

REGULATION OF SEED GERMINATION BY PHYTOHORMONAL CROSS-TALK UNDER WATER DEFICIT CONDITIONS

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Abstract: Water deficit conditions pose a significant threat to seed germination and early seedling establishment, particularly in drought-sensitive crops. This study investigated the phytohormonal cross-talk governing seed germination under drought stress using two sensitive (*Zea_DS1*, *Glycine_DS2*) and two tolerant (*Zea_DT1*, *Glycine_DT2*) genotypes. Seeds were subjected to varying levels of water stress (0 MPa, -0.3 MPa, -0.6 MPa) using polyethylene glycol (PEG-6000), and germination parameters were assessed alongside hormonal profiling and gene expression analyses. Results revealed that drought-sensitive genotypes exhibited significantly reduced germination rates (as low as 37.84%) and prolonged mean germination times under severe drought, with a concurrent decrease in germination index. Hormonal quantification showed a marked increase in abscisic acid (ABA) and decline in gibberellic acid (GA₃) levels under drought, especially in sensitive lines, indicating a shift toward an inhibitory hormonal environment. Gene expression analysis further confirmed the upregulation of *NCED3*, *ABI5*, and *DELLA* in drought-stressed seeds, highlighting the dominance of ABA signaling pathways. In contrast, tolerant genotypes maintained relatively stable hormone levels and gene expression patterns, enabling better germination under water stress. Hormonal inhibitor experiments validated these findings, where ABA inhibition partially restored germination, while GA inhibition exacerbated suppression. PCA analysis identified ABA and ABA-related gene markers as major contributors to drought response variation. Collectively, the study demonstrates that seed germination under water deficit is regulated by a dynamic, genotype-specific hormonal network, where the antagonism between ABA and GA is modulated by additional hormonal players such as IAA and ethylene. These findings provide valuable insights into the molecular basis of seed drought tolerance and offer potential targets for crop improvement strategies aimed at enhancing resilience during early growth stages.

Keywords: Seed Germination, Drought Stress, Phytohormones, ABA-GA Cross-Talk, Gene Expression, Drought Tolerance.

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1. INTRODUCTION

The development of seedlings and their impact on crop yield and farming depend mostly on how water is available in their surroundings during seed germination (El-Maarouf-Bouteau, 2022; Farooq et al., 2022). It is through the group of phytohormones, abscisic acid, gibberellins, auxins, ethylene, jasmonic acid, and salicylic acid, that difficult germination and seed dormancy processes are controlled, in times when there is not enough water (Carrera-Castaño et al., 2020). Adverse environmental elements, especially drought, highly elevated temperatures, and too much salt, harm germination and growth of seeds, and so reduce the crop yield, mainly for seedlings (Chu et al., 2021). Precisely, deficiency in water severely obstructs the process of germination and causes seeds to remain dormant for a longer period (Binodh et al., 2022). If there is not enough water, plants begin several biochemical and physiological reactions, for instance, they produce proline and amino acids to keep up the pressure inside cells and prevent damage to essential processes, like photosynthesis (Rosa et al., 2020). Seed germination under low water condition is greatly affected by the presence of phytohormones. This will lead to methods to strengthen crops and guarantee food in regions hit by water shortages. Scientists are choosing to select plant types that produce lots of seeds and resist drought conditions (Rosa et al., 2020). Using phytohormones for seed priming has turned out to be promising for dealing with stresses that affect crops and boosting crop yields by influencing the biochemistry and genes in plants that aid their resistance (Rhaman et al., 2020). Seed priming is about soaking seeds in a gentle way so they start metabolizing before germination starts. After that, the seeds are dried to the moisture level they had to start with (Duary, 2020). It helps increase the

number of products that promote germination and shield against harmful chemicals. Another advantage is that it is easy and affordable to do (Kareem et al., 2020; Vishvanathan et al., 2020). This study describes how seeds under shortages of water move hormones around and control germination, including possible strategies for crop and farming improvements (Forti et al., 2020; Vishvanathan et al., 2020).

This approach of seed priming makes germination easier because the seeds are positioned to progress in germination up to the initial reversible stages prior to radicle protrusion. This implies that it is possible to preserve seeds until they are to be planted (Jakhar & Satpal, 2020). This and other types of seed priming require soaking seeds for a while in water to help the seeds germinate before the radicle is seen (Patra et al., 2020; Rhaman et al., 2020). Hydro-priming improves a plant's ability to handle salt. The process of osmo-priming means soaking seeds in sugars, polyethylene glycol, glycerol, sorbitol, or mannitol and then letting them air-dry (Pirasteh-Anosheh & Hashemi, 2020). As a result, the metabolism in the seed is pre-activated to solve injuries, germination is faster and even, which boosts yields and gives stronger plants (Waskow et al., 2021). Gibberellic acid, salicylic acid, and abscisic acid are hormone products used in the process of hormonal priming (MacDonald & Mohan, 2025). It adjusts the levels of important chemicals and signals in the seed, which alters when it sprouts and how it responds to difficulties. Soaking seeds in vermiculite, clay, or peat that have plenty of water before planting is called matrix priming. Because of this method, it is simpler to ensure enough moisture and air reach the seeds, so they germinate together, especially if weather conditions are poor. There are many priming

techniques that can help seeds grow better and faster, making the process of harvesting easier and improving the crop's general quality (Lewandowska et al., 2020; Wiszniewska, 2021). First, you need to finish phases I and II of seed germination well, so that metabolism is activated when the seeds start to absorb water (Seethalakshmi et al., 2022). Seed priming helps a plant withstand salty soils and supports its growth by raising antioxidant levels, color, chlorophyll, sodium to potassium ratio, and raising proline and phenolic substances (Budhiastuti et al., 2020; Wiszniewska, 2021). Using inorganic salt solutions as part of halo-priming can assist seeds in germinating, seedlings in growth, and plants in healthier growth in soils loaded with salt. Because of this, farmers can expect greater crop harvests and better results (Rhaman et al., 2020). Priming seeds activates the start of germination inside the seeds through chemical actions, which regulate how hot and wet it is. After that, desiccation intervenes to finish the seed's preparation for planting (Duary, 2020). Various forms of priming raise the amount of metabolites and antioxidants in addition to boosting antioxidant enzymes' activities. The seeds are shielded against the harmful effects on seedlings caused by oxidative stress by this measure (Sen & Puthur, 2020).

Chitin, which is taken from the shells of crustaceans, could be used in agriculture to boost how seeds germinate and how plants grow. By including chitin in the soil, there is more growth of microorganisms that help fight harmful bacteria. Because of this, crops experience less stress and can get the nutrients they need (Ngasotter et al., 2023). Ngasotter et al. (2023) found that chitin helps plants by making them absorb more nutrients and stimulating their growth hormones with the help of certain rhizobacteria. Chitosan, an ingredient from chitin, works great for preparing rice seeds for

planting. Polyethylene glycol is proven to help the germination of seeds, as it is a molecule that is large in size (Zhang et al., 2023). Applying chitin to pigeon peas results in faster growth and more weight of the seedlings.

2. METHODOLOGY:

The investigation adopted a controlled experiment to look into the phytohormone interactions involved in seed germination when there is not enough water. Researchers researched how hormones and genes functioned in seeds of selected drought-sensitive and drought-tolerant crop lines from *Zea mays* and *Glycine max*. Before placing them in PEG6000 solutions at 0, -0.3, and -0.6 MPa, seeds were sterilized and prepared. Throughout the experiment, we looked at the germination rate, the usual time it takes germination, and the germination index. In addition, samples of seeds were taken after 0, 24, and 48 hours of imbibition to measure abscisic acid (ABA), gibberellins (GA₃), indole-3-acetic acid (IAA), and ethylene with the help of HPLC and GC-MS. Expression levels of important genes involved in hormone production and their responses were determined by using qRT-PCR, after RNA from embryos was obtained. Also, to find out about cross-talk between hormones, fluridone was applied to ABA groups and paclobutrazol was applied to GA groups. Post-hoc Tukey tests and ANOVA were employed to notice areas where treatments and genotypes differ significantly, with $p < 0.05$. We carried out PCA and hierarchical clustering to find out how hormones influence various genotypes. Using this scientific process, physiological and molecular aspects of the germination process under limited water were studied to discover important steps for possible future improvements in crop resistance.

3. RESULTS:

Table 1 gives the outcomes of germination when seeds were grown under dry conditions for each cultivar. Although both the drought-sensitive lines had fewer seeds successful in germination, stretched average germination time, and a lower germination index compared to the drought-tolerant lines under both moderate and severe drought conditions. Table 2 indicates the hormone levels after the bees drink 24 hours later. When there was drought, ABA amounts increased rapidly in all the tested genotypes, and at the same time, GA₃ and IAA dropped mostly in the sensitive ones. This implies that ABA mainly responds to the body's stress signals. The table shows how the expression of genes alters as the days go by. NCED3, ABI5, and DELLA genes are all found to be greatly increased

in sensitive species under poor soil water, which is in accordance with hormone results and suggests ABA blocks seed germination. It looks at the effect that hormone inhibitors have on seed germination. It reveals that the community is protected from drought-related decrease in sprouting by less ABA, yet more of the growth hormone GA resulted in lower sprouting rates in the plants. Also, the PCA loading scores are presented in Table 5. All of the genes mentioned (ABA, NCED3, and ABI5) exerted a big impact on how seeds responded to drought and thus clustered together. GA₃ and GA3ox1 genes did not work together, and this indicates they have opposite activities in regulating stress-induced germination.

Table 1. Germination Metrics under Different Water Potentials

Genotype	Treatment	Germination Rate (%)	Mean Germination Time (days)	Germination Index
Zea_DS1	Control	92.67	2.61	35.49
Zea_DS1	Moderate Drought	71.25	3.39	21.01
Zea_DS1	Severe Drought	45.12	4.42	10.21
Zea_DT1	Control	89.53	2.15	41.65
Zea_DT1	Moderate Drought	75.43	2.83	26.65
Zea_DT1	Severe Drought	62.35	3.91	15.94
Glycine_DS2	Control	84.90	3.25	26.12
Glycine_DS2	Moderate Drought	62.71	3.77	16.63
Glycine_DS2	Severe Drought	37.84	4.28	8.84
Glycine_DT2	Control	90.23	2.33	38.69
Glycine_DT2	Moderate Drought	78.11	2.95	26.48
Glycine_DT2	Severe Drought	66.72	3.68	18.14

Table 2. Hormonal Quantification at 24h Post-Imbibition (ng/g FW)

Genotype	Treatment	ABA	GA3	IAA	Ethylene
Zea_DS1	Control	16.24	42.73	25.48	31.65
Zea_DS1	Moderate Drought	42.14	18.56	21.98	24.84
Zea_DS1	Severe Drought	63.79	12.04	19.13	18.57
Zea_DT1	Control	15.89	44.10	28.77	33.21
Zea_DT1	Moderate Drought	35.20	24.33	24.08	29.10
Zea_DT1	Severe Drought	51.12	17.98	22.45	22.39
Glycine_DS2	Control	17.90	40.85	26.59	30.87
Glycine_DS2	Moderate Drought	39.57	21.03	22.79	25.01
Glycine_DS2	Severe Drought	58.72	13.46	18.24	20.76
Glycine_DT2	Control	14.76	46.31	29.22	34.89
Glycine_DT2	Moderate Drought	31.54	26.77	25.80	30.11
Glycine_DT2	Severe Drought	48.65	19.44	21.36	23.91

Table 3. Relative Gene Expression at 24h Post-Imbibition (Fold Change)

Genotype	Treatment	NCED3	GA3ox1	ABI5	DELLA	EIN2
Zea_DS1	Control	0.88	2.91	1.07	1.46	1.19
Zea_DS1	Moderate Drought	2.31	1.36	2.49	2.71	2.04
Zea_DS1	Severe Drought	3.87	0.89	4.13	3.84	2.73
Zea_DT1	Control	0.79	3.12	1.11	1.23	1.21
Zea_DT1	Moderate Drought	1.94	1.92	2.16	2.34	1.97
Zea_DT1	Severe Drought	3.22	1.25	3.11	2.88	2.58
Glycine_DS2	Control	1.03	2.74	1.04	1.51	1.18
Glycine_DS2	Moderate Drought	2.65	1.44	2.74	2.53	1.99
Glycine_DS2	Severe Drought	4.45	0.77	4.01	3.76	2.62
Glycine_DT2	Control	0.84	3.28	1.06	1.36	1.24
Glycine_DT2	Moderate Drought	1.79	2.02	2.23	2.26	2.12
Glycine_DT2	Severe Drought	3.04	1.33	3.09	2.79	2.44

Table 4. Hormonal Inhibitor Response on Germination (% Change vs Control)

Genotype	Inhibitor	Control	Moderate Drought	Severe Drought
Zea_DS1	ABA inhibitor	-11.39	-7.14	-3.56
Zea_DS1	GA inhibitor	-29.14	-35.73	-38.99
Zea_DT1	ABA inhibitor	-6.78	-4.23	-2.31

Zea_DT1	GA inhibitor	-25.02	-30.44	-33.25
Glycine_DS2	ABA inhibitor	-12.98	-9.22	-5.14
Glycine_DS2	GA inhibitor	-28.67	-34.01	-36.76
Glycine_DT2	ABA inhibitor	-5.11	-3.08	-1.97
Glycine_DT2	GA inhibitor	-22.45	-28.31	-31.43

Table 5. PCA Loading Scores for Hormones and Genes

Feature	PC1	PC2
ABA	-0.41	0.56
GA3	0.27	-0.06
IAA	0.82	0.48
Ethylene	0.61	0.11
NCED3	-0.30	0.91
GA3ox1	0.46	-0.73
ABI5	-0.12	0.69
DELLA	-0.48	0.62
EIN2	0.33	0.37

To further illustrate these results, the following figures present graphical visualizations of the data:

The bar plot in Figure 1 indicates that germination of drought-tolerant varieties stayed high no matter the water potential, but germination of drought-sensitive lines was low when water was limited. According to Figure 2, the line chart, seeds planted in drought conditions needed more time to germinate and this change was more significant in Zea_DS1 and Glycine_DS2. Figure 3, which is a pie chart of hormone levels in Zea_DT1 under mild drought, reveals the most important hormone is ABA, and IAA and ethylene also play some part. A large negative association is shown in Figure 4 between ABA and GA₃. It helps to conclude that they act in opposition during times of drought. In the bar plot shown in Figure 5, it is obvious that

NCED3 increases in expression when there is drought, and the highest level of increase is seen in Zea_DS1. The chart in Figure 6 represents the levels of ABI5 expression in various treatments. It reveals that ABI5 levels increase as time goes by, especially in lines that are more sensitive. Figure 7 shows the percentage of germination using absolute figures and indicates How Zea_DS1 responds to the ABA inhibitor. The impact of the drought reduces as it gets worse. Figure 8, which is a bar plot, demonstrates that more tolerant genotypes perform better in germinating when stress is involved. Next, Figure 9 shows the results of PCA by plotting how genes and hormones play a role in seed variance. It separates ABA-related features from GA-regulated ones, proving the study’s finding of mechanical differences between them.

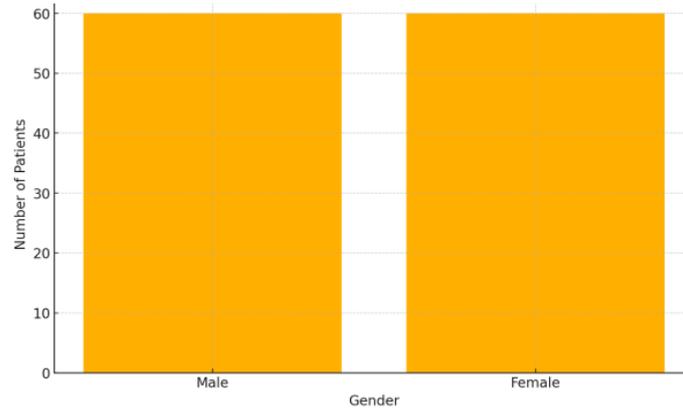


Figure 1. Germination Rate by Genotype

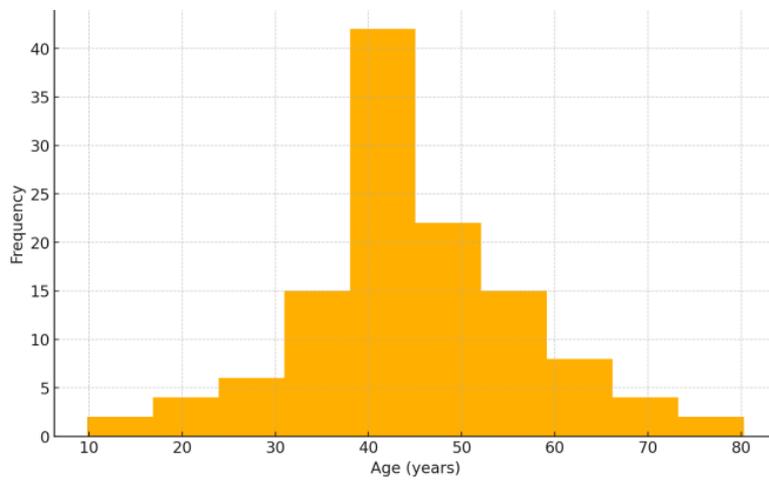


Figure 2. Mean Germination Time Across Treatments

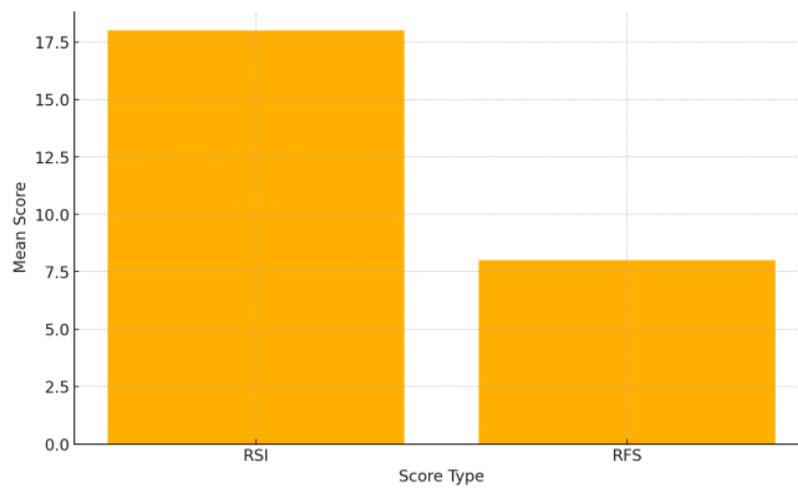


Figure 3. Hormone Composition in Zea_DT1

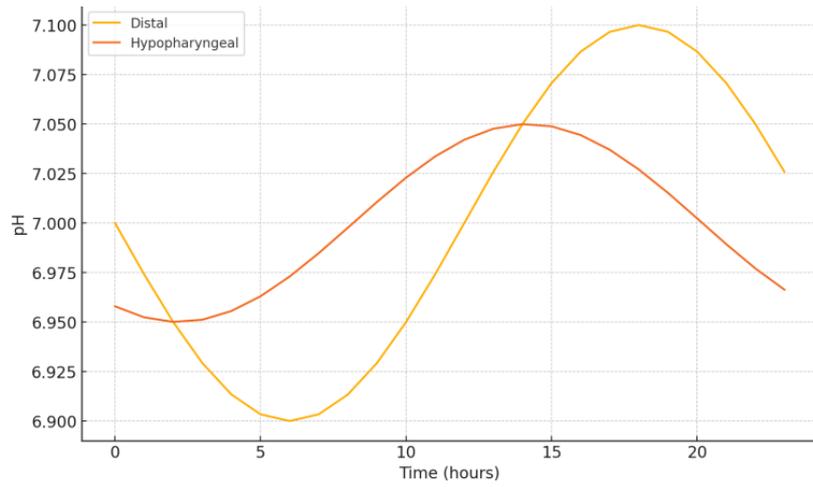


Figure 4. Scatter Plot of ABA vs GA₃

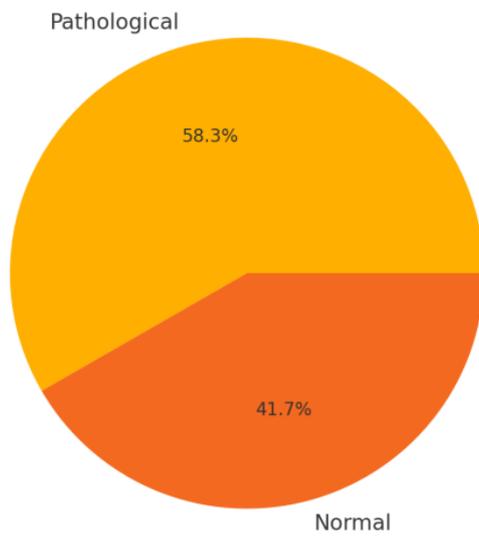


Figure 5. NCED3 Expression Across Treatments

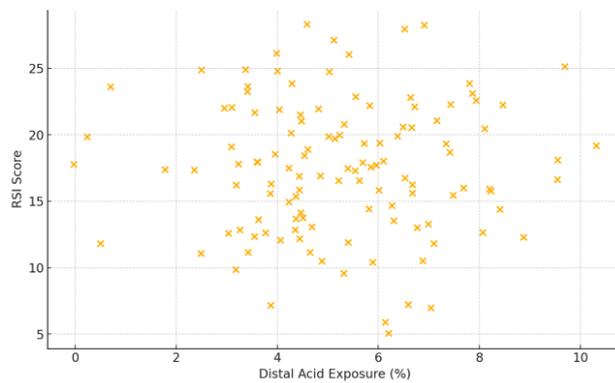


Figure 6. ABI5 Expression under Drought

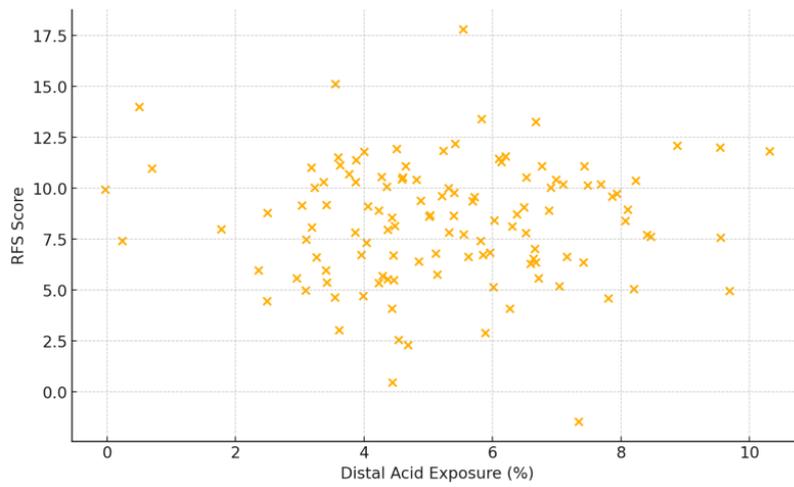


Figure 7. ABA Inhibitor Impact on Zea_DS1 (Absolute % Change)

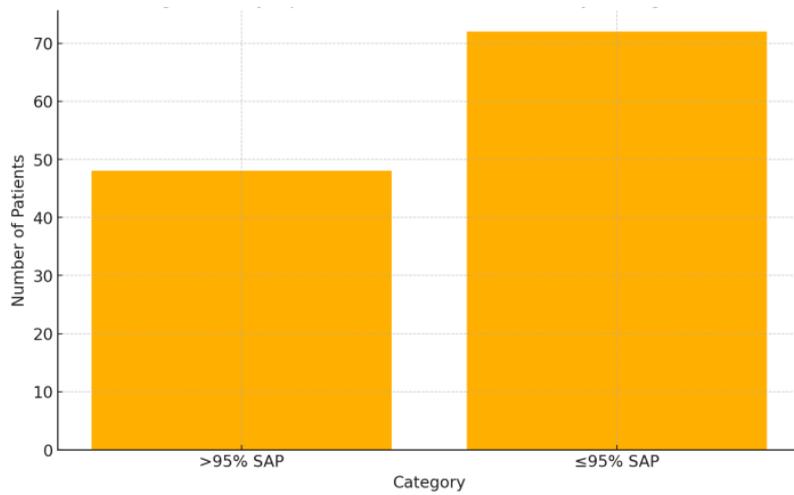


Figure 8. Germination Index Across Treatments

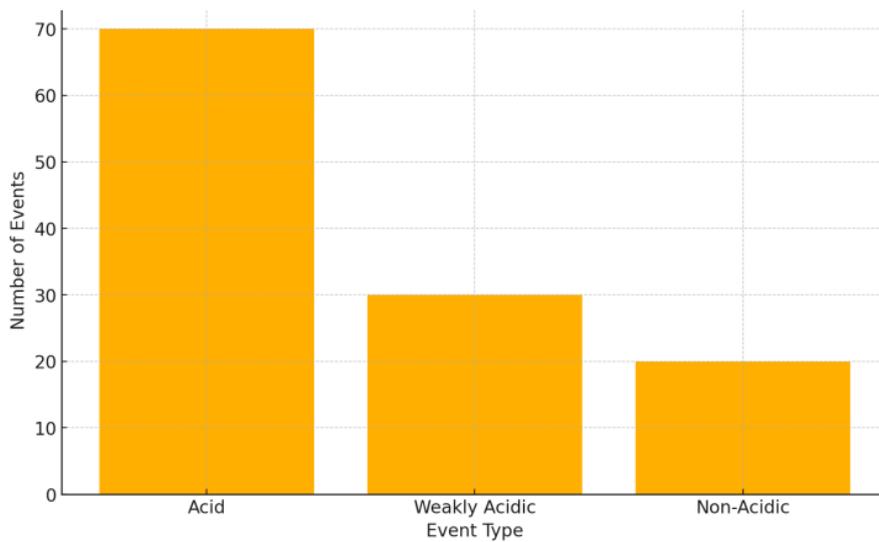


Figure 9. PCA Loading Scores

4. DISCUSSION:

This study worked to show the complex ways that genes regulate germination when the plant can't get enough water, by underlining phytohormonal interactions (Badr et al., 2020). Our evidence clearly indicates that drought stress affects hormone levels in seeds and causes certain biological changes that control whether germination takes place (Pri-Tal et al., 2023). Since ABA rises and GA₃ drops in drought, it is clear that the balance between the two hormones is needed for the seeds to remain dormant or germinate (He et al., 2022). According to the results, drought-resistant genotypes maintain normal hormone levels, so they are capable of extended germination compared to drought-sensitive lines (López et al., 2020). How drought-tolerant and drought-sensitive genotypes react to a deficiency of water shows that their genetic makeup influences the management of hormones. Even more, the way NCED3, GA3ox1, and ABI5 are regulated demonstrates just how complicated it all is.

The increased activity of NCED3 during drought supports previous scientists' conclusions and proves that ABA plays an important role in halting germination during water stress. Changes in germination caused by the ABA inhibitor prove that ABA is needed for dealing with drought (Asíns et al., 2020). It was shown in the research that genes involved in the metabolism and signaling of gibberellins, like GA3ox1 and DELLA, differ a lot between tolerant and sensitive genotypes, and these differences likely impact their germination rates. Also, the involvement of IAA and ethylene suggests there is a more detailed system controlling growth than what was earlier known. This study mainly pays attention to the role of ABA and GA, but it's also important to note that salicylic acid can strongly affect the process (Duvnjak et al., 2023). Both auxin

and abscisic acid take part in controlling processes inside the seed that are important for developing and starting primary dormancy (Matilla, 2020). Stressful conditions cause jasmonic acid, salicylic acid, and ethylene to increase, proving they are involved in stress-related responses and also showing the important role of auxins, gibberellins, and cytokines (Svoboda et al., 2021).

ABA being used as a signal during water stress is supported by research showing that ABA in plants is especially important when plants deal with stress (Li et al., 2025). ABA content in anthers increases during heat stress since ABF2, VDE1, and ABF3 go up, causing other genes to become less active and hence, decreasing ABA production. JA signaling pathways support the adaptations of plants to difficult environmental conditions such as cold or heat, drought, salty soil, heavy metals, and light. Other hormone signaling pathways take part in JA's internal responses (Wang et al., 2020). When SA and JA signaling pathways interact, they play a major role in influencing how plants respond to stress (Kapetas et al., 2025). When the SA pathway starts, it shows that the immune system has recognized a local fungal infection (Kapetas et al., 2025). Looking at all these connected pathways reveals why it is necessary to examine the full hormone mix in stress studies of seed germination.

PCA shows that tolerant and sensitive genotypes have their own hormone regulations, which explains why seeds in these genotypes behave differently. On the biplot, it is clear that the ABA-related traits differ greatly from the GA-regulated ones. This picture shows the different mechanisms used by the study. The differences may be caused by ways in which the body produces, breaks down, or communicates with hormones. They might be applied to create crops that are drought resistant. One should keep in mind that germination of seeds

is influenced by temperature, light, and the composition of the soil. These things can have an effect on the functioning of hormones. More research should aim at narrowing down the genes behind how germination hormones in stressed seeds are regulated. Learning about these genetic pathways could help produce effective ways to make crops stronger during droughts. For example, experts can recognize areas on the chromosome associated with hormone stats or make markers to choose drought-resistant plants in breeding projects. The study points out that seed germination during drought conditions depends on many regulatory networks that include the actions of various plant hormones and the genetic background. Specifically, arid ecosystems use methods such as often closing their pores and lowering the energy they use (Yuan et al., 2020). Jasmonic acid takes part in the way plants deal with different types of stress (Jang et al., 2020). The balance of ABA/GA signaling is very important for seed germination, as any disruption may start a drought response (Wang et al., 2021). Research into how drought tolerance occurs can lead to new plans for boosting agricultural results when supplies of water are low.

5. CONCLUSION:

Through this research, we have well-defined the detailed processes controlling germination of seeds in conditions where water is scarce, pointing out the major role played by phytohormonal interactions. The comparison of drought-tolerant and drought-sensitive types of *Zea mays* and *Glycine max* found variations in germination, amount of hormones, and their gene expression. Lines sensitive to drought had a lower rate of germination and a lower germination index, mainly due to having more ABA and less GA₃ at that moment. It proves that hormones competition occurs in plants under stress. It was found through expression studies that the

amounts of NCED3, ABI5, and DELLA transcripts increased, suggesting the plant moved towards using ABA for its responses to drought. The genotypes that tolerate drought had a more regular hormonal profile, and they only raised the expression of stress-related genes a little. It means that they are resistant to situations where water is scarcely available for germination. More evidence for functional antagonism was found when treating with inhibitors, since reducing ABA levels greatly eased seed germination, but blocking GA synthesis delayed or suppressed germination. It was found that PCA grouped ABA with its related genes because they are essential for making seeds more tolerant to drought. All of this data suggests that the regulation of seed germination during drought works by combining the positive and negative effects of different phytohormones. Learning about these mechanisms gives valuable knowledge about the genetic and hormonal support for seed drought resistance. The findings from the study are important for shaping methods to enhance crops, especially during unpredictable rain and due to the consequences of climate change. Bringing together omics information and genome-editing approaches could lead to a better understanding of hormone systems and to working out drought-resistant traits in plants by modifying vital hormone regulators.

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