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REVIEW

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Mission ‘Sustainable Agriculture’: Mitigating Abiotic Stress with Nano Particles

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In agro-ecosystems, abiotic stress effects can create havoc diminishing productivity and severely deteriorating yield and yield quality. To meet the rising food and feed crisis, rigorous control of productivity and yield losses in agriculture due to environmental stress must be executed. Coupled with climate change, abiotic stress is causing havoc to crop physiology, productivity and quality of agricultural produce. With the SDG 2 target of Zero Hunger to an unprecedented 8.5 billion by 2030, such massive loss of agricultural yield and economy poses a huge challenge. Stress mediated responses of plants are multiple and varied. Nanotechnology is an emerging field which could profoundly affect crop stress physiology through biotechnological and biochemical interventions to usher in a new era of Sustainable Agriculture and Zero Hunger. Such interventions may be suggested for a paradigm shift towards sustainable agriculture and to meet the massive global challenge of 70% rise in crop output for the rising millions of 2050.

Key words: abiotic stress, sustainability, crop stress physiology, phytonanotechnology, stress resilient crops

ABIOTIC STRESS AND CROP PRODUCTIVITY

Climate change is a major threat to crop productivity and yield globally, and is causing serious damage to food security (Watts et al. 2021). With climate change already taking serious proportions, abiotic/environmental stress is significantly on the rise and is expected to take mammoth proportions in the near future. Temperature (low and high), water (drought and flood) and salinity pose the greatest challenges to crop productivity, supply and ultimately food security (Kopecka *et al.* 2023). Abiotic stress causes extensive decrease in crop production through detrimental effect on plant growth and development, metabolism and reproduction. The rapidly changing seasonal patterns due to global warming, is providing additional fuel to the already deteriorating environmental scenario. Significant effects are damaged photosynthetic organelles, oxidative stress injuries and membrane instability while the ability to withstand these stresses differs noticeably across species. They possess powerful sensors or signal transduction pathways which coordinate biophysical stimuli and biochemical events which guide them toward optimal growth, development and survival.

The report of COP 15 states, that the proportion of drought affected plants has increased more than twice since the 1980s. When plant roots get limited water supply or when transpiration rate is very high due to prevailing environmental conditions, plants experience water stress. Water deficiency leads to water stress which could be either due to prolonged drought or high salinity. Salinity may result in a condition commonly known as ‘physiological drought’ where plants are unable to take up water despite its availability. Plants growing in areas with non-uniform precipitation may also be subjected to water stress. Plants can usually overcome limiting situations but with a compromise in total biomass and yield.

A combination of stresses usually affects a crop plant differently as compared to individual stress effects. Drastic reduction in global yield of wheat and maize due to temperature stress has been reported and drought stress has caused further decline in productivity (Matiu et al. 2017). Plant perception and response to stress is determined by the nature of the cumulative stress effect and their interaction.

STRESS PERCEPTION AND RESPONSES OF PLANTS

Abiotic stress responses of plants indicate their multilevel nature; involvement of numerous processes which include detection, reception, signal transduction, transcription, processing of transcript, translation and subsequent post-translational protein alterations (Zhang *et al.* 2022). The cumulative effect of water and temperature stress during unfavourable environmental conditions, like all other abiotic stresses are injurious to crop plant physiology and metabolism and consequently lower productivity, yield and quality of produce (Sen and Mukherji 1998a,b, 1999a, 2000, 2006, 2007, 2016, 2020). Natural mechanisms in plants – morphological, physiological with biochemical, to withstand drought as epigenetic plasticity and activation of crucial genes have been observed by Ghafar *et al*. (2021). Relative water content (RWC), a crucial determinant of drought stress in leaves is the first reported stress response (Hussain *et al.* 2018) and strongly links with leaf growth and transpiration rates (Kapoor *et al.* 2020).

There are several reports of interactions and crosstalk among the different biochemical pathways. Coordination is mediated by varied signaling mechanisms *viz*. reactive oxygen species (ROS) - (functioning both in signaling and toxicity), redox and hormonal, retrograde and anterograde besides systemic signaling throughout the plant. Of the several and varied effects of abiotic stress on plant metabolism, is the ample formation of harmful ROS like hydrogen peroxide, superoxide anion radical, hydroxyl radical *etc*. in chloroplasts, mitochondria, peroxisomes, plasma membrane and cell wall (Noctor and Foyer, 2016) causing severe damage to DNA, proteins, carbohydrates, lipids, photosynthetic pigments and other essential constituents (Raja *et al.* 2017). The reactive nitrogen species too mediate stress responses of plants controlling gene expression and hence enzyme activity.

Studies reveal that to combat abiotic stress *viz.* water/drought, activation of antioxidant defence serves as an effective adaptive mechanism (Hasanuzzaman *et al.* 2018). Other adaptation strategies include osmotic adjustment where soluble proteins and sugars, proline, glycine betaine *etc*. build up as compatible osmolytes or osmoprotectants (Sen and Mukhherji 1998a, Per *et al.* 2017). Osmolytes being highly soluble and completely non-toxic do not interfere with the normal cellular metabolism. The scavenging enzymes catalase, peroxidase, superoxide dismutase, ascorbate peroxidase, glutathione reductase, polyphenol oxidase, ascorbic acid oxidase and other associated enzymes along with non enzymatic scavengers like carotenoids, flavonoids, ascorbic acid, polyphenols, glutathione attempt to detoxify the free radicals (Gill and Tuteja 2010, Sen 2020, 2023 Nikoleta-Kleio *et al.* 2020).

While favourable seasonal periods are characterised by high rate of photosynthesis (Sen and Mukherji 1999b), elevated level of biomolecules *viz.* nitrogen, protein, amino acid, carbohydrates and phenol contents (Sen and Mukherji 1998a,b) increased ATP content and ATPase activity (Sen and Mukherji, 2007) along with high respiratory rates and activities of respiratory enzymes during these times (Sen and Mukherji, 2006) signify a peak metabolic phase, the unfavourable seasons manifest the reverse. Manifold increase of proline along with elevated rate of activities of chlorophyllase, polyphenol oxidase, acid phosphatase and alkaline phosphatase indicate the stressful seasonal periods equivalent to abiotic stress phase. These periods are marked by profuse production of reactive oxygen species (measured as MDA and total peroxide contents), accompanied by reduced cleansing and decreased detoxification of these ROS by the antioxidants (carotenoids, ascorbic acid) and antioxidant enzymes (SOD, catalase, peroxidase, ascorbate peroxidase, glutathione reductase), according to Sen (2023). All these aspects significantly promote the produce and quality of produce of agricultural crops (Sen 2016, 2020, 2024).

The reproductive stage of any plant is the worst affected by abiotic stresses thus causing a massive loss of yield and economic penalty. Pollination, flowering, grain filling, fruit formation, nutritional quality of yield, are all severely affected. Abiotic stresses have been reported to hamper germination, nutrient uptake, photosynthetic efficiency, respiratory pathways and nutritional attributes of crop plants. The biochemical and enzymatic parameters which undergo considerable variations under seasonal abiotic stress serve as functional bioassay indices of the prevailing stress, while the plants acting as a gauge of the existing environmental conditions function as effective bio-indicator species. Thus, plant response to environment indicates the vast significance of seasonal environmental and/or abiotic stress on agricultural productivity.

NANOTECHNOLOGY IN MITIGATION OF ABIOTIC STRESS

It is suggested that nanoparticles ameliorate abiotic stress and stressors by increasing photosynthetic efficiency, controlling pathogenic attack, increasing the activities and amounts of ROS scavenging enzymes as well as non enzymatic ROS scavenging components (Al-Khayri *et al.* 2023). Nanotechnology with the use of nano-scale products as fertilizers, pesticides, fungicides, herbicides etc. is a new approach to mitigate abiotic stress and shift towards sustainable agriculture. Nanoparticles due to their easy solubility, size and ability to traverse cellular barriers can be effectively taken up by plants and hence well serve the purpose of effective drivers of improved crop production both quantitatively and qualitatively (Al-Khayri *et al.* 2023).

Wu and Li (2022) opined that nanotechnology has the potential to improve abiotic stress tolerance. Nanofertilizers improve plant growth and metabolism by targeting soil quality, growth hormone stimulation, resistance to all kinds of stress (Cinisli *et al.* 2019, Khairy *et al*. 2022). Cinisli *et al*. (2019) found the entry route of NPs in plants affects processes like germination, photosynthetic organelles and efficiency, antioxidant activity etc. A targeted delivery approach with nanomaterials has been proposed by Santana *et al.* (2020) for chloroplast conversion to ‘chloroplast factory’ for improved photosynthetic efficiency under low light.

Phytonanotechnology is a green chemistry technology supporting the use of eco-friendly reagents.

Different plant parts such as root, stem, bark, leaf, flower, fruit, seed, epidermis etc. can synthesize nano particles of Pd, Pt, Au, Ag, Fe, Cu, Zn and Se. Plant mediated production of nano particles or phytonanotechnology being green synthesized is a safe and sustainable approach to crop production (Khan *et al*. 2022). There have been reports by Sharma *et al.* (2009) and Iravani (2011) highlighing effective and economic production of green nano particles from plant sources. The Wet Technology of nanoparticle production is the green technology that uses biological systems - tissues, membranes, enzymes etc.

Stress induced damage is mitigated possibly by use of detoxification pathways and action of enzymatic antioxidants (Sarraf et al. 2022). Physical and chemical properties, purity, technique of production and administered dosage all contribute to the effectiveness of nano particles. Different nano materials like Au NPs, SiO_2 NPs, mesoporous silica NPs, Chitosan NPs have been reported to significantly improve growth and development of crop plants viz. rice, wheat, potato, soybean, onion etc. (Dubey and Mailapalli 2016). Nano materials enhance germination, improve photosynthetic rate, mineral uptake thereby enhancing crop productivity, yield and quality (Nair, 2016). Nano materials have also been reported to be very effective in stress combat in a wide variety of abiotic stresses viz. heat, cold, salinity, drought, osmotic and heavy metal in a large number of crop plants through the modification of enzymatic actions and biochemical pathways. Thus nano materials may be judiciously used for abiotic stress mitigation in agricultural crops (Jiang et al. 2021).

According to Ahmed *et al.* (2021), nano particles have a considerably high potential for retention of nutrients and hence can successfully balance nutrient losses due to abiotic stress. Heavy metal stress as well as drought stress can also be well ameliorated by iron oxide nano particles (Adrees *et al.* 2021), silicon nano particles significantly decreases the effects of salinity stress (Haghighi and Pessarakli, 2013) while titanium nano particles diminished oxidative stress (Song *et al.* 2012)

Genetic improvements along with proper conventional methods are considered effective in combating abiotic stresses. Genome editing consisting of CRISPR/Cas9 (clustered regularly interspaced short palindromic repeat/Cas9, TALENS (transcription activator-like effector nucleases), ZFN (zinc finger nucleases) could provide suitable alternatives with reports of improved traits, enhanced productivity and nutritional attributes (Matres *et al.*2021, Mushtaq *et al*. 2021). Emphasis is also on crop breeding with the primary objectives of stress tolerance and stress resistance, cost friendly SNP profiling, DNA methylation and over expression/knockdown.

Stress priming is stress conditioning where low intensity or short term stress exposure results in more resilient plants to further stresses (Liu et al. 2022). Plants in a sensitized condition promptly respond with increased amplitude to further such stress exposures, a phenomenon called 'defense priming' or 'trained immunity' which induces 'stress memory'. Plants due to stress memory are thus facilitated to retain the stress imprints for such future exposures. Priming can cause both somatic and trans-generational memory improving plant adaptation to changing environmental conditions by modifying gene expression levels. Priming is determined by a number of factors such as duration, type, intensity, plant species, age of plant and others (Nair *et al.* 2022).

SUSTAINABLE AGRICULTURE - THE FUTURE AHEAD

The current worldwide agriculture and food system is unsustainable across all three pillars of sustainability viz. environmental, social and economic. There must be major paradigm shifts at all levels – global and local – and in all sectors, from food production to consumption, to achieve the SDGs related to poverty, food and nutrition security, health, rural development and environment. The five key principles may serve as concrete guidelines – increasing productivity, employment and value addition in food systems, protection and enhancement of natural resources, improvement of livelihoods to foster inclusive economic growth, enhancement of resilience of people, communities and ecosystems and adapting governance to new challenges. Against the backdrop of climate change and population explosion with the steep rise in food demand, sustainable solutions to food crisis must be sought.

To meet the rising food and feed crisis, rigorous control of productivity and yield losses in agriculture due to environmental stress must be executed. Use of eco friendly bio-based materials are now suggested practices for sustainable agriculture. Plant extracts, essential oils, agricultural product waste materials, plant growth promoting bacteria, biological nitrogen fixation (Mukherjee and Sen, 2021a,b) arbuscular mycorrhizal fungus may be suggested for shifting towards sustainable agriculture.

A major objective in plant breeding is the development of stress resilient crops and economically important plants with the potential to combat and adapt to abiotic *viz.* water, drought, temperature stress. Water use efficiency (WUE), a determinant of yield quality and survival under prevailing water stress serves as a significant selection criterion. Studies on stress response mechanisms are designed to meet the rising food crisis and achieve sustainable agriculture. Despite significant progress in genetic approaches and techniques such as molecular breeding and QTL mapping with several transgenic methods there is still a long way to zero hunger, the ultimate and basic need of humankind on this planet.

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CONFLICTS OF INTEREST

The authors declare that they have no potential conflicts of interest.

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