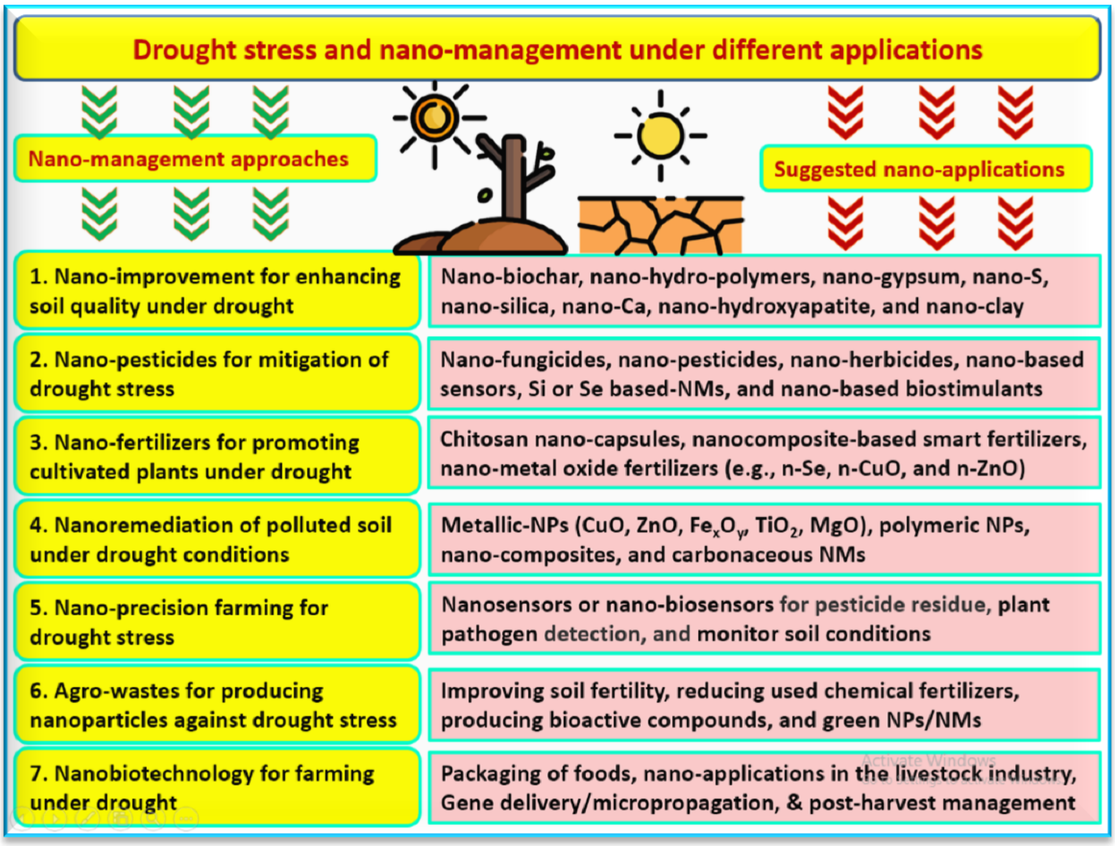


**Fig. 6. Nano-management practices to address drought stress and suggested nanomaterials for mitigation of that stress.**

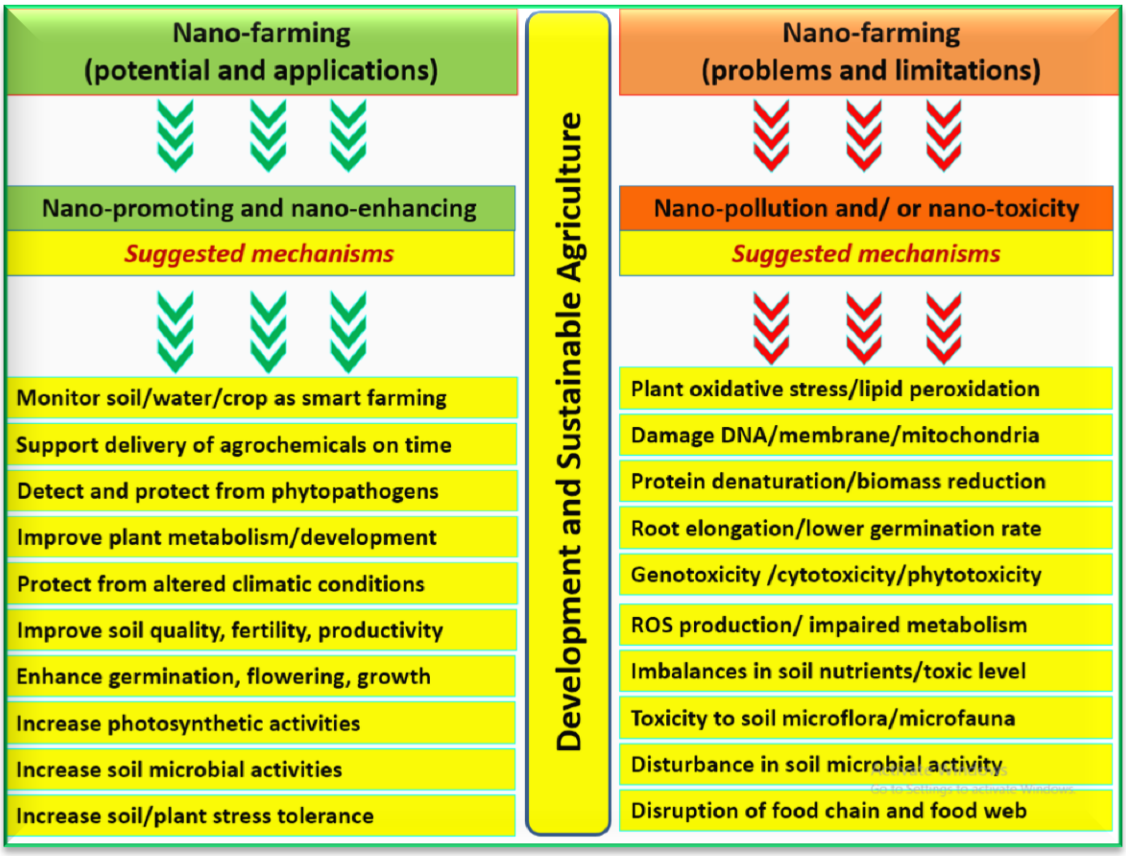


**Fig. 7. Positive and negative aspects of the use of nanomaterials in agriculture (adapted from El-Ramady et al. 2023).**

**Table 2. Table 2. Overview of studies where nanomaterials have been applied for the mitigation of drought stress in various crops and with suggested mechanisms involved.**

| Nanomaterial | Cultivated crop | Suggested mechanism under drought stress | Reference |
|---|---|---|---|
| Iron nano-oxide | Soybean (*Glycine max* L.) | Using seed priming at 300 ppm + foliar spraying 15 ppm of nano increased antioxidant activities (CAT, SOD), and water productivity under drought stress | Farajollahi et al. (2023) |
| ZnO-NPs | Mulberry (*Morus alba* L.) | Applied nano at 10 ppm, as soil and foliar improved the growth of cuttings, antioxidant enzymes, and biomass | Haydar et al. (2023) |
| Cu–Zn-magnetic NPs | Tomato (*Solanum lycopersicum* L.) | Nano-antifungal agents inhibited ergosterol biosynthesis and managed *Fusarium* wilt | Bouqellah (2023) |
| ZnO-NPs | Wheat (*Triticum aestivum* L.) | ZnO NPs (250 ppm) enhanced drought tolerance by improving RWC, MSI, Zn-content, chlorophyll, protein/osmolyte contents and antioxidant enzymes | Pandya et al. (2023) |
| Zinc-chitosan-salicylic acid (ZCS) NPs | Wheat (*Triticum aestivum* L.) | ZCS-NPs (100 ppm) mitigated drought stress by improving osmotic status, enhancing osmo-protectants synthesis, activating anti-ROS-enzymes | Das et al. (2023) |
| Nano Chitosan-glycine betaine | Bread wheat (*Triticum aestivum* L.) | Nano-seed priming (100 mM) for 18 h improved growth under combined drought and heat stresses by adjusting osmotic status, conserving tissue water, and activating the antioxidant defense systems | Al Masruri et al. (2023) |
| Carbon nanoparticles | Maize (*Zea mays* L.) | Seeds were enhanced by priming 80 μg/ml (nano) with compost and AMF under drought, increasing enzyme activities of ascorbate peroxidase, dehydro-ASC reductase, and mono-dehydro-ASC reductase | Alsherif et al. (2023) |
| Biological nano-silica | Wheat (*Triticum aestivum* L.) | Nano 60 ppm was the effective dose for improving plant tolerance to drought by lowering $H_2O_2$ and lipid peroxidation and increasing relative water content and enzyme antioxidants (APOx, CAT, and SOD) | Boora et al. (2023) |
| Abscisic acid-loaded ZnO-NPs | Maize (*Zea mays* L.) | Nano improved growth under drought by reducing lipid peroxidation and increasing antioxidant activities (catalase, ascorbate peroxidase, and peroxidase) | Fatima et al. (2023) |
| Glycine betaine-ZnO nano-composite | Coriander seeds (*Coriandrum sativum* L.) | Applied NPs (at 100 ppm) mitigated oxidative damage by up-regulating antioxidants, decreasing the production of ROS, and reducing potential in plantlets | Hanif et al. (2023) |
| Molybdenum trioxide NPs | Green peas (*Pisum sativum* L.) | Applying 50 ppm $MoO_3$-NPs increased leaf area, nodule number, and the yield of a drought-stressed pea by activating CAT, APOx, SOD, and GPx enzymes | Sutulienė et al. (2023) |
| Carbon nanoparticles | Chili pepper (*Capsicum annuum* L.) | Applying nano (6 ppm) alleviated drought stress by regulating chlorophyll content, water status, osmo-protectants, and enzymatic antioxidants in seedlings | Alluqmani and Alabdallah (2023) |

**Abbreviations:** Relative water content (RWC), Membrane stability index (MSI), catalase (CAT), superoxide dismutase (SOD), glutathione peroxidase (GPx), and activity of ascorbate peroxidase (APOx)

Nano-fertilizers have great potential for alleviating drought stress. Positive effects after application of NMs have been found in numerous studies. These include CaO-NPs (75 ppm) in canola (Mazhar et al. 2022), biological $Fe_3O_2$-NPs (0.6 – 1.2 mM) in wheat (Noor et al. 2022), biological nano-silica (60 ppm) in wheat and other crops (Boora et al. 2023), iron nano-oxide (priming 300 ppm + spraying 15 ppm) in soybean (Farajollahi et al. 2023), nano-priming of ZnO-NPs (250 ppm) in wheat (Pandya et al. 2023), and foliar applied zinc-chitosan-salicylic-NPs in wheat (Das et al. 2023).

Nanopesticides have successfully been applied to drought-stressed crops for the control plant pathogens. One example is the application of nano Se and Si to boost the productivity of common bean under *Alternaria* leaf spot disease stress (Taha et al. 2023). Nanomaterials have also been used to detect plant pathogens through tools like nano-biosensors, nano-coding, nano-diagnostic kits, and nano-pore sequencing (Shivashakarappa et al. 2022).

The main mechanisms of stress relief are due to controlling the release of active ingredients in nanofertilizers or nanopesticides. This may create pH changes, alter enzyme activities, or change light, temperature, or redox potential in the agro-environment (Shen et al. 2023). It is important to protect the active ingredients in nanopesticides and nanofertilizers by applying nanocarriers. There is a need for further research on optimizing the performance of the applied NMs. Key issues in addition to efficiency will be lowering their costs and avoiding nanotoxicity problems (**Figure 7**).

Application of nanomaterials for the mitigation of stresses such as drought has been examined for different farming systems (El-Ramady et al. 2023) and for the concept of "*farm-to-fork*" (Abdalla et al. 2022). Suggested mechanisms of NM function are summarized in **Table 2**. The general mechanism includes increased tolerance to drought stress by increasing plant enzyme activities and reducing the generation of ROS. Extensive additional research is needed to understand the underlying physio-biochemical and molecular mechanisms of NMs, their translocation and accumulation in plants, groundwater, the soil microbial community, farm animals, and humans under drought conditions.

## 7. Conclusions

Drought stress has the ability to cause serious damage to cultivated plants both directly and/or indirectly. Drought limits nutrient and water uptake, decreases net photosynthesis, and leads to disturbances in plant enzyme activities and metabolism. Indirect impacts include disturbances in nutrient uptake balance, intensification of oxidative stress, and impacts on water and food resources as well as human health. Furthermore, drought stress can reduce the growth and yield production of many crops. In the last few decades, numerous efforts have been made to find multilateral solutions for integrated drought management. This may reflect on many global issues such as exploring new soil and water resources, expanding agricultural lands, and enhancing crop productivity under challenging environmental conditions. Nano-management of drought stress is considered a promising and sustainable solution, especially if using biological or green nanomaterials. However, an intensive application of engineered materials may lead to pollution and nanotoxicity. Thus, in all drought-prone nations, drought management should be considered an urgent need with a focus on reducing drought risks. This requires convincing natural resource managers and policy makers to adopt a proactive approach to managing drought conditions. The right drought management should be considered a potential tool to sustain food production and security under soil resource-limited conditions.

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