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ON
MORPHO-PHYSIOLOGICAL AND BIOCHEMICAL CHANGES OF WHEAT UNDER DROUGHT STRESS AND ITS REMEDIATION PROCESSES

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MORPHO-PHYSIOLOGICAL AND BIOCHEMICAL CHANGES OF WHEAT UNDER DROUGHT STRESS AND ITS REMEDIATION PROCESSES[1]

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ABSTRACT

The study sought to investigate the effects of drought stress on the wheat’s morpho-physiological and biochemical deviation and to assess the efficacy of various remediation strategies. Wheat plants were subjected to varying levels of drought stress, and morphological, physiological, and biochemical parameters were studied at various stages of plant growth. Drought stress significantly reduced plant height, leaf area, root length, chlorophyll content, photosynthetic rate, water use efficiency, decreased in relative water content, light interception, membrane stability index, and aslo decreased cytokinins, gibberellins, and auxins hormones resulting in reduced plant growth and development and increased membrane injury, concentrations of reactive oxygen species and proline according to the findings. Furthermore, antioxidant enzymes like catalase and superoxide dismutase were found to increase in response to drought stress, indicating oxidative stress in the plants. The study used a variety of strategies to mitigate the effects of drought stress, including the use of plant growth regulators and osmoprotectants. The application of proline and ascorbic acid significantly improved plant growth and physiological parameters, indicating their potential as effective drought stress remediation strategies in wheat plants. These findings have significant implications for crop production in drought-prone areas, and the methods used in this study may be useful for future research in those areas.

Keywords: Drought, morphology, physiology, biochemical changes, plant hormone, remediation

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CHAPTER I

INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops globally, providing a major source of food for humans and livestock. Archaeological evidence of wild emmer suggests that wheat was first cultivated in the southern Levant, with finds dating back to 9600 BC (College and Conolly *et al*., 2007). According to genetic analysis of wild einkorn wheat, it was first grown in the Karacadag Mountains of south-eastern Turkey (Hogan *et al*., 2013). World wheat production in 2020 was 761 million tonnes, making it the second most-produced cereal crops (https://en.wikipedia.org/wiki/Wheat., 2023). The volume of wheat production in Bangladesh in FY 2020-21 stood 12.45 lakh metric tonnes (Statistics, B. B., 2022). Despite its importance, wheat production faces numerous abiotic stresses, including drought stress, which is considered one of the major limiting factors to wheat production worldwide (Shao *et al*., 2019). Drought stress reduces crop productivity and causes significant economic losses, particularly in regions where water resources are limited (Hussain *et al*., 2018).

Morphological changes in plants are the visible changes that occur in the plant's external structure under different environmental conditions (Cao *et al*., 2019). Drought stress induces various morphological changes in wheat, including reduced plant height, leaf rolling, decreased leaf area, reduced stem diameter, and lower biomass production (Anjum *et al*., 1017). Drought stress also leads to the early senescence of leaves and increased root length and density to explore deeper soil layers for water uptake (Kothari *et al*., 2019).

Physiological changes refer to the functional and metabolic changes that occur in the plant's physiological processes under different environmental conditions (Cao *et al*., 2019). Drought stress affects various physiological processes in wheat, including photosynthesis, transpiration, and stomatal conductance (Shah *et al*., 2020). Under drought stress, the photosynthetic rate and stomatal conductance decrease due to the closure of stomata to reduce water loss through transpiration (Hakeem *et al*., 2021). As a result, there is a reduction in the carbon assimilation rate and a decrease in the accumulation of dry matter in the plant. Furthermore, drought stress also alters the water use efficiency (WUE) of wheat, which is defined as the amount of biomass produced per unit of water consumed by the plant (Zhang *et al*., 2019). Under drought stress, wheat plants exhibit higher WUE due to the reduction in transpiration and stomatal conductance (Gao *et al*., 2019).

Drought stress also leads to various biochemical changes in wheat, including alterations in the levels of osmolytes, phytohormones, and antioxidant enzymes (Kesh *et al*., 2022). Osmolytes are small organic molecules that help plants to cope with water stress by maintaining cellular turgor and stabilizing enzymes (Zhang *et al*., 2019). Proline is one of the most commonly accumulated osmolytes in wheat under drought stress (Sabagh *et al*., 2019). The accumulation of proline helps maintain cellular turgor and stabilize the structure and function of enzymes under drought stress (Shao *et al*., 2019).

Despite many researches heave been done on this problem, there are still some gaps. One of the main gaps in the research is the lack of consistency in the methods used to induce drought stress. Different studies have used different levels and durations of water deficit stress, making it difficult to compare the results and draw meaningful conclusions.

Another research gap is the need for more studies on the remediation of wheat under drought stress. While there have been some studies on the use of various remediation techniques such as irrigation, foliar application of nutrients, and genetic modification, more research is needed to fully understand their effectiveness and potential limitations.

Objectives

Based on above facts, the objectives of this review paper are:

- **i.** To find out the specific morpho-physiological and biochemical responses of wheat that occur under drought stress;
- **ii.** To find out the remediation approaches that contribute to drought tolerance in wheat.

CHAPTER II

MATERIALS AND METHODS

This seminar paper is entirely a review paper. All of the information was gathered from secondary sources. I read various books, journals, proceedings, reports, publications, the internet, and other materials related to this topic while preparing the review paper. My major professor and course instructors provided me with helpful advice and information. After gathering all available information, I compiled that information and prepared this seminar paper.

CHAPTER III

REVIEW OF FINDINGS

Drought stress has a significant impact on wheat plant growth and development by altering their morphological and physiological characteristics (Farooq *et al*., 2014). Drought stress reduces plant growth, chlorophyll content, photosynthetic rate, and water use efficiency, as well as increasing oxidative stress and membrane damage (Alqudah & Sallam *et al*., 2019). Furthermore, drought stress alters plant reproductive growth and reduces wheat grain yield and quality (Pradhan *et al*., 2012).

3.1 Some Morphological deviation of wheat under drought

3.1.1 Seedling Establishment

Water is required for seed germination; however, while other conditions may be ideal, drought stress prevents seed imbibition and, as a result, inhibits germination. Correspondingly, it reduces seedling vigour and has an impact on germination by lowering water intake. Drought stress manifests itself in the early stages of crop development by reducing seed germination, resulting in poor stand establishment (Patil *et al*., 2022).

3.1.2 Plant Height

Several studies have investigated the impact of drought stress on wheat plant height, and the results are consistent. In most cases, drought stress leads to a decrease in plant height. For example, a study by Farooq *et al*., (2009) showed that wheat plants subjected to drought stress had significantly shorter plant height compared to well-watered plants. The reduction in plant height was attributed to reduced cell elongation in the stem, as well as a decrease in the number of cells in the stem. Another study by Liu and Zhang *et al*., (2016) investigated the effect of drought stress on two wheat cultivars with different drought tolerance levels. The results showed that the cultivar with higher drought tolerance had a smaller reduction in plant height under drought stress than the cultivar with lower drought tolerance. This suggests that the ability to maintain plant height under drought stress is an important trait for drought tolerance in wheat.

Under severe water scarcity, wheat cell elongation can be altered by interrupting water flow from the xylem to the surrounding elongating cells (Anjum *et al*., 2011). Reduced water availability causes a drop in turgor pressure and protoplasm dehydration, impaired mitosis, which can result in reduced cell expansion and cell division, and thus growth is reduced (Gautam *et al*., 2021).

3.1.3 Leaf Area

Under drought stress, wheat leaves tend to become smaller in size, resulting in a decrease in leaf area. This response is due to the reduction in cell size and number in the leaf tissues. Wheat under drought stress had a reduction in leaf area compared to well-watered plants (Polo *et al*., 2011).

3.1.4 Changes in Tillering

Under moderate drought stress, wheat plants may exhibit reduced tillering as they allocate more resources towards root growth to access deeper soil moisture. This may result in fewer tillers but with a larger and more extensive root system. Severe and prolonged drought stress, the tillering capacity of wheat may be significantly reduced, leading to a decline in grain yield (Memon *et al.*, 2022).

3.1.5 Spike Length

Drought stress reduces wheat spike length due to the negative impact of water deficit on spike elongation and development (Memon *et al.*, 2022). Several studies have been conducted to investigate the impact of drought stress on wheat spike length. Drought stress, for example, reduced the spike length of wheat varieties by 7.5% to 13.7% (Kaur *et al*. 2020). (Hlaváčová *et al*., 2018) found that under severe drought stress wheat spike length decreased.

Table 1**.** Mean, range, and standard deviation (SD) of traits of 36 wheat genotypes in water stress (WS)

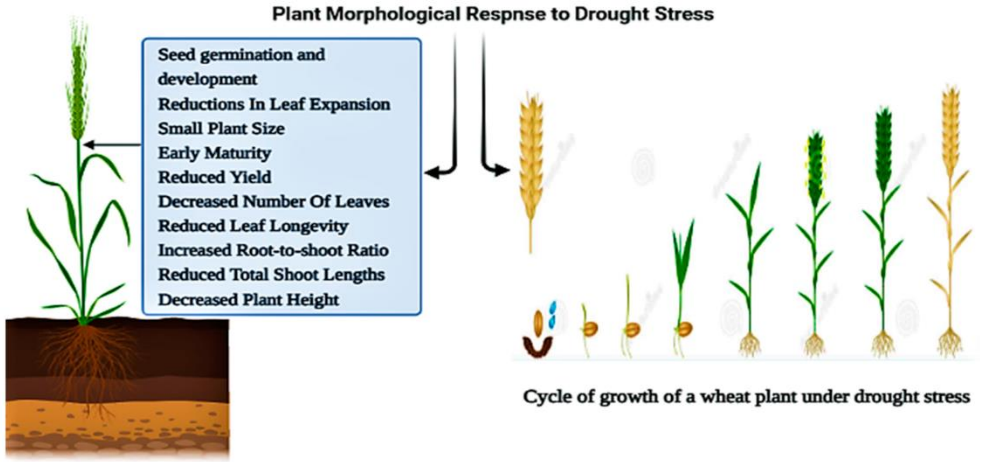
Traits	**Well Watered (WW)**			**Water Stress (WS)**		
	Mean	**Range**	**SD**	**Mean**	**Range**	**SD**
Second leaf area (cm^2)	32.2	24.7–44.4	4.41	17.4	7.61–24.0	3.65
Flag leaf area (cm^2)	45.6	33.8–54.7	4.35	17.3	8.04–30.3	5.05
Plant height (cm)	98.2	68.5–109.6	7.02	70.2	55.1–79.2	5.11
Peduncle length (cm)	14.0	6.98–24.3	2.86	11.5	5.24–18.1	3.09
Tiller's plant^{-1} (No.)	3.85	2.60–6.80	0.83	2.74	1.40–4.20	0.54
Spikelet's spike^{-1} (No.)	19.3	16.0–25.0	1.28	16.2	13.0–19.0	1.34
Spike length (cm)	11.9	8.0–14.1	1.06	10.2	7.70–11.9	0.85
Days to booting (No.)	69.6	66.0–75.0	2.28	63.1	58.0–68.0	2.42
Days to heading (No.)	72.9	69.0–78.0	2.07	65.8	62.0–71.0	2.10
Days to maturity (No.)	112.4	107–121	2.21	94.2	92.0–97.0	1.07
Grain yield plot^{-1} (g)	504.3	330.0–670.0	69.2	133.7	74.0–202.0	27.7
Harvest index (%)	21.5	15.9–26.1	2.06	16.9	10.0–23.0	2.76
Tiller per square meter (No.)	577.1	420.0–780.0	83.2	497	224.0–844.0	152

(Source: Memon *et al*., 2022)

According to the Memon *et al*., (2022) the value of traits of wheat mentioned in the table decreased significantly in stress condition then well water condition.

3.1.6 Increased Root-to-Shoot Ratio

The root-to-shoot ratio is an important factor to consider when studying the effects of drought stress on wheat. As a response to water scarcity, the wheat plant often allocates more resources to its roots to increase its ability to absorb water from the soil, resulting in an increase in the root-to-shoot ratio (Comas *et al*., 2013 and Cattivelli *et al*., 2008). The above-ground growth of the plant may be stunted due to the shift in resource allocation (Farooq *et al*., 2014). Various factors can influence the root-to-shoot ratio of wheat, such as the severity and duration of drought stress and the genetic makeup of the plant (Xu *et al*., 2018). Overall, monitoring the root-to-shoot ratio is a useful approach to understanding the morpho-physiological and biochemical changes in wheat under drought stress. It provides insights into the plant's water uptake and resource allocation strategies, which could help in the development of effective drought mitigation techniques (Fang *et al*., 2015)



(Source: Wahab *et al*., 2022)

Figure 1. Effect of drought stress on morphological aspects of wheat.

3.2 Physiological deviation of wheat under drought

3.2.1 The Relative Water Content (RWC)

RWC is regarded as a plant water status metric that reflects the metabolic activity of the plant organization. In most plants, it is used as an indicator of dehydration (Anjum *et al*., 2011). Several studies have investigated the RWC of wheat under drought stress, and the results have shown that under water deficit, the RWC of wheat decreases significantly. Schonfeld *et al*., (1988) found that drought stress reduced the amount of RWC in wheat, with the tolerant genotype having the highest RWC. Golparvar *et al*., (2013) reported that the RWC of wheat cultivars decreased under drought stress, while proline, soluble carbohydrates, and chlorophyll content increased. Farooq *et al*., (2009) highlighted the impact of drought stress on wheat, and showed that the RWC of wheat plants was significantly reduced under water-deficit conditions.

Table 2. RWC (relative water content), IWC (initial water content) and RWL (rate of water loss) of wheat under non-stress and water stress

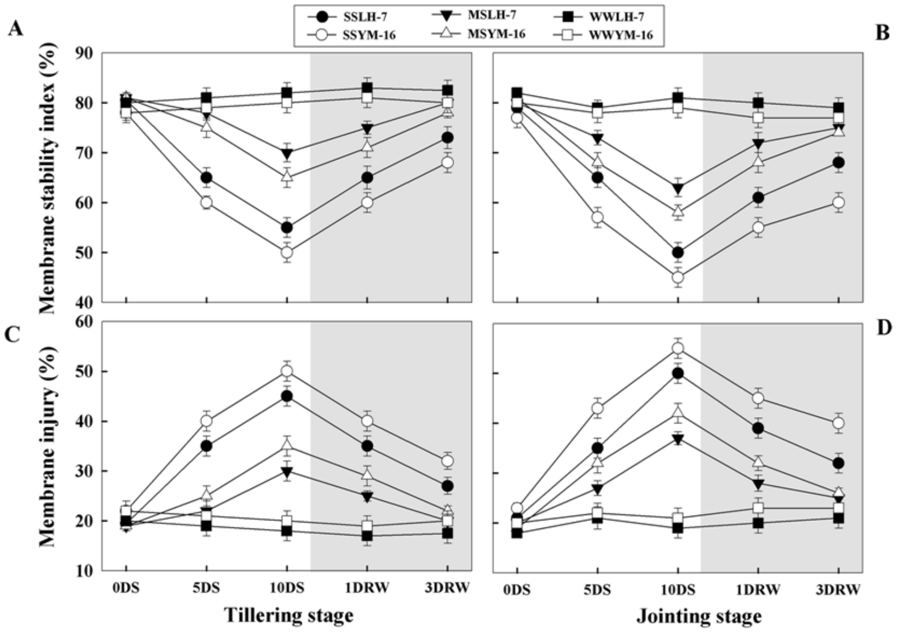
Genotype	RWC		IWC		RWL	
	Non stress	Stress	Non stress	Stress	Non stress	Stress
Zoro	87	86	2.18	2.55	4.69	4.29
Moreno	91	89	2.59	2.6	5.22	5.42
Lasko	90	86	2.73	2.52	5.97	5.92
Prego	91	86	2.61	2.17	5.71	4.42
Alamos 83	89	83	2.3	2.12	6.5	5.69
'Osta-Gata' (Wheat)	90	83	2.58	2.06	7.43	5.29
'Roshan'(wheat)	47	81	2.29	2.29	7.12	5.01

(Source: Lonbani *et at*., 2011)

According to the Lonbani *et al*., (2011) under both conditions, 'Moreno' and 'Prego' triticale cultivars had the highest RWC, while 'Roshan' (wheat) and 'Zoro' (triticale) cultivars had the lowest (Table 2). Drought tolerance was assigned to the 'Moreno' triticale cultivar, while drought sensitivity was assigned to the 'Roshan' wheat cultivar. Drought stress caused an average decrease in rate of water loss (RWL) in this study, which may indicate some inhibiting mechanisms of water loss under drought stress. This finding is consistent with that of (Golestani, Araghi and Asad *et al*., 1998), who discovered a decrease in RWL under stress conditions in wheat. Triticale genotypes had lower RWL than wheat genotypes. This could indicate that triticale genotypes use water more efficiently than wheat genotypes under drought stress conditions. Under water stress conditions, the RWL of cultivars 'Prego,' 'Roshan,' and 'Osta-Gata' decreased significantly. This phenomenon demonstrates that the most likely mechanisms for water retention in the leaf under stress conditions are leaf rolling or a decrease in leaf area.

3.2.2 Membrane Stability Index (MSI) and Membrane Injury (MI)

The study of the changes in membrane stability index and membrane injury of wheat under drought stress and non-drought stress conditions is crucial to understanding the response of wheat to water deficit (Abid *et al*., 2018). A study conducted by Farshadfar *et al*., (2014) examined the response of wheat plants to drought stress and found that the MSI of wheat plants decreased significantly under drought stress conditions. The study showed that the MSI of wheat plants decreased from 72.7% to 49.4% under drought stress conditions. This indicates that the plasma membrane of the wheat plants was more susceptible to damage under drought stress conditions, leading to a decrease in the MSI. Another study conducted by Hasanuzzaman *et al*., (2021) investigated the effect of drought stress on the MSI and MI of wheat plants and found similar results. The study reported that the MSI of wheat plants decreased significantly under drought stress conditions, with a decrease of up to 39%. Additionally, the study also reported a significant increase in MI under drought stress conditions, with an increase of up to 43%. These results indicate that drought stress can cause significant damage to the plasma membrane of wheat plants, leading to a decrease in MSI and an increase in MI.



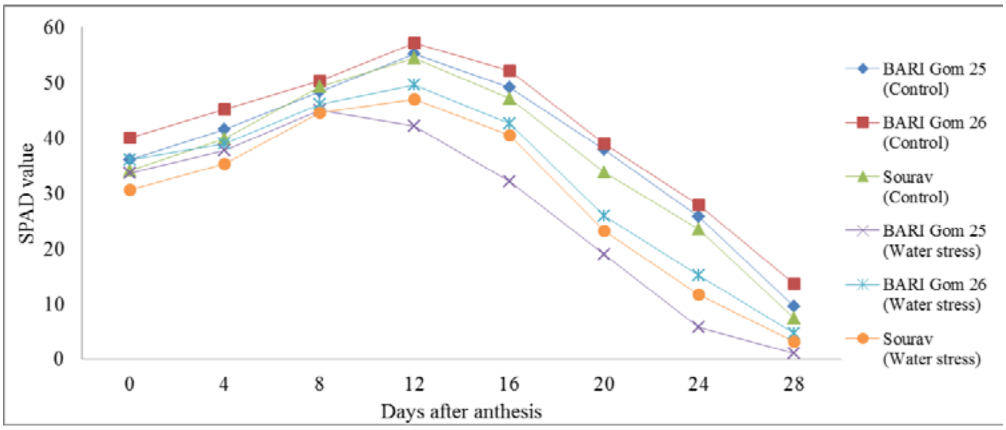
(Source: Abid *et al*., 2018)

Figure 2. Effect of drought stress (SS: severe stress, MS: moderate stress, and WW: well watered) MSI and MI in the wheat cultivars Luhan7 (LH-7) and Yangmai16 (YM-16).

According to the Abid *et al*., (2018) the magnitude of the decline in MSI was greater for plants treated with SS than for plants treated with MS, and it was more pronounced at jointing than at tillering. During stress periods, tolerant plants maintained significantly higher MSI and lower MI than sensitive cultivars. Both MSI and MI recovered progressively to WW levels by 3DRW in MS plants after re-watering, whereas SS plants showed incomplete recovery within the same re-watering time frame. Regardless of the growth stage at which stress was imposed, MSI and MI showed similar recovery trends.

3.2.3 Chlorophyll (SPAD value)

Chlorophyll is a major component of chloroplasts for photosynthesis, which increases biomass production and grain yield (Kaur *et al*., 2020). Abid *et al*., (2018) investigated SPAD value of wheat plants under drought stress. The findings showed a significant decrease in the SPAD value of the drought-stressed plants compared to the control group. This decline in SPAD value was attributed to the reduction in chlorophyll content caused by water scarcity, which subsequently resulted in a reduction in the plants' photosynthetic capacity.



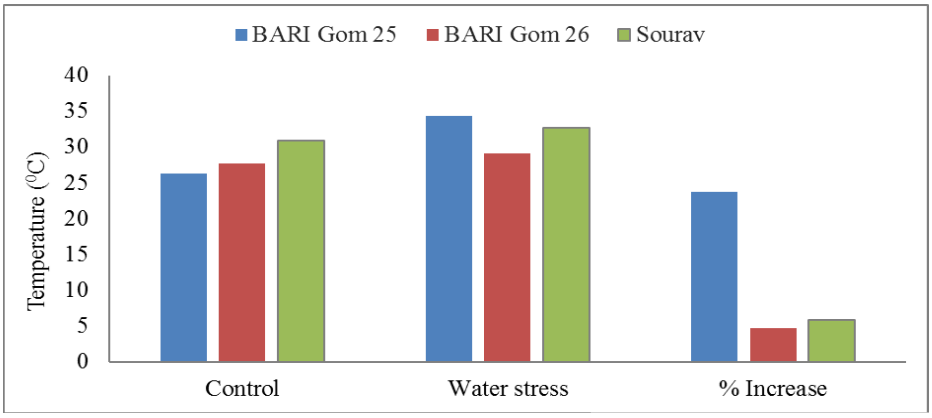
(Source: Tasnima *et al*., 2016)

Figure 3. SPAD values of wheat varieties under water-stress conditions.

According to Tasnima *et al*., (2016) SPAD values were recorded from 0 days after anthesis (DAA) to 28 DAA under control and water deficit conditions in three wheat varieties where under control and water deficit conditions, the SPAD value gradually increased up to 12 DAA, then decreased in all varieties except BARI Gom 25, where it decreases after 8 DAA. This could be due to leaf senescence, regardless of variety. At 12 DAA, BARI Gom 26 had the highest SPAD value (57.13) under both control and water deficit conditions (49.53). Under control conditions, Sourav (54.45) had the lowest SPAD value, but under water deficit conditions, BARI Gom 25 (42.16) had the lowest value. Water deficits accelerated senescence by accelerating the loss of leaf chlorophyll and soluble proteins, and the loss was greater in sensitive plants than in tolerant plants (Saed-Moucheshi *et al*., 2014). Chlorophyll content has decreased from 13 to 15%.

3.2.4 Canopy Temperature

Under water stress conditions, the canopy temperature of wheat varieties increased. This could have happened as a result of increased respiration and decreased transpiration caused by stomatal closure (Tasnima *et al*., 2016). Siddique *et al*., (2000) found that leaf temperature in drought-stressed wheat plants was higher than in well-watered plants at both the vegetative and anthesis stages. Because of water stress during the anthesis stages, canopy temperature varied significantly among the varieties.



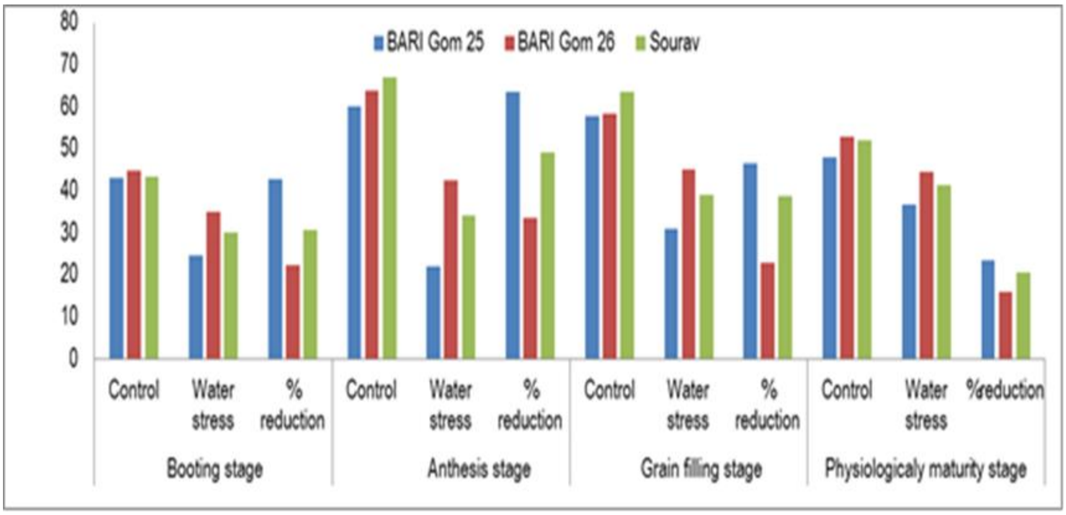
(Source: Tasnima *et al*., 2016)

Figure 4. Canopy temperatures of wheat varieties when water is scarce.

According to Tasnima *et al*., (2016) under control conditions, the highest canopy temperature was recorded in Sourav (30.830C), followed by BARI Gom 26 (27.730C), and the lowest in BARI Gom 25 (26.230C), but in water deficit conditions, the highest canopy temperature was recorded in BARI Gom 25 (34.38^{0}C), followed by Sourav (32.73^{0}C), and the lowest in BARI Gom 25 (29.09^{0}C).

3.2.5 Light Interception

Barutcular *et al*., (2016) discovered that wheat plants exposed to drought stress had lower intercepted PAR than those grown in well-watered conditions. The study also revealed that the decrease in intercepted PAR was caused primarily by a decrease in leaf area index (LAI) and leaf angle. Liu *et al*., (2020) investigated the effect of different irrigation regimes on winter wheat intercepted PAR. The intercepted PAR of wheat was significantly lower under severe drought stress compared to well-watered and moderate drought stress conditions, according to the findings. The study also revealed that the decrease in intercepted PAR was caused primarily by a decrease in LAI and leaf chlorophyll content.



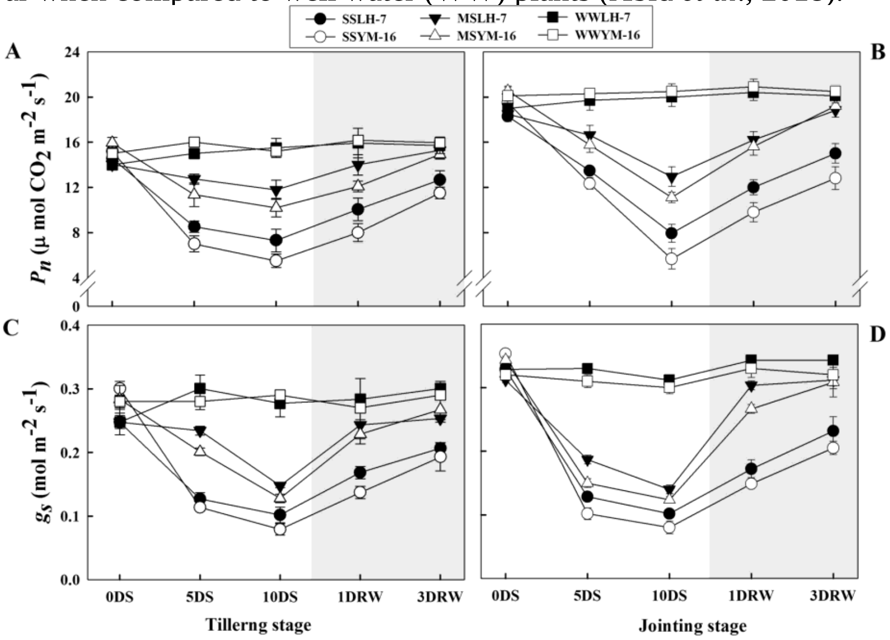
(Source: Tasnima *et al*., 2016)

Figure 5. Intercepted PAR of wheat varieties under water-stress conditions.

Under control conditions, BARI Gom 26 had the highest amount of light interception at booting (44.92%) and physiological maturity stage (52.86%), but Sourav had the highest at anthesis (67.06%) and grain filling (63.60%). In the presence of water stress, BARI Gom 26 had the highest light interception at booting (34.89%), anthesis (42.45%), grain filling (45.04%), and physiological maturity stage (44.42%). Under both conditions, BARI Gom 25 had the lowest light interception at all growth stages. However, under water deficit stress, BARI Gom 25 showed the greatest reduction, while BARI Gom 26 showed the least reduction across all growth stages. Because of increased leaf area, canopy radiation interception increased throughout the growing season. Because the leaves temporarily wilted or rolled as a result of the water stress, the radiation interception ability was reduced, as observed in the field. Moayedi *et al*., (2011) and Qamar *et al*., (2011) found that limited irrigation significantly reduced accumulated radiation interception compared to frequently irrigated crop plants

3.2.6 Net Photosynthetic Rate and Stomatal Conductance

Wheat plants are commonly exposed to drought stress, which can have a significant impact on their chlorophyll content and photosynthesis. Studies have shown that drought stress can lead to a decrease in the chlorophyll content of wheat plants (Haque *et al*., 2021). This decrease is primarily due to a reduction in the synthesis of chlorophyll molecules and an increase in the rate of degradation of existing chlorophyll. This decrease in chlorophyll content can negatively impact the plant's photosynthetic activity, leading to reduced growth and yield. Drought stress also triggers changes in the photosynthetic activity of wheat plants. Studies have reported a decrease in the rate of photosynthesis and stomatal conductance in wheat plants under drought stress (Siddique *et al*., 1999). This decrease is primarily due to a reduction in the availability of water, which leads to a decrease in the CO_2 assimilation rate and ultimately results in decreased plant growth and yield. Photosynthetic rate (Pn) and stomatal conductance (gs) decreased more in the sensitive cultivar than in the drought tolerant cultivar when compared to well water (WW) plants (Abid *et al*., 2018).



(Source: Abid *et al*., 2018)

Figure 6. Effect of drought stress (SS: severe stress, MS: moderate stress, and WW: well watered) on net photosynthetic rate (Pn) and stomatal conductance (gs).

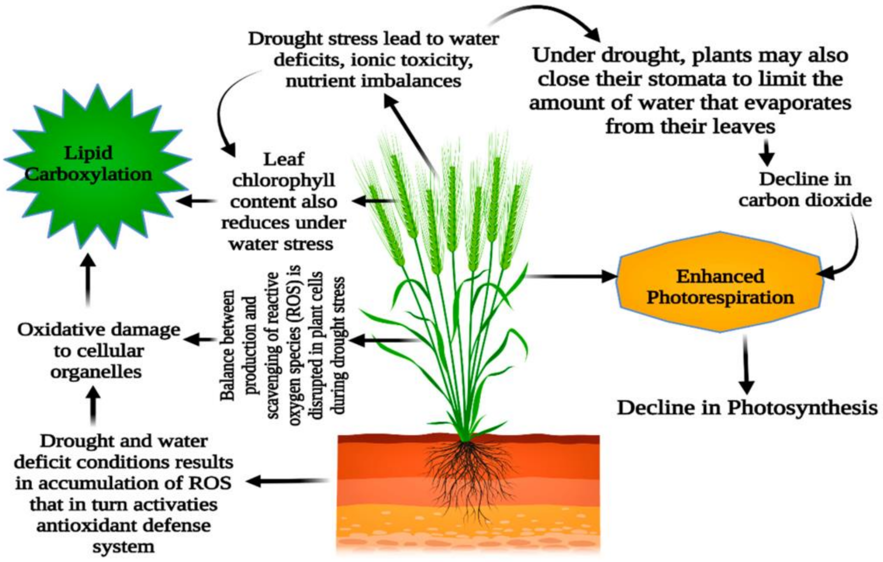
The figure depicts how drought stress reduced net photosynthetic rate (Pn) and stomatal conductance (gs) in WW plants during the stress period. In both cultivars, the magnitude of decline was greater for plants under severe drought stress (SS) during the jointing stage than for plants under moderate stress (MS) during tillering.

3.3 Biochemical Changes

Plant genetics and expressed genes result in the creation of some biochemical substances, the concentration of which determines intrinsic drought (or other abiotic stress) resilience (Passioura *et al*., 2012).

3.1 Production of Reactive Oxygen Species (ROS)

ROSs are free radicals composed of atoms or groups of atoms with at least one unpaired electron (Saed-Moucheshi *et al.*, 2014). Higher concentrations of ROS consisting of O_2^-, hydrogen peroxide (H_2O_2), OH, and $^1O_2$ have been reported to cause oxidative stress, which has typically occurred under drought stress (and other abiotic and biotic stresses) (Hassinen *et al*., 2011). Drought stress causes increased ROS; phytotoxic levels of which are hazardous, resulting in cellular damage and even death (Hasanuzzaman *et al.*, 2021). Plants can scavenge/detoxify ROSs by producing various types of antioxidants. Antioxidants are divided into two types: enzymatic antioxidants and non-enzymatic antioxidants (Saed-Moucheshi *et al.*, 2014). Superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and other enzymatic antioxidants that remove oxidative reactive agents are examples of enzymatic antioxidants. These antioxidant enzymes are known to significantly reduce superoxide (O_2) and hydrogen peroxide (H_2O_2) levels in plants (Hossain *et al*., 2015).



(Source: Wahab *et al*., 2022)

Figure 7. Effects of drought on wheat’s morpho-physiological and metabolic processes.

3.3.2 Malondialdehyde (MDA) Content

Malondialdehyde (MDA) is a key product of the thiobarbituric acid reaction in lipid peroxidation(Yang *et al*., 2015).

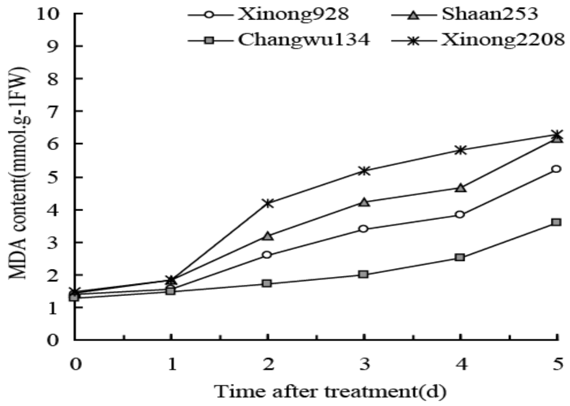


Figure8. MDA content in drought-stressed wheat seedling leaves (Source: Yang *et al*., 2015).

The MDA content of Xinong2208 and Shaan253 seedling leaves increased significantly on the second day of drought stress, as shown in Fig.8. MDA content increased faster in Xinong2208 and Shaan253 seedling leaves after five days of continuous drought stress than in Changwu134 and Xinong928 (Yang *et al*., 2015).

3.3.3 Changes in the Activities of Enzymatic Antioxidant

The enzymatic activities of CAT (catalyses), SOD (superoxidase dismutase), and APX (ascorbate peroxidases) are increased during drought stress (Tabarzad *et al*., 2017)

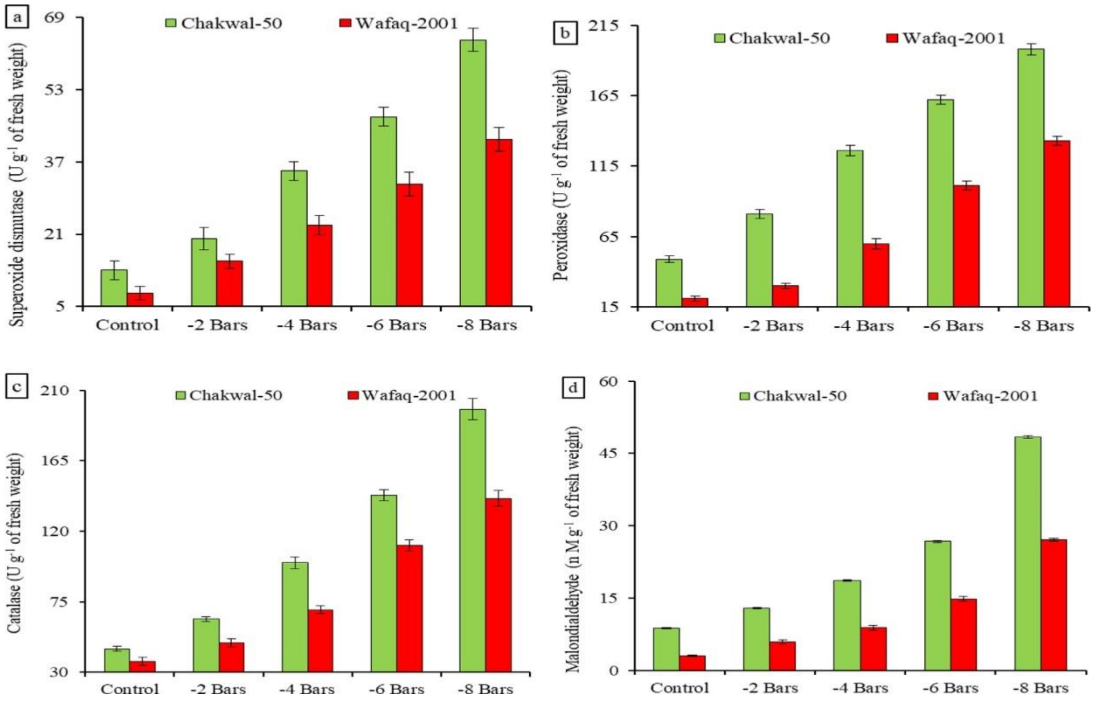


Figure 9. Drought stress effects on catalyses, superoxidase dismutase, peroxidases and malondialdehyde content (Source: Qayyum *et al*., 2021).

The activities of CAT and SOD, APX and MDA increased rapidly under drought condition. Activity peaked on the last day of drought stress (10DS). Except for APX, which exhibited higher activity during the tillering stage than the jointing stage under SS, overall antioxidant enzyme activities were higher under SS than MS with no significant. At both growth stages, the tolerant cultivar had higher antioxidant enzyme activity than the sensitive cultivar. Even after 3DRW, CAT, SOD, and APX activities decreased after re-watering but remained higher in SS plants than in WW plants (Abid *et al*., 2018).

Several studies have reported an increase in antioxidant enzyme activities, such as superoxide dismutase (SOD) and catalase (CAT), in wheat plants under drought stress (Li *et al*., 2020). This increase is an adaptive response to the oxidative stress that occurs under drought stress conditions. However, prolonged exposure to drought stress can lead to decreased antioxidant enzyme activities, which can further exacerbate the negative effects of stress on the plant's physiology (Huseynova *et al*., 2015).

3.3.4 Hormonal Changes

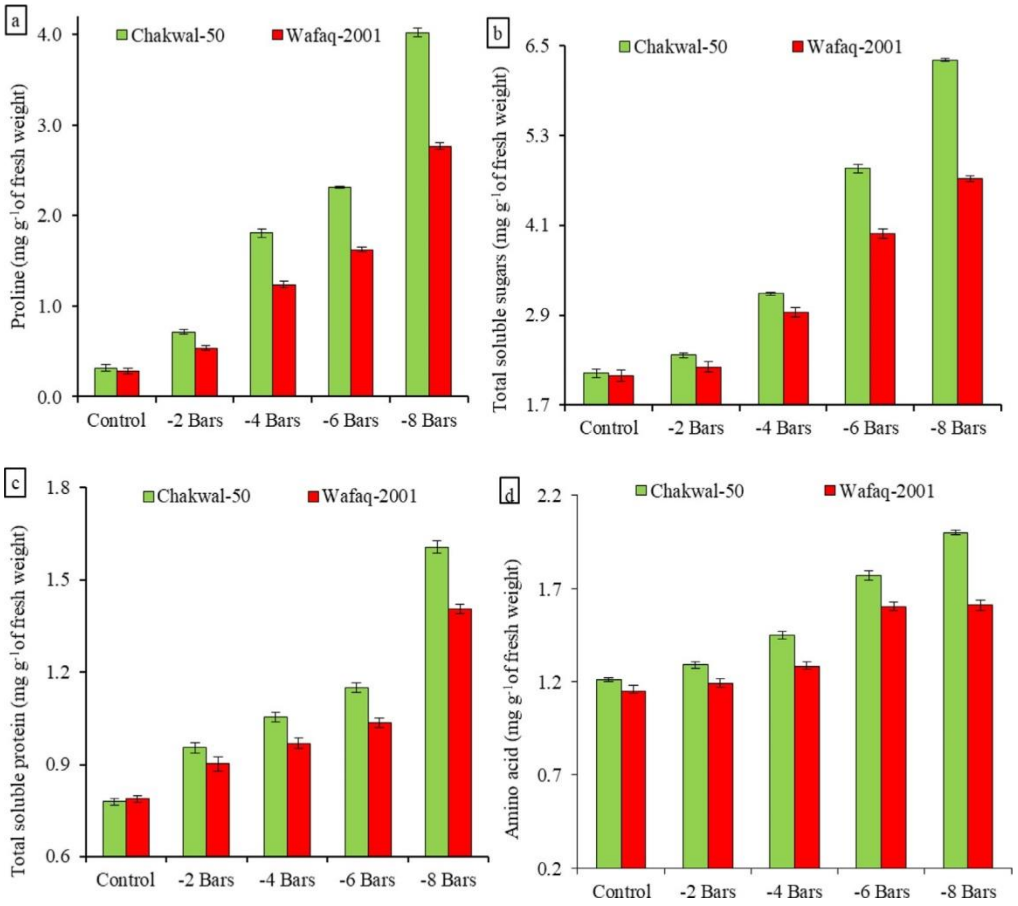
Studies have shown that drought stress can cause changes in the levels of different hormones in wheat plants, including abscisic acid (ABA), cytokinins, gibberellins, and auxins (Sabagh *et al*., 2021). ABA is a hormone that plays a crucial role in regulating the plant's response to water stress. Under drought stress, there is an increase in ABA levels in wheat plants, which helps to close the stomata and conserve water. On the other hand, cytokinins, gibberellins, and auxins are hormones that promote plant growth and development. Studies have shown that drought stress can cause a decrease in the levels of these hormones in wheat plants, resulting in reduced plant growth and development (Sabagh *et al*., 2021).Under drought stress, there is an upregulation of genes involved in ABA biosynthesis and signaling, as well as a downregulation of genes involved in cytokinin biosynthesis and signaling. These changes in gene expression help to enhance the plant's response to drought stress by promoting water conservation and reducing growth and development (Bhargava *et al*., 2013).

3.3.5 Accumulation of Osmolyte

Drought stress can cause a range of biochemical changes in wheat plants, including changes in enzyme activity, protein content, and osmolyte accumulation. One of the most well-studied biochemical changes in wheat plants under drought stress is the accumulation of osmolytes, such as proline and soluble sugars. Osmolytes play a crucial role in maintaining cell turgor and stabilizing proteins and membranes under drought conditions. Several studies have reported an increase in proline and soluble sugar content in wheat plants under drought stress (Qayyum *et al*., 2011). In addition to osmolyte accumulation, drought stress can also induce changes in enzyme activity in wheat plants. For example, a study conducted by Yu *et al*., (2020) found that the activity of enzymes involved in carbon and nitrogen metabolism, such as sucrose synthase and glutamine synthetase, increased in wheat plants under drought stress. These changes in enzyme activity may help to regulate metabolism and maintain plant growth and development under drought conditions. Another study found that under drought stress, total proteins and TOT-pentosans (mostly AX) rose whereas β-glucan concentration declined in wheat (Rakszegi *et al*., 2019).

3.3.6 Changes of amino acids, soluble proteins and proline contents

Drought stress increased the concentration of soluble protein, free amino acids and proline (Abid *et al*., 2014).



(Qayyum *et al*., 2021)

Figure 10. Changes in proline (a), total soluble sugars (b), total soluble protein (c) and amino acid content (d) in Wafaq-2001 and Chakwal-50 under water deficit stress.

Proline, total soluble sugars, total soluble protein, and amino acid content increased in both Chakwal-50 and Wafaq-2001 cultivars under water stress but the highest increase occurred at 8 bars (Qayyum *et al*., 2021).

Table 3. Biochemical changes in wheat plants under drought stress

Biochemical Changes	Effect of Drought Stress	Reference
Osmolyte Accumulation	Increase in proline and soluble sugar content	(Yu *et al*., 2020)
Enzyme Activity	Increase in sucrose synthase and glutamine synthetase activity	(Yu *et al*., 2020)
Protein Content	Increase in total protein content, decrease in β-glucan	(Rakszegi *et al*., 2019)

3.4 Drought Remediation approaches

3.4.1 Wheat Drought Tolerance through Foliar Spray

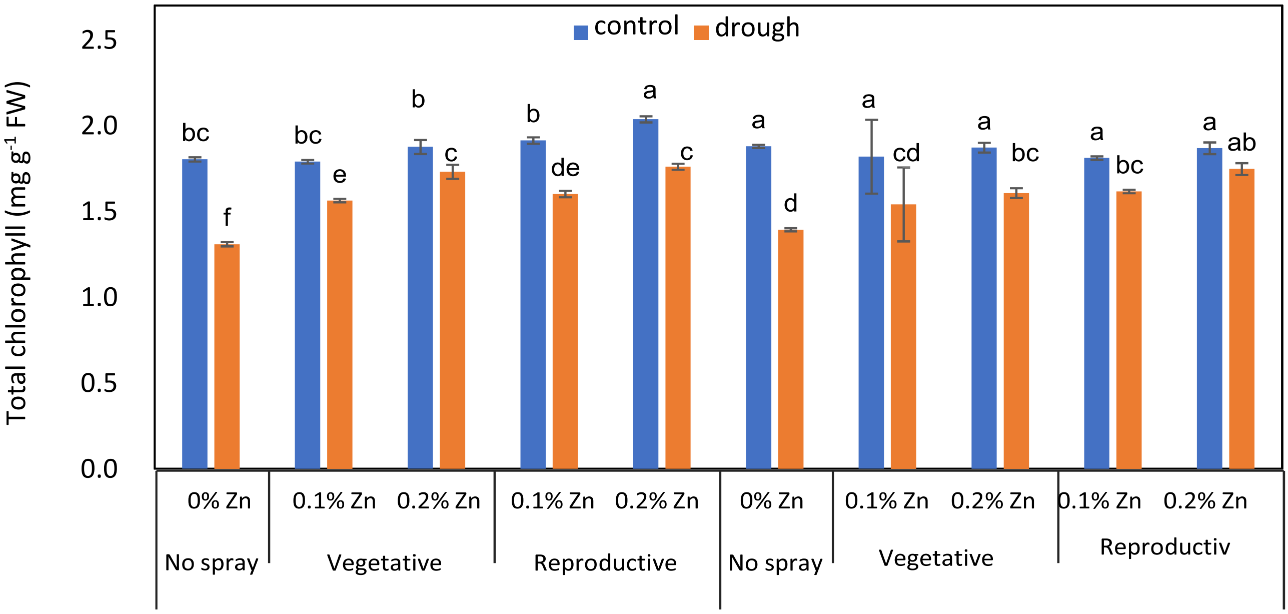
Foliar application is extremely effective because the chemicals contained in foliar sprays are easily accessible to plants (Muhammad *et al*., 2006).

3.4.1.1 Foliar Application of Salicylic Acid

Salicylic acid (SA), a hormone-like substance, has been discovered to play an important role in increasing photosynthetic rate as well as stomatal conductance and transpiration (Akhtar *et al*., 2013). Several studies have found that Salicylic acid (SA) improves plant resistance to salinity, drought, and high temperatures. In drought-stressed wheat crops, foliar application of salicylic acid (SA) and its derivatives improved drought tolerance (Bandurska *et al*., 2013). At the tillering stage of wheat, foliar application of SA (100 mg/L or 0.1 g/L) improved shoot-root fresh and dry weights, lengths, stomatal conductance, chlorophyll (a, b, and total contents), transpiration rate, and net photosynthetic rate (Ahmad *et al*., 2021).

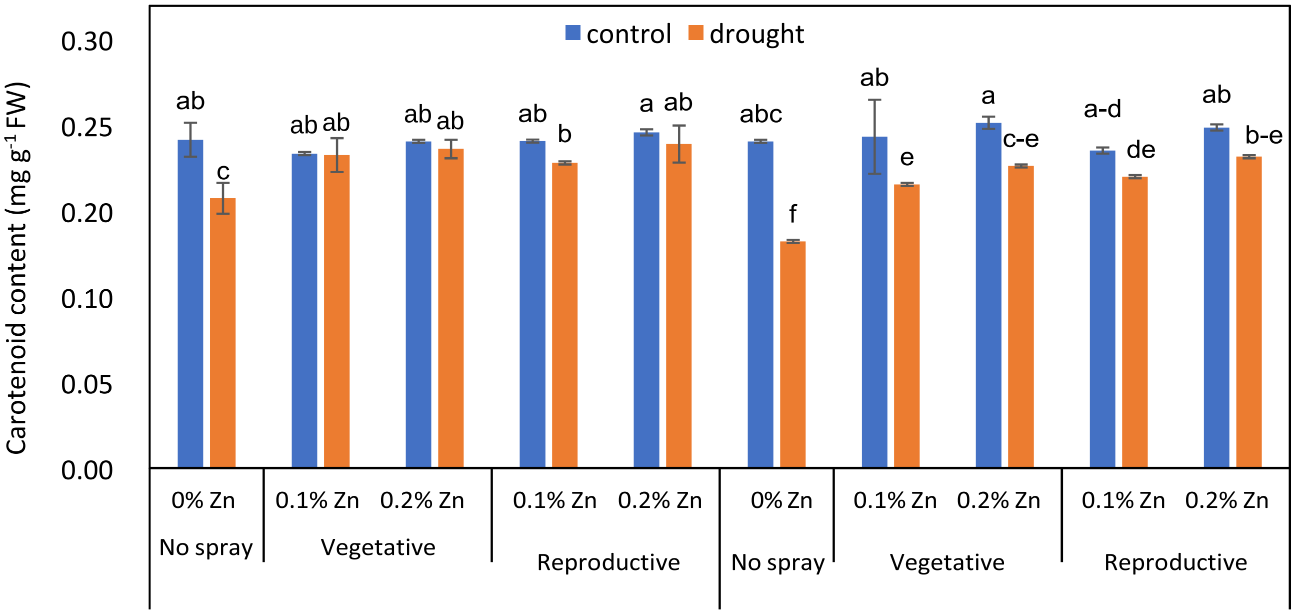
3.4.1.2 Foliar Application Potassium, Ascorbic acid, Zinc

Aerial application of potassium and amino acids augmented the phosphorous content of leaf, potassium content of leaf, leaf's chlorophyll content (SPAD Value) and the relative water contents of leaf (Ahmad *et al*., 2018). Malik *et al*., (2015) investigated the efficacy of ascorbic acid treatments in wheat and discovered that ascorbic acid application in the rooting medium was the most effective, followed by foliar application and seed priming. Foliar application of ascorbic acid increased wheat yield and chlorophyll content by moving minerals from leaves to flowers and by increasing CAT and APX activity (Hafez and Gharib *et al*., 2016). Foliar application of Zn at 0.2% at the vegetative stage of wheat improved drought tolerance by increasing shoot and grain Zn content, chlorophyll content, shoot biomass, grain weight, and grain yield (Anwar *et al*., 2021).



(Source: Anwar *et al*., 2021)

Figure 11. Effect of foliar spray of zinc at the vegetative and reproductive stages of wheat on the total chlorophyll content under drought stress.



(Source: Anwar *et al*., 2021)

Figure 12. Effect of foliar spray of zinc at the vegetative and reproductive stages of wheat on the carotenoid content after under drought stress.

3.4.3 Wheat Drought Tolerance through Molecular Breeding

Drought tolerance is a quantitative trait found in many plants (Zhu *et al.*, 2002). Typically, screening tests such as chlorophyll fluorescence are used to assess wheat genotypes' drought tolerance (Sayar *et al.*, 2008). Two drought-tolerant mutant wheat lines, DHML-9 and DHML-50, were developed using haploid breeding and mutagenesis (Khan *et al.*, 2001). Water stress-related genes and QTLs can be used to improve drought tolerance in wheat (Budak *et al.*, 2013). Researchers use QTL mapping to investigate drought-resistance genes in wheat (Ma et al., 2022). Identifying QTLs for drought resistance is critical for crop breeding because it provides valuable targets. Quantitative trait loci (QTL) analysis is an effective method for identifying QTL and has been used in crop gene mining (Ma *et al.*, 2022). Drought tolerance QTLs have been identified in wheat, specifically for physiological traits such as net photosynthesis, relative water content, cell membrane stability, and so on (Gupta *et al.*, 2017). Several drought tolerance traits have already been discovered to be associated with a large number of QTLs. Some QTLs have been reported to account for up to 20% of the phenotypic variation in each of these individual traits (Ma *et al.*, 2022).

Table 4. Locations of quantitative trait loci (QTL) for drought tolerance traits in wheat

Chromosomal location of QTL	Drought tolerance QTL-associated traits	Mapping populations	Reference
6A	Plant height, plant vigour, and coleoptiles	RILs produced by crossing between Chinese semi-dwarf wheat, Chuanmai 18, with a tall breeding line, Vigour 18	(Spielmeyer *et al.*, 2007)
2A	Coleoptile and shoot length, extrusion length, awn length, grain weight, and RWC	Core collection	(Ahmad *et al.*, 2014)
1D, 2A, 2B, 2D, 3A, 4A, 4A, 5B, 5D, 6D, 7A, 7D	Root diameter, volume, surface area, crossings, forks, and tips	spring wheat cultivar, Devon, and synthetic hexaploid accession, Syn084, were used to develop an advanced backcross population	(Ibrahim *et al.*, 2012)
1B, 2B, 3B, 5B, 7B	Grain weight, spike weight, spike number /spike, spike HI, HI,	RILs developed from a cross of geno- types	(Golabadi *et al.*, 2011)
3BL	Grain production	From a cross between line RAC875 and variety Kukri, a doubled haploid (DH) population was developed.	(Ibrahim *et al.*, 2012)
3B, 6A	length of coleoptile	RILs resulting from the cross of durum wheat cultivars Omrabi5 and Belikh2	(Nagel *et al.*, 2014)

(Source: Mwadzingeni *et al.*, 2016)

3.4.4 Wheat Drought Tolerance through Seed Treatment

One promising strategy for improving wheat drought tolerance is seed treatment (Z. Ahmad *et al*., 2018). Different types of seed priming: hydro-priming is the dehydrating seeds before seed sowing (H. Singh *et al.*, 2015). The most common method is osmopriming, which involves hydrating seed in a low osmotic aerated solution (Lutts *et al*., 2016). Finally, chemo-priming is the use of chemical molecules to increase tolerance (Jisha *et al*., 2013). Selenium (Se) seed priming improves drought tolerance in wheat seedlings by increasing germination (Nawaz *et al*., 2012). According to Raza *et at*., (2023) seed priming with silicon nanoparticle (Si-NPs) increased chlorophyll contents, relative water content, plant height, spike length, number of grains per spike, 1000-grain weight, grain yield per plant. The study also found that it reduced ROS increased harvest index. Drought stress control in wheat using plant-growth-promoting bacteria, *Bacillus amyloliquefaciens* 5113-treated seedlings showed a slightly better survival. Without bacteria drought stress slightly effected the survival of the 4-day-old wheat seedlings whereas bacteria-treated seedlings showed a priming effect with better tolerance to drought stress (Kasim *et al*., 2013).

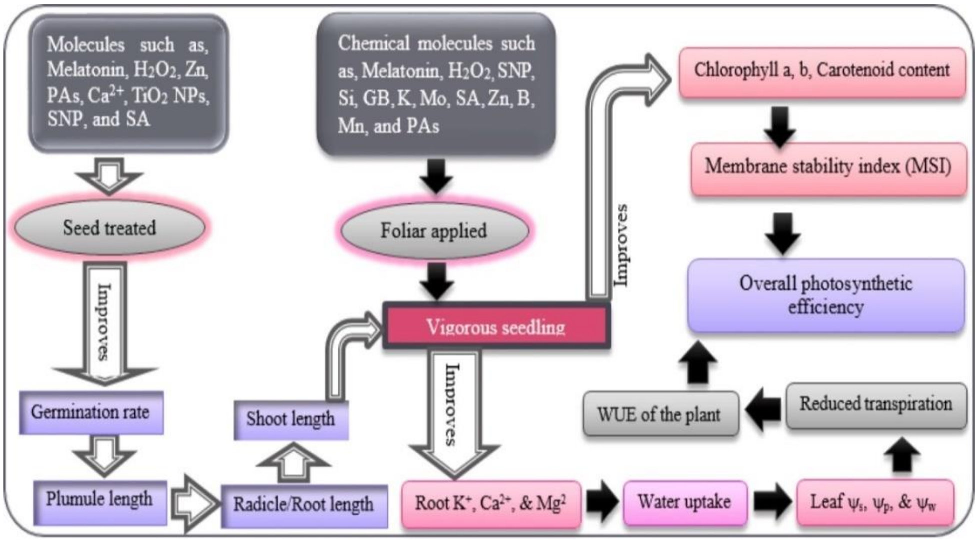
Table 5. Effects of Si-NPs on various wheat parameters under drought stress

Treatments	**Si-NPs application**	**Plant height**	**Spike length**	**NGPS**	**GW**	**GY**	**BY**	**HI**
Control	NP0 = 0 mg/L	66.7	6.43	33.2	32.3	22.1	60.0	37.0
	SiNP3 = 900 mg/L	70.2	7.13	36.3	34.4	25.3	67.0	37.8
Drought at tillering stage	SiNP0 = 0 mg/L	44.9	4.90	22.3	18.5	10.5	55.0	19.1
	SiNP3 = 900 mg/L	54.5	5.93	27.8	27.9	15.5	61.0	25.4
drought at flowering stage	SiNP0 = 0 mg/L	43.3	5.07	25.2	19.9	11.0	57.3	19.3
	SiNP3 = 900 mg/L	55.3	6.07	27.8	27. 9	17.0	65.0	26.4
Drought at grain filling stage	SiNP0 = 0 mg/L	41.5	5.13	21.5	18.0	9.5	53.0	17.9
	SiNP3 = 900 mg/L	53.1	5.90	28.7	26.3	16.0	60.0	26.7

(Source : Raza *et al*., 2023)

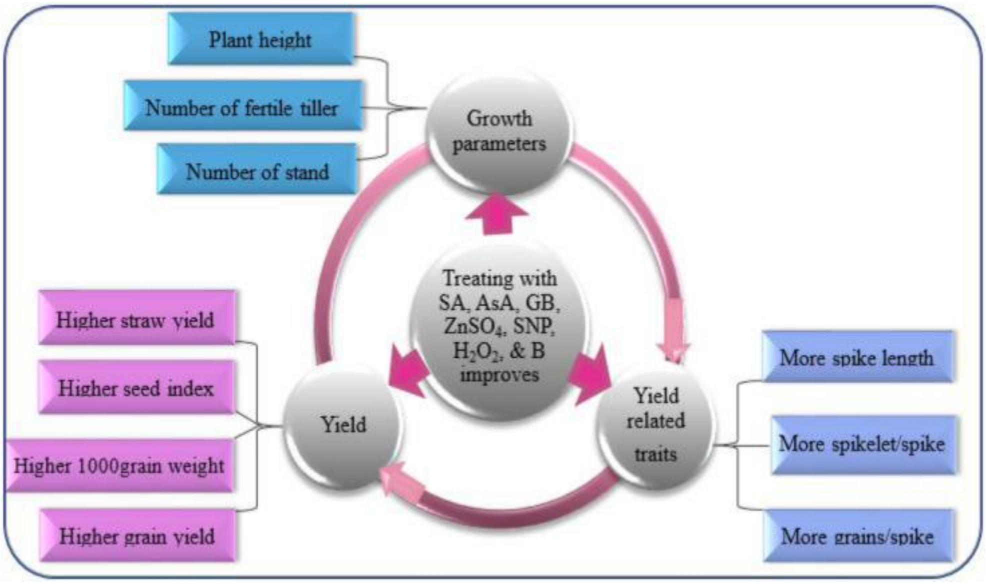
*Plant height (cm), spike length (cm), number of grains per spike (NGPS), 1000-Grain Weight (GW, g), Grain Yield per Plant (GY, g), Biological Yield per Plant (BY, g), and Harvest Index (HI) were all affected by Si-NPs application at different stages of wheat growth under drought stress conditions.

According to the table, application of Si-NPs under water-stressed conditions significantly influenced the yield attributes, as shown in Table 5. Drought stress reduced spike length (27.81, 21.18, and 22.82%), grain yield (83.59, 79.56, and 66.22%), and HI (67.7, 64.07, and 57.3%) in DGFS, DFS, and DTS, respectively. Under both control and stress conditions, silicon nanoparticle applications reduced the negative effects of water scarcity.



(Source: Malko *et al*., 2022)

Figure 13. Chemical substances and treatment methods affect wheat physiology.



(Source: Malko *et al*., 2022)

Figure 14. Responses of growth, grain yield, and yield-related characteristics to priming compounds.

CHAPTER IV

CONCLUSION

Drought stress is a major challenge for wheat cultivation, and it causes a range of morpho-physiological and biochemical changes that negatively impact plant growth and yield. According to the findings, drought stress reduced plant height, leaf area, root length, chlorophyll content, photosynthetic rate, water use efficiency, decreased relative water content, light interception, membrane stability index, and decreased cytokinins, gibberellins, β-glucan and auxins hormones caused decreased plant growth and development and increased membrane injury, concentrations of ROS. Dought also increase proline, soluble sugar content and total protein content. Several remediation processes have been proposed to mitigate the adverse effects of drought stress such as foliar application of exogenous substances like potassium, ascorbic acid, Zinc and salicylic acid (100 mg/L or 0.1 g/L) improved shoot-root fresh and dry weights, lengths, stomatal conductance, chlorophyll, transpiration rate, and net photosynthetic rate, seed treatment with silicon nanoparticle @ 900 mg/L improved plant height, spike length, number of grains per spike, 1000-grain weight, grain yield, biological yield and harvest index and molecular breeding also improved drought tolerance of wheat. These remediation practices can reduce the negative effects of drought stress on the morpho-physiological and biochemical changes of wheat by increasing root growth, nutrient uptake, photosynthesis, relative water content, increasing membrane stability index, decreasing membrane injury and increasing accumulation of osmolytes, such as proline and soluble sugars. They have shown promising results in enhancing the tolerance of wheat plants to water scarcity. However, more research is needed to improve our understanding of the mechanisms underlying drought stress and to develop more efficient strategies for enhancing the resilience of wheat crops. It is essential to prioritize research in this area to ensure food security and sustainable agriculture in water-limited regions.

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