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Morphological and physiological response of sorghum under drought stress condition: Review

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Abstract

For more than half a billion people in developing nations, especially in arid and semi-arid locations where drought stress is a significant limiting factor, sorghum is an economically significant and staple food crop. Despite being usually regarded as tolerant, sorghum nonetheless suffers severely from drought stress, which lowers its productivity and nutritional quality throughout its principal cultivation areas. Thus, for the crop to be more drought-tolerant, understanding both the effects of stress and plant response is essential. This review sought to deepen our knowledge of and offer new perspectives on sorghum's capacity for drought resistance as a contribution to the creation of cultivars that are more tolerant to changing climates and the impacts of drought on the growth and development of sorghum, including the osmotic potential that hinders the germination process and embryonic structures, photosynthetic rates, and imbalance in source-sink relations that affect seed filling and frequently show up as a significant decrease in grain yield and quality. The mechanisms of sorghum's response to drought-stress are discussed. The mechanisms involve morphological and physiological changes. Using contemporary plant breeding techniques, it seems conceivable to create regionally adapted sorghum cultivars that are drought tolerant and nutrient rich, according to the studies described in this article.

Keywords: Morphological, physiological response, sorghum, drought stress condition

Introduction

After rice and wheat, sorghum (*Sorghum bicolor*) is one of the most important cereal grains eaten in India. The southern states of Karnataka and Andhra Pradesh as well as Maharashtra are where the crop is largely grown. Together, these three states produce around 80% of the country's total output. The other states that produce sorghum include Rajasthan, Gujarat, and Madhya Pradesh. With 7.15 million tonnes produced in 2007, India ranked third in the world for sorghum production, and the above-mentioned areas and states account for 95% of the nation's sorghum production (GOI 2007). Sorghum stover, in addition to grain, is a crucial feed in India's livestock industry for dairy and draught animals, especially during the dry seasons when other feed supplies are scarce.

Over 500 million people, especially in poor nations in the semi-arid and arid tropical regions, depend on sorghum as a significant staple crop. It offers nourishment that is high in protein, fibre, and free of gluten (McCann *et al.* 2015; Impa *et al.* 2019) [26, 19]. It is utilised as a source of feedstock for the creation of bioethanol in addition to being used for human nourishment (Mathur *et al.* 2017) [24]. Even though sorghum is regarded as a drought-tolerant crop and can be productive in low-input environments, drought stress brought on by a lack of water impairs its ability to absorb nutrients from the soil and mobilise and transport those nutrients (Yu *et al.* 2015; Sarshad *et al.* 2021) [24]. In semi-arid and dry regions, which are prone to water constraint, sorghum is mostly grown. For example, 60% of the land in Sub-Saharan Africa where sorghum is frequently produced is deemed vulnerable to recurrent droughts (Hadebe *et al.* 2017) [16], while 80% of sorghum is grown in the US under non-irrigated circumstances, where water is a major limiting factor and significantly lowers production. The most common abiotic stress that sorghum encounters in its primary producing areas is considered to be drought stress (Assefa *et al.* 2010) [24]. Because of this, a lot of research has gone into understanding the impacts of drought stress on sorghum and its stress tolerance mechanisms in order to create tolerant cultivars and implement effective mitigation techniques in the sorghum-producing process. Numerous research has examined how drought stress affects sorghum. Stress has an impact on sorghum's physical and chemical characteristics as well as its growth and development from seed through reproductive and grain-filling stages, which results in a significant decrease in grain production and quality (Kapanigowda *et al.* 2013; Sehgal *et al.* 2018; Bobade *et al.* 2019; Queiroz *et al.* 2019) [13, 36, 7, 30]. Alterations in transpiration rate, remobilization of photosynthetic assimilates, water use efficiency, and biochemical changes involving proline and other metabolites are all part of the plant's reaction to stress (Husen *et al.* 2014; Fracasso *et al.* 2016; Badigannavar *et al.* 2018; Zhang *et al.* 2019a) [4, 18]. Direct impacts of stress, which are also related with energy and fitness costs, can completely destroy a crop, but they frequently appear as a large loss in grain production and a decline in nutritional quality (Fischer *et al.* 2019) [14]. Therefore, in food-insecure and drought-prone locations where sorghum is a key crop, drought stress may result in malnutrition. Because sorghum grain-protein is already poorly digestible (Duodu *et al.* 2003) [13] and because drought can make it even less digestible (Impa *et al.* 2019) [19], poor nutrient absorption from consumed sorghum grown under drought stress, the effects of drought on sorghum nutritional quality are particularly intriguing.

There is a need for a general review that will give an overview of the current body of knowledge, identify any gaps, and suggest how it might be applied in breeding programmes because the majority of the recent review papers on sorghum-drought concentrate on particular topics, such as the impact of stress or plant response. Here, we analysed the earlier and more recent research on how drought affects sorghum plant growth and development, grain filling, yield, and nutritional content. We discussed the physiological mechanisms underlying the crop's tolerance to drought and combined effects of biotic and abiotic stress which affect the yield and growth of sorghum.

Impact of drought stress on growth and development of sorghum

Numerous studies have shown that sorghum seed germination rates and percentages are significantly reduced by polyethylene glycol (PEG)-induced drought stress (Jafar *et al.* 2004; Bayu *et al.* 2005; Bobade *et al.* 2019; Queiroz et al. 2019) [7, 20, 30, 6]. Similar results were obtained when there was a severe reduction in the percentage of seed emergence at two different soil water content levels (field capacities of 60% and 40%). (Bayu *et al.* 2005) [6]. When the osmotic potential level was reduced from zero to roughly 0.8 MPa, both the percent germination (PG) and germination rate index (GRI), as well as the amount of water absorbed by seeds, were all significantly reduced (Oliveira and Gomes-Filho 2009) [27]. In low osmotic potential situations, the mean germination time (MGT) was longer, whereas in high osmotic potential environments, the GRI was significantly greater. Starch synthesis and the process of generating ATP are impacted by reduced seedling vigour, GRI, and PG as a result of drought stress through increased respiration rate (Queiroz *et al.* 2019) [30]. Variable sorghum genotypes have different quantities of starch, according to research. Not enough research has been done on the adaption mechanisms that vary between different genotypes and how a water scarcity affects starch production during seed germination. The root reason of the delayed germination was shown to be the extremely negative osmotic potential, which negatively affected the seeds' capacity to take up water during the first stage of the germination process (Queiroz *et al.* 2019) [30]. In order for seeds to successfully imbibe during the imbibition phase and initiate germination, the metabolic activities of the seed must be revived, and the expansion of the embryonic axis must be encouraged. In order for plants to adjust their internal osmotic potential to match their surroundings, they need extra time when they are under severe drought stress. After germination, the growth of the radicle, hypocotyl, and plumule (which contains the coleoptile and mesocotyl) can be significantly slowed down by drought stress (Bayu *et al.* 2005; Reiahi and Farahbakhsh 2013; Queiroz *et al.* 2019) [30, 6]. Queiroz *et al.* (2019) [30] hypothesise that a decrease in the turgor of the radicle cells, which inhibits cell division and elongation, may be the reason for the suppression of radicle development and growth under water deficit conditions. This may affect the phases of plant growth and development that follow. For instance, Bayu et al. (2005) [6] demonstrated that both mild and severe water deficit conditions led to a shortening of the coleoptile and mesocotyl. The mesocotyl and coleoptile are essential for successful plant emergence and early vigour. Mesocotyl and coleoptile elongation indicate poor seedling emergence and establishment in water-scarce situations. In addition, the rate of dry weight, shoot elongation, and root growth are all significantly slowed by a shortage of water (Takele 2000; Jafar *et al.* 2004; Bobade *et al.* 2019; Queiroz *et al.* 2019) [20, 7]. Likely as an adaptation reaction to water-deficit conditions, Bayu et al. (2005) [6] also showed an increase in the root to shoot ratio and osmotic potential levels. A decrease in either or both of the two primary cellular growth characteristics, cell turgor and wall extensibility, could also be the reason for the slowed rate of shoot development (Queiroz *et al.* 2019) [30]. Studies show that drought-sensitive sorghum cultivars are more negatively impacted by water scarcity on vegetative growth than drought-tolerant cultivars. The drought-sensitive cultivar had shorter shoot and root lengths than the drought-tolerant genotypes under drought stress, according to a study by Fadoul *et al.* (2018). Given that their root systems can quickly reach moist soil levels for water uptake and rapidly penetrate the upper soil layers, this implies that cultivars that can form long and wide root systems may have more successful seedling establishment.

The effect of drought stress on sorghum yield

Even in cultivars that are acclimated to drought, such as sorghum, which is one of the finest drought-tolerant crops, considerable production losses can still result from drought stress (Assefa *et al.* 2010, Sabadin *et al.* 2012) [3, 33]. This might be viewed as a loss in grain yield as a result of the fitness cost of the tolerance mechanisms. Unpredictable and insufficient precipitation frequently significantly lowers grain yield in locations with a lack of water (Hattori *et al.* 2005) [17]. This suggests that drought stress can impair grain yields at any stage of crop development because it is true even when the drought stress occurs at the seedling stage (Gano *et al.*, 2021) [15]. Although under normal circumstances, stress is continually present across numerous stages of development, practically all prior research has concentrated on the impact of the stress happening during a particular developmental stage. Grain yield was decreased by more than 36% and 55%, respectively, due to drought stress during the vegetative and reproductive periods (Assefa et al. 2010) [3]. Therefore, although drought stress can decrease grain output at any developmental stage, the stress during reproductive phases has a more significant impact. This is due to the fact that during reproductive stages rather than the early vegetative stages, there is a stronger association between the environment and grain yield and quality. Sarshad *et al.* (2021) [24] shown that reproductive stages such as flowering, pollination, microsporogenesis, and seed filling are crucial and can negatively affect grain yield (Kebede *et al.* 2001). The stage of seed filling in particular is thought to be the most vulnerable to drought stress because it involves numerous metabolic activities, a variety of enzymes, and transporters that are found in the leaves and seeds (De Souza *et al.* 2015; Sehgal *et al.* 2018) [11, 36].

Drought stress has an impact on sorghum output both before flowering (panicle formation) and after flowering (between flowering and grain development) (Adugna and Tirfessa 2014) [1]. In a study on sorghum, Kapanigowda *et al.* (2013) [21] found that drought stress both before and after flowering significantly lowers grain yield and quality. In contrast to a drought during the pre-flowering stages, a drought during the post-flowering stages has a more severe effect on grain output. For instance, sorghum farmers in Burkina Faso and Ethiopia reported that severe drought during the post-flowering stages is a significant barrier to sorghum output (Ouedraogo *et al.* 2017; Derese *et al.* 2018) [28, 12]. Similar to this, Burke *et al.* (2018) [8] showed that post-flowering development stage sorghum productivity was severely impacted by drought stress due to early plant mortality and smaller seeds (Burke *et al.* 2018) [8]. In a historical study conducted over two years with 30 sorghum cultivars, it was discovered that post-flowering stage drought stress reduced grain output by around 50% (Batista *et al.* 2019) [5]. To comprehend how a lack of water affects the synthesis of starch, following germination, and metabolic response of sorghum seeds, metabolic and enzyme experiments are necessary. Due to a lack of egg insemination inside the ovary, drought stress during pollination can result in a considerable reduction in grain yield (Sarshad *et al.* 2021) [24]. This is connected to the fact that sufficient moisture, which is a limiting factor under drought stress circumstances, is needed for the transport of pollen grains from male to female organs and contact with the eggs in the ovary. Contrarily, research by *Sarshad et al.* (2021) [24] revealed that drought stress following grain filling had no appreciable negative impact on gain yield. The effect of stress following grain filling may alter the moisture content and metabolism of mature seeds, which may have transgenerational effects, particularly on germination rate and early seedlings of progeny, albeit this has not been empirically proven. Overall, research has demonstrated conclusively that drought stress lowers grain yield; however, the severity of the stress depends on a number of variables. The length and severity of the stress, the stage of the plants' development, their genotype, the existence of other confounding pressures, and seasonal fluctuations all affect how much damage the drought stress causes. Due to the multigenic nature of drought tolerance and the potential for significant variation in reported results, this is particularly essential.

Combined effects of drought stress and other major biotic and abiotic factor on plant growth and development

Drought interaction with other abiotic stresses

Numerous stressors that may worsen the effects of drought-induced stress or increase plant tolerance are constantly a threat to plants thriving in their natural habitats. The production and quality of sorghum grain are known to be significantly impacted by a number of abiotic stresses, including nutrient shortage, aluminium toxicity, water logging, salinity, and low and high temperature extremes (Tari *et al.* 2013) [39]. For management techniques to be optimised, drought stress tolerance to be induced, and sorghum breeding to be accelerated for developing resistance to these stresses, it is essential to understand the impacts of these stresses happening concurrently with drought stress.

In drought-stressed sorghum, it has been demonstrated that increased CO2 concentration decreased stomatal conductance, maintaining whole-plant metabolism, and increasing grain protein content (De Souza *et al.* 2015) [11]. This shows that sorghum is a hardy crop that can continue to be important for subsistence farmers as a crop for food security in the face of climate change. However, only two CO2 concentration levels were employed, and the study was not carried out in different environments to account for variations brought on by other environmental conditions that might have impacted how drought and heat stress interacted. Evaluation of how sorghum's exposure to heat and drought conditions at various growth stages affects ethanol production (Ananda *et al.* 2011) [2]. Similar to this, Impa et al. (2019) [19] examined the impacts of heat and drought independently and found that both affect the yield and nutritional value of sorghum. Although heat and drought are significant stresses in sorghum production, the sorghum genotypes in the studies by Impa *et al.* (2019) [19] and Ananda *et al.* (2011) [2] were grown in two environments that either experienced heat stress or drought stress, making it impossible to draw conclusions about the interactions between the two stresses.

Sorghum's soil water content (SWC), leaf relative water content (RWC), leaf water potential (), and leaf osmotic potential decreased when drought and heat stress were applied together (Machado and Paulsen 2001) [23]. In comparison to the impacts of the stresses alone, the co-occurrence of these stresses may have a more detrimental effect on the plants. A number of crops, including sorghum, are affected by functional biochemistry during heat and drought stress, which also lowers grain yield and nutritional quality (Sehgal *et al.* 2018) [36]. In sorghum cultivars cultivated under drought stress conditions, with varied levels of drought tolerance, application of silicon increased root growth, maintained photosynthetic rate, and increased stomatal conductance, according to a study by Hattori *et al.* (2005) [17]. This suggests that the negative impacts of drought on plant growth and development can be reduced by adding silicon to the soil. According to Burke *et al.* review's drought stress during the post-flowering period enhanced sensitivity to charcoal rot and water lodging (2018). When compared to well-irrigated plants, the severity of the stalk and charcoal rot disease in sorghum plants under drought stress circumstances was less severe (Kapanigowda *et al.* 2013) [21]. These findings imply that the interplay between drought and other abiotic pressures is complicated, especially in natural settings where a number of variables are present. However, the existence of sorghum genotypes that are resilient to abiotic stresses including drought and other pressures (Burke *et al.* 2018) [8] suggests the potential for creating cultivars that combine these crucial features.

Microbes-induced drought stress tolerance in sorghum

Plants and the accompanying microbes have lost genetic diversity as a result of crop domestication (Perez-Jaramillo *et* *al.* 2016) [29]. Numerous studies have shown that naturally occurring microbes can benefit plant health, disease resistance, tolerance to abiotic challenges, and yield (Trivedi *et al.* 2020) [41]. Additionally, it is demonstrated that the plant genotypes control the recruitment of microbiomes (Wagner *et al.* 2016) [42]. By easing the effects of environmental restrictions, the interaction between a particular plant genotype and its microbiome is essential for their fitness. However, it's possible that existing sorghum genotypes and varieties weren't created to take use of the advantageous effects of naturally occurring microbes. Thus, there is a lot of untapped potential in microbes to develop drought resistance in sorghum farming. Research by Carlson *et al.* (2020) [9] has shown that the early activation of signalling hormones such brassinolides, salicylic acid, and jasmonic acid by the addition of rhizobacteria to sorghum seedlings enhanced systemic tolerance to drought. The results of this study also suggested that bacterial ACC deaminase may lower plant ethylene levels by cleaving ACC into α-ketobutyrate and ammonia and encouraging plant growth in challenging environments. Therefore, one tactic for surviving drought stress is to modify the sorghum microbiome. Understanding the sorghum-associated microbiomes under various conditions is crucial as a first step before microbiome modification. In drought-stressed sorghum, Xu *et al.* (2018) found that monoderm bacteria, which have strong cell walls but no outer membrane, are more prevalent and had a positive effect on plant growth. The exudation of a particular plant metabolite, glycerol-3-phosphate (G3P), an important precursor to the peptidoglycan production of monoderm bacteria, may have contributed to the increased abundance of monoderm bacteria microbiome in drought-stressed sorghum. Further highlighting the significance of the microbiome in drought tolerance, monoderm bacteria like Actinobacteria were enhanced in drought and heat stressors, positively benefiting plant development (Wipf *et al.* 2021) [43]. Studies are also required to comprehend how bacterial and fungal communities interact and the part they play in sorghum's ability to withstand drought. It is crucial to concentrate on longer-term research in the field to gain a better mechanistic knowledge of the intricate interactions between sorghum and microbes during drought circumstances in order to harness the sorghum microbiomes for drought-resistant sorghum production.

Conclusion

In important sorghum-growing regions, drought is a major limiting factor that significantly lowers productivity. The effects of drought stress exerted at various growth and developmental phases on grain production and quality of sorghum are well recognised, even in the face of climate change and declining water supply. The majority of research have primarily looked at the effects of drought stress that occur during certain plant growth phases, despite the fact that drought stress extending over numerous plant developmental stages is a typical occurrence in important sorghum growing areas. It is crucial to perform well-planned, thorough studies that include all phases of plant growth and development in order to acquire a more complete understanding of the overall impact of drought on sorghum and the traits of plant responses to drought. To avoid the harmful effects of drought stress, it is essential to produce drought-tolerant cultivars that are suitable for a variety of agro-climatic conditions, especially in the arid and semi-arid regions. In this regard, the first step toward the production of drought-tolerant cultivars with a variety of desirable traits is the discovery of sorghum genotypes with great tolerance to drought stress. A well-planned study must take into account for checking the variability in the intensity and length of drought stress during the crop growing season, and variation in edaphic environments across the main sorghum-producing regions in order to identify suitable genotypes for drought tolerance.

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