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Integrative Strategies for Enhancing Drought Tolerance in Crops: Advances in Physiology, Genetics, and Agronomic Practices

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ABSTRACT

Water stress is arguably the most hazardous natural stress factor in the current and future climate changes and hence tolerance to water stress in crops is possibly one of the most valuable of agricultural characteristics. With increasing intensity and duration of the droughts, improving the understanding and resilience to drought has assumed importance for food security. To connect with the review topic, the advances in physiological mechanisms, genetics, genomic and related approaches, and managing strategies towards drought tolerance in crops are highlighted. In plants, there are several strategies that are recognized to exist in coping with drought conditions including increasing WUE and osmotic potential and changing the photosynthetic rates. Drought tolerance mechanisms also include signaling mechanism by abscisic acid (ABA) to indicate drought response and also root adaptive mechanisms. Conventional breeding owns the initial framework for the improvement of drought tolerant varieties at genetic level, while molecular breeding, marker assisted selection (MAS), genetic engineering and transgenic have speed up this progress. The application of new technologies during the post-genomic period and the study of epigenetic changes have expanded the knowledge during the past decade and bred more efficient techniques. Conservation and management of water, effective use of soil, use of bio stimulants and plant growth regulators, agro forestry and mixed farming is important in order to reduce the effect of drought on crops.

Keywords: *Drought Tolerance, Crop Resilience, Root Adaptations, Genetic Engineering, Agroforestry, Genomic Selection.*

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INTRODUCTION

Global climate remains to rise, the occurrences and severity of verbalization such as long-lasting droughts are likely to rise and this will exert more pressure to the already stressed agricultural systems. (Ahmad et al., 2024) In addition to that, this increasing variability of rainfall pattern does not only jeopardize the quality and quantity of agricultural productivity but also complicate the problems of soil erosion, water deficiency and pest invasion thus destabilizing the production of food. (Rhodes, 2014) In this regard, the improvement of drought resistance in crops becomes a very pressing task, which is not only for the regions characteristically desert but for the regions, which increasingly undergone considerable water deficit due to climate change. (Le Houérou, 1996) Of the social impacts that drought brings, the economic impacts are of great significance. Most of these countries in the developing world depends on agriculture so much that they rely on it for employment and income. (Le Houérou, 1996)Hence, efforts to enhance the capability to endure drought conditions is really a matter of equally, sustainable agriculture, economic and social stability. There is now a growing understanding in the scientific literature that to improve the endurance against droughts, all the various strategies must be linked. (Subbarao et al., 1995) This includes providing simple and complex germplasm enhancement, utilizing conventional cross breeding along with the biotechnological techniques and thereafter enhancing the resource use efficiency in regard to water and soil health. This intersectionality of the approaches leads to a promising direction up to the max effect of drought resilience, where CEPs are integrated with sustainable agricultural practice that results in increased crop drainage. (Misra & Tewari, 2024)

- It is therefore clear that technology plays a very important role in tackling drought issues. Many technological tools and especially data analytics, remote sensing, and machine learning bring new opportunities of crops health, drought prognosis, and resource management. (Kumar et al., 2024) They make it possible for farmers to utilize the data in exercising better coordination in the rationing of water for use in the drought affecting crops and periods, in order to increase yields. (Rockström et al., 2002) On a larger scale, policy support and international cooperation are required to advance such innovations and bring it to the farmers in the field. Keeping this in mind, it is crucial that governments, research institutions and the private sector create an enabling environment that supports the development of drought tolerant crops, its adoption by small holders and making sure that such developments bring about the desired impact of increased food production and climate resilience. (Fisher et al., 2015) This review not only seeks to explore the current state of scientific studies on drought tolerance but also the socio-economic, technological and policy factors that are important in harnessing and application of advancements in this area into the global agricultural systems. (Mikiciuk et al., 2024) Therefore, by developing an elaborate review of drought tolerance, this review seeks to support the future generation of more wholesome and sustainable agriculture that will be able to withstand climate change and feed the increasing world population. (Shiferaw et al., 2014)

Scope of the Review

This review will comprehensively cover three main areas of research and development in drought tolerance, providing a holistic view of the current advancements and future directions in this critical field:

- Physiological Mechanisms: This section will describe how plants deal with water deficit at the molecular level with emphasis on WUE, OA, and PS under stress, ABA and root traits. In this piece of work an emphasis will be laid on how plants are able to perceive, come up with response mechanisms, and withstand conditions of drought stress, an aspect that will assist in explaining on how growth and productivity can occur under conditions of water limitation. This section will thereafter analyze how these physiological facts can be used to create better drought sustainable crops through intercession (Farooq et al., 2009).

- Genetic Approaches: This section will provide on the accomplishments or the improvements made on the genetic engineering for drought tolerant crops. The fact that traditional breeding was involved in the initial development of drought tolerance will also be discussed in addition to techniques of advanced molecular breeding that are currently in use such as the MAS and QTL. (Quarrie, 1996) The concepts of genetic engineering and transgenes will be highlighted, where particular emphasis will be made on the fact that these approaches concern the introduction of definite genes which provide for drought tolerance DREB, CBF, and others Specific attention will be paid to the epigenetic factors including DNA methylation and histone modifications that take part in the regulation of drought responses, with focus on further breeding or biotechnological implications. (Ashraf, 2010).
- Management Strategies: This section shall look at measures that can be taken in managing effects of drought on crops. In this we will also focus more on the sophisticated approaches to managing water such as precision irrigation, deficit irrigation and moisture retention technologies. Application of organic matter, conservation tillage and mulching will be implemented for assessment of efforts on enhancement of water retention in soils and minimization of drought effects. (Xing & Wang, 2024) Drought management will be discussed as comprising of crop choice approaches, drawn from drought-resistant variety and planting calendar options. Application of bio stimulants and plant growth regulators to increase the drought stress tolerance of plants will be discussed, as well as their application on different cropping systems. (Rastogi et al., 2024) Also, the review will discuss on the advantages of agroforestry and mixed cropping that involves establishing trees and crops in the same farming systems. Examples of the application of these strategies will be also presented in the form of case studies and examples of different geographical areas and cropping systems. (Ray & Majumder, 2024).

Thus, it is intended that this review provides a clear understanding of the many-faced approaches needed to improve the current knowledge on the physiological mechanisms, genetic programs, and management skills that expect to coordinate drought tolerance in crops. (Abdallah et al., 2021) These strategies will be highlighted to integrate in a comprehensive and holistic manner to offer feasible solutions that will potentially build and sustain a healthy base for agricultural practices much as the challenges presented by global climate change increase. The review will also make us aware of the need to conduct research and improve on the implementation of interdisciplinary research in dealing with drought stress in agriculture. (Alharbi et al., 2024).

2. Various Aspects and Physiological Processes for Understanding Drought Tolerance

Water Use Efficiency (WUE): Water Use Efficiency (WUE) is one of the most important factors for plants and particularly under water stress conditions. This is expressed in terms of ratio where the biomass yield is equal to the quantity of water that the plant consumes. Plants with higher WUE are more advantage during dry periods this is because they are able to produce more yield with little water than plants which have low WUE. This trait is especially essential in regions whereby water rationing to farmers is a major drawback in the regions with low rainfall regimes. (Stanhill,

1986) Water limited conditions are managed by plants through various ways as explained below. Stomatal regulation is one of the major strategies where stomata present on the surface of the leaves are closed to avoid water loss through the process of transpiration. However, this also reduces the amount of carbon dioxide that can be utilized for purposes of photosynthesis and this is always a delicate balancing factor which plants consider. (Sinclair et al., 1984) This regulation can be supported with help of numerous physiological and morphological alterations for example appearance of small stomata or the formation of waxy cuticle which additionally decreases evaporation of water. Another is the root structure or architecture as is often described by researchers. (Bramley et al., 2013) Succulent plants are the best example because they possess a deep root system that enables them to reach deep water sources to supply their needs especially when there is drought. These roots not only draws water from areas undetectable to plants with shallow root systems but also enhances the actual surface area for absorption hence maximizing water intake by the plant. In some species, root plasticity, the capacity to remold root growth in response to available water in the soil augments WUE by furthering root development according to the density of the water supply. (Hatfield et al., 2001).

Some plants have adapted to have C4 or CAM photosynthetic processes rather than the C3 that is common in most crops, a fact that shows more water efficient. C4 and CAM plants have developed ways of reducing the loss of water while at the same time increasing the rate that in which photosynthesis occurs thus enabling them to survive in arid conditions. (Kumar et al., 2017) This physiological adaptation directly benefits higher WUE through its capacity of sustaining productivity with less water. However, osmoregulation that is an accumulation of solutes such as proline and glycine betaine might be used by ants in cases of water scarcity to sustain the cell turgor pressure. This process assists in maintaining the metabolic functions as well as growth in lean times thereby indirectly assisting in higher WUE. (Orsenigo et al., 1997) Others are such factors like soil type, the temperature, and humidity of the environment affects WUE too. For instance, improved soil aeration accompanied by good drainage favors the development of deeper root structures which enable plant to absorb water and thus improve WUE. (Andrade et al., 2009) Also, low temperatures contribute to slow down the evaporation of water through stomata hence conserving water while enhancing the growth of the plants. Higher WUE is one of the goals important in the breeding strategies focused at creating drought resistant varieties of crops. (Sage, 2001) Thus, through the deliberate breeding of these traits that contribute to WUE, breeder will be in a position to develop varieties that can tolerate drought stresses. This is so because climate change impacts are expected to enhance the magnitude and incidence of drought, thus the need to come up with crops with high WUE for the future food security. (Lombardini & Rossi, 2019).

Osmotic Adjustment: Another important component known as osmotic adjustment is also employed by the plants to combat the unfavorable conditions of drought stress. This process involves the build-up of compatible solutes, osmotic as or osmolytes include glycine and betaine. Solutes are small organic structures that are non-harmonized to excite characteristically physiological biochemical reactions and therefore retain cellular function in stress. (Blum, 2017) The buildup of these osmolytes aids in reducing the osmotic pressure of the cell allowing it to retain water and retain its turgidity, which can be defined as cell pressure exerted against the cell wall. This turgor pressure is crucial for the mechanical support of plant cells so that the cells should not burst during dry periods. (Munns, 1988) Osmotic adjustment enables a plant to maintain more or less its normal metabolic activity even where there is water deficiency on the outside. The major importance of sustaining turgidity is simple – most of the plant's activities such as photosynthesis, nutrient absorption, cell division and growth and overall survival during a drought are highly dependent on it. This mechanism also contributes to the postponement of wilting which is usually the first sign that the plant is under drought stress. (Chen & Jiang, 2010).

A plant s ability to maintain turgidity or avoid wilting can be explained by the osmotic adjustment because this results on maintaining as much leaf area as possible for photosynthesis which in return promotes growth and productivity of plants. (Sanders & Arndt, 2012) Stress protectants such as proline and glycine betaine do not only help to sustain cell turgor, but they also have molecular protective functions. They help to maintain protein integrity and membrane integrity, protect the photo synthetic machinery, and detoxify ROS generated under drought stress conditions. (Shabala & Shabala, 2011) This protection function aids in reducing damage to cells and in guaranteeing that cellular metabolic processes can go on despite unfavorable conditions. They also found that osmotic adjustment can be species-dependent or genotypes dependent when compared across varieties within a species. There are certain plants which have capability of osmotic adjustment more than the other plants and so such plants are more tolerant to drought. (Babu et al., 1999) This character can also be associated with the capability of this plant to quickly load osmolytes in response to the osmotic stress, which is a useful parameter for the estimation of adaptive potential of the plant to the conditions of water deficit. Osmotic adjustment is therefore one of the most important selection criterial used in breeding programs for drought tolerance. (Zivcak et al., 2016) Plant breeders can thus develop varieties that are capable to withstand drought stresses by selecting or genetically engineering plants that possess high osmolyte accumulation capacities. For instance, plants that can synthesize proline or glycine betaine well during the periods of water shortage can do so effectively which means that they germinate better and have better yields than other plants that are less resistant. (Bernstein, 1961) Investigations on the genetic and molecular mechanisms regulating osmotic adjustment are still continuing so as to pinpoint out molecular control of genes for osmolytes synthesis and their transport. Knowledge of these regulatory mechanisms may open new ways of developing improved drought tolerance in crops, using one or more of the above methods. (Girma & Krieg, 1992).

Photosynthesis under Drought Stress: This study showed that drought affected the process of photosynthesis, which is the process by which plant utilizes light energy to produce chemical energy. Stomatal closure, as a result of water shortage, reduces the access to carbon dioxide hence decreased photo synthetic rate. (Chaves et al., 2009) This in turn has consequences on the gross efficiency of the plant, as photosynthesis correlates directly with biomass build up and yield. It is established that during drought conditions, there is a suppressed rate of photosynthesis hence carbohydrate formation may be depressed beyond the energy demand of the plant, growth and reproduction. (Zahra et al., 2023) Ways used by plants to protect themselves under drought conditions include the following. One such process is Non-Photochemical Quenching or NPQ, whereby, extra light energy is converted to heat to avoid injury to the photosynthetic machinery. (Zargar et al., 2017) Surplus light is prevented from damaging the photosystem II (PSII) through a process of photo inhibition particularly in situations where water is scarce for the production of water consuming photosystems. Thus, NPQ aids in lowering the likelihood of formation of Reactive Oxygen Species which as we know are detrimental to the chloroplasts and other internal structures. (Zargar et al., 2017) They may also change the chlorophyll content and the quality in response to the light conditions so as to avoid damage during the period of water deficit. For example, lowering the amount of chlorophyll slows the absorption of over amount of light which is desirable since photosynthesis ability of a plant is already affected by drought. Some plants may also synthesize more carotenoids, these are pigments that help to shield chlorophyll pigments from damage by quenching singlet oxygen and other lethal reactive species. (Chaves et al., 2009).

ABA Signaling and Drought Response: ABA is a prominent plant hormone which has been identified to play a central role in drought stress and as a signal molecule that controls the plant's perception as well as management of drought stress. (Nakashima & Yamaguchi-Shinozaki, 2013) ABA accumulates in a plant during drought mainly produced in the roots and translocated to the shoot where it triggers several physiological and molecular changes that would enable the plant to conserve water and thus survive. (Soma et al., 2021) One of the primary activities of ABA is to promote stomatal closure an essential procedure as a way of minimizing water loss through transpiration (Soma et al., 2021) Stomata are small conducting pores on the epidermis of a leaf and are responsible in the exchange of gases with the atmosphere, particularly the uptake of CO2 required in the process of photosynthesis and the letting – out of oxygen. But, open stomata also help the release of water vapor resulting in great loss of water to the surrounding. (Campalans et al., 1999) Due to the shutting of the stomata, which it brings, ABA reduces this loss of water, but at the same time, less carbon dioxide enters the plant for the process of photosynthesis is limited. The above trade-off shows that plants are in a dilemma on the best way to balance on water conservation and growth. (Davies et al., 2005).

ABA signaling also induces the expression of those stress-responsive genes, which can assist the plant to grown optimally under drought environment. These genes are involved in several protective processes; for instance the process of osmotic adjustment that involves production of osmolytes such as proline and glycine betaine whereby the pressure or the firmness of the plant cell to contain water is maintained even under low water availability on the soil. (Zhang et al., 2006) This osmotic balance is essential for maintaining cellular process and prevent wilting under drought stress. Stress induced osmotic adjustment, abscisic acid signaling enhanced the antioxidant system in the plant. (Zhang et al., 2006) Due to drought stress, generation of radicals is therefore leading to immense formation of reactive oxygen species (ROS) which leads to oxidative impairment on lipids, proteins and DNA. ABA stimulates the transcription of genes involved in the synthesis of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidases, which are known to neutralize ROS and hence alleviate oxidative stress. This is a kind of an antioxidant defense that helps to maintain cellular structure and protect the organisms when there is a lack of water. (Davies et al., 2005).

Root Adaptations: Each plant organ has adapted to perform specific tasks seen in drought tolerance for instance roots are the main organs through which plants obtain water. Due to the root system characters, plants growing in arid regions or put under drought conditions have different capacity to survive and produce when compared with those under favorable irrigation regime (Srikanth et al., 2016) Drought-tolerant plants generally possess deep and extensive root system which facilitates the plants to get access to the water resources that are unavailable to other species. In particular, a good rooting depth is useful in areas where moisture is available at the surface only slightly and deep water tables are located. The other parameter that can also affected drought stress is the root: shoot ratio. (Srikanth et al., 2016) The root to shoot ratio, in which the plants root system is larger as compared to the shoot system, is generally well adapted to drought. This is due to the fact that a plant with extensive root ball has more area to soak water, and hence is able to take maximum amount of water to the surface even if the soil is dry. (Rao et al., 2016).

A healthy and strong root system will be of great help in enhancing the plant stand by granting it a better hold in the soil thereby minimizing cases of wilting and plant collapse due to water shortage. (Rao et al., 2016) Other aspects of root architecture which include root geometry as well as distribution and branching of roots also affect drought tolerance. It has been found that while drought-tolerant plants have roots that are extended deep into the soil, they also have a higher lateral root spread in the order of the radius in a circle to allow the plant to search for water and nutrients in a larger volume of soil. This extensive root system raises the likelihood of coming across these sources of water in the course of searching for water in the soil especially in the dry periods. (Srikanth et al., 2016) There are some plants that show a phenomenon known as root plasticity in which plant roots modify the orientation and branching patterns to adapt to the fluctuations in relative soil water availability. Under drought conditions the plants may invest more resources to root growth and make the root systems to penetrate deeper into the soil or increase on the lateral root growth to maximize on the amount of water that is taken up. (Rao et al., 2016) This plasticity enables the plant to regulate the amount of water it takes in depending on the existing conditions hence, enhancing it ability to withstand drought. These root adaptations not only assist in water absorp-tion, but also in using the best of the facilities for the distri-bution and the remaining part of the water, which makes them drought resistant in totality of the plant. (Srikanth et al., 2016).

3. Molecular Genetics for Improving Drought Stress Tolerance

Traditional Breeding Techniques: Conventional breeding has always been used in the development of crops that are tolerant to drought for many years. Some of the specific achievements associated with this process are described below: By identifying certain plants with favorable quality attributes and cross breeding these plants, the breeders have been able to come up with plant varieties that are capable of doing well under drought like situations. (Mahmood et al., 2019) Some examples include the drought tolerant maize, rice and wheat that have seen improved yields especially in the drought prone areas and which are crucial in food security in areas that experience water shortage most of the time. (Quarrie, 1996).

The conventional breeding method takes advantage of the Genetic variation inside crop species as well as closely related wild type relatives. Researchers choose their parent plants to possess the best characteristics including deeper root systems, water use efficiency or osmotic adjustment and these plants are crossed in a way that the offspring acquires these characteristics. (Quarrie, 1996) Over many generations of selection, plant breeders are able to select plants that are drought performing well and new cultivars can be bred and are able to survive in the water limited environment. (Mahmood et al., 2019) This however is disadvantageous since traditional breeding has its disparity and drawbacks. It is a time-consuming process most of the time many generations of selection are used to get the right traits. However, its long life cycle may be a disadvantage especially if the environment changes fast due to the effects of climate change which require crops that are resistant to the change. It has been observed that the genetic pattern of drought tolerance is mutagenic and polygenic that includes many genes as well as gene-gene interaction. (Mahmood et al., 2019) This is a disadvantage that makes it hard to push changes through conventional breeding methods for big improvements since the breeder is going to be faced with the dilemma and challenge of having drought tolerance alongside with yield or disease tolerance or crop quality. (Quarrie, 1996).

Molecular Breeding and Marker-Assisted Selection (MAS): Molecular breeding and Marker-Assisted Selection (MAS) have brought real changes into the breeding process offering breeders much more effective tools to improve crops. (Wakchaure et al., 2015) These techniques utilize increased knowledge on molecular biology and genetics to isolate and amplify for particular-gene or quantitative trait locus (QTL) that may be linked to wanted characteristics including drought tolerance. Since the markers are short sequences of DNA which are closely linked to genes of interest breeders can monitor the inheritance of such traits in the breeding population so that development of improved crop varieties can be accelerated. Let us discuss the benefits that MAS have for us over conventional breeding techniques. (Jiang, 2013) A major advantage derived from such a system is the potential to choose for a trait, which may be very hard to quantify or is associated to some factor just like drought resistance. (Wakchaure et al., 2015) Because MAS utilizes the genetic markers of the trait and not the actual phenotypic manifestation of the trait, the breeders can make the selections at a preflowering stage and under conditions of different environments. (Jiang, 2013) This not only shortens the process of the development of new varieties, but also enhances the reliability of selections as biotic variability is thereby held at its lowest. (Jiang, 2013) A third useful attribute of MAS is that that the various traits can be placed into a single variety of plant through a process known as gene pyramiding. It means that in the context of drought tolerance, the breeders are able to select for other important traits including disease resistance, yield stability, grain quality and so on, which assure, the developed varieties are not only drought tolerant but they also meet all other desirable agronomic and market standard. With multiple trait selection, the crops are well adapted to the many faceted and difficult environments prone to drip and thus developing drought resistance crops. (Henkrar & UDUPA, 2020).

Genetic Engineering and Transgenic Approaches: Genetic engineering forms the other useful approach to improving drought tolerance in crops. This makes the development of transgenic plants more effective since one can introduce specific genes which are attributed to drought resistance to the plant in question. For example, the DREB (Dehydration-Responsive Element Binding), CBF (C-repeat Binding Factor) among other genes have been successfully incorporated into crops to enhance drought tolerance. (Wakchaure et al., 2015) These genes typically work by increasing the plant's ability to cope with water deficit in one way or the other, for example by increasing the biomass of roots, increasing osmotic solute accumulation and increasing protection against oxidant injury. Even more capabilities have been added to the docket through the CRISPR-Cas9 and other such gene-editing technologies. (Henkrar & UDUPA, 2020) These technologies help to make changes within plant genome and it is possible to develop crops with improved features such as drought tolerance without using genes belonging to other organisms. This precision minimizes other side effects likely to be caused by these transgenic crops to other traits or other interactions within the ecological systems and also leads to more public acceptance of GMOs. Also through CRISPR-Cas9 system, multiple genes can be targeted and edited at the same time, improvements in several drought-tolerance traits can be 'stacked' consecutively into a single plant variety for better performance under water-deficit conditions. (Song et al., 2023).

Omics Approaches: New molecular platform technologies such as genomics, proteomics and metabolomics have expanded greater knowledge in plant drought tolerance. These approaches enable the scientist to look at the whole genomic, proteomic as well as metabolite data from plants under drought stress to determine the relevant traits and pathways associated with drought stress. (Hasin et al., 2017) For instance, genomics has shown that genes that we thought used in response to drought are actually interconnected in elaborate networks, proteomics and metabolomics have found proteins and metabolites that are involved in the processes of protecting plants from water deficit. (Fukushima et al., 2009) Hence, integration of such omics data has allowed for the discovery of new genes and molecular markers that play a role in drought tolerance. The visualization of these networks enable a richer and comprehensive picture of the underlying systems in controlling for drought, laying the ground for better breeding strategies. (Hasin et al., 2017) For instance, by integrating genomic information with phenotype records, scientists can determine, which genes correspond to valuable characteristics, thus improving the selection and breeding processes. In addition, the combination of omics with high-throughput phenotyping platforms for quick screening of large populations enable fast development of drought tolerant crops. (Fukushima et al., 2009).

Epigenetic Modifications: Epigenetics is a set of modifications that occur in gene expression without any changes in the sequences of DNA, which are very essential in stress responses in plants such as drought stress. (Kanwal & Gupta, 2012) During drought stress, different epigenetic mechanisms that control gene expression have been identified as DNA methylation, histone modification and non– coding RNA. These changes can turn on or turn off the required gene in the plants in response to a given stimulus in the environment thus allowing the plants to respond quickly. (Murr, 2010) Knowledge of epigenetic changes provides new possibilities to produce drought resistant crops. In this way, by choosing for epigenetic characteristics, or by giving specific epigenetic modifications, the breeders can eventually increase the susceptibility to drought in crops much more than by using only genetic methods. (Patel & Wang, 2013) For instance rearrangement of genes to enhance root growth or water use efficiency is selectable during breeding exercises hence the creation of germplasm that could better do well under water stress. Furthermore, since epigenetic changes are also known to be reversible, this present method is less of an invasively permanent solution to enhancing the organism's ability to withstand drought and other adverse environmental conditions without genetically modifying the plant. (Kanwal & Gupta, 2012).

4. Effects of Drought in Crops

Water Management Practices: Drought is one of the biggest challenges affecting crop production and therefore conservation of water should be well done. Methods of irrigation like drip irrigation, sprinkler system and others tend to minimize wastage of this natural resource by providing water directly in the root zone. These method is more applicable in dry areas such as the arid and the semi-arid regions since water is very hard to come by. (Yu et al., 2021) Other methods such as Rain water management and the use of soil moisture sensor can also assist farmers in proper management of water to be used on crops to give the right amount at the right time. Other ways through which water can be used more efficiently include scheduling irrigation according to crop water requirement or practices such as deficit irrigation. (Bodner et al., 2015) Crops can be raised strictly on the vulnerable amounts of water without much of a decrease in yields, thus, the farmers can cut down on how much water they use. Even though, when it is applicate right properly, the deficit irrigation can improve some crop quality attributes, for instance the concentration of fruit in vineyards, this by applying stress to some determined phases of development. (Yu et al., 2021).

Soil Management Techniques

It is with this understanding that the next sub-investment area targeting management of soils is seen to have a strong relationship with drought tolerance. Further addition of organic matter such as compost or manure assists in developing cur structure thus improving the water retention capability. (Al-Kaisi et al., 2013) This makes the possibility of having more water for the crops especially during seasons that it is known to be extremely dry or during certain months of the year. Besides, soil amendments-influence the population and activity of the soil Microbial-DNA and this may also help in stressing condition nutrients for plants growth. (Farooq et al., 2009) Other method is mulching which involves placing a layer on the surface of the soil and can either be organic or inorganic matter. Another advantage of mulching is that on evaporation it reduces and at the same time regulates on the temperature of the soil which is very crucial factor during the dry season. In addition, they assist in reducing the competition by weeds since their germination will also be hampered by water as well as nutrients. (Chrysargyris et al., 2018) Conservation tillage is also one that does not disrupt the surface of the soil to a large extent and is also useful in the conservation of water on the surface of the soil. It also regulates the flow of water hence reducing situations of soil erosion and also allows for the retaining of more water for use by plants. Conservation tillage can also enhance the physical of the top soil for gradual enhancement in root growth and water intake which are so crucial in conservation of water. (Farooq et al., 2009).

Crop Management Practices

One of the easiest methods to address the issue of drought is through management where one of them is choosing the right crop varieties that are resistant to the drought. These varieties are bred or genetically modified to have higher stress tolerance to water deficit so as to guarantee relatively better yields during dry seasons. (Iqbal et al., 2020) Other strategies include intercropping and crop rotation which will ensure that farmers do not produce a single variety of crop so that in the event of a drought, all their produce is under threat of being destroyed. Changing in planting dates and crop calendars is another recommended way to deal with drought. (Ray et al., 2018) The selection of appropriate time for planting can help in avoiding critical and unfavorable dry periods and, therefore, the growth phase of the crops will be achieved during a relatively better term. In other ways, beside crop selection for a specific farming area the crop watering needs can also be managed across the season by changing the types of crops that are cultivated, or by grouping crops according to their water demand or root penetration in the ground. (Iqbal et al., 2020).

Bio stimulants and Plant Growth Regulators

Auxin-type substance, including seaweed extracts, humus acids, and various amino acids, are finding application as bio stimulants that increase plants' resistance to drought stress. It is due to these matter it stimulates root formation, increases nutrient content and assists plant to withstand stress period such as drought. (Gupta et al., 2023) Bio stimulants also improve the natural defense mechanisms of a plant by hardening it against similar environmental factors including, high levels of salts, and high or low temperatures. (Khan et al., 2020) Another useful method is the use of plant growth regulators, such as cytokines and gibberellins to reduce the effects of water deficit stress. Some of these regulators control the growth and development of the plant and enabling crops to perform well under stress indicators. (Gupta et al., 2023) For instance, cytokines can extend the time for leaf senescence thus maintaining the photosynthetic machinery during periods of drought while on the same note, gibberellins can increase stem and root growth, which would increase the ability of the plant to find water. (Sabagh et al., 2021).

Agroforestry and Mixed Cropping Systems

Combining agroforestry and agronomic crops is the best practice since it involves having trees and crops in the same field, this provide the following advantages in combating drought. Trees also help strengthen the ground structure, lessen evaporation, and this lessens water stress of crops due to the shade provided by the trees. (Gao et al., 2018) Second of all, trees are able to develop a large root system that can gather water and nutrients from deeper, or farther levels of the ground which annual crops cannot, making it stronger as a whole. In addition to this, use of mixed cropping also supports water conservation as well as the improvement of the water retention capacity of the soil. (Rivest et al., 2013) The integrity of these system can allow the other plant species to occupy other levels of the soil and minimize competition for water hence improving water use efficiency. (Bai et al., 2016) This is particularly helpful in regions prone to drought which have produced case studies indicating that these systems can help enhance the communities' ability to cope with the challenge, and guarantee more stable yields in the process. (Burgess et al., 2022) For instance, in south of Sahara regions, agroforestry practices have been credited with increasing crop returns and other revenue avenues such as from timber and fruits among others gotten from trees. (Dagar et al., 2020).

5. Exploratory Sample of Drought Resistant Plants

Maize: Maize is one of the world's major cereal crops, and there has been a great improvement on the breeding and genetic engineering and modification of the crop to withstand drought. Selection process in breeding programs has enhanced improved root system, higher water use efficiency and osmotic adjustment. (Fisher et al., 2015) There are modifications which enhance genes that allow the growth of maize under conditions of water stress; this can be viewed as adaptation to negative environments. (Edmeades, 2008) For instance, with the development of DREB gene, it has been possible to breed high yielding drought stress responsive maize varieties capable of performing well under drought conditions mainly during reproductive phase such as flowering and grain filling. (Makate & Makate, 2019).

Rice: Rice, a staple food for more than half the world's population, has also improved considerably in Drought Tolerance. Grow traits including deep rooting system as well as water use efficient have also improved through breeding. (Fukai & Cooper, 1995) Biotechnological methods have involved the use of genes giving rice plants abilities to endure drought with a view of increasing yield reliability under conditions of water shortage. (Casartelli et al., 2018) Also, the current advancement of aerobic rice varieties that are well adapted to grow on upland condition is another source of relief to mankind in sparing water while at the same time increasing production. (Fukai & Cooper, 1995).

Wheat: Wheat is the other crop that has received a boost in drought tolerance from new technologies on food production. (Bao et al., 2023) On its own with such measures like use of drought resistant plant varieties and proper planting dates have been adopted alongside genetic advancements to enhance water343 resistant in wheat. (Hussein et al., 2024) Subsequently, breeding programs have been applied to the factors such as root depth, WUE, osmotic adjustment and the like to improve drought tolerance. During the establishment of drought-tolerant genes from wild relatives has also been instrumental in producing new wheat varieties suitable to grow under unfavorable conditions where water stress is apparent. (Mwadzingeni et al., 2016).

Other Crops (Soybean, Sorghum, etc.)

Soybean and sorghum among other crops also have another area of focus under drought tolerance. Most of these crops are produced in areas that are badly affected by drought, hence the need to develop early maturing drought resistant varieties. (Derese et al., 2018) For example, due to its initial drought tolerance, programs that have bred sorghum to give better root penetration and water use efficiency. Soybean breeding has also centered on the increases in root structure and further aims at osmotic adjustment to guarantee high yield even under water constraint (Hadebe et al., 2017) Current breeding work also goes ahead a building up the desirable characteristics of the crop that will enable it to perform well under drought conditions. This research is particularly critical since climate change is anticipated to cause frequent and severe drought situations, and thus there is need to develop crops that can effectively cope with these conditions**.** (Derese et al., 2018).

6. Future Perspectives and Challenges

Integrating New Technologies:

The future of drought tolerance in crops, in other words, is in technology that applies Artificial Intelligence (AI), machine learning, and precision agriculture. These technologies could assist in identifying likely locations and times that drought would occur, on how to use water and where to apply the best practices of management. (Bampi & Reis, 2011) AI/Machine learning can review big data for determining optimal applications for improving drought tolerance across various crops. Use of sensors and GPS, data analysis that enables farmers to apply water, nutrients and other productions appropriately under drought are known as precision agriculture. (Monteiro et al., 2021).

Climate Change and Evolving Drought Patterns:

As the climate continues to change that the pattern of droughts will also change in the future with some areas experiencing long, severe droughts. This makes drought tolerance to be a dynamic issue, which calls for constant work and research to tackle. (Cook et al., 2018) Next strategies will have to be capable of recognizing these changes and to adapt to them using the best of both worlds, traditional and scientific practices to develop sustainable structures for agriculture. It will be the challenge of breeding programs to create varieties which not only withstand drought but also perform well in different production environments in different areas and climatic conditions. (Dai et al., 2018).

Policy and Socio-Economic Considerations:

There will be inevitable reliance on the governmental policies and international cooperation towards increasing production of drought resistant agriculture. Some of the strategies that will be imperative in catering for this increasing drought are; Research and development policies that will encourage development of crops that can withstand drought and enable sharing of such knowledge with other countries through policy formation. (Binimelis & Myhr, 2016) There is also the need to have policies to deal with some of the repercussions of drought in the socio-economic context of a country, including supporting smallholder producers, water conservation measures and climate moist agriculture. (Falck-Zepeda, 2009).

CONCLUSION

This review has revealed real progress has ever been made in physiological, genetic, and management practices that have collectively improved the status of drought tolerance in crops and has provided a model system for combating the effects of drought on agriculture. The advancement in technology on the development of new drought resistant varieties through conventional breeding techniques and biotechnology techniques as well as the adoption of improved water and soil management practices offers a package solution to the problems of water deficit. However, to address the challenges of drought tolerance all these strategies require an additional imprint of modern technological ones that enables precision agriculture and genomics for developing strong agricultural systems which can survive the stiffening ecological challenges. The effective uh, utilization of these strategies will need an integrated effort of scientists, policy makers, and the farmers so as to ensure that the innovation are assimilated to enhance sustainable changes in crop yields and food security. Also, due to climate change, there is an increase in drought conditions hence research and coming up with new ways of handling the current research is vital. Hence, by continuing with more research and innovations in sciences and technology the agricultural industry will be in a position to feed the increasing global population under these trying times.

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REFERENCES

Abdallah, A. M., Jat, H. S., Choudhary, M., Abdelaty, E. F., Sharma, P. C., & Jat, M. L. (2021). Conservation agriculture effects on soil water holding capacity and water-saving varied with management practices and agroecological conditions: A Review. *Agronomy*, *11*(9), 1681.

Ahmad, U., Hussain, M., Ahmad, W., Javed, J., Arshad, Z., & Akram, Z. (2024). Impact of global climate change on maize (Zea mays): physiological responses and modern breeding techniques. *Trends Biotech Plant Sci*, *2*(1), 62-77.

Al-Kaisi, M. M., Elmore, R. W., Guzman, J. G., Hanna, H. M., Hart, C. E., Helmers, M. J., Hodgson, E. W., Lenssen, A. W., Mallarino, A. P., & Robertson, A. E. (2013). Drought impact on crop production and the soil environment: 2012 experiences from Iowa. *Journal of Soil and Water Conservation*, *68*(1), 19A-24A.

Alharbi, S., Felemban, A., Abdelrahim, A., & Al-Dakhil, M. (2024). Agricultural and Technology-based strategies to improve water-use efficiency in Arid and Semiarid areas. *Water*, *16*(13), 1842.

Andrade, J. L., Cervera, J. C., & Graham, E. A. (2009). Microenvironments, water relations, and productivity of CAM plants. *Perspectives in biophysical plant ecophysiology: a tribute to Park S. Nobel*, 95-120.

Ashraf, M. (2010). Inducing drought tolerance in plants: recent advances. *Biotechnology advances*, *28*(1), 169-183.

Babu, R. C., Pathan, M. S., Blum, A., & Nguyen, H. T. (1999). Comparison of measurement methods of osmotic adjustment in rice cultivars. *Crop Science*, *39*(1), 150-158.

Bai, W., Sun, Z., Zheng, J., Du, G., Feng, L., Cai, Q., Yang, N., Feng, C., Zhang, Z., & Evers, J. B. (2016). Mixing trees and crops increases land and water use efficiencies in a semi-arid area. *Agricultural Water Management*, *178*, 281-290.

Bampi, S., & Reis, R. (2011). Challenges and emerging technologies for system integration beyond the end of the roadmap of nano-CMOS. VLSI-SoC: Technologies for Systems Integration: 17th IFIP WG 10.5/IEEE International Conference on Very Large Scale Integration, VLSI-SoC 2009, Florianópolis, Brazil, October 12-14, 2009, Revised Selected Papers 17,

Bao, X., Hou, X., Duan, W., Yin, B., Ren, J., Wang, Y., Liu, X., Gu, L., & Zhen, W. (2023). Screening and evaluation of drought resistance traits of winter wheat in the North China Plain. *Frontiers in Plant Science*, *14*, 1194759.

Bernstein, L. (1961). Osmotic adjustment of plants to saline media. I. Steady state. *American Journal of Botany*, *48*(10), 909-918.

Binimelis, R., & Myhr, A. I. (2016). Inclusion and implementation of socio-economic considerations in GMO regulations: needs and recommendations. *Sustainability*, *8*(1), 62.

Blum, A. (2017). Osmotic adjustment is a prime drought stress adaptive engine in support of plant production. *Plant, cell & environment*, *40*(1), 4-10.

Bodner, G., Nakhforoosh, A., & Kaul, H.-P. (2015). Management of crop water under drought: a review. *Agronomy for Sustainable Development*, *35*, 401-442.

Bramley, H., Turner, N. C., & Siddique, K. H. (2013). Water use efficiency. *Genomics and Breeding for Climate-Resilient Crops: Vol. 2 Target Traits*, 225-268.

Burgess, A. J., Cano, M. E. C., & Parkes, B. (2022). The deployment of intercropping and agroforestry as adaptation to climate change. *Crop and Environment*, *1*(2), 145-160.

Campalans, A., Messeguer, R., Goday, A., & Pagès, M. (1999). Plant responses to drought, from ABA signal transduction events to the action of the induced proteins. *Plant Physiology and Biochemistry*, *37*(5), 327-340.

Casartelli, A., Riewe, D., Hubberten, H. M., Altmann, T., Hoefgen, R., & Heuer, S.

(2018). Exploring traditional aus-type rice for metabolites conferring drought tolerance. *Rice*, *11*, 1-16.

Chaves, M. M., Flexas, J., & Pinheiro, C. (2009). Photosynthesis under drought and salt stress: regulation mechanisms from whole plant to cell. *Annals of botany*, *103*(4), 551-560.

Chen, H., & Jiang, J.-G. (2010). Osmotic adjustment and plant adaptation to environmental changes related to drought and salinity. *Environmental Reviews*, *18*(NA), 309-319.

Chrysargyris, A., Xylia, P., Litskas, V., Mandoulaki, A., Antoniou, D., Boyias, T., Stavrinides, M., & Tzortzakis, N. (2018). Drought stress and soil management practices in grapevines in Cyprus under the threat of climate change. *Journal of Water and Climate Change*, *9*(4), 703-714.

Cook, B. I., Mankin, J. S., & Anchukaitis, K. J. (2018). Climate change and drought: From past to future. *Current Climate Change Reports*, *4*, 164-179.

Dagar, J. C., Sileshi, G., & Akinnifesi, F. (2020). Agroforestry to enhance livelihood security in Africa: research trends and emerging challenges. *Agroforestry for Degraded Landscapes: Recent Advances and Emerging Challenges-Vol. 1*, 71-134.

Dai, A., Zhao, T., & Chen, J. (2018). Climate change and drought: a precipitation and evaporation perspective. *Current Climate Change Reports*, *4*, 301-312.

Davies, W. J., Kudoyarova, G., & Hartung, W. (2005). Long-distance ABA signaling and its relation to other signaling pathways in the detection of soil drying and the mediation of the plant's response to drought. *Journal of plant growth regulation*, *24*, 285-295.

Derese, S. A., Shimelis, H., Laing, M., & Mengistu, F. (2018). The impact of drought on sorghum production, and farmer's varietal and trait preferences, in the north eastern Ethiopia: implications for breeding. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, *68*(5), 424-436.

Edmeades, G. O. (2008). *Drought tolerance in maize: an emerging reality*. International Service for the Acquisition of Agri-Biotech Applications ….

Falck-Zepeda, J. B. (2009). Socio-economic considerations, Article 26.1 of the Cartagena Protocol on Biosafety: What are the issues and what is at stake. *AgBioForum*, *12*(1), 90-107.

Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., & Basra, S. M. (2009). Plant drought stress: effects, mechanisms and management. In *Sustainable agriculture* (pp. 153-188). Springer.

Fisher, M., Abate, T., Lunduka, R. W., Asnake, W., Alemayehu, Y., & Madulu, R. B. (2015). Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: Determinants of adoption in eastern and southern Africa. *Climatic Change*, *133*, 283-299.

Fukai, S., & Cooper, M. (1995). Development of drought-resistant cultivars using physiomorphological traits in rice. *Field crops research*, *40*(2), 67-86.

Fukushima, A., Kusano, M., Redestig, H., Arita, M., & Saito, K. (2009). Integrated omics approaches in plant systems biology. *Current opinion in chemical biology*, *13*(5-6), 532-538.

Gao, X., Liu, Z., Zhao, X., Ling, Q., Huo, G., & Wu, P. (2018). Extreme natural drought enhances interspecific facilitation in semiarid agroforestry systems. *Agriculture*, *Ecosystems & Environment*, *265*, 444-453.

Girma, F. S., & Krieg, D. R. (1992). Osmotic adjustment in sorghum: I. Mechanisms of diurnal osmotic potential changes. *Plant Physiology*, *99*(2), 577-582.

Gupta, S., Bhattacharyya, P., Kulkarni, M. G., & Doležal, K. (2023). Growth regulators and biostimulants:

upcoming opportunities. In (Vol. 14, pp. 1209499): Frontiers Media SA.

Hadebe, S., Modi, A., & Mabhaudhi, T. (2017). Drought tolerance and water use of cereal crops: A focus on sorghum as a food security crop in sub-Saharan Africa. *Journal of Agronomy and Crop Science*, *203*(3), 177-191.

Hasin, Y., Seldin, M., & Lusis, A. (2017). Multi-omics approaches to disease. *Genome biology*, *18*, 1-15.

Hatfield, J. L., Sauer, T. J., & Prueger, J. H. (2001). Managing soils to achieve greater water use efficiency: a review. *Agronomy journal*, *93*(2), 271-280.

Henkrar, F., & UDUPA, S. (2020). Marker assisted selection in plant breeding. *Moroccan Journal of Agricultural Sciences*, *1*(5).

Hussein, E., Darwish, M. A., Yassin, M. M., & Elsayed, M. I. (2024). Tolerance Evaluation of Some Bread Wheat Genotypes to Water Deficit through Exploratory Factor Analysis. *Alexandria Journal of Agricultural Sciences*, *69*(4), 420-445.

Iqbal, M. S., Singh, A. K., & Ansari, M. I. (2020). Effect of drought stress on crop production. *New frontiers in stress management for durable agriculture*, 35-47.

Jiang, G.-L. (2013). Molecular markers and marker-assisted breeding. *Jiang, G.-L. Plant Breeding from Laboratories to Fields*, 45-85.

Kanwal, R., & Gupta, S. (2012). Epigenetic modifications in cancer. *Clinical genetics*, *81*(4), 303-311.

Khan, N., Bano, A. M., & Babar, A. (2020). Impacts of plant growth promoters and plant growth regulators on rainfed agriculture. *PloS one*, *15*(4), e0231426.

Kumar, V., Sharma, A., Soni, J. K., & Pawar, N. (2017). Physiological response of C3, C4 and CAM plants in changeable climate. *The Pharma Innovation*, *6*(9, Part B), 70.

Kumar, V., Sharma, K. V., Pham, Q. B., Srivastava, A. K., Bogireddy, C., & Yadav, S. (2024). Advancements in drought using remote sensing: assessing progress, overcoming challenges, and exploring future opportunities. *Theoretical and Applied Climatology*, *155*(6), 4251-4288.

Le Houérou, H. N. (1996). Climate change, drought and desertification. *Journal of arid Environments*, *34*(2), 133-185.

Lombardini, L., & Rossi, L. (2019). Ecophysiology of plants in dry environments. *Dryland ecohydrology*, 71-100.

Mahmood, T., Khalid, S., Abdullah, M., Ahmed, Z., Shah, M. K. N., Ghafoor, A., & Du, X. (2019). Insights into drought stress signaling in plants and the molecular genetic basis of cotton drought tolerance. *Cells*, *9*(1), 105.

Makate, C., & Makate, M. (2019). Interceding role of institutional extension services on the livelihood impacts of drought tolerant maize technology adoption in Zimbabwe. *Technology in Society*, *56*, 126-133.

Mikiciuk, G., Miller, T., Kisiel, A., Cembrowska-Lech, D., Mikiciuk, M., Łobodzińska, A., & Bokszczanin, K. (2024). Harnessing Beneficial Microbes for Drought Tolerance: A Review of Ecological and Agricultural Innovations. *Agriculture*, *14*(12), 2228.

Misra, R., & Tewari, N. (2024). Gendering the Impact of Climate Change on Agriculture in Asia. In *Climate, Environment and Agricultural Development: A Sustainable Approach Towards Society* (pp. 237-248). Springer.

Monteiro, A., Santos, S., & Gonçalves, P. (2021). Precision agriculture for crop and livestock farming—Brief review. *Animals*, *11*(8), 2345.

Munns, R. (1988). Why measure osmotic adjustment? *Functional Plant Biology*, *15*(6), 717-726.

Murr, R. (2010). Interplay between different epigenetic modifications and mechanisms. *Advances in genetics*, *70*, 101-141.

Mwadzingeni, L., Shimelis, H., Tesfay, S., & Tsilo, T. J. (2016). Screening of bread wheat genotypes for drought tolerance using phenotypic and proline analyses. *Frontiers in Plant Science*, *7*, 1276.

Nakashima, K., & Yamaguchi-Shinozaki, K. (2013). ABA signaling in stress-response and seed development. *Plant cell reports*, *32*, 959-970.

Orsenigo, M., Patrignani, G., & Rascio, N. (1997). Ecophysiology of C3, C4 and CAM plants. *Handbook of photosynthesis*, 1-25.

Patel, D. J., & Wang, Z. (2013). Readout of epigenetic modifications. *Annual review of biochemistry*, *82*(1), 81-118.

Quarrie, S. A. (1996). New molecular tools to improve the efficiency of breeding for increased drought resistance. *Plant growth regulation*, *20*, 167-178.

Rao, I. M., Miles, J. W., Beebe, S. E., & Horst, W. J. (2016). Root adaptations to soils with low fertility and aluminium toxicity. *Annals of botany*, *118*(4), 593-605.

Rastogi, M., Kolur, S. M., Burud, A., Sadineni, T., Sekhar, M., Kumar, R., & Rajput, A. (2024). Advancing water conservation techniques in agriculture for sustainable resource management: A review. *Journal of Geography, Environment and Earth Science International*, *28*(3), 41-53.

Ray, R. L., Fares, A., & Risch, E. (2018). Effects of drought on crop production and cropping areas in Texas. *Agricultural & Environmental Letters*, *3*(1), 170037.

Ray, S., & Majumder, S. (2024). Water management in agriculture: Innovations for efficient irrigation. *Modern agronomy*, 169-185.

Rhodes, C. J. (2014). Soil erosion, climate change and global food security: challenges and strategies. *Science progress*, *97*(2), 97-153.

Rivest, D., Lorente, M., Olivier, A., & Messier, C. (2013). Soil biochemical properties and microbial resilience in agroforestry systems: effects on wheat growth under controlled drought and flooding conditions. *Science of the Total Environment*, *463*, 51-60.

Rockström, J., Barron, J., & Fox, P. (2002). Rainwater management for increased productivity among small-holder farmers in drought prone environments. *Physics and Chemistry of the Earth, Parts a/B/C*, *27*(11-22), 949-959.

Sabagh, A. E., Mbarki, S., Hossain, A., Iqbal, M. A., Islam, M. S., Raza, A., Llanes, A., Reginato, M., Rahman, M. A., & Mahboob, W. (2021). Potential role of plant growth regulators in administering crucial processes against abiotic stresses. *Frontiers in Agronomy*, *3*, 648694.

Sage, R. (2001). Environmental and evolutionary preconditions for the origin and diversification of the C4 photosynthetic syndrome. *Plant Biology*, *3*(03), 202-213.

Sanders, G. J., & Arndt, S. K. (2012). Osmotic adjustment under drought conditions. In *Plant responses to drought stress: From morphological to molecular features* (pp. 199-229). Springer.

Shabala, S., & Shabala, L. (2011). Ion transport and osmotic adjustment in plants and bacteria.

Shiferaw, B., Tesfaye, K., Kassie, M., Abate, T., Prasanna, B., & Menkir, A. (2014). Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: Technological, institutional and policy options. *Weather and climate extremes*, *3*, 67-79.

Sinclair, T. R., Tanner, C., & Bennett, J. (1984). Water-use efficiency in crop production. *Bioscience*, *34*(1), 36-40.

Soma, F., Takahashi, F., Yamaguchi-Shinozaki, K., & Shinozaki, K. (2021). Cellular phosphorylation signaling and gene expression in drought stress responses: ABA-dependent and ABA-independent regulatory systems. *Plants*, *10*(4), 756.

Song, L., Wang, R., Yang, X., Zhang, A., & Liu, D. (2023). Molecular markers and their applications in marker-assisted selection (MAS) in bread wheat (Triticum aestivum L.). *Agriculture*, *13*(3), 642.

Srikanth, S., Lum, S. K. Y., & Chen, Z. (2016). Mangrove root: adaptations and ecological importance. *Trees*, *30*, 451-465.

Stanhill, G. (1986). Water use efficiency. *Advances in agronomy*, *39*, 53-85.

Subbarao, G., Johansen, C., Slinkard, A., Nageswara Rao, R., Saxena, N., Chauhan, Y., & Lawn, R. (1995). Strategies for improving drought resistance in grain legumes. *Critical reviews in plant sciences*, *14*(6), 469-523.

Wakchaure, R., Ganguly, S., Praveen, P., Kumar, A., Sharma, S., & Mahajan, T. (2015). Marker assisted selection (MAS) in animal breeding: a review. *J. Drug. Metab. Toxicol*, *6*(5), e127.

Xing, Y., & Wang, X. (2024). Precision agriculture and water conservation strategies for sustainable crop production in arid regions. *Plants*, *13*(22), 3184.

Yu, L., Zhao, X., Gao, X., Jia, R., Yang, M., Yang, X., Wu, Y., & Siddique, K. H. (2021). Effect of natural factors and management practices on agricultural water use efficiency under drought: A meta-analysis of global drylands. *Journal of Hydrology*, *594*, 125977.

Zahra, N., Hafeez, M. B., Kausar, A., Al Zeidi, M., Asekova, S., Siddique, K. H., & Farooq, M. (2023). Plant photosynthetic responses under drought stress: Effects and management. *Journal of Agronomy and Crop Science*, *209*(5), 651-672.

Zargar, S. M., Gupta, N., Nazir, M., Mahajan, R., Malik, F. A., Sofi, N. R., Shikari, A. B., & Salgotra, R. (2017). Impact of drought on photosynthesis: Molecular perspective. *Plant gene*, *11*, 154-159.

Zhang, J., Jia, W., Yang, J., & Ismail, A. M. (2006). Role of ABA in integrating plant responses to drought and salt stresses. *Field crops research*, *97*(1), 111-119.

Zivcak, M., Brestic, M., & Sytar, O. (2016). Osmotic adjustment and plant adaptation to drought stress. *Drought Stress Tolerance in Plants, Vol 1: Physiology and Biochemistry*, 105-143.