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Impact and Response of Drought Stress in Pigeonpea (*Cajanus cajan* L.): A Review

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ABSTRACT

Global food security is desperate due to biotic and abiotic stress because of change in climate and increase in population. Among various abiotic stress, drought severely affects the growth and productivity of crops. Drought stress due to climate change is the severe threat for grain legume production. Pigeonpea (*Cajanus cajan* L.) is the important sources of protein for human nutrition and also to enhance the soil fertility. It is the resilient crop which can tolerate under drought condition when compared to other legume crops. Even though, change in climate hinder the growth and productivity of pigeonpea especially drought stress. The reduction in yield mainly depends on the time of onset, intensity and duration of drought stress. Especially drought stress during late flowering and early pod development severely affects the yield in pigeonpea. This review examines the morphological, physiological, biochemical and molecular impacts of drought stress on pigeonpea plants. In order to improve resilience and maintain crop output in the face of shifting climatic circumstances, tackling the intricacies of drought stress in pigeonpea agriculture necessitates a multimodal strategy incorporating agronomic, physiological, biochemical and molecular methodologies.

Key words: Antioxidants, Antitranspirants, Drought, Pigeonpea, Water availability.

Legumes are essential for human nutrition and agricultural sustainability because of their high protein content and capacity to enhance soil health. But the great susceptibility of legumes especially, pigeonpea to abiotic conditions like drought has deleterious consequences on crop growth and yield. Pigeonpea (*Cajanus cajan*) growth and development are under adverse conditions due to drought stress at several phases, including as germination, flowering and pod setting. This results in decreased seed germination, changed photosynthetic capacity and decreased reproductive success. Drought stress impacts the morphological level of plants by preventing growth, decreasing leaf area and influencing pod production. Changes in leaf temperature, water-use efficiency, chlorophyll concentration, photosynthesis, transpiration and nutrient absorption are among the physiological reactions to drought stress.

Lipid peroxidation and cellular component damage are two different outcomes of oxidative stress and reactive oxygen species (ROS) buildup at the biochemical level. Pigeonpea plants use a wide range of mechanisms to withstand the low water stress, including as ABA-mediated stomatal closure, antioxidant defense systems, osmolyte buildup and the activation of stress-responsive genes. In addition, for minimizing the detrimental impacts of low water stress on pigeonpea production are covered. These methods include microbial inoculation, agronomic techniques, cultivar breeding initiatives and the use of anti-transpirants. Even though drought stress presents difficulties, current research aimed at comprehending the molecular processes behind pigeonpeas' reaction to drought stress offers encouraging paths for creating hardy varieties via genomics-assisted breeding techniques.

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The nutritional and health advantages of legumes are widely recognized, as they play an important part in promoting the sustainability of the agricultural system. In human diets and cattle feed they represent the much significant monopolistic supplier of vegetable protein (Anwar *et al.,* 2022). When most of the legumes are grown as an intercrop in agriculture (*e.g.,* in combination with grains) or as part of crop rotation, the number of pests, diseases and weeds is reduced and smallholder farmers' income and total farm output are raised. Legumes are important economically and commercially, but they are given low importance than cereals according to boosting the agricultural output. The legumes are under pressure from a range of abiotic stressors (Pandey *et al.,* 2017). Research on stress resistance mechanisms has been the reason to the discovery of tolerance traits in plants and the molecular control of genes that respond to stress. A few of these studies have opened up new avenues for studying the molecular underpinnings of stress responses by plants and identifying unique traits and related genes for the genetic enhancement of agricultural plants

(Rane *et al.,* 2021). The tolerance mechanism can be induced through treating the plants with antioxidants by any exogenous substances against the drought stress (Rozita *et al.,* 2012).

Importance of pigeonpea (*Cajanus cajan*)

Cajanus cajan, commonly known as red gram, pigeonpea, arhar, or tur, is India's most significant pulse, following chickpea and globally, a key crop in semi-desert parts. Protein (21-28%), carbs, lipids, vitamins and minerals are all abundant in it (Singh *et al.,* 2020). Plants have developed intricate signaling networks that comprise phytohormones, secondary messengers, transducers and receptors in order to recognize various stressors and adjust to shifting environmental circumstances. To sustain plant growth and production, these innate systems facilitate stress signaling and the genes responsive to stress are activated and expressed (Yokotani *et al.,* 2013). Since pigeonpeas are extremely sensitive and have unique crop characteristics, breeding them has proven more challenging than with other nutritional legumes (Choudhary *et al.,* 2011). Notable consequences of climate change are drought stress and heat stress, which are significant abiotic stress factors influencing crop failure and output. Drought breaks the symbiotic relationship between pigeonpeas and reduces growth, which ultimately results in decreased crop output (Anjum *et al.,* 2017). The production is greatly impacted by all of these variables, yet the genotypes that are resistant to these abiotic pressures have not changed much. Therefore, the goal of this study is to review the literature on abiotic pressures and talk about strategies to increase pigeonpea resistance to these limitations.

Drought stress on legume plants

Leguminous plants exhibit diverse reactions and susceptibilities when faced with the initiation of aridity; however, without exception, the ultimate crop production is notably diminished. This phenomenon is associated with diminished seed germination and a reduction in photosynthetic potential (Chowdhury *et al.,* 2016). Also, drought stress can cause translocation of assimilates in reduced amount and fixation of carbon is also affected (Mondal *et al.,* 2011), (Zlatev and Lidon 2012). The reproductive organs can be affected by the stress condition and flowering time can also be varied from the usual one (Samarah *et al.,* 2009). Not only these but also the sterility of pollen grains is affected terribly (Sehgal *et al.,* 2018). Followed by the growth of pods and the grain setting will also get affected (Croser *et al.,* 2003); (Liu *et al.,* 2004); (Vadez *et al.,* 2012). Such impacts are stated in Fig 1.

Drought exerts an impact on various particulars of growth and development in legumes, encompassing sprouting, growing shoot and root, photosynthesis and the reproductive phase. As a consequence of global warming, drought has come up as a highly uncontrolled and unpredictable factor that consistently curtails crop production and brings about detrimental outcomes on legumes. Research has revealed that intense drought situations disrupt morphology, physiology and growth duration of the plant, while humidity levels assume a pivotal role in activating enzymes during germination, thereby facilitating a clear-cut view on vulnerability of plants to drought stress especially during the germination. The most important phases of plant life such as germination and reproductive exhibit a heightened susceptibility to low availability of water. Under low water stress conditions, considerable reduction in germination rate of soybean was observed (Heatherly, 1993). Li *et al.* (2018) has reported that the drought stress can be commonly seen at the seedling stages of pigeonpea. Furthermore, the regulation of stomata is also regarded as a primary physiological determinant to maintain the utilization of water during drought stress (Makbul *et al.,* 2011). The intricate nature of the drought stress impact on the ultimate crop returns encompasses a wide array of intricate processes, including but not limited to fertilization, gametogenesis, embryogenesis and grain formation (Farooq *et al.,* 2014). Drought significantly impacts the plant's capacity to generate additional economic parts and enhance germination rate. As a result, the crop return is diminished (Pushpavalli *et al.,* 2014).

Drought stress on pigeonpea

Pigeon pea is a *kharif* crop cultivated as a rainfed crop and it is recognized for its resilience to drought due to its extensive root system. The major groups include extra early and early types which typically finish the life cycle when the monsoon season recedes. Nevertheless, these types frequently experience terminal drought during their reproductive phase. The challenge due to drought

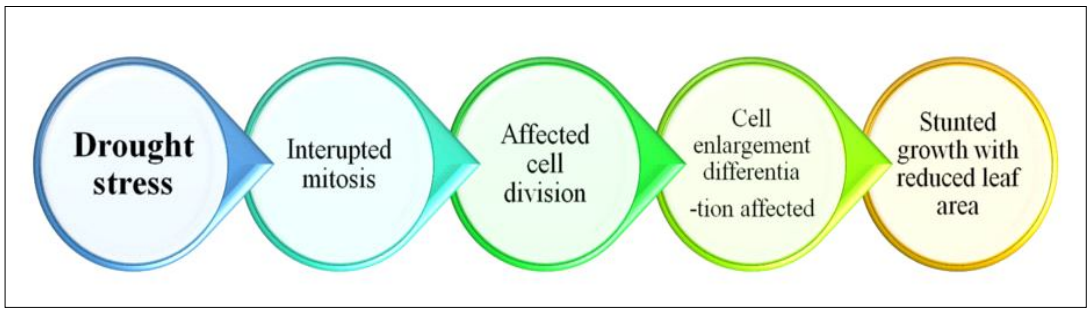


Fig 1: Impact of drought stress in legumes.

intensifies for medium and long duration varieties of pigeonpea, as their critical stages of water requirement such as flowering and pod filling coincide with a severe deficiency of soil moisture without supplemental water application (Choudhary *et al.,* 2011). Notable range of osmotic adjustment (OA)which has improved leaf development during drought stress has been reported (Likoswe and Lawn, 2008). The first technique utilized against terminal drought stress is a wide range of genotype duration such as long, early and extra-early length of duration and genotype duration which is similar to expected time of available water in soil (Serraj *et al.,* 2003). The preservation of fractional canopy light interception and leaf area index (LAI) in pigeonpea with sort duration of life cycle seems to suggest genotypic drought resistance. Tiny pods with comparatively a smaller number of seeds per pod, big 100-seed weight, poor blooming synchrony and the capacity to maintain TDM are some traits that can enhance short-duration pigeonpea's drought resistance (Lopez *et al.,* 1997); (Lopez *et al.,* 1996).

Moisture stress applied during the pre-flowering stage has been linked to the largest decreases in nodule nitrogenase activity (70-90%), photosynthetic rate (50-71%) and respiration rate (31-45%) of the roots and nodules (Fig 2). It has been noted that large-seeded cultivars are more susceptible than small-seeded ones. It has been discovered that cultivars with small sized seeds which is having an indeterminate habit of growth are drought tolerant than those with an alternate kind (determinate growth habit). In cultivars with unpredictable development, relative water content (RWC) value and water retention value observed in leaves were similarly greater (Kuhad *et al.,* 1989). Reduced growth and development, which results in a decrease in fresh biomass; decreased chlorophyll content, which results in a decreased rate of photosynthesis; decreased leaf relative water content (RWC); and a greater accumulation of osmolytes, such as proline, sucrose, carbohydrates that are soluble, *etc*., are some of the ways that plants react to water stress (Khanna, 2024).

When two cycles of low water stress and its recovery occurs, the genetic variation is shown in leaf water potential, vegetative growth, photosynthesis, RWC and stomatal conductance. They recommended using water status metrics, particularly RWC, as drought tolerance markers for breeding pigeonpeas (Kimani *et al.,* 1994). In many agricultural plants, osmosis adjustment is thought to be a key physiological process for drought adaptation. Additionally, a strong association between the average osmotic adjustment during drought stress conditions and the mean leaf osmotic potential is seen in 26 short duration pigeonpea genotypes 60-92 days after sowing. Of the genotypic variance in OA, average osmotic potential of leaf explained variation at the rate of 72%. Considerable genotypic variance was found in the degree, duration and onset of osmotic adjustment. Furthermore, it is advised that improving drought resistance in pigeonpea by magnifying these two features should not be a top focus because pigeonpea has higher osmotic adjustment and high tolerance towards dehydration than other crops (Subbarao *et al.,* 2000). Paclobutrazol (PBZ) and ABA's roles in pigeonpea osmoregulation caused by drought (Jaleel *et al.,* 2008).

Pigeonpea has substantial physiological and biochemical changes as a result of increasing water stress. To choose high-yielding genotypes that preserve cell turgor in environments with water deficiency, one might utilize the RWC parameter. Increased proline buildup during stress conditions suggested that proline is a crucial osmoregulatory solute in plants. Pigeonpeas are shielded from harmful oxidative reactions by an antioxidant defense system which is highly efficient, as evidenced by the elevated activity of enzymes such as peroxidase (POD) and superoxide dismutase (SOD) (Kumar *et al.,* 2011). Additionally examined were the activities of metabolite components such as polyamines and glycine betaine, as well as antioxidative enzymes such as glutathione reductase, glutathione-s-transferase and ascorbate peroxidase. With the exception of ascorbate peroxidase in stress due to heavy metals, the content of glycine betaine and the activity of antioxidant enzymes shown a notable rise when exposed to all stresses (Radadiya *et al.,* 2016). Numerous physiological indicators, including RWC, proline accumulation, MSI and others, have been employed as plant health analysis metrics in the context of abiotic stressors. In plants that are not able to survive extreme environmental circumstances, these factors change more quickly than in ones that can (Pahal *et al.,* 2024).

Impact of drought stress on morphological characters in pigeonpea

The growth encompasses genetic, physiological, ecological and morphological processes in addition to their complex interrelationships. It involves cell division,

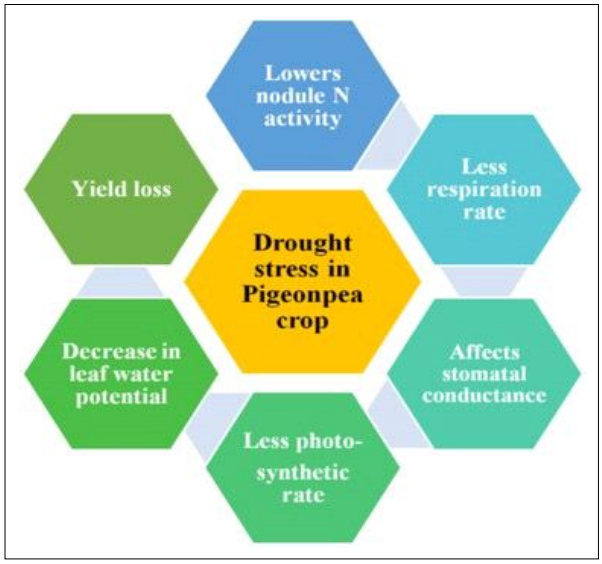


Fig 2: Impact of drought stress in pigeonpea.

expansion and differentiation. The amount and quality of plant development are determined by these events, which are impacted by the scarcity of water. One of the physiological processes most susceptible to dryness is cell development, which is caused by a decrease in turgor pressure (Taiz and Zaiger, 2006). When there is an intense scarcity of water, cell elongation at higher plant level can be prevented by stopping the passage of water through xylem to nearby cells which are elongated (Farooq *et al.,* 2008).

The mesophyll cells which are present in leaves faces water loss during a drought. The contraction of roots and the leaves undergoes prompted accumulation when there is a severe water deficit. When water stress first arises, leaf growth is reduced because cell multiplication is suppressed (Fathi and Tari, 2016). For a number of grain legume species, leaf abscission is less vulnerable to soil moisture deficiencies than leaf area growth. When plants experience water stress, their manufacturing of the stressed hormone is increased, making them more sensitive to it and causing them to shed their leaves (Rozita *et al.,* 2012). Conversely, there is a considerable correlation between the immensity of leaf aging and reduction of leaf-area development brought on by drought (Sarkar *et al.,* 2021). In pulses such as cowpea and red gram, the flowering and pod-filling stages under drought stress facilitated the aging process and ablation of older leaves at the base (De Souza *et al.,* 1997). The dryness had a significant effect on both the quantity of pods and height of the plant. During the vegetative and anthesis stages, the number of pods was affected additively by drought, but shoot height was unaffected (Busse and Bottomley 1989). Rhizobia change morphologically during a drought, which lowers infection and reduces legume nodulation (Fig 3), (Busse and Bottomley, 1989). Reduced soil moisture caused pigeonpea infection thread numbers to drop dramatically. Drought also caused lenticels to disappear and decreased the outside diameter of pigeonpea nodules (Zhu *et al.,* 2021).

Impact of drought stress on physiological traits in pigeonpea

The temperature of grain legumes' leaves increases when they are stressed by water. Compared to well-watered plants, drought-stressed plants exhibited higher leaf temperatures (Fig 3). It differs between species, even between subspecies of the same species (Monclus *et al.,* 2006). At the plant level, the proportion of amount of dry matter production to the amount of water consumed is the definition of water-use efficiency (Monclus *et al.,* 2006). Plants that can withstand drought maintain a high water-use efficiency by minimizing loss of moisture. On the other hand, water-use efficiency dropped sharply when plant growth was significantly impeded (Farooq *et al.,* 2009).

Long believed to be a criterion of pigment photo-oxidation and break down of chlorophyll, drought-induced chlorophyll depletion (Anjum *et al.,* 2011). Under drought stress reduction of chlorophyll content occurs (Fig 3); the amount of this decline varies depending on the length of drought and its intensity (Fathi and Tari, 2016). While anthesis under stress influenced these levels at plant developmental stage, vegetative stage and become a cause of lowering chlorophyll a, chlorophyll b and total chlorophyll values in both the stages. The absence of influence on the ratio of chlorophyll a to b implies that chlorophyll b is not susceptible to drought more than chlorophyll a (Mafakheri *et al.,* 2010). But it seems to depend on the cultivar and kind of crop.

All the photosynthetic apparatus's essential elements, like electron transport, CO_2 supply management in stomata and the reduction cycle of carbon are affected by drought (Awasthi *et al.,* 2014). Total concentration of chlorophyll is

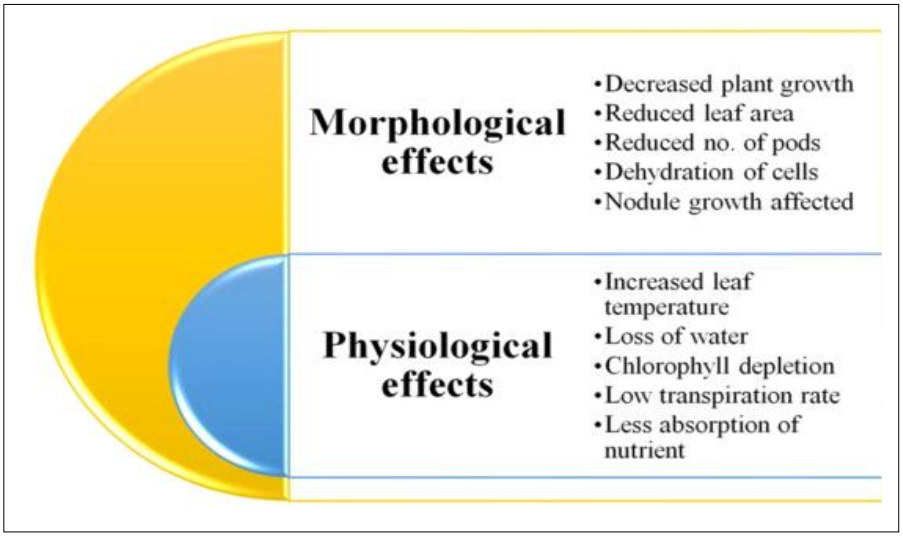


Fig 3: Physiological and morphological effects of drought stress in pigeonpea.

reduced under drought conditions, which results in the reduction of capacity for gathering of light and reduced photosynthetic rate (Fathi and Tari, 2016). Variation in leaf photosynthesis due to partial stomatal closure or collapse of mesophyll cell which results in turgor loss happens under drought stress (Farooq *et al.,* 2009). This state results in the suppression of the carboxylation process and ribulose-1,6-bisphosphate (RuBP) regeneration, while photorespiration rises (Zhu *et al.,* 2021). Reduced water content in the tissue can be a cause of the rise in the activity of rubisco binding inhibitors. Additionally, to meet the decreased needs for NADPH generation, non-cyclic electron transport is hindered, which lowers ATP synthesis (Farooq *et al.,* 2009). Abscisic acid (ABA), a growth inhibitor, has long been recognized as a root-to-shoot stress signalling component (Schachtman and Goodger, 2008). After stomatal closure, abscisic acid is produced, which appears to prolong or magnify the effects of the initial block, which abscisic acid stores (Matysik *et al.,* 2002). Because of the smaller leaf area, there is less water input from the soil and less transpiration (Fathi and Tari, 2016). When dryness occurs in plants they initially react with stomatal closure, which in turn limiting the exchange of gases linking the interior of the photosynthetic site and the surroundings (Mafakheri *et al.,* 2010).

Impact of drought stress on nutrient availability in pigeonpea

Reduced water availability from drought frequently results in decreased tissue concentrations and overall nutrient absorption in plants (Fig 3). Lack of water has a major impact on absorption of nutrients by roots and translocation to aerial parts of the plant (Farooq *et al.,* 2009). Along with water, several essential elements are absorbed by roots, including N, Si, Mg and Ca. However, dry circumstances hinder the diffusion of these elements and their mass movement, slowing down development processes of the plant (Barber, 1995). Reduced transpirational flow, disruptions to the unloading process and nutritional intake might all contribute to a reduction in the absorption of inorganic nutrients. Moisture stress results in the rise of amount of N, a P reduction and little noticeable effect in case of K (Garg, 2003). In conclusion, availability of nutrients, absorption, translocation and metabolism are all decreased under drought stress. Drought, for instance, lowers biological N-fixation due to the reduction of available assimilates and flow of oxygen into legume nodules. Drought stress also causes the decreased availability of nitrogen due to (i) diminished nitrate levels in root and nitrate reductase activity in leaves; (ii) the decrease in nitrogenase activity in nodules (Fig 3) caused by available carbohydrates and enzyme action of sucrose synthase. Furthermore, drought conditions also seem to decrease the efficiency of nutrient uptake in the legumes as a result of restricted action of enzymes like nitrate reductase, sucrose synthase and the symbiosis of legume roots and rhizobium (Ullah and Farooq, 2022).

Impact of drought stress on yield traits in pigeonpea

Diminished rate of germinating seeds and the growth of weak, unhealthy plants are the initial and main effects of drought stress (Kaya *et al*., 2006), (Harris *et al.,* 2002). The intricate relationship between water shortage and yield involves several processes, including production of gametes, fertilization, development of embryo and grain development (Farooq *et al*., 2014). The two stages of plant growth that are particularly susceptible to drought are flowering and reproductive development. Conversely, the degree of floral abortion varies according on the plant's floral position (Fang *et al.,* 2010). In racemes of soybeans

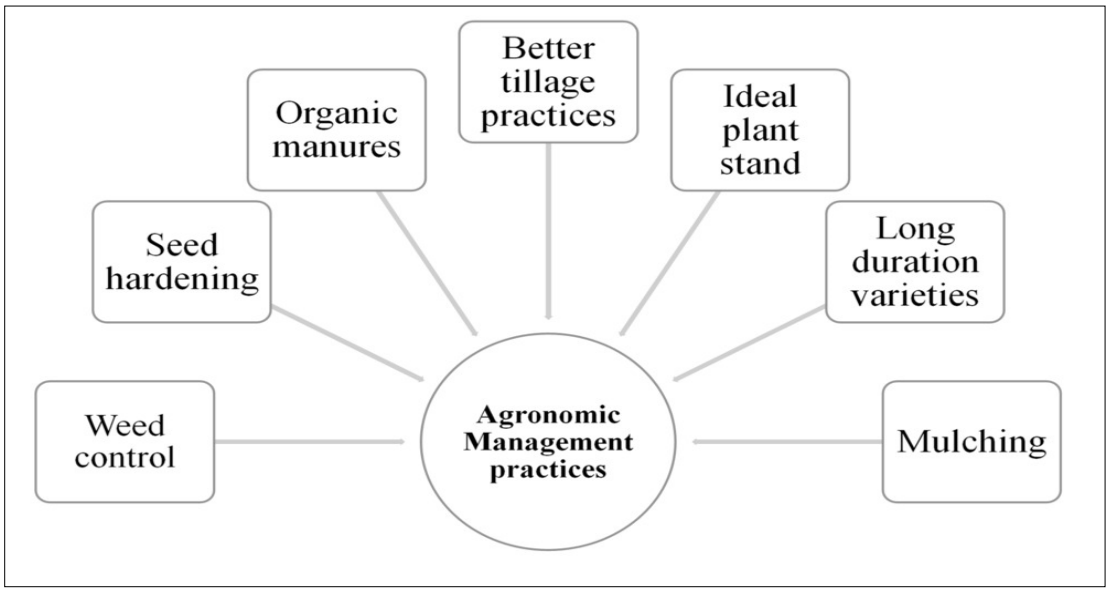


Fig 4: Approaches to overcome drought stress by agronomic management in pigeonpea.

(*Glycine max* L.), proximal places have a higher number of pods than in the away positions due to the decreased supply of assimilate in the raceme (Zhu *et al.,* 2021). Drought stress can cause a decreased flowering time scenario, producing flowers of tiny size with nectar of poor quality in deficit amount. Despite the fact that very few pollinators are drawn to this situation, as the grain legumes are self-pollinating, it does not preclude pollination; nonetheless, the lack of photosynthates restricts embryo development (Al-Ghzawi *et al.,* 2009).

Grain composition and its development are both impacted by drought. The decrease of protein synthesis brought on by dryness is the root source of the reduction in legume seed quality. In water-limited situations, the accumulation of protein in legume grains is decreased considerably at the same time, either process of nitrogen fixing as well as partitioning are impeded (Singh, 2007). Numerous yield-determining physiological mechanisms in plants are impacted by water stress (Farooq *et al.,* 2009). Drought stress reduces harvest index, photosynthetic active radiation and radiation efficiency, which in turn lowers crop yields (Fathi and Tari, 2016). Stressed plants during the vegetative stage did not yield significantly more than stressed plants at flowering stage or at either the vegetative and flower bud opening stages (Mafakheri *et al.,* 2010). For example, moisture stress prior to anthesis becomes a cause for comparatively sudden anthesis, whereas limited water condition after flower buds opened can cause decrease the time to development of grains (Estrada *et al.,* 2008). Grain yield was negatively impacted by post-anthesis drought stress, where the severity of the drought is not under consideration (Samarah, 2005). Limited water situation can decrease reproductive yield up to 40-45% (Farooq *et al.,* 2008) and flowering yield up to 40-45% (Nam *et al.,* 2001) in pigeonpea at several phenological phases of crop development. Grain and legume yields are decreased by drought stress in a variety of phenological phases, soil textures and agroclimatic zones, also it is different for different species (Daryanto *et al.,* 2015).

Impact of drought stress on oxidant and antioxidant activities in pigeonpea

The rise in the amount of reactive oxygen species (ROS) and its popular outcome, oxidative stress is also happening on account of drought stress, which upsets the balance created by antioxidant defense mechanism and ROS generation (Farooq *et al.,* 2009). Although carotenes, also known as isoprenoid molecules, are a crucial component of the plant defense mechanism, oxidative stress can easily harm them (Savita *et al.,* 2020). Increased dryness and the build-up of ionic compounds in the top soil around the root are the main causes of osmotic stress and ion toxicity (Fathi and Tari, 2016). Less CO_2 in the leaf causes less carboxylation and more electrons to be directed toward the production of ROS (Farooq *et al.,* 2009). As ROS develop in the thylakoids due to water stress, β-carotene is destroyed. This may affect the PSI and PSII core complexes as β-carotene is their important component. The cell material such as lipids, proteins and genetic material are oxidatively damaged when ROS levels (O_2^-, H_2O_2 and OH^- radicals) rise sharply (Savita *et al.,* 2020). A very hazardous physiological reaction during drought stress is the attack of free radicals against the cell membrane lipids (Thankamani *et al.,* 2003). Increased levels of ROS lead to higher levels of malondialdehyde (MDA), a highly reactive chemical related to damage caused by oxidation (Moller *et al.,* 2007). When compared to normal conditions, drought stress enhanced the peroxidation of proteins and lipids in pea by four times (Moran *et al.,* 1994).

Abiotic stress dramatically reduces legume's ability to fix N2 and this loss is frequently linked to oxidative damage. Reduced antioxidant defense in nodules and alterations in the redox balance appear to be connected with the reduced rate of nitrogen fixing during stress caused by non-living factors (Escurado *et al.,* 1996; Gogorcena *et al.,* 1997 and Jebara *et al.,* 2005). The primary reaction that happens in nodules under moisture stress is diminishing enzyme activity of sucrose synthase (SuSy) (Galvez *et al.,* 2005). More recent research indicates that ROS are involved in the pathways as signals that cause SuSy and nitrogen fixation to reduce in unfavorable circumstances (Marino *et al*., 2006). Reactive oxygen species are dangerous chemicals for aerobic organisms. They strongly oxidize the components of their cells and may be particularly damaging to legume nodules (Becana *et al.,* 2000). An antioxidant defense mechanism is triggered and oxidative stress may develop in nodules when legume roots are under moisture stress (Zabalza *et al*., 2008). Therefore, large number of nodules and variety of antioxidant defenses which shield the organization of nodules that prevent excessive nodule respiration and maintain the activity of the nitrogenase complex (Blokhina *et al.,* 2003 and Jebara *et al.,* 2005).

The antioxidant defense system of plants controls the harm caused by active oxygen and maintains regular cellular function. It has been discovered that proline mobilization and assembly enhance plant resistance to drought stress (Nayyar and Walia, 2003). As an initial response to water stress, plants store proline (Anjum *et al.,* 2011). It acts as a signal component to alter the cellular oxidative potential, to give stability to subcellular formations, to trap free radicals and also as a cushion for cellular redox potential (Szabados and Savoure, 2010). Antioxidant defense is how plants respond to oxidative stress, it can be with the action of enzymes and also without enzyme involvement. Enzymatic defense is the most successful kind of defense (Farooq *et al.,* 2008). The most significant enzymes in this case are glutathione reductase (GR), catalase (CAT), peroxides (POD) and superoxide dismutase (SOD) (Farooq *et al.,* 2013). Apart from this, non-enzymatic elements like glutathione and carotenoids can also contribute to the antioxidant system. Enzymes

SOD, POD and CAT can trap reactive oxygen species directly or not immediately via regulating non-enzymatic defense mechanisms in plants (Anjum *et al.,* 2011).

In order to keep leaves turgid during drought stress, solute absorption occurs within the cell (Savita *et al.,* 2020). When the collection of osmolytes to reduce the osmotic potential of cell is enough, the cell continues to uptake moisture and maintain turgor at water potentials which is lower than the standard (Fathi and Tari, 2016). Scientists know that compatible solutes, such amino acids and carbohydrates, are inevitable in plant cells. During osmotic stress, compatible soluble low molecular weight compounds often operate as guardians by interfering with biological activity within cells. Apart from their major role in osmoregulation, these compounds may also play a critical part of maintaining enzymes and membrane structure, by removing active oxygen free radicals (Farooq *et al.,* 2009). Proline accumulation is considered to help plants tolerate stress (Verbruggen and Hermans, 2008).

Molecular mechanism in pigeonpea against the drought stress

Many genes exhibit either increased or decreased expression under drought stress conditions (Ingram and Bartels, 1996). In order to unravel the molecular mechanisms underlying response of pigeonpea towards drought, research was conducted on ICP151, ICPL8755 and ICPL227. The investigation involved the selection of 51 genes utilizing Hidden Markov Model (HMM) to spot out the protein domains associated with genes which have stress responsive mechanisms. Specifically, the study focused on ten genes, including those encoding U-box proteins, H^+ antiporter proteins and universal stress proteins, from the poll of 51 genes, related to drought (Auspa). The identified genes serve as valuable targets for further molecular research aimed at understanding and enhancing drought resistance in pigeonpea (Sinha *et al.,* 2016). Transcriptome analysis has identified a variety of drought-induced genes, which can be classified as regulatory genes and functional genes (Chinnusamy *et al.,* 2004). The products of the first group genes control the other genes by manipulating their impression during drought, like protein phosphatases; transcription factors kinases, such as sons of sevenless (SOS) kinases, calcium-dependent protein kinases (CDPKs) and mitogen-activated protein kinases (MAPKs) (Xiong *et al.,* 2002). During stress, the second category that shields the cell directly includes LEA proteins, antifreeze proteins, mRNA-binding proteins, water-channel proteins, chaperones, detoxifying enzymes, osmo-protectants, essential enzymes for osmolyte biosynthesis, free radical scavengers and several proteases' gene products (Bray, 2002). The genes which are recognized can undergo validation at chronological order across diverse genetic scenario. This validation process aims to detect variations in sequence level, facilitating the creation of gene-based markers. These markers are instrumental in crop improvement efforts, aiding in breeding lines and hybrids evolution with enhanced tolerance through genomics-assisted breeding strategies (Jha *et al.,* 2020; Thudi *et al.,* 2014). Resistance towards drought in transgenic plants is also related to coding genes for heat-shock and LEA proteins (Ali *et al.,* 2017).

Management of drought stress in pigeonpea

Insufficient soil moisture during the establishment of seedlings leads to poor plant stand, which is a primary factor in low rainfed yields of pigeonpea. The best planting methods under circumstances when soil moisture is not ideal require more research. To reconcile the tension between sparse populations' preferred water consumption and dense populations' preferred photosynthesis, one must grasp the principles defining the optimal plant population of crops in moisture-deficient conditions. Cropping systems that maximize the few quantities of accessible soil moisture should be further developed. Wide range of studies are required to complete comprehending of the reactions under water deficiency to other agronomic parameters, such as fertilizer application and tillage practices (Singh and Das, 1987). When compared to farmers' practices, abiotic stress management strategies greatly improved production, net profit and the B:C ratio (Singh *et al.,* 2019). Deep summer plowing, bulky organic manures (farmyard manure), mulching (dust, vertical and crop residue mulching), seed hardening (sodium benzoate, KH, PO, succinic and ascorbic acids), weed control, runoff collection and recycling, maintaining an ideal plant stand and choosing long-duration varieties, however, may all help to partially reduce the drought (Fig 4), (Ahlawat *et al.,* 2005).

Plant growth-promoting bacteria (PGPB) is inducing resistance towards various abiotic stresses in numerous plants. In the current study, the ability of Firmibacteria (*Paenibacillus stellifer* M3T4B6, *Bacillus azotoformans* MTCC2953 and *Bacillus aryabhattai* KSBN2K7) to produce stress tolerance in pigeonpea under pot culture conditions was investigated. Under pigeonpea, several parameters, such as osmolytes, stress enzymes and antioxidants which are physiologically as well as biochemically important, were assessed during various scenarios of stress (*i.e.*, 50% and 25% field capacity) as well as in an unstressed state. Significant physiological and biochemical differences were found between plants infected with firmibacteria and control plants under circumstances of moisture stress. The proline and genes responsive towards drought are expressed, which is mediated by bacterial inoculation and enhance drought tolerance in pigeonpea, was analyzed and identified through quantitative real-time polymerase chain reaction. The outcomes demonstrated that when comparing the tolerance towards drought in inoculated plants and uninoculated control plants, *Bacillus aryabhattai* inoculation has shown the drought-responsive genes at an increased

rate (*C. cajan* 29830 and *C. cajan* 33874) and proline gene at a decreased rate. *Bacillus aryabhattai* may therefore be suggested to induce increased tolerance towards drought stress in pigeonpea right after the field evaluation (Devi *et al*., 2021).

The most difficult issue facing breeders today is breeding for drought and their efforts have been mostly ineffective thus far. This is partially because the annual variations in the arid environment disguise genotypic behavior. By creating a large number of early and extra-early cultivars, they are more successful in introducing drought-escape mechanisms, while efforts to promote tolerance or avoidance have shown the least results. A larger focus has to be placed on screening wild species and land races for the discovery of resistant sources, in addition to utilizing hybrids and polyploids, which have higher genetic potential and are likely to be more tolerant to drought due to heterotic effects. In order to confront terminal and unexpected droughts, breeders should strive to evolve plant types with quick and deep root development, changeable stomata under stress, dehydration tolerance and indeterminateness (Ahlawat *et al.,* 2005). Short-duration pigeonpeas may be more resistant to drought if they have certain traits, such as the capacity to sustain TDM, low flowering synchrony, tiny pod with less number of seeds per pod and big 100-seed weight (Lopez *et al.,* 1997).

Antitranspirants are substances or materials that, by shrinking the size and quantity of stomata, lessen the amount of water lost from plant leaves (Vala and Chavda 2010). Crop plants can minimize their water loss by employing growth retardants like cycocel to inhibit overall plant development or by utilizing antitranspirants like PMA (stomata closure type) to prevent water loss. On average, transpiration suppressants resulted in a notable enhancement of the pigeonpea plant's growth properties, namely plant height and dry weight. Antitranspirants improved the availability of nutrients and moisture, which produced an environment that was favorable for the plants in terms of their growth and development (Ansari *et al.,* 2012).

CONCLUSION

Finally, drought stress affects several growth stages of the plant, development and yield, posing serious obstacles to pigeonpea farming. It has been clear from this debate that under moisture stress pigeonpea plants undergo physiological and biochemical changes, which can lead them to decreased water intake, compromised photosynthesis, changed hormone levels and oxidative damage. In the end, these impacts lead to lower agricultural output, weakened seed quality and financial losses for farmers. A number of tactics is identified and proved scientifically to lessen the adverse conditions caused by drought stress in pigeonpea, such as breeding programs that produce and adopt drought-tolerant cultivars, effective irrigation techniques, mulching techniques that preserve soil moisture and the application of exogenous substances like osmo-protectants and plant growth regulators.

Conflict of interest

The authors declare that they have no conflict of interest.

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