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Sorghum as a Model Crop for Drought Stress Tolerance

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Abstract: Sorghum is one of the most significant C4 cereal crops grown in dry and semi-arid regions of the world. It is a major staple crop for millions of people in Sub-Saharan Africa and South Asia. Drought is an important constraint on agricultural production and productivity around the world. It has a significant impact on plant growth, development, and yields. Drought stress risks food security by having a substantial impact on sorghum growth and development, grain yields, and nutritional quality. Sorghum has become known as a drought-tolerant model crop when compared with many other crops. Its ability to withstand extreme environmental conditions makes it a feasible model crop for studying abiotic stress responses and developing stress-tolerant crops. Sorghum response and/or tolerance mechanisms include morphological, physiological, and molecular changes. Drought stress tolerance mechanisms in sorghum include drought escape, early flowering, stay-green, drought avoidance, leaf area, osmotic adjustment, stomata-mediated drought responses, cuticular wax production, root characteristics, and drought tolerance. Biotechnology and its advanced approaches, such as QTL, marker-assisted backcrossing, genetic engineering, and others, are used for screening drought-tolerant genotypes that can withstand drought stress. Therefore, focusing on the drought-tolerant genotypes will boost the speed of the sorghum breeding program, which will feed millions of people worldwide, particularly in Sub-Saharan Africa.

Keywords: Drought, Drought Tolerance, Grain Yield, Sorghum, Stay-Green

1. Introduction

Sorghum (*Sorghum bicolor* L.) is an annual grass in the Poaceae family with a C4 metabolism. The crop originated between 8,000 and 5,000 years ago in Northeastern Africa [1]. It is a photosynthetically proficient C4 plant that provides enormous amounts of grains, forage, sugars that ferment, and cellulosic fibers for a number of uses that encompass bioenergy and bio-industrial feedstocks [2]. After maize, rice, wheat, and barley, sorghum is the world's fifth major cereal crop [3]. In 2020, global sorghum production was 29.8 million metric tons (MMT), with a production rate of 1.5 metric tons per hectare (t ha1) [3]. Global sorghum production was estimated at 60.06 million metric tons in 2021–2022. Nigeria stands first in total production with 7 million metric tons (12%), followed by the US, Sudan, and Mexico (Figure 1). It is a food security crop for about 500 million people in nations with low incomes, mostly in dry and drought-prone areas where moisture stress is significant. [4].

Drought is a recurring incident that threatens agricultural productivity and has a global impact on the livelihoods of people [5]. It has an impact across many African sorghum-producing countries [6]. Drought is anticipated to become more prevalent in the future due to climate change [7]. Nevertheless, the consequences of drought on agricultural output depend on rainfall distributional trends compared to overall annual rainfall. As a result, drought is nowadays a serious issue for crop development and growth, particularly in tropical countries [8]. Drought stress impacts nearly all stages of plant development; nevertheless, the emergence of seeds and the early seedling growth phase [9] as well as reproduction phases, particularly in sorghum [10], are extremely vulnerable and crucial. It reduces plant health, development, and growth and reduces production by limiting carbon absorption, stomatal conductance, and cell turgor [10, 11]. The wilting of leaves and loss in leaf surface indicate moisture stress indications on crop plants, as are bud or flower production, sink number, total development, and crop yield [10, 12]. Understanding the impact of drought on crops is therefore critical for generating better varieties with consistent high crop production. Crop responses to drought stress, on the other hand, are multifaceted and differ depending on climatic circumstances, the frequency and length of the stress, the plant's species and diversity, and the plant's physiologic stages at the time of the stress occurred [13].

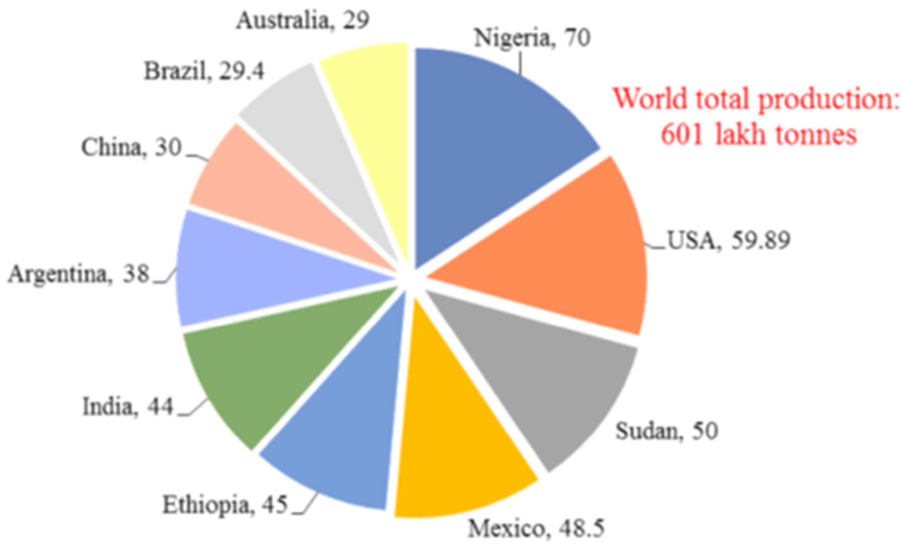

Figure 1. *Global sorghum production from 2021–2022 (Source: USDA, fas.usda.gov)).*

2. Sorghum as a Model Crop

Sorghum bicolor, a C4 cereal crop used for food, feed, and biofuel, has been found to be drought tolerant [14, 15]. It is a major source of food in developing countries, several of which are particularly vulnerable to climate change [16]. Sorghum was cultivated in Africa 8000 years ago, and its adaptation to arid environments shows that drought tolerance developed at domestication [16-18]. Sorghum is a drought-resilient crop due to its domestication in dry environments. Therefore, it is an ideal model crop for studying drought-stress mechanisms of response in an agriculturally and economically valuable cereal crop. Furthermore, the variation in genetic makeup within sorghum genotypes or accessions, as well as its relatively small diploid genome and close relationship to Zea mays, make it a good candidate for identifying and clarifying drought tolerance genetic processes in related grasses [19-21].

3. Importance of Sorghum

Sorghum is an essential food source in many dry, semi-desert, and tropical areas around the globe due to its being more tolerant and prolific than other crops when exposed to diverse environmental conditions. It is abundant in fiber and protein and also contains more calcium, phosphorus [22], and potassium than rice or wheat [23]. Sorghum possesses essential human health and nutritional properties, and the fact that it is gluten-free makes it an ideal choice as an option to wheat for use in the making of special meals for people with celiac disease who are gluten-sensitive [24, 25]. It consists of resistant starch, which may decrease digestion, particularly in orphan, but is significant in the fight against human obesity and as a source of food for diabetics [26]. Sorghum also contains a lot of fiber and bioactive components such as tannins, phenolic acids, anthocyanins, phytosterols, and policosanols. These phytochemicals are desired in human food due to their antioxidant activity, which benefits health. Certain sorghums contain a high concentration of unique phytochemicals that have anti-cancer effects as well as producing bran with more antioxidant properties than fruits or berries [24, 25, 27, 28]. Sorghum is a key grain crop that is also used to make alcohol, bioethanol, and fuel, not just food.

4. Drought Stress

Drought remains one of the most important abiotic factors affecting crop production globally [29]. It reduces plant productivity by causing the closure of stomatal pores and lowering the photosynthesis process as well as growth [30]. Plant adaptability and reaction to drought are consequences of complex biological mechanisms such as physiological, biochemical, genomic, proteomic, and metabolomic alterations [31]. Drought-sensitive sorghum cultivars showed stress-related physiological alterations, including a shift in photosynthetic rate [32]. According to the research [33], drought stress lowers stomatal conductivity and evaporation rates, raises the quantity produced and leaves the temperature, reduces chlorophyll and Rubisco, increases O2 evolution, and decreases PEPCase function in sorghum. According to multiple studies [32, 34], drought-tolerant sorghum cultivars had significantly higher Fv/Fm and photosynthesis rate values. Besides their capacity to escape or withstand drought, photosynthesis restoration on rehydrate is critical in determining crop drought tolerance and avoiding grain yield loss [35]. Transpiration efficacy in drought-resilient sorghum cultivars was similar across normal and drought-stressed crops; however, in drought-susceptible genotypes, there was a substantial statistical difference between control and drought-stressed plants [32]. Furthermore, during the stress caused by the drought period, cultivars that proved greater resilience to stress had a significantly greater WUE than those that were more sensitive [32]. In sorghum, grain yield has been observed to be significantly associated with water removal and absorption efficiency [36]. Drought-resistant cultivars maintain moisture for use during the grain-filling stage in drought-prone regions and have lower stomatal conductivity and transpiration levels at the vegetative stage [37].

5. Impacts of Drought Stress on the Sorghum Crop

Sorghum, as a significant crop for climate change resilience, is outstanding for smallholder farmers in Africa and Asia who have no access to irrigation to sustain food security [38]. Climate change has resulted in the instability of weather patterns, particularly in arid areas where the duration of dry periods has increased, resulting in crop wilting and food shortages. Figure 2 shows the impact of drought stress on sorghum plants in Ethiopia.

Figure 2. Impacts of drought stress on sorghum in Ethiopia, Photos—January 2016. (Source: Adebe et al., 2017).

5.1. On Sorghum Growth and Development

Drought stress will have a considerable impact on plant growth early in the growing season. Seedling deaths are of great concern in arid regions where drought damage is prevalent, and they are most severe during seedling emergence and maintenance under the combination of extreme drought and high-temperature conditions [39]. Drought can cause standing mortality in the sorghum following entire emergence but before seedling establishment [40]. Drought stress is possibly affecting the initial stages of plant growth (germination, emergence, and seedling establishment). Consequently, the impact of drought-induced moisture deficits on the initial embryonic stages of sorghum has attracted considerable attention. Nevertheless, there are significant differences in sorghum genotypes' reactions to varying degrees of drought-related stress. Drought stress can be detrimental to plant development at the beginning of the growth period; however, when late rainfall rates are sufficient, plants recover rapidly [41]. It reduces the seedling's vigor, germination rate index, and percent germination by increasing the respiration rate, which affects starch synthesis and energy generation (adenosine triphosphate (ATP)) [40]. According to the research [42], when drought stress was subjected, the shoot and root lengths of drought-sensitive genotypes were shorter than those of drought-tolerant genotypes.

5.2. On Sorghum Grain Yield

Drought stress affects grain yields through decreasing in seed size, quantity, or weight per panicle, as well as other agricultural characteristics [43]. Furthermore, it raises both direct and indirect agricultural expenses, decreasing yield and productivity. Despite the reality that sorghum is one of the most resilient drought-tolerant plants, adapted to a wide range of agroecology as well as low-input food production, extreme drought might result in considerable yield losses [44]. Grain yields in water-stressed locations are often reduced due to unexpected and insufficient rainfall [45]. According to the research [46], in a sorghum study, drought stress affects grain quality and yield both before and after flowering. Drought stress during the pollination stage could result in a considerable drop in the yield of grains due to the failure of egg implantation within the ovaries [43]. It may also limit the quantity of grain per panicle, which has a direct effect on grain yield during the flowering stage [47]. Drought stress during the post-flowering period lowered grain yield by roughly 50%, according to a two-year classic study involving 30 sorghum varieties [48].

5.3. On Sorghum Nutritional Quality

Several studies have shown how drought stress affects the nutritional content and composition of sorghum, resulting in crop alterations. It alters the interactions between morphophysiological traits on the one hand and source action and sinking strength on the other [49], alters grain physical and chemical properties [50], and decreases nutrients, mineralization, and membrane permeability [51]. Growing sorghum genotypes in dry environments, for example, decreased grain micronutrient content (Zn, Fe, Mn, and Cu) [50]. Drought stress resulting during the phase of flowering caused lower total starch, amylase, and amylopectin accumulation, which corresponds to the activity of enzymes on sugar nucleotide precursors during the filling of grains, such as starch synthase (SSS), granule-bound starch synthase (GBSS), starch branching enzyme (SBE), and starch debranching enzymes (DBE). In other studies, it increased the amount of total protein while decreasing the total soluble carbohydrate, crude protein, and proline concentrations in sorghum [43].

6. Drought Stress Tolerance Mechanisms in Sorghum

Plants have a variety of morphological, physiological, and biochemical adaptation processes in response to drought in order to thrive and live in harsh environments. Drought escape, drought avoidance, osmotic adaptations, staying green, leaf area, waxiness on the stem, root shape and architecture, transpiration efficiency, and solubility solute secretion are all significant mechanisms in drought tolerance [52].

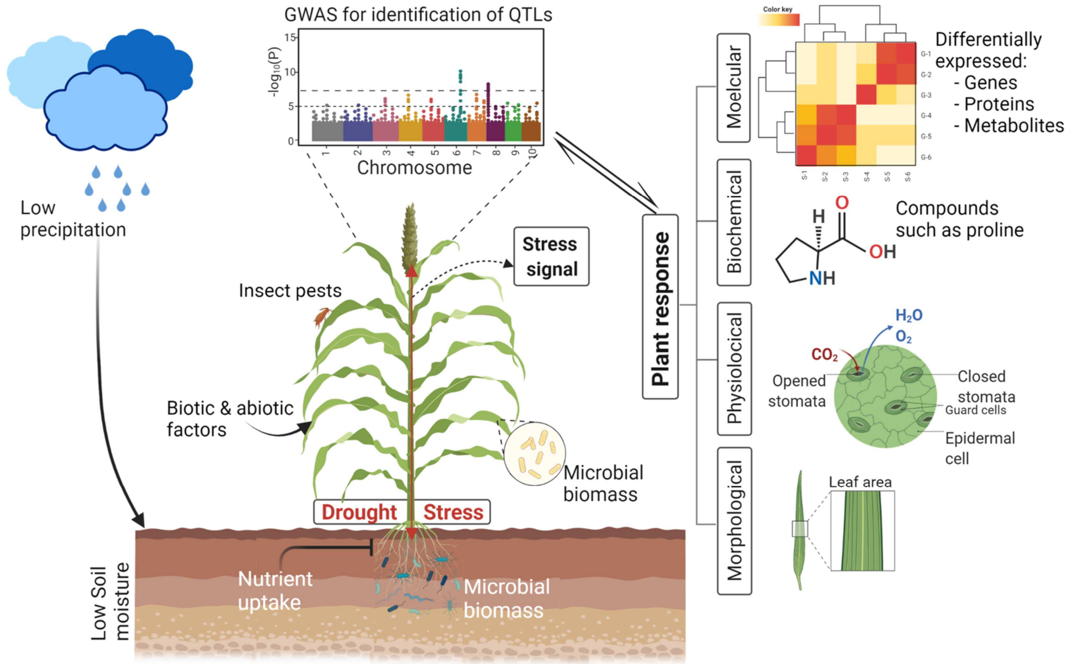

__Figure 3.__ Diagrammatic depictions of the morphological, physiological, biochemical and molecular responses of sorghum to drought stress. This figure was created with BioRender (https://biorender.com/).

6.1. Drought Escape

Drought escape is a typical adaptation strategy that enables a crop to end its entire lifespan prior to a drought happening. Drought-resistant varieties end their lives prior to the appearance of extreme drought stress. During several field trials, an early flowering phenotype is used as a primary drought escape selection index for yield under drought conditions. A drought-escape sorghum phenotype is a germplasm that exhibits distinct responses to photoperiodism and homeostasis for bearing time [53].

6.2. Drought Avoidance

Drought-affected crops prevent dehydration by retaining significantly greater tissue levels of water, whether through increased intake of water or reduced loss of moisture through transpiration. Plants or cultivars with an earlier phenotype are known to be referred to as water spenders, whereas those with the latter are referred to as water savers. Water-spending plants survive droughts by expanding their root length, which assists in water absorption. Water savers, on the other hand, cover a portion of their stomata in order to reduce transpiration water loss and save soil moisture. Furthermore, drought stress is avoided by activating the osmotic adjustment mechanism, which includes solute buildup [10, 54].

6.3. Early Flowering

Drought stress during flowering decreases silk elongation, lengthens the anthesis silking delay, and reduces ovule fertilization and kernel abortion. Early flowering and short reproductive periods are essential characteristics under extreme drought circumstances because they reduce exposure to dehydration during the critical flowering and post-anthesis grain-filling periods [55]. In environmental settings with insecure rainfall or terminal dryness, flowering before the start of a development restricting drought is a key approach to guaranteeing yield production.

__Figure 4.__ Early-flowering sorghum varieties (Source: online, March 16, 2016 From a Press Release)

6.4. Leave Area

Drought stress causes varying responses in water consumption efficiency in leaves. Water usage efficiency at the level of the leaf is intimately tied to the physiological mechanisms controlling CO_2 and H_2O gradients between the leaf and the air around the leaf [56]. Optimal leaf area is critical for optimum photosynthetic performance in a drought scenario. Furthermore, in drought-prone areas, optimum leaf area is critical to achieving high dry matter content and grain yields [57]. Sorghum's drought resistance was greatly influenced by leaf area. In regions prone to drought, the leaf area of sorghum is reduced to reduce water loss through evapotranspiration. Plant consumption of water and biomass buildup must take into account soil water evaporation rate, transpiration from the leaves, and plant growth style. Implementing techniques that minimize soil water evaporation and shift more water towards transpiration can improve water usage efficiency at the canopy level [56].

Figure 5. *Photograph showing the stay-green trait in sorghum the field in Petancheru, India. Thephotograph was taken at the post-flowing stage with no supplemental irrigation. Sorghum plants on the right have the stay-green trait (B35), whereas plants on the left are senescent varieties (R16) (Kumar et al., 2011).*

6.5. Stay Green

Plants expressing stay green to keep functioning leaves that are green for an extended period of time as water shortage happens in the filling of grains [5]. Stay green is a moisture-stress adaptability trait seen in sorghum and other crops. Stay-green sorghum genotypes can preserve grain filling in drought condition. Grain yield and stay-green are goal qualities in grain sorghum breeding for wide adaptability to varied environments [58]. Staying green has been shown to improve tolerance of post-flowering dryness in sorghum grain. A number of QTLs linked with stay green have been found in sorghum; consequently, improving transmission of this trait into appropriate genetic backgrounds is critical [59]. According to the research [60], pre-flowering canopy variables were slightly connected with stay-green values for leaf senescence, while canopy factors had a considerably larger linkage with leaf senescence. This finding revealed that canopy size before flowering had little effect on the production of a stay-green phenotype after flowering. The examined cultivars' resistance strategies included accelerated leaf senescence to reduce water loss and increased root length density to explore the deeper soil layers for moisture [60]. Sorghum line B35, a descendant of a hybrid between Ethiopian durra and Nigerian landrace, is a highly potential line carrying the 'stay green' phenotype and is often used as a trait source across regions [61]. Thus, green sorghum helps increase grain yields in both well-irrigated and drought-prone environments.

6.6. Osmotic Adjustment

Osmotic adjustment is defined as a net solute increase that results in a decrease in tissue osmotic potential. Both osmolytes can accumulate in both the roots and the shoots, but their accumulation in both tissues serves different functions [39]. Water flow from higher concentration (soil) to lower concentration (tissue) happens as the water potential decreases due to decreasing osmotic potential [62, 63]. Osmotic adjustment was shown to be highly associated with deep root systems in sorghum, as indicated by the research [64, 65]. Sorghum leaves adjusted osmotically at a rate of at least 0.1 MPa per day as the lowest leaf water potential declined at a rate of around 0.15 MPa per day [66]. The shoots' osmotic adjustment prevents wilting and maintains relative water content and stomatal conductance [67, 68].

6.7. Stomata-Mediated Drought Responses

Stomata serve a crucial role in plant carbon absorption as well as water loss processes. The cultivars physiologically adjusted to earlier water limits by closing their stomata, which decreased their transpiration and photosynthetic rate [60]. Stomata in drought-stressed plants are likely to close during midday vapor pressure deficit (VPD) and open primarily in the early morning when temperatures are lower before VPD becomes too high [69]. This function protects the plant's tissue hydration status, minimizing excessive loss of water through evaporation. Variations in leaf temperature can also be used to monitor this process. Despite stomatal closure avoiding transpirational water loss, it lowers CO_2 availability, impacting photosynthesis, plant development, and grain yield [70, 71]. Non-stomatal alterations affecting the rate of photosynthesis include reduced chlorophyll content, which decreases the plant's ability to collect sunlight and affects assimilation formation and transportation [21, 70].

6.8. Cuticular Wax Production

Cuticular wax is the primary barrier that covers above-ground tissues in numerous species of plants, and it plays essential roles in plant abiotic and biotic stress tolerance. It is now implicated in defensive mechanisms against extreme UV radiation, high temperatures, bacterial and fungal diseases, insects, high salinity and low temperature [72]. Sorghum generates epicuticular wax (EW) in its leaves, sheaths, and culms. Epi-cuticular wax reduces transpirational and non-transpirational (nonstomatal) water loss and defends plants from extreme drought stress, besides providing insect pest resistance [73]. A recent study demonstrated that short RNAs (sRNAs), such as microRNAs and small interfering RNAs, played essential roles in stress-induced plant adaptation. Furthermore, leaf cuticle and surface wax have crucial resilience to stress attributes, and several regulator genes regulate wax formation [74].

6.9. Root Traits

Plants are more vulnerable to harsh drought conditions, and roots perform key functions in plant survival, development, and reproduction. Plant roots have evolved to be the first organ that monitors and adjusts for shifts in soil moisture on morphological, anatomical, and molecular scales [75]. Roots serve as the vegetative organs in charge of water and nutrient intake as well as interaction with the soil microbes, and they play a vital role in dry tolerant to stress [76]. Roots have developed a capacity to modify their root structure architecture (RSA) characteristics when subjected to water stress [77-80]. Long and branched roots are one of the fundamental and indispensable traits for crops to tolerate droughts [81]. Small, fine root diameters, long, particular root lengths, and root length density at depths in soil with sufficient moisture are root traits associated with plant production during moisture stress [82]. As a result, roots play an important role in plant life because they take soil resources from deeper soil layers, and phenotyping allows for the comprehension of diversified root properties [83].

Sorghum gains access to more water via deeper root systems [5]. In dry circumstances, low xylem diameters in targeted seminal roots preserve water from the soil deep below the soil surface to be utilized for plant development, resulting in increased crop yields. Larger root growth angles result in root elongation towards deeper soil layers, which is regarded as an essential characteristic for drought access to and collection of deep soil water [84, 85]. Under drought-related condition, smaller diameter roots, higher SRL, and enhanced root hair density or length can enhance plant water uptake while reducing the plant carbon investment required for that uptake. Furthermore, plant hydraulic performance under drought stress could have been enhanced by greater capacity for nocturnal refilling of embolized xylem and alterations in inter-vessel pit structure to prevent turbulence [82]. Understanding root changes in response to water scarcity at many levels may thus offer a basis for choosing and growing drought-tolerant crop varieties.

6.10. Drought Tolerance

Sorghum is well-known for its capacity to withstand stress caused by drought, both intermittent and terminal. Tolerance behavior is influenced by the presence of a complicated and prominent root system, the ability to maintain an adequate amount of stomatal conductance over time, and the maintenance of internal tissue water potential via osmotic adjustment and phenological flexibility [10, 54, 86].

7. Role of Biotechnology in Sorghum Tolerance to Drought Stress

Various biotechnology techniques have been used in sorghum crop improvement for drought tolerance. Marker-assisted backcrossing (MABC), quantitative trait loci (QTL), genetic engineering, and others are the most commonly used. Crop gene transformation techniques have been applied to identify and transfer the genes relevant to drought tolerance.

7.1. Maker-Assisted Backcrossing in Sorghum

Backcrossing is the transfer of alleles at one or more loci from the donor parent to the elite recurrent parent [87]. Backcrossing can be tedious and time consuming; the use of molecular markers has been important in identifying QTLs related to the expression of traits of interest. For example, several markers (simple sequence repeats and single nucleotide polymorphisms) have been chosen for mapping QTLs of stay-green in sorghum. These markers simplify breeding procedures by lowering the time it takes to release new, superior varieties and reducing breeding cycles. After six backcrosses, the introgression of elite trait alleles is achieved, with 99.2% genome recovery of recurrent parents [87]. Due to climate change in most regions of the world, researchers have focused on generating new drought-tolerant cultivars. A variety of molecular markers, such as delayed leaf senescence, leaf rolling, chlorophyll content, water-use efficiency, and yield, have been used to discover QTLs associated with stay-green in sorghum [88-90]. Some QTLs are found in all habitats, while others are found only in a few [91]. Backcrossing with an abundance of polymorphic, high-resolution, high-throughput, co-dominant, and informative molecular markers, such as SSRs and SNPs, is suggested to leverage QTLs from donor parents to recurrent parents [92]. SSR markers, for example, have identified Stg1-Stg4 QTLs that account for 10–30% of the phenotypic variation in drought tolerance in sorghum (Table 1). ICRISAT recently used SNP markers in sorghum to map Stg3A and Stg3B QTLs in chromosomes. These QTLs are very successful at delaying leaf senescence during post-flowering drought stress. In Tanzania, Mwamahonje, A. et al. inserted Stg3A and Stg3B QTLs into farmers' preferred sorghum varieties [93]. The QTLs were successfully introgressed by SNP markers snpSB00049, snpSB00053, and snpSB00054 for the Stg3A QTL and snpSB00101, snpSB00102, and snpSB00103 for the Stg3B QTL, which accounted for 30% of the grain yield increase and stay-green in water-stressed conditions. However, several of the markers failed to discover QTLs, indicating the need for more Stg3A and Stg3B mapping to diversify important drought-tolerance improvement.

Table 1. *Molecular markers and stay-green QTLs for drought tolerance in sorghum.*

Molecular markers	QTL	Position in Chromosome	PV (%)	Reference
Xtxp114, Xtxp38, xiabx378, SSR markers	Stg1	SB1-03	20	[94, 95]
XnhsbSFCIIP67, Xtxp120, Xtxs584, and Xtxp31, SSR markers	Stg2	SB1-03	30	[94]
Xtxs1307, Xtxs1111, Xtxp1, Xtxp56, Xtxp286, SSRs markers	Stg3	SB1-02	16	[90]
Xtxs713, Xtxs387, Xtxp225, Xtxp15, SSR markers	Stg3	SB1-05	10	[90, 96]
snpSB00049, snpSB00053, and snpSB00054, SNPs markers	Stg3A	SB1-02	31	[93, 97]
snpSB00101, snpSB00102, and snpSB00103, SNPs markers	Stg3B	SB1-02	31	[93, 97]

7.2. QTL Pyramiding for Drought Tolerance in Sorghum

QTL pyramiding is the process of crossing one NIL to another, constructing distinct beneficial QTLs, and then using marker-assisted selection to develop novel lines with both helpful traits. Pyramiding QTLs for stress-tolerant traits and yields is advised with progressive increases in warmth and lack of moisture, particularly in arid environments, although the pyramiding approach is tedious and time-consuming [98]. Transfer of desirable traits from donor parents to the recipient is advised for the same species [99]. Drought tolerance in sorghum is improved by QTL pyramiding; nonetheless, efficiency in a well-irrigated condition is greater than performance in a water-stressed condition. Introgression lines with Stg3 and Stg1+2, for example, reduce yield by 10% in water-stressed conditions compared to well-irrigated conditions, showing better tolerance than other Stgs, which show 18–23% as moderate tolerance in sorghum [100]. Nevertheless, findings show that under drought stress conditions, crude protein, total soluble carbohydrate, and proline contents raise; this increase results in an improvement in grain quality nutrition, which enhances human health [43]. Pyramiding is the combination of QTLs with varying effectiveness to improve the expression of stay-green characteristics. The use of molecular markers assists in the detection of QTLs that may be pyramided to improve drought tolerance in sorghum [96]. Pyramiding of QTLs may fail to enhance sorghum stay-green due to incompatible gene activity, which prevents the expression of the traits needed. Pyramiding success is dependent on genetic architecture and accurate mapping of trait QTL [100]. Only the best expression of the trait of interest is chosen for further investigation in multi-location trials before being approved as a new variety during QTL pyramiding.

According to the research [101], locating QTLs for stay-green expression using molecular markers is critical for pyramiding to increase the heritability of new lines. Every QTL contributes a modest percentage to stay-green trait expression, which requires pyramiding to combine QTLs for expression. Pyramiding of stay-green QTLs in sorghum during pre-flowering and post-flowering drought increases the potential of producing new, promising lines with desirable traits through marker-assisted backcrossing [102, 103]. These findings help plant breeders assess the potential QTLs of introgressed traits that can be generated following pyramiding [104]. For successful pyramiding, appropriate molecular markers for mapping QTLs must be used to facilitate sorghum molecular breeding programs. Only pyramided QTLs that show trait expression are suggested for selection in sorghum improvements in the pyramiding study.

7.3. Genetic Engineering for Drought Tolerance in Sorghum

The application of genetic engineering techniques holds great promise for enabling the generation of transgenic crops with little or no influence on the plants' physiological and morpho-biochemical characteristics. Most of the genes linked to drought tolerance are also linked to resilience to other environmental conditions [105]. Genetic transformation is an effective method of improving cultivated plant genetics. Tissue culture challenges, such as phenolic pigment accumulation and low regeneration frequency, have slowed progress in sorghum transformation. Longer durations of screening required for the recovery and regeneration of putative transgenic crops frequently hampered sorghum transformation condition optimization. The presence of methylation of the DNA in sorghum cells, which inhibits the functioning of transmitted genetic material, is likely responsible for sorghum's poor transferability [106]. Genetic engineering methods are particularly essential for modifying protein and starch levels, vitamin and micronutrient concentrations, protein fraction nutritional value, and resistance against environmental stresses [107].

7.4. Multi-Omics Research Advances in Drought Stress Tolerance in Sorghum

Water is one of the most basic needs for the development of plants. Plants adapt to water trouble by changing their morphology, physiology, and biochemistry in order to cope with direct and indirect consequences and live and/or flourish [108-110, 31]. Drought reactions in plants are categorized into three categories: drought escape, avoidance, and tolerance, which have been thoroughly investigated in previous studies [111, 112, 71]. To investigate and mine essential genes linked with strong drought tolerance in sorghum, RNA-seq was used to profile the up-and down-regulated genes linked with drought stress in the drought-tolerant sorghum cv. XGL-1, revealing that numerous genes with differential expression in the roots have been increased in functions such as sucrose metabolism and the raffinose family oligosaccharide biosynthetic process [113].

Functional investigations in sorghum indicated that the SbHKT1; 4 gene regulates cellular ion homeostasis and improves tolerance to drought and salt stress [114]. Various research efforts have recently used the comparative technique to discover DEGs across stress-tolerant and stress-sensitive sorghum genotypes. A transcriptomic comparison of drought-sensitive and drought-tolerant genotypes (IS20351 and IS22330) revealed that the former responded to stress by hydrolyzing carbohydrates in roots, whereas the latter gained tolerance by increasing the synthesis of anti-osmotic agents and antioxidants (e. g., proline, betaine, and glutathione) [32]. Proteomics has also been applied to analyze the protein dynamics of sorghum roots in response to osmotic stress caused by PEG [115]. During drought stress, the concentrations of MDA and proline were steadily raised, as were the activities of superoxide dismutase (SOD), peroxidase (POD), and polyphenol oxidase (PPO). Proteomic analysis of osmotic-induced proteins in BTx623 roots detected proteins involved in protein synthesis, degradation, and defense [115]. These proteomic studies in sorghum are likely to show that cultivars that are drought-tolerant tend to up regulate their stress-related signaling, protein synthesis, and antioxidant activity to acquire improved drought tolerance.

8. Conclusion

Drought is a complex phenomenon that has an impact on agriculture by reducing its production all over the world. Plants respond to drought stress in a number of ways. Sorghum has higher resilience to unfavorable environmental conditions than other grain crops. Sorghum is a drought-tolerant grain crop that is used as food for millions of people living in dry-land areas. It can provide good yields even when water is scarce. Sorghum is regarded as an important crop species for studying the genetic and physiological mechanisms underlying drought tolerance in higher plants. Biotechnology, with its new and advancing approaches, can be used to overcome the problem of drought stress in crops. Due to the small genome size of sorghum, advanced biotechnology techniques have proven reliable for identifying genes related to more complex drought tolerance. Because of its potential to withstand drought under harsh climate change, it represents the future hope crop that will be the source of food for billions of people globally.

Conflict of Interest

The author has not declared any conflict of interests.

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