



From Roots to Leaves: The Adverse Effects of Moisture Deficit

*Dikshesh Rai, Sandeep Manuja, Vinod Sharma, Purneshwer Thakur and Shubham Sharma

Department of Agronomy, CSK HPKV, Palampur, Himachal Pradesh, India

*Corresponding Author's email: dikshesh98@gmail.com

Water scarcity poses a major challenge to agriculture, severely limiting plant growth and productivity worldwide. When plants face moisture stress, vital processes like photosynthesis, nutrient absorption, and growth are hampered, leading to stunted development, poor flowering, and reduced yield. This results in significant yield reductions that threaten food security. This article discusses about the plant's response through different changes such as smaller leaves and deeper roots, molecular signalling that activates stress defences, and biochemical adjustments producing protective compounds. Understanding these complex responses is essential to developing resilient crops and sustainable farming practices in an increasingly water-scarce world.

Introduction

Water is essential for sustaining life, agriculture, and ecosystems. Although about 70% of the Earth's surface is water, only 1% is accessible freshwater suitable for irrigation and human consumption. Globally agriculture consumes over 70% of this freshwater, underscoring its critical dependence on water for crop growth and productivity (FAO, 2023). India faces a severe water crisis impacting agriculture and millions of people. Approximately 600 million Indians are living under high to extreme water stress and agriculture consumes approximately 85% of available freshwater (World Bank, 2025). This crisis is aggravated by climate change, population growth, poor water management, and environmental degradation, placing enormous strain on agriculture and food security (NITI Aayog, 2023).

Moisture stress in plants occurs when they lack sufficient water to meet their physiological needs, severely impairing key processes such as photosynthesis, nutrient uptake, and growth. Factors like drought, irregular rainfall, high temperatures, and soil salinity reduce water availability to the crops. This causes stomatal closure to minimize water loss, but also inhibits key enzymes responsible for carbon assimilation, reducing photosynthetic efficiency. These effects lead to stunted growth, flower and fruit abortion, poor grain filling, resulting in significant yield reduction. To overcome these challenges different mitigation measures have proven effective. Agronomic practices like cover cropping, intercropping, using drought tolerant varieties like DRR Dhan 100 etc. helps in moisture retention and reduces production losses thus increasing the productivity of the crop. Different studies have shown that using these agronomic practices in moisture stress areas can alleviate the effect of moisture stress on crops. Additionally, adopting moisture-conserving technologies like drip irrigation optimizes water use efficiency by delivering water directly to the root zone. The application of hydrogels helps retain soil moisture, while anti-transpirants and bio-stimulants reduce water loss and improve plant stress tolerance.

Moisture stress

Moisture stress in plants occurs when water availability is insufficient to meet their physiological needs, causing disruption in vital processes like photosynthesis, nutrient

uptake, and growth. The classification of moisture stress by Theodore C. Hsiao (1973) is widely recognized, categorizing water stress based on soil water potential and the corresponding reduction in leaf relative water content (RWC). According to Hsiao, moisture stress is grouped into three levels:

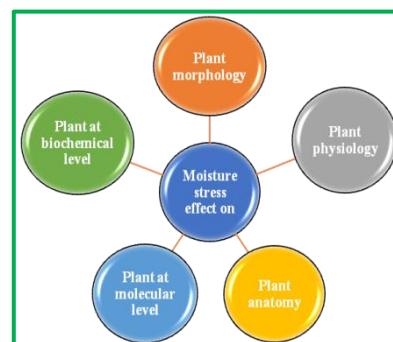
Categories	Soil water potential	Reduction in leaf relative water content (%)
Mild stress	- 0.1	8-10
Moderate stress	- 1.2 to – 1.5	>10-20
Severe stress	< - 1.5	> 20

Effect of moisture stress on plant

Effect on morphology: Moisture stress significantly alters plant morphology by inhibiting key growth parameters and promoting adaptive changes to conserve water. Plants subjected to moisture deficit typically display reduced plant height, shortened shoots, smaller or fewer leaves, and stunted root development.

- ✓ **Growth and biomass accumulation:** Under moisture stress, cell division & elongation is reduced, which stunts growth of shoots and reduces overall plant height. Water shortage limits plant's ability to produce new cells and expand existing ones, leading to compact and smaller plants. This smaller stature reduces the plant's capacity to capture light and compete for resources. The combination of smaller shoots and leaves leads to an overall decrease in fresh and dry biomass above ground. This limits the plant's photosynthetic machinery, resulting in less energy production for growth & yield. Lower biomass can reduce crop stands & increases vulnerability to environmental stresses.
- ✓ **Leaf area and size:** The size and number of leaves diminish as water scarcity limits cell expansion during leaf development. This results in reduced leaf area, which directly lowers photosynthesis capacity. Leaves may turn yellow due to chlorophyll degradation from oxidative stress, and rolling or curling of leaves occurs as a protective mechanism to decrease exposed leaf surface and reduce water loss. Additionally, premature leaf aging (senescence) and shedding (abscission) are common responses caused by hormonal changes, particularly elevated abscisic acid (ABA) which signals to conserve water.
- ✓ **Root-to-shoot ratio:** It Plants respond to moisture deficit by reallocating resources to root development. Roots grow deeper and branch extensively to explore a larger soil volume for water. This often increases the root-to-shoot biomass ratio, prioritizing water absorption over above-ground growth. Enhanced root systems also improve the plant's anchorage and its ability to survive drought, but with above-ground biomass reduction. These morphological changes help to limit water loss but also result in lower total biomass and poor crop stands, especially if stress occurs during early or reproductive stages. Overall, moisture stress disrupts normal plant architecture, impacting both survival and productivity.

Effect on plant physiology: Moisture stress profoundly affects plant physiology, disrupting various processes vital for growth, development, and survival. It primarily leads to stomatal closure, which reduces transpiration and the intake of carbon dioxide, causing a marked drop in photosynthesis rates. This reduction is aggravated by decreased leaf area, limited movement of assimilates, and altered cell water relations. Respiration rates can initially increase under mild stress, but severe or prolonged moisture deficit reduces cellular respiration and overall energy availability. Plants experience higher production of abscisic acid (ABA) and ethylene while levels of growth-promoting hormones like cytokinin's and gibberellins decline, contributing to leaf senescence, stomatal closure, and reduced branching. Additionally, there is a drop in nutrient uptake and metabolism: nitrogen fixation, nutrient assimilation, and root activity all decrease, with leguminous crops showing especially negative responses.



- ✓ **Effect at cellular level:** On a cellular level, water stress disrupts membrane integrity, leading to greater accumulation of reactive oxygen species (ROS). This oxidative stress increases the activity of antioxidant enzymes but may result in damage to cell membranes and disruption of metabolic reactions if prolonged. Overall, moisture stress impairs physiological functions like photosynthesis, respiration, hormone balance, and nutrient uptake, ultimately restricting plant growth and yield.

Effect on anatomy of plant: Moisture deficit, commonly referred to as moisture stress or drought stress, exerts profound effects on the anatomy of plants, resulting in a series of structural adaptations aimed at survival under limited water availability. These anatomical changes occur in various plant organs, including leaves, stems, and roots, fundamentally altering their functional capabilities.

- ✓ **Effect on leaves:** Leaves are the primary sites for photosynthesis and transpiration, making them highly sensitive to moisture stress. One of the earliest anatomical responses to water deficiency is a reduction in leaf size, which minimizes surface area and thus the potential for water loss through transpiration. The thickness of the leaf cuticle, a protective waxy layer, often increases under moisture stress. Inside the leaf, the mesophyll cells (which conduct photosynthesis) often become smaller and more compact, reducing intercellular air spaces. This densification decreases the internal surface area for transpiration, thereby conserving water but at the expense of CO₂ diffusion efficiency, potentially limiting photosynthesis.
- ✓ **Effect on stem and structural tissue:** Moisture stress influences the internal structure of stems by thickening cell walls in both parenchymatous and supporting tissues. The increased thickness enhances mechanical strength, preventing collapse under the stress of dehydration and maintaining vascular integrity. Moisture stress can cause a reduction in the diameter of xylem vessels, that minimizes the risk of cavitation and embolism—air bubbles that block water transport pathways during drought.
- ✓ **Adaptations in root anatomy:** Roots under drought tend to elongate more rapidly and penetrate deeper layers of soil to explore available moisture below the surface. This is accompanied by increased branching and root hair density, expanding the absorptive surface area. At the microscopic level, moisture stress often induces an increase in the development of suberized (waxy) barriers like the Casparian strip in the root endodermis, which regulates water and nutrient intake and reduces loss of water back into dry soil areas.
- ✓ **Xeromorphic traits:** Plants adapted to arid conditions often develop xeromorphic anatomical traits that are enhanced or induced by moisture stress. These include thickened leaves or stems (succulence) that store water, reduced leaf surface area (sometimes with modified spines or scales instead of traditional leaves), multiple epidermal layers, and extensive trichome coverage. These traits collectively reduce water loss and optimize water storage.

Effect at molecular level: At the molecular level, moisture stress triggers a complex network of responses in plants aimed at adapting to water deficit and maintaining survival. One of the earliest reactions is the generation of signalling molecules such as reactive oxygen species (ROS), calcium ions (Ca²⁺), and the plant hormone abscisic acid (ABA). These molecules act as messengers that alert cells to stress and initiate protective mechanisms. ABA plays a central role by inducing stomatal closure to reduce water loss and activating stress-responsive genes that encode for proteins like late embryogenesis abundant (LEA) proteins, Osmo protectants, aquaporins, and detoxification enzymes that help mitigate damage from ROS and maintain cellular osmotic balance. ROS function both as damaging agents and signalling molecules, triggering antioxidant defences to control their levels and prevent oxidative damage. At the gene regulation level, transcription factors such as DREB, MYB, and NAC families are activated to switch on drought-responsive genes that help adjust metabolism, protect photosynthesis, and enhance water-use efficiency. There are also molecular adjustments in carbohydrate metabolism and cellular membrane stability that support energy

supply and cell integrity during stress. Plant cells sense moisture stress through molecular sensors in roots, which communicate drought signals to shoots through hormonal and ion-mediated pathways, coordinating whole-plant responses. Together, these molecular mechanisms modulate physiological adaptations that allow plants to reduce water loss, maintain metabolic activity, and survive periods of low water availability.

Effect on biochemical level: At the biochemical level, moisture stress induces several key changes in plants that help them adapt to water deficit but also reflect stress damage. One important response is the accumulation of osmolytes such as proline, soluble sugars, glycine betaine, and free amino acids, which help in osmotic adjustment, protecting cellular structures and maintaining water balance and stabilize cellular structures against dehydration. Proline, in particular, acts as an osmoprotectant and antioxidant, facilitating stress tolerance.

- ✓ **Production of ROS and oxidative stress:** Moisture stress also results in increased production of reactive oxygen species (ROS) like hydrogen peroxide and superoxide radicals, which cause oxidative damage to lipids, proteins, and nucleic acids. To counteract oxidative stress, plants activate antioxidant defence systems, including enzymatic antioxidants such as superoxide dismutase (SOD), catalase (CAT), peroxidases, and non-enzymatic antioxidants like glutathione and carotenoids.
- ✓ **Hormonal regulation and enzymatic activity:** The levels of stress hormones like abscisic acid (ABA) increase, which regulates stomatal closure and activates stress-responsive biochemical pathways. Nutrient uptake and assimilation processes decline, affecting nitrogen fixation and metabolism. Enzymatic activities may decrease overall, leading to reduced metabolic efficiency. These combined biochemical changes allow plants to regulate their internal environment, protect cellular integrity, and improve tolerance to drought, although prolonged stress can lead to reduced growth and yield.

Conclusion

Moisture stress poses a serious challenge to plant growth, profoundly affecting morphology, physiology, anatomy, molecular signalling, and biochemical processes. The adaptive changes plants make—such as reduced leaf area, deeper root growth, hormonal shifts, and accumulation of protective molecules—are essential for survival under water-limited conditions. However, these responses often come at the cost of reduced biomass production and diminished crop yields, especially during sensitive growth stages. To sustain agricultural productivity amid increasing water scarcity, it is crucial to deepen our understanding of these complex plant mechanisms and develop integrated strategies combining drought-tolerant varieties, efficient water management, and innovative agronomic practices. Only through such approaches can global food security be ensured in a changing climate.

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