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Plant Responses To Drought Stress Under Climate Change And Recent Biotechnological Interventions For Mitigation: Mini Review

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ABSTRACT
Climate change has intensified drought stress, posing a major threat to global crop productivity. Plants respond through various adaptive mechanisms involving root architecture remodelling, altered leaf development, and modified reproductive timing. Recent biotechnological interventions offer promising strategies to enhance drought tolerance. CRISPR/Cas9 genome editing enables precise modification of key drought-responsive genes, improving traits such as root growth and water use efficiency. Omics-assisted breeding approaches, including marker-assisted selection and genomic selection, are accelerating the development of drought-resilient cultivars. Microbiome engineering using plant growth-promoting rhizobacteria (PGPR) enhances stress tolerance by regulating hormone levels, root growth, and antioxidant activity. Additionally, nanotechnology and biostimulants improve seed performance, water uptake, and physiological resilience under drought conditions. Despite these advances, challenges remain in translating laboratory successes to field applications. Integrating modern biotechnology with traditional breeding and sustainable agricultural practices is essential for ensuring crop productivity under increasing drought stress driven by climate change.

Key words: *Biostimulants; Climate change; Drought; Genome editing; Plants.*

INTRODUCTION

Climate change is a complex phenomenon involving interactions among living organisms, the atmosphere, and water bodies such as land surfaces, snow, and oceans [1]. It is statistically defined as a change in the mean state of the climate, with respect to parameters like temperature, precipitation, and atmospheric pressure, over an extended period [2]. Climate change presents one of the most pressing global challenges, affecting food security, ecosystems, water resources, and human health. Since before the industrial era, the world's average temperature has increased by about 0.74°C, and carbon dioxide levels have risen from around 280 ppm to 400 ppm as of 2013 [3, 4]. These changes are already affecting farming, especially in developing countries where agriculture is a key source of livelihood. Extreme weather due to climate change has reduced crop yields, increasing malnutrition, poverty, and health problems. In India, warming is most noticeable in the northeast, central, and peninsular regions. For instance, in Punjab, a temperature increase of 1°C, 2°C, or 3°C may reduce grain yields by 5.4%, 7.4%, and 25.1% respectively [5]. Drought—a major abiotic stress-has threatened global crop productivity over the past 50 years [6]. Rising temperatures, changing precipitation, and elevated vapor pressure deficits contribute to water scarcity, intensifying drought-induced plant stress [7]. Under drought stress, especially as intensified by climate change, plants undergo developmental and morphological adaptations to maintain productivity. This paper presents an overview of plant responses to drought stress under climate change and highlights recent biotechnological interventions to mitigate drought effects.

1. **Root developmental responses to drought stress**

Plants deploy several strategies to survive drought stress, including drought avoidance, desiccation prevention, and rapid recovery after rewetting [8, 9]. Root systems are central to drought avoidance since they enable water uptake. Dryland plants typically have deeper root systems than hydrophilic species. Root architectural remodelling (RAR), regulated by hormones like abscisic acid (ABA) and auxin, enhances water access [10]. The DEEPER ROOTING 1 (DRO1) gene improves drought tolerance by modifying root angles [11].

2. **Leaf developmental responses to drought stress**

Leaf growth, dependent on cell division and expansion, is highly sensitive to drought [12, 13]. In *Arabidopsis thaliana*, drought reduces leaf area and cell number [14]. In *Ricinus communis*, larger leaves recover better after drought than smaller ones [15]. Gene expression studies showed ABA signalling and cell wall modifications play key roles in leaf response to water deficit [14]. In *Nicotiana tabacum*, drought increases leaf thickness by altering cell structure and boosting expression of cell wall genes [16]. Expansins, enzymes that loosen cell walls, help maintain leaf expansion during drought, with genetically engineered plants showing greater tolerance [17].

3. **Reproductive developmental responses to drought stress**

Flowering time determines a plant's reproductive success during drought. Some plants escape drought by flowering early, while others delay flowering and optimize water use [18–20]. In *Arabidopsis thaliana*, *FRIGIDA* (*FRI*) delays flowering by activating *FLOWERING LOCUS C* (*FLC*) [21]. Natural variants of *FRI* affect drought response; early-flowering plants tend to escape drought, while late-flowering one's practice avoidance [22, 23].

4. Mitigation strategies

4.1 Crispr/Cas genome editing

DRO1 is a key gene regulating drought-induced root development [11]. CRISPR/Cas9 enables precise editing of drought-responsive genes. Editing *TaRPK1* in wheat improved root branching and yield under drought [24]. In soybean, knocking out *GmHdz4*, a negative regulator of lateral root development, enhanced drought tolerance [25]. Editing *ARGOS8* in maize increased drought tolerance in the field [26]. In rice and tomato, CRISPR-edited genes (*ERA1*, *SlLBD40*, *SlMAPK3*) improved water use and stomatal function [27, 28].

4.2. **Omics-assisted selection and phenotyping**

4.2.1 **Genomic selection and marker-assisted breeding**

Quantitative trait loci (QTLs) such as *Stg1–Stg4* have been incorporated into elite sorghum lines for post-flowering drought resistance [29, 30]. In rice, QTLs *qDTY1.1* and *qDTY3.1* enhanced root depth and yield under drought [31]. In maize, genomic selection doubled genetic gains under drought [32]. Genomic selection captures small-effect loci, enabling accurate, rapid selection [33].

4.2.2 **High-throughput phenotyping and AI**

UAVs and multispectral imaging allow early drought detection and cultivar screening in crops like soybean [34]. AI tools also analyse multi-omics data to identify resilience markers [35].

4.2.3. **Microbiome engineering and PGPR**

PGPR such as *Bacillus*, *Pseudomonas*, and *Azospirillum* improve drought resilience through enhanced root growth, hormone regulation, and antioxidant activation [36, 37, 38]. These microbes produce exopolysaccharides (EPS), ABA, and IAA, supporting water retention and stress response [39, 40]. They also stimulate antioxidant enzymes like SOD, CAT, and POD [41].

4.2.4. **Nanotechnology and Biostimulants**

4.2.4.1 **Seed nanopriming**

Nanoparticles improve seed performance by forming pores in seed coats, triggering aquaporin expression and activating antioxidant pathways [42]. SiO_2 priming in wheat and ZnO priming in soybean/marigold enhanced drought tolerance [43–45]. Recent studies showed biogenic nanoparticles (e.g., Cu, Ni, Co oxides) boost biomass in maize under drought [46].

4.2.4.2 Biostimulants
Seaweed extracts, humic acids, and protein hydrolysates enhance drought resilience by promoting root growth, osmoregulation, and antioxidant defenses [47–49]. *Ascophyllum nodosum* and *Sargassum* extracts improved water uptake and photosynthesis under drought [50, 51]. Humic acids enhance soil water retention and root function [52]. Microbial biostimulants like mycorrhizae strengthen plant water relations [49]. Foliar/seed treatments with biostimulants also improve water use efficiency and stress tolerance [53, 54].

CHALLENGES AND PROSPECTS
Drought is a multidimensional common stress factor that negatively impacts plant growth, development, and metabolism. Thus, drought stress is a complex phenomenon adversely affecting plants at multiple levels. Plants have evolved a variety of tolerance strategies at molecular, developmental, physiological, morphological, and biochemical levels to cope with drought stress. These drought stress responses can be direct or indirect, and include regulation of water content, stomatal movements, leaf senescence, osmolytes adjustment, antioxidant metabolism, photosynthetic activity, and phytohormonal production. Different groups of beneficial bacteria that colonize plant roots promote plant growth and development, and stress tolerance through a variety of strategies. In their role as eco-friendly bio-fertilizers, PGPR can alleviate the detrimental effects of drought on plants by enhancing growth under water deficit through different processes. PGPR can promote plant growth and alleviate drought stress using the same strategies. Drought-stressed plants inoculated with PGPR display several adaptive responses to maintain water potential in the tissues such as osmotic adjustment, production of osmoprotectants and growth regulators, as well as increased antioxidant activity. The application of PGPR can be an effective tool to induce drought tolerance and sustain productivity in drought-stressed plants. Plant biotechnology plays a crucial role in this effort by providing tools such as genetic engineering and advanced breeding techniques to develop crop varieties that better tolerate climate-related stresses. These methods have shown success in maintaining productivity under harsh environmental conditions. However, progress in developing stress-resistant crops has been slow due to scientific and technical challenges. Overcoming these obstacles is vital to produce crops that can sustain in drought conditions and unpredictable climates.

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