

Toward Climate Resilient Soybean Systems Global Review of Socioeconomic Constraints Genetic Mechanisms and Breeding Priorities under Drought Stress

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Abstract

Soybean (*Glycine max*) is an important legume crop for food security and economic development in Tanzania, where climate change is leading to more frequent droughts. Drought negatively affects soybean production, especially in rainfed systems, leading to reduced germination rates, stunted growth, and decreased seed quality and yields. This systematic review seeks to evaluate existing breeding strategies for improving drought tolerance in soybean, drawing insights from global approaches used in countries like the United States, Brazil, India, and China. Following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, the review synthesized findings from 190 studies focused on genetic mechanisms, molecular markers, breeding techniques, and field-level applications. The objective was to identify effective breeding approaches for developing drought-tolerant soybean varieties adapted to the specific environmental conditions of Tanzania. Key results revealed twenty-one important drought-responsive genes, emphasizing their roles in water use efficiency and osmotic adjustment. The study also assessed three indices for evaluating drought tolerance: the Recovery or Compensation Index (RCI), the Standardized Precipitation Index (SPI), and the Membership Function Value of Drought Tolerance (MFVD). This review emphasizes the importance of incorporating advanced biotechnological tools such as CRISPR/Cas9, genomic selection, and omics-based technologies into national breeding programs to accelerate the development of resilient soybean varieties. Economic analyses highlight the value of drought-tolerant varieties in stabilizing yields and improving farmer incomes under erratic rainfall conditions. Therefore, this review advocates for a context-specific breeding approach that addresses climatic variability while leveraging cutting-edge innovations. These efforts are important for strengthening national food security and promoting soybean production amid ongoing climate change.

1.0 Introduction

Soybean (*Glycine max* L. Merrill) is a globally important legume crop, valued not only as an oilseed and a source of livestock feed but also as a provider of protein, calories, and biofuel feedstock [135, 58, 162, 75, 77]. As one of the most important crops worldwide, soybean contributes to food security and supports economies of farmers. Among legume crops, soybean stands out for its exceptionally high protein content, surpassing that of other legumes like dry pea (*Pisum sativum*); Broad bean (*Vicia faba*); chickpea (*Cicer arietinum*); common bean (*Phaseolus vulgaris*); mungbean (*Vigna radiata*); black gram (*Vigna mungo*); lentil (*Lens culinaris*); cowpea (*Vigna unguiculata*); pigeon pea (*Cajanus cajan*); groundnuts (*Arachis hypogea*); white lupin (*Lupinus albus*); blue lupin (*Lupinus angustifolius*); and andean lupin (*Lupinus mutabilis*) and others [134, 98]. The crop is needed by a growing population for sustainable food patterns that are socially acceptable, nutritionally adequate and economically affordable, while also conserving agroecosystems and biodiversity [73].

1.1 World Soybean Production

The global area under soybean cultivation and its annual production have shown a steady upward trend, driven by the rapidly increasing demand for feed proteins and edible oils [67]. The leading producers of soybean worldwide include Brazil, United States, Argentina, and China [131]. Soybean oil accounts for approximately 29% of the total global production of oils and fats [75]. During the 2018-19 period, global soybean production reached 348.71 million metric tonnes. Brazil led soybean production at 125.89 million metric tonnes, followed closely by the United States at 123.66 million metric tonnes, Argentina at 37.79 million metric tonnes, China at 14.19 million metric tonnes, and India at 13.27 million metric tonnes. By the 2022–2023 period, soybean production had risen to 391.17 million metric tonnes.

In 2016, the value of the U.S. soybean crop was over \$41 billion, with the U.S. leading global production at 117.2 million metric tonnes, followed by Brazil at 108 million metric tonnes. That year, 33.8 million hectares of soybeans were planted in the U.S., yielding an average of 3,500 kg per hectare. In the 2021-22 season, Brazil again led global the production with 144 million metric tonnes, while United States produced 119.884 million metric tonnes, Argentina produced 52 million metric tonnes, and China and India produced 19 million metric tonnes and 11.2 million metric tonnes, respectively [75].

Soybeans rank as the fourth largest field crop production by volume, contributing nearly 9% to the total value of global agricultural trade. Since 1961, the average global yield per hectare has grown at a rate of 1.64%, reflecting production efficiency. The success of soybean cultivation in leading producing countries is largely attributed to the availability of extensive land resources, sufficient input supplies, the application of management practices, and reliable access to competitive markets.

1.2 Soybean Production in Africa

Africa contributes less than 1% of the soybean production of total world soybean production, a figure that is negligible and insufficient to meet the continent's demand for soybean products [131, 117]. The major producers are South Africa, Zimbabwe, Malawi, Zambia, Uganda, Ethiopia, Nigeria and Ghana [131]. However, none of these countries currently produce enough soybeans to satisfy their domestic demand, resulting in a heavy reliance on imports [131]. As a result, Africa remains a marginal player in the global soybean market. This limited contribution is further hindered by a persistent yield gap between smallholder and large-scale farmers which is an issue observed not only across Africa but also in many developing and developed nations. Soybean yields in Africa are less than half the global average, leading to production levels that fall far short of meeting the continent's needs. Globally, soybean production has grown at a compound annual growth rate (CAGR) of 4.68% since 1961. In contrast, African production has increased at a faster rate of 6.84% per year which is 48% higher than the global average. However, this growth is primarily attributed to an expansion in the area under soybean cultivation rather than improvements in yield [76]. The top three producers in Africa are South Africa, Nigeria, and Zambia which account for 86% of the continent's total soybean output.

The global average soybean yield stands at 2,761 kilograms per hectare, whereas African producers achieve less than half of that, with an average yield of just 1,259 kilograms per hectare. Within Africa, Egypt leads in productivity, benefiting from irrigation systems that enable yields exceeding 3 metric

tonnes per hectare. Ethiopia and Zambia follow with average yields of 2.2 and 1.8 metric tonnes per hectare, respectively. South Africa, the continent's largest producer, maintains an average yield of 1.7 metric tonnes per hectare. However, in 15 out of the 24 African countries for which yield data is available, average production remains below 1,000 kilograms per hectare, highlighting significant challenges in closing the yield gap across the continent.

Among the 24 African countries with official soybean yield data, the average compound annual growth rate (CAGR) in yield is 0.9%, indicating relatively slow progress in productivity across the continent [27]. However, the top five soybean-producing countries show a more promising average CAGR of 2.0% [27]. Angola leads with the highest yield growth rate at 5.3% per year, followed by Cameroon and Côte d'Ivoire, with CAGRs of 4.92% and 2.88%, respectively [27]. South Africa, Nigeria, and Zambia, while leading the region in total production, have CAGRs of 2.6%, 1.8%, and 1.3%, respectively, indicating that productivity growth remains low [27].

1.3 Soybean Production in Sub-Saharan Africa

Soybean production in sub-Saharan Africa (SSA) is expanding at an annual growth rate of 6.84% [106]. This growth is driven primarily by an increase in the area under cultivation, rather than by significant improvements in yield per unit area [76]. The leading soybean-producing countries in SSA, ranked in descending order of production, are South Africa, Nigeria, Zambia, Uganda, Benin, Malawi, Ghana, Ethiopia, and Mozambique.

Malawi and Zambia have made significant progress in soybean production, where soybeans are now more profitable than maize [76]. The average profit from cultivating soybeans per acre is \$585.70 in Malawi and \$658.75 in Zambia, compared to \$385.80 and \$470.65 for maize in Malawi and Zambia, respectively [76]. Also, Zimbabwe, Malawi, Ghana, Sudan, and Ethiopia have also experienced commercial growth in soybean production. Despite this expansion, soybean cultivation in sub-Saharan Africa (SSA) remains concentrated in a limited number of countries.

1.4 Soybean production in Tanzania

Soybean cultivation in Tanzania has a long history, beginning with the first introduction of soybeans by German traders in 1907 in Amani, Tanga. In 1911, additional soybean introductions were made from Japan, China, and South Africa, further contributing to the crop's early expansion and genetic diversity. Initially, soybeans were considered a minor crop, characterized by limited cultivation area and low production. However, the potential of soybeans was gradually recognized, leading to the establishment of a breeding program in 1955, which yielded positive results by the early 1960s.

During the 1970s, soybean cultivation expanded, and production stabilized at 3,000 tonnes per year. This growth continued in the subsequent decades, driven by increasing demand for animal feed and vegetable oil. By 2026, soybean production had risen to about 32,310 tonnes, up from around 25,900 tonnes in 2022 growing at an average rate of 4.5% year on year. Despite this growth, national demand for soybeans remains high, estimated at 300,000 tonnes, indicating a significant supply-demand gap. The

rising demand for soybean meal for poultry feed, further emphasizes the strategic importance of soybeans for Tanzania's future food security and economic growth.

Most of the soybeans are cultivated by smallholder farmers, who account for over 99% of the country's production. These farmers typically grow soybeans under rainfed conditions, facing challenges such as low productivity, with mean yield of 721 kilogram per hectare, far below the global mean of 2,814 kg/ha. Approximately 94.5% of farmers produce soybeans for cash rather than domestic consumption, as there is a lack of processing facilities. The soybean market is also heavily influenced by middlemen, who control nearly 50% of transactions.

Demographically, most households that grow soybeans are male-headed, accounting for approximately 80%, with most household heads falling within the 40 to 64 age range. The average size of a soybean farm is about 0.53 hectares, which is slightly larger than the national average farm size of 0.43 hectares. Despite this, soybean cultivation occupies only 12% of the total arable land owned by farmers, suggesting considerable room for expansion and intensification of production.

In Tanzania, soybean is recognized as a strategic crop, primarily for food and feed production, and it enhances food security [7]. Key regions contributing to soybean cultivation in Tanzania include Ruvuma, Iringa, Mbeya, Njombe, Rukwa, and Morogoro [7], Mtwara, Lindi, and Tanga show strong potential for soybean production due to favorable environmental conditions.

While soybean cultivation has faced challenges, including fluctuating production and low productivity, there is increasing recognition of soybean's significance to the country's agricultural development. Strategies to increase production levels include improving seed quality, enhancing productivity, and promoting innovations of drought-tolerant, insect pest and disease-resistant soybean varieties. Soybeans are grown by both high and low-input farmers in variable environments, highlighting the need for adaptable solutions to support this crop's growth in Tanzania.

The historical development of soybean cultivation in Tanzania has been supported by various breeding and research efforts. Early research in the 1950s and 1960s at Nachingwea by the Overseas Food Corporation, led to the development of high-yielding, locally adapted varieties. In the 1970s, researchers at TARI Ilonga, Kilosa expanded on earlier studies from Nachingwea by exploring better farming methods, including intercropping, the use of fertilizers, and techniques to promote promiscuous nodulation.

In the 1980s, international agricultural research institutions contributed expertise and support, further advancing soybean breeding research. However, the focus of this research shifted between various centers over the years. By the early 2000s, TARI Uyole, located in the Southern Highlands, emerged as the main hub for soybean breeding in Tanzania, while overall research efforts are coordinated from TARI Ilonga in Morogoro.

The Tanzanian government has recognized the significant role of soybeans in enhancing national food security and supporting economic growth. Also, the increasing export of soybeans is adding to their economic value [151]. For instance, in 2021 Tanzania earned approximately USD 75 million from soybean exports. The rising demand for animal products has made soybeans a vital ingredient in the expanding animal feed industry [73, 122]. Furthermore, soybeans improve soil fertility through nitrogen fixation, making them integral to crop rotation systems that reduce reliance on chemical fertilizers [73, 99]. Soybeans are also important for promoting sustainable agricultural practices by enhancing soil health, a growing concern in Tanzania due to soil degradation [99].

With the ongoing growth of Tanzania's population, there is an anticipated increase in the demand for soybean-derived products like soy milk, tofu, and vegetable oils. Also, the soybean has gained great importance in the global market. Furthermore, the expanding livestock sector, driven by growing population and growing demand for meat, poultry, and dairy products, continues to boost the need for soybeans as a high-quality protein source in animal feeds.

Despite the significant growth in soybean production, rain-fed farming systems continue to face several ongoing challenges [157, 93]. Climate change affects rainfall patterns and increases fluctuations in how often, how severe, when, and how long droughts occur [37]. The erratic rainfall patterns in Tanzania's central and northern regions exacerbate the issue of drought, which is expected to intensify with climate change. Drought stress is strongly associated with the effects of climate change [52]. Drought often results in significant fluctuations and decreases in crop yields, which can cause economic hardships for farmers [107, 113, 161, 98, 31, 144, 52]. Increasing drought occurrences and severity, intensified by climate change, present major obstacles to maintaining productivity [56, 77]. Periods of drought are defined by unstable rainfall under the current and climate change scenario in future are predicted to increase, posing a serious threat of soybean productions [107, 125]. Thus, it is essential to address issues related to water scarcity and other environmental stresses that hinder soybean yields.

To address these challenges, this review synthesizes recent global research on breeding drought-tolerant soybean varieties, gaining knowledge from effective methods used in leading soybean-producing nations worldwide. These countries have developed improved crop varieties exhibiting resilience to drought stress across various agroecological zones. For instance, breeding efforts in Brazil have focused on enhancing water-use efficiency, deep root systems, and drought-resistant physiological mechanisms, all of which are for coping with water stress in arid areas.

In Tanzania, breeding initiatives should be tailored to the country's unique climatic conditions in the central and northern regions most vulnerable to drought. The effects of drought are more severe on soybean varieties that are sensitive to drought compared to those that are drought-tolerant [33]. Therefore, breeding efforts need to focus on identifying and developing soybean varieties that possess characteristics like deep roots for accessing water and greater efficiency in water use to improve drought resilience [98, 77]. By incorporating these traits, soybean productivity can be sustained even in the face of variable rainfall patterns. When breeding for drought tolerance and enhancing soybean

resilience to future climate change, it is important to review the progress made so far, taking into account both successful and unsuccessful approaches [149, 26]. Furthermore, additional research is necessary to deepen our understanding of how soybeans respond to drought conditions, as previous studies have shown varying outcomes [55]. Moreover, evaluating different soybean genotypes is necessary to identify those with greater tolerance to drought [55].

2.0 RATIONALE OF THE REVIEW

Tanzania, like many other Sub-Saharan African nations, is facing escalating challenges related to climate change due to prolonged droughts that reduce the efficiency and output of agricultural production [70, 65]. The country has exhibited a slight downward trend in drought severity, though the change is not statistically significant [85, 65]. These drought conditions adversely affect soybean yields, causing poor germination, stunted growth, and a decline in seed quality for legumes such as soybeans [181]. Traits associated with drought tolerance are influenced by multiple genes which are regulated by multiple molecular mechanisms [137, 138, 154]. involving both additive and dominance gene action [53]. Drought stress in plants is most commonly associated with inhibited growth, considerable impairment of the photosynthetic system, a decline in photosynthetic activity, reduced seed germination, and limited nutrient absorption [35]. Addressing these adverse effects requires a thorough understanding of the physiological impacts, the mechanisms involved, and both agronomic and genetic approaches for effective and sustainable management [35]. As such, identifying long-term solutions to reduce the harmful consequences of drought stress is increasingly critical [35]. In light of these concerns, this review compiles recent findings on climate-smart agriculture, which focuses on resilient and sustainable farming practices designed to cope with extreme climate conditions. When combined with the use of drought-tolerant soybean varieties, these strategies hold strong potential for boosting soybean production in Tanzania.

Recent global progress in plant breeding through tools like gene editing with clustered regularly interspaced short palindromic repeats (CRISPR), genomic selection, the use of molecular markers, and transcriptome analysis has enhanced the capacity to develop soybean varieties that are more tolerant to drought and better suited to changing environments [5, 35, 98, 162, 154]. These modern techniques enable the precise identification of genetic traits related to drought resistance, which accelerates breeding efforts and improves crop resilience [56, 123]. This systematic review draws on these global advancements, providing valuable insights for developing soybean varieties specifically suited to Tanzania's agroecological conditions. Molecular breeding has already been successfully implemented in countries like Brazil, where various soybean varieties have been developed to improve their resilience under conditions of water scarcity [83]. These international practices offer a framework for similar breeding strategies in Tanzania, improving the efficiency of developing drought-resistant soybeans.

By reviewing global practices, this systematic review facilitates the exchange of cutting-edge research and technologies from countries with established soybean breeding programs. This review will enable to understand the valuable genetic resources and breeding methodologies that can be shared significantly

expediting breeding efforts in Tanzania by focusing on creating soybean varieties that can withstand drought conditions.

Alongside the application of international breeding innovations, gaining insights into the genetic variation and adaptability of soybean varieties is important for the development of drought-resilient soybean [44]. Incorporating local genetic resources into breeding programs ensures that the resulting varieties are not only drought-tolerant but also suited to specific local environments [19]. In Tanzania, leveraging landraces and exotic soybean genotypes with inherent drought resistance is important for creating varieties that can thrive in local climatic conditions. This review emphasizes the importance of integrating local varieties into global breeding initiatives to foster the creation of genotypes that combine high productivity with adaptability.

The review also highlights promising results from recent breeding trials and field studies aimed at improving drought tolerance in soybeans. For example, the literature indicates that improved soybean genotypes have demonstrated better performance when exposed to drought stress [58]. These findings underscore the necessity of having field trials and area-specific breeding efforts to enhance soybean resilience to climate change. Furthermore, the review stresses that adapting these results to Tanzania's unique climate and growing conditions is essential for achieving sustainable improvements in soybean production.

Finally, the review addresses the broader socioeconomic implications of developing drought-tolerant soybean varieties. Drought-resistant crops can enhance productivity, increase farmer income, and strengthen food security by ensuring more reliable yields, even during drought periods. By tackling the challenges of drought tolerance, this review provides a comprehensive framework for addressing the soybean production issues faced by Tanzania.

3.0 Materials and Methods

Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [86], a systematic review was conducted to gather relevant studies focused on drought tolerance in soybean breeding. This review concentrated on research that assessed genetic mechanisms, breeding techniques, and practical applications in areas susceptible to drought.

3.1. Approach Used to Search and Select Data Sources

A literature search was carried out across several academic databases, including Google Scholar, PubMed, Scopus, JSTOR, and AGORA. The search utilized a combination of keywords such as "soybean drought tolerance," "breeding strategies," "drought stress in soybean," "climate-resilient soybean," "adaptability," "soybean yield in drought-prone areas," and "Tanzania" and Boolean operators such as AND, OR, and NOR were applied, targeting studies that had been published between 2015 and 2025.

3.2. Eligibility and Disqualification Criteria

Studies were considered for inclusion if they centered on soybean and its breeding for drought tolerance, were published in peer-reviewed journals, and offered valuable insights into breeding methodologies, genetic markers, or field-based assessments related to drought tolerance and climate-smart agriculture. To ensure both quality and relevance, selected studies were required to meet the following criteria: publication in peer-reviewed journals, a focus on soybean breeding, evaluation of performance under both drought and non-drought conditions, relevance to climate-smart agricultural practices, and a publication date between 2015 and 2025. Studies were excluded if they lacked empirical data, focused solely on general agricultural practices without specific relevance to soybean, drought or were reviews or editorials without original research

3.3. PRISMA Approach Guideline

The study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [86] to guide the review process. These guidelines were applied to transparently document the procedure used to identify, screen, and select relevant studies for inclusion in the review. This approach outlined the number of studies retrieved, the screening process, and the final selection based on inclusion and exclusion criteria. Initially, 1200 records were identified through database searches, which were reduced to 1000 after removing duplicates. Of these, 950 records were screened for relevance, resulting in the exclusion of 630. A thorough eligibility assessment was conducted on the full-text articles, resulting in an in-depth evaluation of 425 publications. Following additional screening, 235 studies were excluded, and 190 studies that fulfilled all the inclusion criteria were retained for synthesis and analysis focusing on soybean drought tolerance, specifically examining breeding strategies, molecular markers, and field-level implementations.

4.0 Literature Search

4.1. Effect of Drought Condition on Soybean Growth and Productivity

Drought stress negatively influences several key physiological functions in soybean, such as photosynthesis, transpiration, and nutrient absorption, leading to stunted growth and reduced yield [190]. The impact of drought is severe during the vegetative and reproductive phases, contributing to yield losses [5, 167]. When drought occurs during the seed-filling stage, its effects are intensified, often resulting in fewer seeds per pod and lower seed weight. Also, water scarcity can trigger seed abortion and a decline in the number of pods produced, and impaired nitrogen fixation, all of which disrupt seed development and underscore the urgent need for drought-tolerant soybean varieties.

Soybean plants are vulnerable to water deficits during the flowering period, when water scarcity severely impacts yield [185, 38]. During this phase, drought results in reduced seed number and size, along with impaired pod formation, further limiting yield [107, 172]. Soybean yield can be reduced by as much as 50% when drought occurs during the flowering and pod-filling stages [14]. In addition, water stress

during the reproductive phase diminishes seed size and oil concentration, underscoring the need for sufficient water availability at this stage [79].

Soil moisture availability is important for determining soybean productivity under drought conditions, emphasizing the need for effective water resource management during periods of scarcity. Drought during both the vegetative and reproductive stages significantly impacts seed number and quality, further reinforcing the necessity for stable water availability during these growth periods [49].

A major physiological consequence of drought stress is the reduction in photosynthetic efficiency, which has a direct impact on limiting plant growth [64]. To conserve water under drought conditions, plants initiate stomatal closure; however, this response also limits carbon dioxide intake, thereby hindering photosynthesis and decreasing carbohydrate synthesis [94]. In addition to this, drought-induced declines in nutrient absorption and transpiration further intensify stress effects, contributing to even greater yield reductions [94, 3].

4.2. Physiological and Biochemical Adaptations Under Drought Stress

Drought stress influences the morphology and physiology of soybean plants, negatively affecting their growth patterns, development, and productivity [55, 161]. A key physiological effect of water deficit is the decline in leaf water potential (LWP), which in turn reduces the water potential within developing pods. This reduction hampers water availability to maturing seeds, thereby adversely influencing seed formation and overall yield [125]. Also, drought conditions have been linked to decreased chlorophyll levels in soybean leaves [89]. As LWP drops, turgor pressure declines, prompting stomatal closure. This stomatal regulation serves as an essential drought-adaptive mechanism, helping plants minimize water loss during extended dry periods [54, 157].

Besides stomatal modifications, drought triggers a series of morphological responses [54]. One notable adaptation is an increased root-to-shoot ratio, as root systems often remain more resilient to drought-induced growth suppression compared to shoots [108]. Leaf area index (LAI) is typically reduced, and the formation and efficiency of rhizobium symbiosis which are important for nitrogen fixation are also compromised [6]. During the seed-filling phase, drought conditions can limit germination success and shorten flowering and pod development durations, while also reducing the number of leaves and flowers formed [38].

When soil moisture drops below 75% of its field capacity, growth parameters such as LAI, leaf area duration (LAD), specific leaf area (SLA), net assimilation rate (NAR), crop growth rate (CGR), seed mass per 100 seeds, and seed yield per plant are all negatively affected [6, 31]. To combat such stress, soybean plants activate various defensive mechanisms. These include the generation of reactive oxygen species (ROS), production of stress-associated hormones like abscisic acid and ethylene, and modifications in shoot and root architecture [22, 35, 138, 111, 52]. While short-term measures such as

stomatal closure and osmotic adjustments are generally reversible, prolonged exposure to drought can lead to irreversible alterations, such as reduced shoot growth and long-term metabolic changes [111].

Soybean plants adopt diverse physiological strategies to withstand drought [89]. These include controlling stomatal conductance to reduce water loss and enhancing osmotic adjustments to maintain turgor pressure [109, 52]. Osmolyte accumulation such as proline and soluble sugars is another important adaptation, helping plants preserve cell integrity and function under water-limited conditions [146, 29]. Moreover, antioxidant systems including superoxide dismutase (SOD) and catalase are activated to mitigate oxidative stress caused by drought-induced ROS [35, 128, 111, 97]. Hormonal signaling involving molecules like abscisic acid (ABA), ethylene, and jasmonic acid regulates stress-responsive genes responsible for water-use efficiency, root architecture, and transpiration control [97]. Transcription factors such as the dehydration-responsive element-binding (DREB) protein family also play important roles in enhancing drought tolerance by modulating gene expression [59].

Water deficit interferes with fundamental physiological processes in soybeans, reducing photosynthetic capacity, altering internal water dynamics, and impairing nutrient uptake [61, 29, 3]. Reduced transpiration under drought conditions leads to lower water-use efficiency (WUE) and plant productivity [5, 22, 20]. Furthermore, limited carbon assimilation due to stomatal closure and smaller leaf surface areas contributes to yield declines. When drought coincides with reproductive stages, these effects become more pronounced, often leading to fewer and lighter seeds.

During critical periods such as flowering and pod filling, drought significantly affects seed development by producing a larger proportion of smaller seeds, which negatively impacts both yield and oil concentration. This has serious implications for regions where soybeans are a primary source of food and biofuel feedstock. Biochemically, plants respond to drought by accumulating osmoprotectants like proline and soluble sugars, which help maintain cell turgidity and protein function during water stress [179, 29]. Also, oxidative damage from ROS is mitigated by increased activity of antioxidant enzymes like SOD, catalase, and peroxidases ([35, 97, 104].

Drought-tolerant soybean cultivars typically exhibit stronger antioxidant responses compared to drought-sensitive ones [59]. These tolerant varieties are known to accumulate higher concentrations of proline and other osmolytes, enhancing their ability to survive under limited water availability [113, 112]. They also show elevated activities of antioxidant enzymes, indicating that a robust antioxidant defense system is a key trait for drought resistance [139].

Finally, drought disrupts numerous physiological and biochemical functions, including evapotranspiration, gas exchange, chlorophyll synthesis, and relative growth rates [84]. Under such stress, soybean plants exhibit significantly lower rates of photosynthesis, stomatal conductance, and transpiration, although intracellular CO₂ levels tend to change only slightly in the early phases of water stress [170].

4.3. Impact of Drought on Social and Economic Conditions

Drought poses socioeconomic challenges to soybean production in sub-Saharan Africa, impacting smallholder farmers who depend on vulnerable agroecological systems and face weak institutional support [65]. Evidence from Ghana shows that targeted interventions, such as low-cost input bundles that include certified seed, inoculants, and fertilizer, can empower marginalized groups, like female farmers. These interventions enable them to move beyond subsistence farming by enhancing productivity and providing a buffer against climatic risks [96].

However, in Malawi, despite improvements in household food security and dietary diversity linked to adopting better soybean varieties and agronomic practices, yields remain significantly below their potential (around 1 t/ha) [25]. Systemic barriers, such as poor transport infrastructure, mismanagement of the Farm Input Subsidy Program (FISP), and weak market connectivity, limit the scale of impact [25]. These structural constraints are evident throughout Southern Africa, where soybeans are generally grown as a low-input, rainfed crop. Here, persistent yield gaps of up to 67% are exacerbated by limited irrigation, inadequate policy support, and underdeveloped value chains, making the crop vulnerable to drought.

In Tanzania, recent data indicate that drought conditions have increased food-related household expenditures by 25% and raised the likelihood of food shortages by 12%, underscoring the immediate economic strain on farming households [71]. While indicators like meal frequency and dietary diversity have remained relatively stable, qualitative declines in food quality signal hidden forms of nutritional vulnerability and weakening long-term resilience.

Globally, drought has been shown to reduce soybean yields by over 50%, with cascading effects on household income, labor markets, and regional food security [5]. In Namibia, and Botswana drought has impacted both on-farm productivity and off-farm interconnected rural economies [65]. Similarly, in South Africa, extreme droughts between 2011/ 12 and 2020/21 in 2015 and 2018 significantly reduced yields of crops exacerbating food insecurity among already marginalized populations [65].

4.4. Genetic and Molecular Approaches for Improving Drought Tolerance

Molecular breeding techniques, including marker-assisted selection, quantitative trait loci (QTL) mapping, genome-wide association studies (GWAS), and genomic selection, are extensively utilized to enhance drought tolerance, with their effectiveness largely dependent on the genetic diversity present in target traits [5]. Globally, breeding initiatives have increasingly concentrated on improving drought tolerance in soybean as an objective [119, 66]. A significant challenge lies in identifying the complex traits associated with drought resistance, as multiple genes and signaling pathways interact, complicating the identification of specific traits linked to this ability [63]. Recent progress in genome-wide association studies (GWAS) and quantitative trait loci (QTL) mapping has facilitated the discovery of loci linked to drought tolerance [184]. Genes that influence root architecture are those controlling root length and density which have demonstrated potential in improving drought resilience in soybean [145, 77].

Transgenic strategies have been explored to enhance drought tolerance in plants by overexpressing genes associated with stress response, such as those encoding late embryogenesis abundant (LEA) proteins and dehydrins [62, 39]. Dehydrins (DHNs), a specific subgroup within the LEA protein family, have been identified as key contributors to plant drought stress adaptation [39]. These proteins are broadly expressed throughout the plant when intracellular water levels are reduced, aiding in cellular protection during dehydration [124]. Specifically, dehydrins contribute to desiccation resistance by stabilizing cellular membranes, proteins, and nucleic acids under drought conditions [124]. Also, transcription factors (TFs) are increasingly being applied in the genetic engineering of soybean to enhance tolerance to abiotic stresses [42]. Despite these advancements, the commercial deployment of genetically modified soybean varieties remains restricted in certain areas due to regulatory barriers and societal concerns [110].

Drought tolerance in soybean is governed by a complex molecular framework that includes numerous genes and intricate regulatory pathways [81]. Genetic studies have concentrated on understanding how stress-related genes modulate drought responses [81]. For example, dehydration-responsive element-binding (DREB) proteins have been recognized in soybean as key regulators of gene expression under drought stress conditions [171, 77]. Also, the role of aquaporins has been explored; these proteins facilitate water transport, and the enhanced expression of specific aquaporins can improve drought resistance by ensuring efficient water use.

The use of advanced genomic technologies, such as genome-wide association studies (GWAS) and quantitative trait loci (QTL) mapping, has significantly contributed to the identification of genetic regions associated with drought tolerance in soybean [81]. Through GWAS, researchers have uncovered several QTLs linked to drought-responsive traits, including modifications in root structure, maintenance of leaf water content, and enhancement of photosynthetic performance [163, 184, 77]. These findings provide valuable insights for molecular breeding programs aimed at developing soybean varieties with improved drought resistance.

On the molecular level, drought stress triggers a cascade of signaling events that modulate gene expression and protein production [78]. Among the key components of this regulatory network are transcription factors such as DREB, which play roles in initiating the expression of drought-responsive genes in soybean [187, 188]. These genes are involved in important protective mechanisms, including the synthesis of osmolytes and stress-related proteins that enhance the plant's capacity to withstand water deficiency [78].

The plant hormone abscisic acid (ABA) is recognized as an important mediator in drought response signaling [35, 78, 81]. ABA plays an important role in facilitating drought adaptation by promoting stomatal closure, conserving water, and regulating gene expression under stress conditions [137, 138, 35, 97]. In soybean, ABA-dependent signaling pathways contribute to drought tolerance by regulating genes involved in osmotic balance and root system architecture [35].

4.5. Breeding Strategies for Drought-Tolerant Soybean

Drought continues to pose a significant challenge [65]. Breeding for drought tolerance remains difficult due to the intricate interplay between genetic factors and environmental conditions [100]. Nevertheless, recent progress in genomic technologies has enhanced the efficiency of trait evaluation, expanded the genetic diversity within germplasm collections, facilitated the incorporation of beneficial traits from novel genetic sources, and enabled the discovery of genes responsible for key drought-related characteristics [100]. Marker-assisted selection (MAS) and genomic selection (GS), also help minimize the environmental impact of breeding practices [100]. Advanced breeding methodologies have been widely applied in the development of soybean cultivars with improved drought tolerance [5]. In particular, marker-assisted selection (MAS) has become a key approach for detecting and selecting soybean lines that exhibit resistance to drought stress, significantly improving drought tolerance without sacrificing yield potential [49]. In Brazil, for instance, breeding efforts have concentrated on areas like the Cerrado, which are susceptible to dry spells. The Brazilian Agricultural Research Corporation (EMBRAPA) has successfully developed drought-resistant varieties such as BR 4, Ocepar 4, and BR 48. Soybean varieties developed for drought-prone environments often exhibit enhanced water-use efficiency and deeper root systems, enabling them to perform well under limited water availability and irregular rainfall patterns [180, 12]. One such example is the BR 48 variety, which demonstrates improvements in root depth and water-use efficiency, contributing to its strong drought tolerance. This variety consistently maintains yield stability under drought stress and has shown particular value in regions characterized by intermittent rainfall [12].

Breeding programs have aimed to create soybean varieties with deep root systems, improved osmotic adjustment, and reduced stomatal conductance to help conserve water during dry spells. For example, varieties with deep roots and efficient water use tend to yield better in drought conditions [163]. Tanzania could implement similar strategies in its local breeding programs by selecting for these traits to strengthen resilience against water stress.

In addition to BR 48, several other soybean varieties developed for drought-prone environments possess advantageous traits such as deep root systems, effective osmotic regulation, and high stomatal conductance. These characteristics collectively contribute to maintaining yield stability during periods of water stress. In Brazil, efforts to improve drought resilience in soybean have increasingly combined traditional breeding approaches with molecular tools, leading to the development of varieties that perform reliably under limited water availability [118].

Marker-assisted selection (MAS) has been instrumental in targeting traits associated with water-use efficiency and osmotic adjustment. Through MAS, breeders have successfully identified and incorporated favorable alleles into drought-tolerant genotypes. For example, the USDA-N8002 variety exhibits enhanced root development and improved water-use efficiency, contributing to its notable drought resistance and high yield performance under dry conditions [171]. Similarly, U.S.-bred soybean varieties have benefited from the integration of quantitative trait loci (QTLs) related to osmotic regulation and deep rooting, resulting in genotypes with increased drought resilience [156].

The breeding lines such as R10-5086 and R11-6870 combine strong drought adaptation with high yield potential and agronomic traits like lodging and shattering resistance. These attributes make them promising parental lines for incorporating yield-enhancing genes into both public and private breeding efforts [68]. Moreover, several lines including PI 416937, PI 427136, PI 408105A, PI 471938, PI 424088, PI 081041, N04-9646, DT51, and R02-1325 have shown strong performance under water-deficit conditions, offering valuable genetic resources for future breeding programs [132, 180].

Among these, the Jackson variety stands out for its drought-escape mechanism, attributed to its long and deep root system that facilitates efficient water uptake compared to drought-sensitive cultivars [180, 132]. Jackson has also demonstrated the capacity to maintain nitrogen fixation under drought stress, marked by reduced leaf ureide concentrations [132]. In addition, lines PI 416937 and PI 471938, known for their slow canopy wilting, have been observed to sustain nitrogen fixation during the pod-filling stage under drought conditions. This trait slow canopy wilting may serve as a reliable phenotypic indicator of drought tolerance in soybean, particularly in relation to its ability to preserve nitrogen fixation under water-limited scenarios [132].

In India, molecular breeding has focused on identifying and incorporating genes associated with root development, osmotic adjustment, and leaf water retention [114]. In response to India's highly variable rainfall patterns, the Indian Council of Agricultural Research (ICAR) has developed and identified soybean genotypes with improved drought tolerance. Utilizing advanced molecular techniques such as RNA interference (RNAi) and Virus-Induced Gene Silencing (VIGS), several drought-resilient accessions have been screened and characterized. These include EC 538828, PI 416937, Young, EC 602288, NRC 7, Hardee, and JS 71 – 05, all of which exhibit promising tolerance to water-deficit conditions. Among these, JS 335 is widely adopted for its deep root system and efficient water-use traits, consistently outperforming other varieties in semi-arid areas experiencing water stress [101]. Another variety, Pusa 16, has been recognized for its ability to withstand drought conditions and ability to thrive even with irregular monsoon rains, resulting in stable yields [91].

Selection for high transpiration efficiency and the capacity to maintain photosynthetic activity during drought stress is emphasized [31]. China is employing genomic selection to identify varieties that excel under drought conditions, concentrating on genes associated with water use efficiency and deep rooting [173]. In China, genetic engineering has significantly contributed to enhancing drought resilience. The GmDREB1A transgenic soybean, created by incorporating the AtDREB1A gene from Arabidopsis, demonstrates improved leaf water potential and osmotic pressure during drought stress, leading to higher survival rates and yields in arid environments [188, 186]. These findings provide important guidance for advancing soybean breeding efforts in Tanzania, highlighting the necessity of prioritizing photosynthetic stability and efficient water use in dry periods.

In Africa, where drought poses a considerable threat to food security, breeding initiatives have prioritized the development of varieties with enhanced drought tolerance for sub-Saharan countries. The TGX 1835-10E variety, originating from the breeding efforts of the International Institute of Tropical Agriculture

(IITA), is resilient in drought conditions in West Africa and performs well in countries like Nigeria and Cameroon, where water scarcity affects agricultural productivity (Akinmoladun et al., 2024).

If adapted to Tanzania's breeding programs, these techniques could accelerate the development of drought-resistant genotypes targeting drought-prone areas. By combining advanced molecular tools with traditional breeding practices, Tanzania could enhance drought resilience in its soybean varieties.

4. 6. Soybean Adaptability and Yield Performance

Soybean adaptability differs between drought-prone and non-drought-prone areas, necessitating breeding strategies tailored to each region's environmental conditions [120].

In regions with high rainfall, such as Tanzania's southern highland zone, soybean breeding focuses on maximizing yield potential and enhancing pest resistance. In contrast, areas such as the central and northern parts of the country, which frequently experience drought conditions, breeding efforts should prioritize improving stress tolerance [70], which includes developing soybean varieties with superior root systems and enhanced water conservation mechanisms.

Both the genetic makeup of soybeans and local climate conditions influence their adaptability. In Tanzania, the marked differences in rainfall patterns across regions require distinct breeding approaches [70]. Drought stress significantly impacts soybean yields, diminishing both the quantity and quality of harvests [45]. For example, soybean yields have been projected to decline by approximately 6% with every 1°C rise in temperature, has been estimated in Brazil [119]. Drought-tolerant varieties can achieve yields that are 20–30% higher under drought conditions compared to traditional varieties [166, 152]. By adopting similar drought-tolerant cultivars, Tanzania could stabilize soybean production and mitigate the effects of increasing drought frequency.

4.7. Non-Drought Prone Regions of Tanzania

In Tanzania's non-drought-prone regions, such as the southern highlands and coastal areas, soybean productivity is less affected by water scarcity. Nevertheless, achieving yield stability and enhancing resistance to insect pests and diseases are of objectives. For instance, in Argentina, where the climate is relatively stable, breeding programs aim to maximize yield potential while ensuring disease resistance and water use efficiency [130]. A similar strategy could benefit Tanzania's non-drought-prone regions, with a focus on developing disease-resistant soybean varieties. In these areas, the emphasis is on optimizing yield potential and increasing disease resistance. Non-drought-prone regions of Tanzania, can prioritize improving nutrient uptake, enhancing pest resistance, and optimizing water use efficiency. These strategies are relevant to Tanzania's southern and coastal zones, where boosting soybean productivity and resilience to pests and diseases is essential.

4.8. Drought-Prone Regions

In drought-prone areas of Tanzania like in the central and northern areas, it is essential to select soybean varieties that possess drought-tolerant traits. Traits like extensive root development, effective osmotic adjustment, and the ability to retain leaf moisture contribute to the ability of soybean plants to perform well under water-limited conditions [163, 23, 176, 51]. Research in Ethiopia indicates that drought-tolerant varieties with deep roots can sustain yields even during water scarcity [1].

Tanzania could implement similar breeding strategies by prioritizing varieties that stabilize yields in water-limited conditions. Productive soybean varieties with traits like deep roots and increased water use efficiency perform better in dry environments of India, Ethiopia, and Malawi were tested [61, 4]. Emphasizing these adaptive traits could improve the resilience and yield performance of soybean in Tanzania's drought-affected areas.

4.9 Breeding Techniques for Drought Tolerance in Soybean

This review synthesizes breeding strategies from countries which have successfully developed soybean varieties capable of thriving under drought stress. Breeding for drought tolerance has become a focus, especially in countries where soybean production is essential for food security. The search identified various breeding techniques used globally to produce soybean cultivars with enhanced tolerance to drought conditions, incorporating both conventional and biotechnological approaches.

4.9.1. Conventional breeding

During development of drought tolerant soybean varieties conventional techniques are being used [98]. It involves selecting soybean genotypes with naturally occurring drought-tolerant traits. Selecting local soybean varieties with drought-tolerance traits has proven effective, as these varieties demonstrate resilience. Soybean varieties with improved drought tolerance have been developed through such selection for traits like deep rooting and enhanced stomatal control [161, 60, 133]. There is potential to use wild relatives of soybean, which possess natural drought tolerance traits, to improve existing soybean cultivars through introgression breeding [120]. In Brazil, breeders have concentrated on traits such as improved leaf area efficiency, rapid stomatal closure, and deep root systems, all of which contribute to maintaining yield during water shortages [177]. These traditional breeding methods focus on root architecture, leaf morphology, and water use efficiency, successfully producing soybean varieties that thrive under water-limited conditions [77]. While effective in areas with moderate rainfall, these methods are also beneficial in Tanzania, where drought periods are increasingly common. Pedigree selection, recurrent selection, backcross, artificial mutagenesis as conventional techniques have played an important role in the genetic improvement of drought tolerance [138, 98]. The conventional breeding remains a vital approach for creating soybean varieties which are drought tolerant, though it has proven effective but may not be sufficient for developing new varieties that are more resilient to abiotic stresses, such as drought [18]. Alternative strategies include biotechnological techniques such as mutation breeding, marker-assisted selection (MAS), genetic engineering, and genome editing show significant promise thus can be explored on their own or in enhancing genetic variability and improve drought

tolerance, conventional breeding methods can be effectively complemented by other approaches [18, 77].

4.9.2. Molecular breeding and marker-assisted selection (MAS)

Developing soybean varieties with improved drought tolerance relies heavily on strategic breeding efforts. Advances such as genetic engineering and marker-assisted selection (MAS) have introduced innovative approaches to strengthen drought resistance and enhance the effectiveness of breeding programs [50]. In the Indian context, researchers have applied MAS to identify genes linked to drought tolerance, focusing on key traits including water use efficiency and responses to osmotic stress [121]. Similarly, in the United States, MAS has been extensively applied to identify genetic markers for traits like stomatal conductance, osmotic adjustment, and root depth, all of which contribute to drought resistance [175].

To date genetic engineering techniques have been investigated [154]. In addition, transgenic and genetic modification techniques have been investigated to improve drought tolerance by enhancing the expression of stress-responsive genes. These strategies have shown promise in increasing plant resilience under drought conditions [63, 144]. For example, transgenic soybean lines engineered to overexpress heat shock proteins (HSPs) exhibited greater drought tolerance, maintaining both photosynthetic activity and yield under water-deficit environments [144].

Tanzania's breeding programs could significantly benefit from this molecular approach, allowing breeders to select for drought-tolerant traits more rapidly and efficiently. By incorporating MAS, Tanzania could hasten the development of soybean varieties better suited to its increasingly variable climate. Studies have shown that combining marker-assisted selection (MAS) with traditional breeding techniques has contributed to the development of soybean varieties exhibiting enhanced yield stability under drought stress.

4.9.3. Genomic selection

Genomic selection (GS) combines high-throughput genotyping with sophisticated statistical models to predict the breeding value of soybean genotypes. Research in the United States has demonstrated the effectiveness of GS in identifying lines that exhibit enhanced drought resilience and consistent yield performance under water-limited conditions [20]. Similarly, research conducted in China has employed genomic selection (GS) to assess the breeding potential of soybean genotypes under drought stress [140]. Utilizing high-throughput sequencing technologies alongside computational modeling, GS supports the identification and selection of soybean varieties with improved drought tolerance and stable yield performance. Tanzania could implement these advanced breeding technologies to identify genetic traits that improve soybean resilience in drought-prone areas, thereby expediting the development of crop varieties adapted to the nation's evolving climatic conditions.

4.9.4. Climate-smart agriculture approaches

Countries like South Africa have effectively combined climate-smart agricultural practices with soybean breeding programs to promote drought-tolerant varieties [9]. Key strategies such as crop diversification, efficient water use, and improvements in soil health are being implemented to strengthen the resilience of soybean production systems under shifting climatic conditions. In Tanzania, numerous climate-smart agriculture (CSA) initiatives have been carried out to support these efforts [15]. Integrating drought-tolerant soybean varieties with CSA practices presents a promising approach to enhancing both productivity and climate resilience in soybean farming.

4..10. Integrated agronomic and genetic strategies for alleviating drought stress

A holistic strategy that merges genetic improvement, agronomic practices, and environmental management holds significant potential for improving drought tolerance in soybean. This means that in addition to genetic strategies, agronomic practices are essential for managing drought stress in soybean. The soil texture and drainage capacity significantly influence soybean's ability to cope with water stress, highlighting the need for region-specific agronomic practices and breeding strategies. There is significance of soil water retention and its impact on soybean productivity during drought periods [62]. Precision irrigation methods, such as regulated deficit irrigation, have proven effective in enhancing water-use efficiency without causing substantial reductions in yield [57]. Modifying irrigation timing based on real-time soil moisture levels offers an additional means to reduce drought-related impacts [14]. Conservation practices like mulching and reduced tillage also contribute by improving soil moisture retention, thereby reducing water stress in soybean crops [172]. Similarly, controlled irrigation techniques, including deficit irrigation, can significantly boost water-use efficiency while maintaining acceptable yield levels [61].

The adoption of precision agriculture tools such as soil moisture sensors and remote sensing technologies is becoming increasingly important for monitoring and managing drought stress in soybean fields. For example, a study conducted in Australia demonstrated that utilizing precision irrigation systems guided by real-time soil moisture data led to higher yields during drought by minimizing water loss and optimizing water application.

Combining genetic improvements with agronomic innovations is important for addressing drought-related challenges in soybean production. Integrating drought-tolerant soybean cultivars with precision farming tools like moisture sensors and remote sensing has been shown to improve both water-use efficiency and yield stability under drought conditions [146]. In Brazil, [120] proposed a comprehensive framework that incorporates drought-resilient varieties, advanced irrigation technologies, and optimized planting schedules to mitigate drought impacts. This integrative approach in blending genetic advancements with precision agronomy offers considerable potential for improving drought resilience in soybean. For instance, coupling drought-resistant cultivars with targeted irrigation strategies has been reported to enhance both yield outcomes and water efficiency [155]. Recent findings also emphasize the

importance of breeding drought-tolerant soybean varieties tailored to specific agroecological zones, in conjunction with precision agriculture, as an effective pathway to reduce the adverse effects of drought stress [171].

4.11. Genetic mechanisms of drought tolerance

Drought tolerance in soybean is governed by a complex interplay of genetic components that regulate essential physiological functions, such as water absorption, stress signaling, and yield maintenance under water-deficient conditions [29]. A key adaptive trait is root system architecture; deeper and more expansive root structures enable plants to tap into moisture from lower soil horizons, thereby improving drought resilience [178]. Another important factor is stomatal behavior on efficient stomatal closure during periods of water scarcity minimizes transpiration losses and supports plant survival under drought stress [160].

The osmotic adjustment through the synthesis and accumulation of compatible solutes like proline, helps maintain cellular turgor during dehydration, allowing the plant to better cope with water limitation [153]. Antioxidant defense mechanisms also play a role by mitigating oxidative damage induced by drought stress, thereby preserving cellular integrity and overall plant vitality [48, 174]. Collectively, these physiological and biochemical adaptations enhance soybean performance under drought conditions and represent key targets in the development of drought-tolerant cultivars.

4.12. Field applications of drought-tolerant soybean varieties

Field trials in Brazil and India have shown that drought-tolerant soybean varieties can sustain acceptable yields during dry spells. For instance, drought-tolerant varieties developed in Brazil have consistently outperformed conventional varieties in low rainfall areas [177]. Tanzania could benefit from implementing similar breeding programs that prioritize the selection of drought-tolerant genotypes and conduct field trials to assess their performance in local, real-world conditions. This strategy would ensure that the chosen varieties are well-suited to Tanzania's unique climate challenges.

5. Results and Discussion

Drought stress represents a significant constraint on global soybean production, with impacts on both the productivity and quality of soybean yield [81, 40]. As the effects of climate change become increasingly evident to exacerbate water scarcity in areas vulnerable to drought, the agricultural sector is facing increasing challenges. Consequently, research efforts aimed at developing drought-tolerant soybean varieties have gained considerable momentum. These efforts focus on a range of strategies, including genetic, physiological, and agronomic approaches, to enhance soybean's resilience to water stress [138, 18].

Developing soybean genotypes capable of thriving in drought-prone environments is key to securing food systems and sustainable agricultural production. Drought performance studies consistently demonstrate that drought-tolerant varieties provide greater yield stability under stress conditions. For example, [93] reported a 25% yield increase for drought-tolerant varieties compared to non-tolerant varieties during dry spells. To address these challenges, scientists have made significant progress in improving drought tolerance through genetic advancements, with several studies underscoring the role of genomic tools, marker-assisted breeding, and genetic selection [137, 141, 66]. These innovations are being complemented by an enhanced understanding of the physiological mechanisms that enable soybean to cope with water stress, such as osmotic regulation, antioxidant responses, and efficient water-use strategies.

By integrating genetic improvements with adaptive physiological mechanisms, developing drought-tolerant soybean varieties hold significant potential to enhance yield and production stability in areas facing water scarcity. In addition, adopting best management practices such as techniques that promote soil moisture conservation and the use of precision irrigation can further strengthen the ability of soybean crops to withstand drought stress. Ultimately, enhancing drought tolerance in soybean requires an integrated strategy that combines genetic improvement, physiological adaptation, and agronomic innovations, which is essential to sustaining global soybean production under the pressures of climate change.

5.1. Genetic Improvement and Breeding Strategies

Significant advancements have been achieved in the genetic enhancement of drought tolerance in soybean, largely due to the progress in genomic selection and marker-assisted breeding technologies [132]. As one of the leading global producers of soybean, Brazil has played a pivotal role in this domain by applying genetic approaches to strengthen drought resilience. The identification of genes associated with osmotic regulation, stress-responsive proteins, and antioxidant mechanisms is vital for advancing breeding programs aimed at improving drought tolerance [133]. These genetic targets offer promising avenues for the development of more resilient soybean cultivars.

Likewise, marker-assisted selection (MAS) has proven effective in identifying genetic markers linked to key drought-tolerance traits, including root system architecture, proline content, and osmotic adjustment [175]. These physiological and morphological traits are instrumental in enhancing the crop's capacity to endure water-limited conditions. In the United States, genomic selection has been increasingly adopted to refine breeding precision for drought tolerance in soybean [8]. By leveraging multiple markers associated with drought-adaptive traits, genomic selection provides a more targeted and efficient framework for trait improvement.

In addition, bibliometric and meta-analytical tools have been employed to track emerging trends in genetic strategies for drought resilience in crops [34]. Their findings highlight a growing preference for

multi-trait genomic selection models, which enable simultaneous selection for various drought-related traits, thereby offering a more integrated approach to improving drought tolerance in soybean.

The combination of traditional breeding techniques with modern molecular tools such as MAS and genomic selection has accelerated progress in developing drought-tolerant soybean cultivars [165, 74, 154]. MAS, in particular, allows breeders to target specific drought-resistance genes, thereby shortening breeding cycles and improving the accuracy of selection [171, 154]. Its effectiveness in enhancing drought tolerance without compromising yield highlights its significance in breeding programs tailored for drought-prone environments.

Advanced genetic tools including genome-wide association studies (GWAS), quantitative trait locus (QTL) mapping, and association mapping have been instrumental in identifying genetic loci involved in drought response [137]. These methodologies provide in-depth insight into the genetic basis of drought tolerance by revealing specific genes or genomic regions responsible for the trait. Characterizing these genes enhances our understanding of the underlying biological mechanisms and contributes to more targeted crop improvement strategies.

The adoption of high-throughput technologies, such as whole-genome sequencing and advanced phenotyping systems, has made it possible to conduct comprehensive assessments of genetic diversity in plant populations. These tools support the detection of loci or haplotypes related to drought adaptation, enabling the development of genetic markers that can be employed in breeding initiatives. Moreover, innovative breeding approaches like genomic selection and breeding-by-design are poised to accelerate the creation of soybean lines with superior performance under water-deficient conditions.

Recent research has also pinpointed promising donor parents (see Table 1) that exhibit favorable drought-tolerant traits in soybean. These genetic resources offer substantial value for breeding programs, as they can be strategically integrated into crossing schemes to introduce or enhance drought-tolerant alleles in elite soybean varieties. Ultimately, this contributes to improving both drought resilience and yield potential in soybean production.

Table 1
List of some donor lines with traits related to drought tolerance in soybean

Soybean donor Parents	Traits	Reference
PI 408105, PI 081041, PI 090479, PI 407162	Total root length	[92, 132]
PI 408105, PI 483463, PI 248515, PI 424088	Root angle	[132]
PI 408105, PI 416937, PI 603713, PI 248515	Fibrous rooting	[132]
PI 427136, 4J105-3-4, CL0J1760-6-8,	Number of metaxylem	[132]
PI 416937, Jackson, PI 567690, PI 567731, R02-1325, N05-7432, N04-9646, N06-7194, R09-1069, N06-7543, R07-5235, R09-1121, R07-7044	Canopy wilting	[132]
PI 471938, R05-5559	Canopy wilting	[132]
Jackson, PI 471938, PI 222547, PI 374163, PI 423886, PI 42932, PI 507039, PI 227557, PI 507414, PI 578315B, R02-1325, N05-7432, N04-9646, N06-7194, R09-1069, N06-7543, R07-5235, R09-1121, R07-7044, R05-5559	Maintenance of biological nitrogen fixation capacity during drought stress	[132]
PI 407162	Root thickness	[92]
Wandou-37	Pod development	[32]

5.2. Drought-induced Physiological Processes and Adaptive Responses

Understanding the physiological mechanisms underlying crop responses to water stress is essential for accelerating breeding efforts aimed at enhancing drought tolerance [138]. Soybean employs a diverse range of physiological adaptations to mitigate the adverse impacts of drought. One of the key traits contributing to drought resilience is the stability of photosynthesis, where genotypes capable of sustaining higher photosynthetic rates under limited water availability tend to perform better under stress conditions [31]. Root architecture also plays a role; deeper root systems enable plants to extract moisture from deeper soil layers, thereby improving drought adaptation [145].

Another important adaptive mechanism is the plant's antioxidant response, which serves to mitigate oxidative stress triggered by drought. Studies have shown that drought conditions increase the activity of antioxidant enzymes, which help neutralize reactive oxygen species (ROS) and protect cellular components from damage [48, 174, 104]. These findings highlight the importance of targeting genes associated with antioxidant pathways in soybean breeding programs focused on drought resilience.

Osmotic adjustment is involving the accumulation of compatible solutes such as proline. These osmolytes help maintain turgor pressure and cellular functions during dehydration, enabling plants to continue physiological processes under drought conditions. Soybean varieties that demonstrate more efficient osmotic regulation often show improved drought tolerance [59].

Additional physiological adaptations to drought in soybean include improved stomatal behavior, antioxidant production, and enhanced proline accumulation. Drought-tolerant genotypes typically exhibit a greater capacity to synthesize proline, which contributes to osmotic balance during periods of water scarcity [143]. Similarly, well-developed antioxidant systems offer protection against oxidative damage, thereby promoting greater yield stability under stress [48, 174].

These physiological traits are not uniformly expressed across all genotypes, as drought response varies among soybean cultivars. Traits such as enhanced proline biosynthesis and robust antioxidant activity play important role in minimizing oxidative damage, thereby preserving growth and yield potential even under prolonged drought conditions [129, 146]. Furthermore, efficient stomatal regulation is a trait which is more prevalent in drought-tolerant lines contributes to improved water-use efficiency by minimizing unnecessary water loss [54, 160]. Collectively, these adaptive mechanisms are foundational for developing soybean varieties that can maintain productivity under water-limited conditions.

5.2.1 Drought stress and compensation mechanisms in soybeans

Drought stress poses a major environmental challenge for soybean plants, negatively impacting their physiological and metabolic processes [30]. However, when the stress surpasses a certain threshold, these plants can trigger a compensation response during rehydration. This response involves beneficial physico-biochemical changes that allow the plants to recover. In some cases, the plants may even overcompensate, showing improved growth and metabolic processes compared to their initial state. These adaptive mechanisms play important role in mitigating the negative impacts of drought, enhancing plant survival, and contributing to improved crop productivity [183, 52].

5.2.2 Compensation mechanism in soybean

Compensation is a well-documented phenomenon in soybeans, typically observed following stress or injury. It serves as a self-regulatory mechanism that helps plants recover from environmental challenges. In terms of water management, compensation demonstrates a plant's ability to rebound from stress and effectively use available water [105]. This trait is important for sustainable soybean production practices, especially in drought-prone areas, as it highlights the plant's resilience to water deficits.

5.2.3 Genotypic variation of soybean in compensation responses

Soybean genotypes display varying responses to drought stress, with certain genotypes demonstrating higher levels of tolerance by preserving key traits such as leaf area and chlorophyll content during the vegetative stage under water-limited conditions [161]. This suggests that certain soybean varieties possess inherent self-regulatory mechanisms, referred to as compensation, which help them withstand

both abiotic stresses and physical injury [16]. After rehydration, these genotypes can show positive growth compensation or even overcompensation in metabolic recovery [30]. This indicates their capacity to recover from drought-induced damage, resulting in improved growth after rewatering. However, a drought-tolerant soybean variety may exhibit partial drought resilience because it can recover its photosynthetic traits, although it does not improve its leaf thermal traits [37].

5.2.4 Importance of compensation for water use efficiency

Compensatory mechanisms play an important role in enhancing water-use efficiency in plants, particularly in regions frequently affected by drought. In soybean, the capacity to recover from drought and demonstrate compensatory growth following rehydration is a key trait for breeding efforts focused on improving drought resilience and yield stability [87]. Studies have highlighted specific genotypes, such as Ovidiu F and Steara, which show higher drought tolerance with only slight reductions in agronomic traits (Table 2). Conversely, genotypes like 14004 S1-4 exhibit significant sensitivity to water stress, experiencing substantial declines in performance [87]. These results emphasize the importance of understanding and leveraging compensatory growth responses in soybean as a strategy to enhance drought tolerance and optimize yield potential under variable moisture conditions.

Table 2 Recovery or Compensation index (RCI) under optimal conditions of water supply, water stress and after rehydration						
Genotype	Plant height (cm)	Aerial biomass accumulation (g d.m/plant)	root length (cm)	Root biomass accumulation (g d.m/pl)	The leaf surface (mm2)	Chlorophyll content (SPAD units)
14004 S1-4	-0.47	-0.54	-0.17	-0.78	0.39	-0.07
14007 S1-3	-0.63	0.34	-0.02	0.71	0.99	0.97
14024 S1-7	-0.20	0.20	-0.37	-0.13	0.98	-0.06
04046 S1-101	-0.66	0.69	0.79	1.00	0.61	-0.06
09022 S1-2	-0.79	-0.56	0.74	-0.49	-0.46	0.95
Safta F	-0.61	-0.38	-0.04	-0.84	-0.44	0.97
Steara	0.33	-0.02	2.14	0.97	0.87	0.91
Ovidiu	0.15	-0.09	0.27	0.98	0.56	0.16
Source: [87]						

The Recovery or Compensation Index (RCI) is an important tool for evaluating the capability of soybean genotypes to recover from drought stress. It does this by comparing their performance under optimal

water supply, during water stress, and after rehydration. A positive RCI signifies that the genotype not only recovers but may also surpass its pre-drought performance, indicating enhanced growth and physiological functions. This suggests a high level of resilience and valuable potential for breeding drought-tolerant, water-efficient varieties. In contrast, a negative RCI reflects poor recovery after rehydration, indicating a high sensitivity to drought and low resilience, making such genotypes less desirable for drought-prone environments. An RCI of zero indicates that the genotype returns to its pre-drought state without any significant improvement or decline, suggesting moderate resilience but a lack of enhanced recovery potential. For instance, a genotype with a positive RCI of + 0.2 shows a 20% improvement post-rehydration, while a negative RCI of -0.2 indicates a 20% reduction in growth compared to pre-drought conditions, signaling poor recovery.

5.3. Agronomic Practices for Drought Mitigation

Beyond genetic advancements, agronomic interventions play an important role in reducing the impact of drought stress on soybean production. To decrease yield losses due to water scarcity and expand soybean cultivation areas, various adaptive agronomic strategies are implemented, aligned with plant defense responses to drought stress [164]. Practices such as mulching and conservation tillage are widely recognized for their effectiveness in conserving soil moisture, regulating soil temperature, and lowering evaporation rates [28]. Specifically, organic mulching has been shown to prevent soil degradation, enrich soil organic matter, and enhance the soil's capacity to retain water [28]. By maintaining moisture within the root zone, mulching extends the period during which plants can access water, thereby improve water-use efficiency and reduce moisture loss through evaporation [36]. These methods are particularly beneficial in arid and semi-arid regions, where they contribute to stabilizing and improving soybean yields under drought conditions [16].

The use of precision irrigation and regulated deficit irrigation techniques ensures efficient water use by minimizing excess application while supplying sufficient moisture during phenological stages, such as flowering and pod development [61, 155, 158]. These targeted irrigation strategies support optimal crop performance under drought by aligning water supply with the plant's physiological demands during its most sensitive growth periods.

5.4 Soil Moisture Management for Improved Soybean Yield

The escalating pressures of global climate change and increasing water scarcity demand innovations in both agricultural productivity and sustainability [154]. Implementing sustainable farming practices such as mulching and conservation tillage has proven to be effective in enhancing soybean yields under drought conditions. These approaches are beneficial in dry areas as they improve soil moisture retention, an important factor for maintaining crop performance during water stress [172, 154].

Moreover, integrated water management strategies, including regulated deficit irrigation in combination with soil conservation practices, enable more efficient water utilization. These approaches ensure that plants receive adequate moisture during key developmental phases while preventing the negative effects of excessive irrigation [46, 154]. Such irrigation strategies not only support plant growth but also

enhance water-use efficiency, which contributes to greater productivity in water-limited environments [57].

To achieve optimal yields under drought-prone conditions, it is essential to integrate advanced breeding methods with improved soil and water management practices. Selecting drought-tolerant genotypes that can perform well under reduced irrigation is important for minimizing yield losses and enhancing the profitability of soybean cultivation in regions with limited water supply [164]. For instance, a study by [93] maintained soil moisture at 40% of field capacity by weighing potted plants every two days and replenishing water to restore the target moisture level. The findings revealed that soybean varieties Dering 2 and Deja 2 exhibited strong drought tolerance at 40% field capacity, maintaining similar performance in seed yield, 100-seed weight, and number of pods per plant compared to plants grown under optimal moisture conditions. The Stress Tolerance Index (STI) values for Dering 2 and Deja 2 reached 1.03 and 0.83, respectively (Table 3), indicating their resilience under limited water availability.

Table 3
Response of Soybean varieties at 40% field capacity

Variety	Plant Height	Number of Branches	Number of Pods	100 seed weight	Seed yield (g/plant)	STI for 40% Field Capacity
Dering 1	78.67a	4.67a	40.83a	7.25gh	4.17ac	0.74a
Dering 2	65.67cde	2.33efg	29.00b	10.21d	4.68 a	1.03 cd
Deja 1	75.17ab	2.50ef	34.83ab	8.89ef	3.52 ab	0.62ab
Deja 2	86.17a	3.67c	30.67b	10.49cd	5.23 ac	0.83c
Devon 1	76.83ab	3.50cd	32.50ab	8.25fg	2.70 cd	0.73a
Dega 1	60.83e	1.50hi	18.67c	18.94a	4.75 a	0.76a

Source: [93]. Means that are followed by the same letter(s) do not differ significantly based on LSD at 5%

5.5 Molecular Tools for Enhancing Drought Tolerance

The integration of advanced phenotyping tools, molecular breeding techniques, and genetic engineering holds significant promise for developing drought-resilient soybean varieties [5, 162]. Among these, the CRISPR/Cas9 gene-editing system represents a powerful tool in soybean improvement, enabling precise modification of target genes and offering enhanced control over traits associated with drought tolerance [98, 77]. This approach allows researchers to effectively navigate the complex genetic architecture underlying drought response in soybean [98].

Recent innovations in genomic selection (GS), CRISPR/Cas9 technology, and omics-based methodologies have significantly advanced the potential to enhance drought tolerance in soybean [137,

141, 35, 154]. Genomic selection facilitates the rapid development of drought-tolerant cultivars through the accurate identification and incorporation of beneficial alleles [165, 8, 74, 154]. In parallel, gene-editing techniques enable the targeted alteration of specific genes implicated in drought adaptation, contributing to the production of more resilient genotypes [22, 187, 188]. Moreover, several drought-responsive genes (Table 4) have been identified in soybean, which are activated under water-deficit conditions and play important role in modulating the plant's physiological and molecular responses to drought stress. Understanding and manipulating these genes through modern breeding and gene-editing strategies provides an effective pathway for enhancing drought tolerance in soybean.

Table 4
Some of identified genes for drought tolerance in soybean

Gene /transcription factors	Function for drought tolerance	References
LHY1a and LHY1b	LHY1a and LHY1b regulate drought tolerance by modulating ABA signaling pathway	[5]
GmEF8	Improved resilience to drought	[169]
GmXTH1	Enhanced root architecture, relative water content and increased antioxidant enzyme activity	[169]
GmDHN9 and GmMYB14	Reduction of leaf dimension, leaf petiole length, leaf area, Modification of leaf petiole angle and increased yield	[22] [22]
GmTGA15	Enhancement of chlorophyll and proline levels under drought conditions	[24)
GmNTF2B-1	Enhances reactive oxygen species (ROS) detoxification during drought stress	[22]
GmGRAS37	Exhibits increased root hair development to enhance drought tolerance	[142]
GmWRKY12	Improves drought tolerance as demonstrated by a transgenic hairy root assay	[115]
GmWRKY27	Elevates proline accumulation levels	[136]
GmNFYA13	Boosts the transcriptional activity of stress-related gene	[159]
GmPOD40	Enhances photosynthetic efficiency and antioxidant function	[2]
GmSOG1	Promotes the accumulation of antioxidant enzymes and improves tolerance to drought stress	[88]
GmZFP4	Increases root length	[126]
ERECTA	Increases the capacity to resist drought stress	[13]
AtAREB1	Sustains an elevated rate of photosynthesis	[43]
DREB	Enhances the ability to tolerate drought stress	[188, 42, 104]
GmDREB6	Increases proline buildup, helping them withstand drought by stabilizing cell membranes and minimizing water loss.	[80]
GmDREB2A	Improves traits related to growth and yield	[42, 69]
WRKY20	Promotes increased plant height and yield	[82]
GmDHN9	Manages ROS homeostasis and increases tolerance to drought stress	[39]

Gene /transcription factors	Function for drought tolerance	References
GmLEA4 4_19	Improves plant height and yield amid severe drought stress	[47]

5.6. Impact of Drought on Soybean Characteristics

Drought conditions, characterized by decreased rainfall, elevated transpiration, lowered groundwater levels, and alterations in soil cover, are major contributors to yield losses in soybean [41]. These environmental stresses reduce the hydrophobic effect, potentially leading to protein denaturation and a phase shift in membranes from the lamellar to the reversed hexagonal structure [124]. Also, water scarcity brings plasma and endosomal membranes into closer proximity, promoting lipid transfer and modifying membrane permeability [124]. These changes initiate a cascade involving ion influx, elevated production of reactive oxygen species (ROS), and subsequent oxidative damage to lipids, proteins, and nucleic acids processes that can culminate in plant death [124].

The detrimental effects of drought on soybean yield and seed quality are especially severe during reproductive stages, rather than the vegetative phase [132, 41]. Limited water availability during flowering and pod-filling stages drastically reduces seed size and oil content [182, 167]. Under extreme drought, soybean yield can decline by as much as 50%, underscoring the urgency of developing drought-resistant cultivars to ensure stable production [148]. Moreover, drought-induced alterations in seed composition, particularly in oil and protein levels, negatively influence both the nutritional quality and commercial value of soybeans [49].

Table 5
Effects of drought stress on different characteristics of soybean.

Impact of Drought Stress	Reference
Reduces cadmium uptake	[11]
Reduces photochemical efficiency	[10]
Impacts both water content and fresh root weight	[147, 17]
Leads to stomatal closure following severe stress exposure	[109]
lowers the chlorophyll content	[102]
Results in suppressed sugar metabolic activity, decreased nitrogen content, and reduced levels of soluble proteins	[33]
Decreases nutrients storage reserve	[150]
Leads to a reduction in the number of fertile pods produced	[72, 31]
Leads to a reduction in grain yield	[21]

5.6. 1. Standardized precipitation index (SPI)

The Standardized Precipitation Index (SPI) is widely utilized to classify drought events and assess the extent of soybean yield reduction under varying drought intensities [41]. Positive SPI readings reflect average or above-average precipitation, whereas a value of zero represents normal rainfall conditions during a given time frame. The stage at which water deficiency occurs is a key factor influencing the magnitude of yield loss [14]. Specifically, drought during the vegetative phase in the early season tends to have a less pronounced effect on yield than water stress experienced during the reproductive phase later in the season. Consequently, strategies such as breeding soybean varieties for drought tolerance and shifting planting dates earlier in the season are considered promising approaches to enhance yield potential. These practices can indirectly support grain filling, thereby sustaining the crop’s economic viability [103].

Table 6
Effect of drought intensity on soybean based on Standardized Precipitation Index (SPI)

SPI	Drought Intensity	Impact on soybean	References
-0.5 to - 0.7	Abnormally Dry	Impairs crop development, resulting in growth retardation that may not be entirely reversible	[41]
-0.8 to - 1.2	Moderate Drought	Causes partial injury to crops	[41]
-1.3 to - 1.5	Severe Drought	There is a high probability of crop loss	[41]
-1.6 to - 1.9	Extreme Drought	Severe declines in crop production	[90, 41].
-2.0 or less	Exceptional Drought	Extensive and severe reductions in crop yields	[90, 41]

5.6.2 Membership function value of drought tolerance (MFVD)

The Membership Function Value of Drought Tolerance (MFVD) serves as an integrative index that assesses and compares drought tolerance across different genotypes by combining various physiological and yield-related characteristics. This method has also been applied to pinpoint drought-tolerance genes during the germination phase. By incorporating 14 distinct traits, the MFVD approach addresses the shortcomings of evaluating traits individually and provides a more comprehensive measure of drought resistance. Also, the MFVD has been used to identify soybean varieties exhibiting drought resistance during both the vegetative and reproductive growth stages [161].

5.6.2.1 Application of MFVD in soybean drought evaluation

The research by [161] through evaluation of several traits during the vegetative stage, including root/shoot ratio (R/S), total root length (TRL), leaf area index (LAI), and root surface ratio (RSR). Their

findings indicated that these traits collectively explained 73.7% of the total variation observed in the membership functional variation distance (MFVD). Notably, LAI and RSR exhibited higher heritability, suggesting their usefulness as dependable markers for assessing drought tolerance. Also, during the reproductive stage, characteristics such as seed number per plant (SPP), yield per plant (YPP), plant height (PH), pod number (PB), main stem node number (MSNN), and stem branch number (STB) were analyzed, accounting for 94.3% of the variation in MFVD.

5.6.2.2 Correlation of MFVD with other drought tolerance indices

The correlations were observed between the MFVD and other drought tolerance indices, demonstrating strong associations between MFVD and drought tolerance coefficients across multiple traits. The study effectively identified several drought-tolerant genotypes, including LD24, JD36, and TF31 during the vegetative stage, as well as TD37 and LD26 in the reproductive stage, providing valuable germplasm resources for breeding efforts (Table 7). This finding indicates that MFVD effectively reflects the drought tolerance potential of different genotypes, highlighting its usefulness in breeding and selection processes.

Table 7
Assessment of drought-tolerant soybean genotypes across all growth stages based on MFVD

Group	Tolerance and Yield	Genotypes
I	Drought resilience in combination with superior yield performance	DD14, JD36, JD37, LD18, LD24, LD25, LD29, LD30, SN12, SN16, SN17, TF31, TD39, TD43, TD45, TD46, TD48, TD49, TD50, TD55, TD56, TD57, YW9
II	Lack of drought tolerance despite achieving high yield	LX2, TD47
III	Tolerance to drought conditions paired with decreased crop yield	DD11, KY11, LD17, LD23, LD26, LD31, TD37.
IV	Low yield accompanied by vulnerability to drought conditions	DD12, DD13, DD15, FD17, KY12, L08–28, LD15, LD21, LD22, LD28, SN8, SN10, SN11, TD38, TD40, TD42, XY11, YW6.

Source: [161].

In field experiments conducted according to MFVD by [161], over two years in a semi-arid region, fifty soybean genotypes were categorized into four separate groups according to their relative drought index (RDI) and yield outcomes. Group I included 23 drought-tolerant genotypes including LD24, JD36 and TF31 with RDI values exceeding the average (0.93) and yields surpassing the mean (2785.95 kg ha – 1), demonstrating both high drought tolerance and superior yield at the vegetative growth stage. Group II, consisting of only two genotypes, showed above-average yield but exhibited a lower response to drought stress, indicating a lack of drought tolerance despite their high productivity. Group III comprised seven

genotypes, such as TD37 and LD26, which displayed higher-than-average yields and strong drought resistance during the reproductive growth phase. Finally, Group IV contained 18 genotypes characterized by low yield and below-average RDI values, reflecting poor drought tolerance and limited performance under drought conditions.

5.7 Global and Regional Perspectives on Drought Resilience

This review aims to examine recent drought events both globally and regionally, assessing their impact on affected areas (Table 8), the preparedness and response mechanisms implemented, and the importance of incorporating local perspectives in drought response and management. In addition, it seeks to highlight key lessons for enhancing the future resilience of soybean production. The review also demonstrates that regionally tailored approaches are essential for managing drought and can offer valuable insights applicable to different countries worldwide.

Soybean production in Eastern and Southern Africa has seen recent growth and is projected to continue rising due to increasing demand for soybean-based products [116]. Given the common incidence of droughts in these regions, soybean cultivation remains viable owing to the crop’s inherent drought resilience [116, 41].

The studies reviewed also highlight variations in drought tolerance research and breeding, with a focus on specific countries. Drought tolerance in soybean varieties varies across different climatic zones, and breeding programs need to consider local environmental conditions [4]. In Malawi and Ethiopia, initiatives are underway to breed drought-resistant soybean varieties, which play important role in enhancing food security across Sub-Saharan Africa.

Table 8
Drought events in some selected countries

Country	Drought Events	Economic loss	References
Argentina	2009, 2012, and 2018	The value loss of soybean was estimated at USD \$18,598 which is calculated to represent 0.85% of the Gross Domestic Product	[130]
US	2012, 2017	Crop failures affecting corn, sorghum, soybean, and other crops, resulting in losses totaling \$34.5 billion	
South African	2015–2016	reduced summer crop production	
Malawi	2015–2016	reduced soybean yields dramatically	
Brazil	Some years from 1973 to 2023	Drought-related yield losses are estimated at 11.65%, equating to 280 million tons or approximately USD 152 billion	[41]

5.8 Differences in Soybean Adaptation

Understanding genetic variation in the photoperiodic regulation of flowering time in crops like soybean is fundamental for facilitating adaptation to new environmental conditions [134]. In efforts to breed for greater adaptability, a major focus lies in the development of mid-maturing, high-yielding soybean cultivars capable of maintaining optimal performance under both favorable and drought-prone conditions throughout the growing season [16]. Also, breeding programs aim to produce soybean varieties with enhanced adaptability to diverse environmental settings in areas with shortened growing periods [127].

At the molecular level, one strategy plants employ to manage abiotic stress involves the activation of late embryogenesis abundant (LEA) gene family proteins [124]. LEA proteins are known to contribute to plant growth regulation and defense responses under drought stress conditions [47]. For example, the protein encoded by *GnLEA4_19* has been shown to increase plant height even under severe drought. *GmLEA4_19*, in particular, is important for enhancing drought tolerance and has been utilized in generating transgenic soybean lines with improved yield and stress tolerance [47].

However, drought tolerance varies significantly among soybean cultivars, driven in part by local environmental factors and the genetic control of flowering time. For instance, the gene *GmFT3a*, a homolog of the *FLOWERING LOCUS T (FT)* gene in soybean, was shown to accelerate flowering under long-day (LD) conditions, but not under short-day (SD) conditions, indicating its potential role as a floral promoter in non-inductive photoperiods [168].

Further genetic analysis of 176 soybean accessions revealed that the *GmFT3a-Hap2* haplotype is linked to early maturity. This genetic trait could be instrumental in adapting soybean varieties to higher latitudes, as it regulates genes involved in signaling and metabolic pathways [168]. Developing soybean cultivars for new environments, particularly those characterized by varying photoperiods and latitudinal differences, requires genetic diversity in photoperiod responses. Such variation is important for maximizing yield potential when introducing crops to northern latitudes [134, 189, 135].

In certain countries, such as Malawi and Ethiopia, soybean varieties have been developed with specific drought adaptation mechanisms tailored to local climates [4]. Conversely, in areas not typically affected by drought, breeding efforts should prioritize yield enhancement through advanced genetics and improved nutrient management, rather than drought resilience [41, 3]. It is essential to acknowledge the variability in drought tolerance and environmental adaptation [26]. Therefore, soybean breeding strategies must be customized to the particular agroecological challenges of each region [4].

For example, in drought-prone regions such as parts of the Central Corridor and Northern Zone of Tanzania, the development and deployment of drought-tolerant genotypes with strong osmotic adjustment capabilities and efficient water use are imperative. These regional considerations highlight the importance of a targeted breeding approach aimed at producing soybean cultivars with both high yield potential and environmental adaptability. One such example is *Wandou 37*, a drought-tolerant variety developed in China that demonstrates broad adaptability and consistently high yields under variable growing conditions [32].

5.9 Economic Implications for Breeding Drought Tolerant Varieties

Moisture stress occurring during the mid to late reproductive phases of soybean development can disrupt nitrogen fixation, hinder plant growth, and reduce yield potential. This is primarily due to oxidative stress caused by an accumulation of reactive oxygen species (ROS) [33, 7]. Given the economic burden associated with irrigation, the breeding and development of drought-tolerant soybean varieties offer a more practical and cost-effective solution. These varieties are better equipped to withstand unfavorable environmental conditions in short-term droughts during the growing season and help sustain yields in water-limited environments [127, 77].

In parallel, the adoption of climate-smart agricultural techniques has been shown to effectively lessen the adverse effects of drought stress [15]. When used in conjunction with drought-resilient genotypes, these practices enable farmers in drought-prone regions to achieve more consistent yields while optimizing resource inputs. Moreover, advancements in breeding for drought tolerance contribute to improved efficiency in resource utilization and support environmentally sustainable farming by lowering the ecological footprint of production systems [5, 178].

Drought stress poses a substantial threat to soybean productivity, often resulting in significant yield reductions and economic setbacks for producers [130]. For example, in Argentina a leading global producer of soybeans, recent drought events have led to a projected decline in output from 50.2 million tons in the previous season to around 40 million tons. In this context, early flowering has emerged as a valuable trait, not only to support early maturity but also to reduce exposure to drought during developmental stages such as flowering [127, 77]. Consequently, the development of early maturing soybean cultivars represents a promising strategy to reduce vulnerability to short-season droughts. This approach carries notable economic benefits by improving yield stability, lowering input costs, and enhancing food security [127].

In India, Madhya Pradesh accounts for the largest share of soybean cultivation, with approximately 78% of the area being rainfed. The adoption of drought-tolerant soybean varieties, such as the NRC-7, has been highlighted for its economic benefits in mitigating the risks associated with erratic rainfall patterns [95]. The NRC-7 variety, known for its drought resistance, has been shown to offer a significant advantage, with an 84% increase in economic surplus per hectare compared to other varieties. This advantage primarily stems from the variety's ability to reduce income risk for farmers under drought conditions [95].

The economic advantage of adopting the NRC-7 variety is not only reflected in increased yields under normal conditions but also in its potential to minimize economic losses during periods of drought. This risk-reducing effect is a key benefit, as it highlights the variety's superior resilience to water stress, leading to less volatility in farmer incomes during adverse climatic conditions. In fact, the economic loss

incurred during drought conditions is lower for NRC-7 compared to other soybean varieties, emphasizing its importance in risk management for farmers [95].

The yield advantages of improved soybean varieties such as NRC-7, JS 93 – 05, and JS 95 – 60 were assessed using the economic surplus model, a method that captures both productivity gains and reductions in production risk. Specifically for NRC-7, the analysis highlighted the substantial benefits associated with risk mitigation, reinforcing the importance of developing and disseminating drought-tolerant cultivars. These results not only demonstrate the economic viability of such varieties but also establish a useful approach for guiding the development of resilient crop types to strengthen agricultural sustainability under climatic stress.

For stakeholders in Tanzania, including researchers and farmers, the development and adoption of drought-resilient varieties like NRC-7 could yield comparable benefits. Such varieties help reduce dependence on consistent rainfall, thereby promoting income stability and enhancing food security. India's experience with these varieties showcases their substantial economic impact and serves as an instructive model for implementing sustainable soybean production strategies in Tanzanian regions facing similar drought-related challenges.

6. Conclusion

In conclusion, effectively tackling drought stress in soybean production demands an approach that integrates genetic improvement, physiological insights, and agronomic practices. Recent research from major soybean-producing countries emphasizes the important roles of soil characteristics such as texture, drainage, and moisture retention in boosting drought resilience. Nonetheless, there remains a need for further investigation into the complex polygenic basis of drought tolerance in soybean. Gaining a more thorough understanding of the intricate interplay between drought-responsive genes and environmental conditions is important for breeding soybean varieties that combine high yield performance with strong drought adaptability.

This review emphasizes the potential of integrating advanced biotechnological tools, such as CRISPR-Cas9, with other breeding techniques to precisely modify drought-related traits in soybean. Future breeding programs must combine drought tolerance with other essential agronomic traits.

The findings discussed in this review offer an important foundation for Tanzania, where drought significantly threatens soybean production. By highlighting drought-tolerant genotypes identified in this study, the review points to potential sources of drought-resilient donor parents that Tanzania can utilize to expand its germplasm resources for soybean breeding programs. Economic factors are also important in the adoption of such varieties. Considering the costs associated with irrigation and the unpredictability of rainfall leading to possible crop failures, drought-tolerant soybean cultivars represent a practical and sustainable option. These varieties not only reduce susceptibility to adverse environmental factors but also ensure consistent productivity during short growing seasons and periods of drought. The potential economic benefits, such as increased yields and risk mitigation during

droughts, are important for farmers and enhance income stability in areas vulnerable to climate variability.

This review also highlights tools such as the Recovery or Compensation Index (RCI), which measures a genotype's capacity to rebound from drought stress, providing greater accuracy in selecting genotypes with enhanced resilience. By pinpointing varieties that exhibit strong recovery responses following rehydration, breeding efforts can be directed toward improving both drought recovery and overall growth under limited water availability. Also, the Standardized Precipitation Index (SPI) was examined as a metric for classifying drought severity and assessing its impact on soybean yield reduction. The Membership Function Value of Drought Tolerance (MFVD) index, which integrates multiple physiological and yield-related traits to evaluate and compare drought tolerance among genotypes, was also considered in this context. By combining insights from this review, Tanzania can make significant strides in developing drought-tolerant soybean varieties that ensure food security and contribute to soybean farming practices in a changing climate.

Declarations

Author contributions: **FMR** conceived the study design, conducted the material search, performed the data analysis, and drafted the original manuscript. **CM** provided supervision, contributed to the initial study idea and provided substantial revisions that enhanced the intellectual content of the work. **ABK** provided supervision, offered technical guidance, assisted with data validation and analysis, and reviewed and edited the manuscript. **GMT** provided overall supervision, contributed to the conceptualization of the research, guided the methodology, and critically reviewed and edited the manuscript.

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Table 9

Table 9 is available in the Supplementary Files section.

Figures

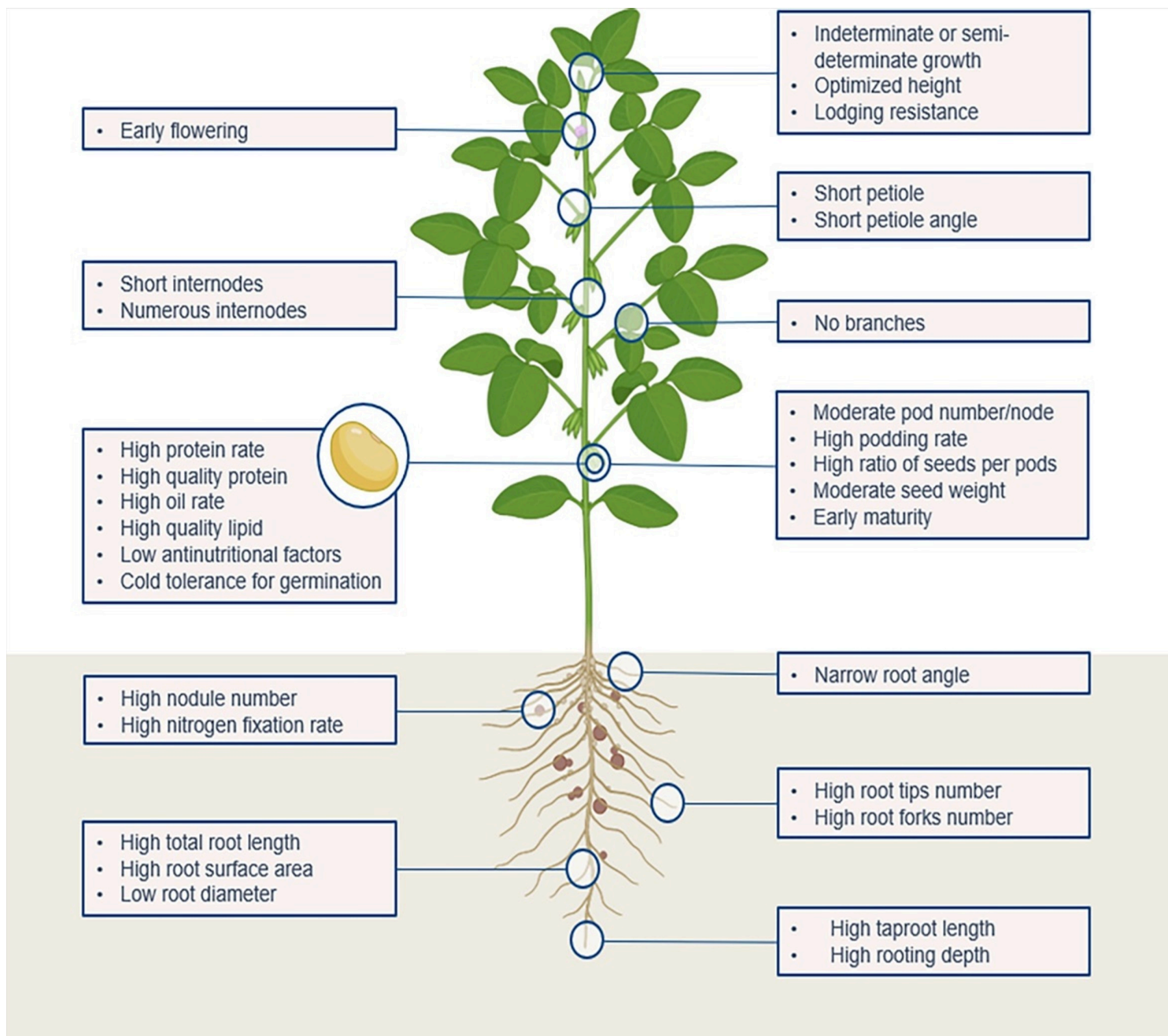


Figure 1

Some of traits to be targeted for soybean breeding [77]

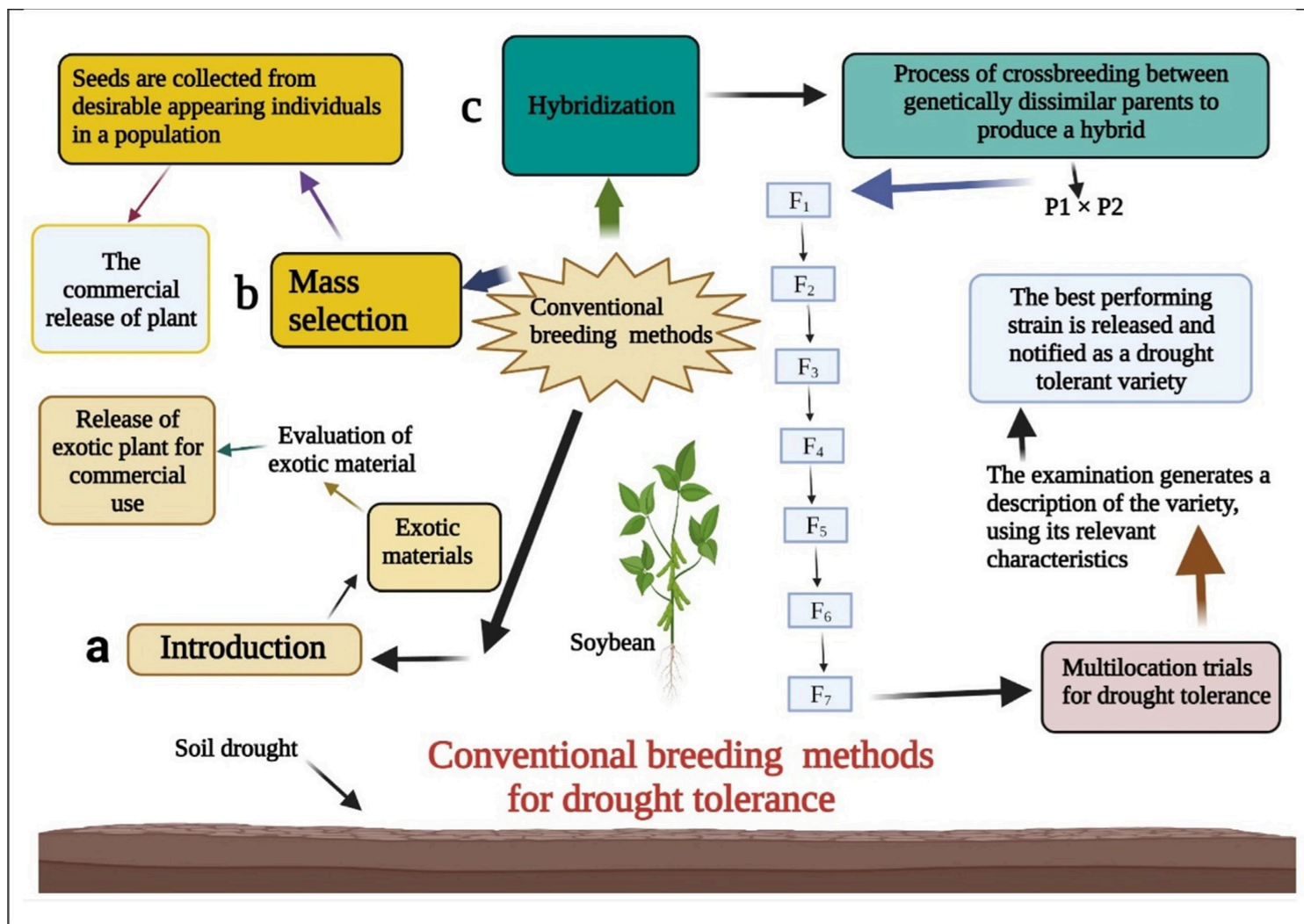


Figure 2

Conventional breeding approaches which are widely utilized to develop drought-tolerant soybean genotypes, aiming to enhance soybean growth and yield performance under drought stress conditions [98].

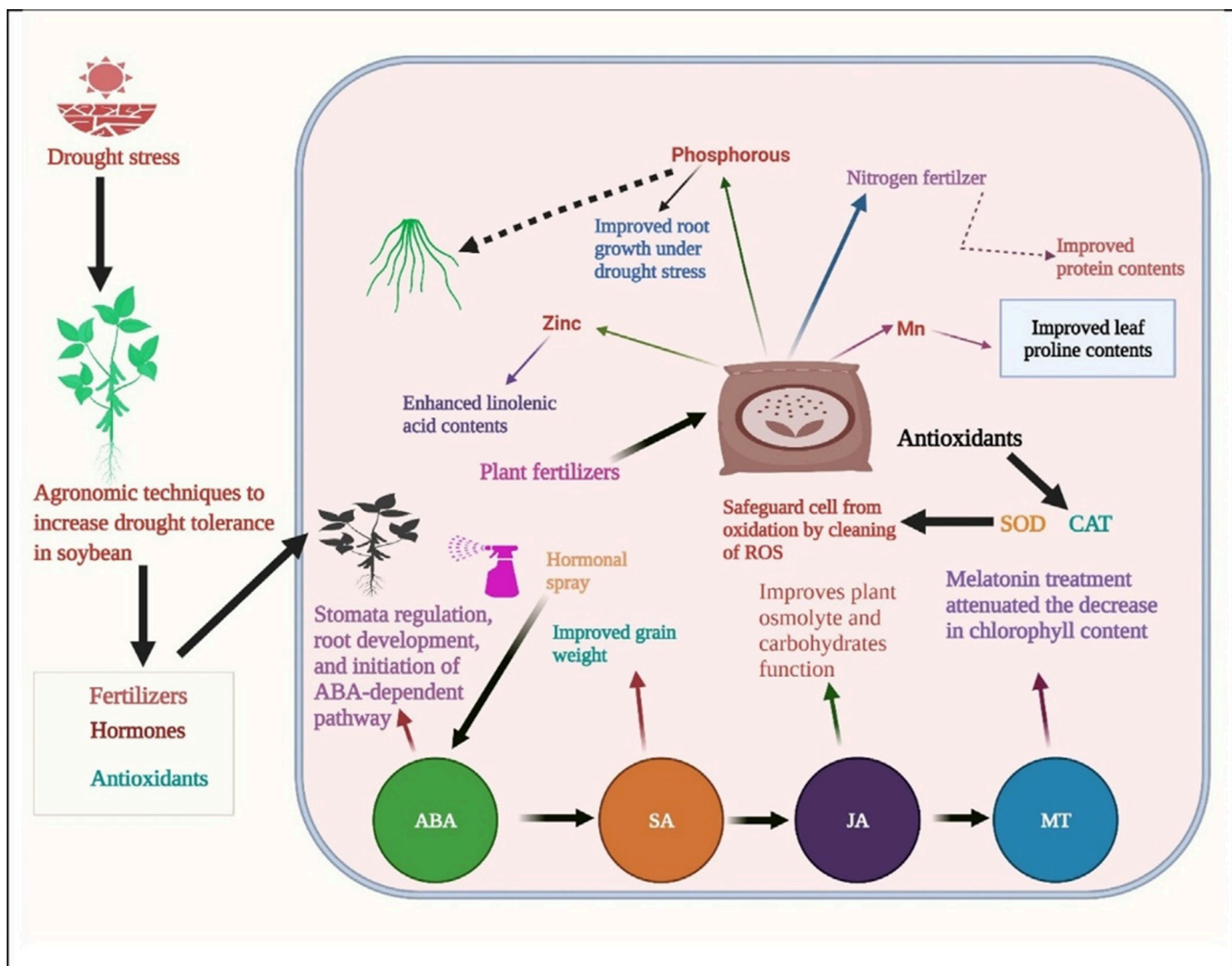


Figure 3

The application of agronomic interventions including fertilizers, plant growth regulators, and antioxidants which have been employed to enhance drought tolerance and protect soybean plants from the adverse impacts of drought stress [98].

Supplementary Files

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- [Table9.docx](#)