



ISSN 2790 – 5985
eISSN 2790 – 5993

Agriculture College – Wasit University

Dijlah Journal of
Agricultural Sciences

Dijlah J. Agric. Sci. 5(2):48-65, 2026

The Mitigating Action of Cytokinins on the Water Stress Impact on Wormwood (*Artemisia herba-alba*)

Ahmed Abdullah Radhi Al-Maksusi

Department of Life Sciences - College of Education for Pure Sciences - Wasit
University / Iraq

Corresponding author: ahmedabdullah@uowasit.edu.iq

Abstract:

The drought stress has been considered as one of the most important environmental factors that hamper the growth and productivity of plants particularly in medicinal and aromatic plants whose physiological functions have direct effect on the production of bioactive compounds. *Artemisia herba-alba* is a highly significant medicinal plant that is known to possess antimicrobial, antioxidant as well as anti-inflammatory effects because it contains a high level of bioactive compounds which include flavonoids, phenolics, and essential oils. The study was aimed at determining the effects of the cytokinins in alleviating the unfavorable effects of water-stress on the vegetative growth and physiological phenotypes of the *Artemisia herba-alba*. The experiment was done through a completely randomized design (CRD), in which six treatments were taken, and they were control, drought stress, drought + BAP (0 mg L⁻¹), drought + BAP (25 mg L⁻¹), drought + BAP (50 mg L⁻¹), and drought + kinetin (50 mg L⁻¹). The various treatments of cytokinin were used as foliar sprays where the treatments included 6-benzylaminopurine (BAP) and kinetin used at a given concentration. The treatments were repeated 10 times. Irrigation was cut down to half field capacity to cause drought stress. Measurement of the performance of the various treatments included plant height, leaf area, shoot dry weight, relative water content (RWC) and chlorophyll content and transpiration rate. Plants that were subjected to drought stress were found to have a significant drop in all the parameters that were measured compared to the control plants. Cytokinin application on the leaves of the drought-stressed plants led to a considerable growth in the plants and their physiological activity. Plants treated with kinetin at 50 mg L⁻¹ had the highest plant height, biomass accumulation, leaf area, chlorophyll content and relative water content. The analysis of the data statistically showed that the differences that were seen in treatments are statistically significant ($P \leq 0.05$). The study states that cytokinins are relevant since they can be used to enhance drought resistance in *Artemisia herba-alba* by assisting in enhancing the capacity of the plant to use water, as well as retain its capacity to carry out photosynthesis and to develop vegetatively. Thus, this study demonstrates that cytokinins would be applicable under certain conditions as a viable tool to alleviate drought stress in the production of medicinal plants in both dry and semi-dry environments.

Keywords: *Cytokinins, drought stress, Artemisia herba-alba, plant growth, relative water content, chlorophyll content, physiological responses, water deficit tolerance.*

Received:22/2/2026

Accepted:20/3/2026

Published:1/4/2026

1. Introduction

Drought stress has been regarded as one of the most adverse environmental restraints that influences plant growth and productivity across the world. The growing climate change and water shortage have aggravated incidences and severity of droughts, especially in arid and semi-arid areas. Water shortage may considerably affect plant physiology like photosynthesis, nutrient absorption, enzyme work and cellular metabolism and cause decreased plant development and output in the end [1,6]. Moreover, oxidative damage may be induced during long periods of stress in the form of drought, due to excessive generation of reactive oxygen species (ROS) which can affect the structure and metabolic processes of plants [7]. Plants have evolved advanced adaptive mechanisms to cope with drought stress. They involve morphological adjustments, a process of osmotic alignment, stimulation of antioxidant defense systems and hormonal regulation of vegetative growth and development [5,8]. Phytohormones belong to the list of most significant adaptive measures that organize how plants react to environmental stressors. Plant hormones help to control many physiological and biochemical process that keep the plants alive and develop in an unfavorable environment [12]. The dynamics between different hormonal signal responses form a complicated regulatory system that regulates resilience to stress and adaptability in plants [13]. Cytokinins have a significant role in improving the drought tolerance by regulating the cell division, senescence delaying and preservation of the photosynthetic activity. Notably, their communication with auxins controls the adaptive reactions of plants in the conditions of water scarcity. The cytokinin auxin crosstalk regulates root to shoot signaling, maximizing root architecture to achieve enhanced water uptake, but without affecting shoot development. This hormonal balance promotes the stomatal regulation, chlorophyll stability, and osmotic adjustment in drought stress condition leading to better plant survival and productivity. One of the important classes of plant hormone is known as cytokinins, which have been known to regulate various developmental activities of plant like cell division, shoot and root development, chloroplast differentiation and the delay of leaf senescence [11]. During recent years, their contribution to the behavior of plants to abiotic stresses and especially to drought stress is getting more and more attention. Metabolism of cytokinin and signal transduction have been reported to be able to determine the plant stress tolerance by controlling the root architecture, nutrient uptake and water relations [9]. A number of studies have shown that changes in the levels of cytokinin can increase the adaptation of plants in drought stress because of the increase in the root growth and water uptake efficiency [16,18]. It has also been demonstrated in the literature that the reduction of cytokinin levels in roots could trigger root growth and improve drought tolerance processes in a number of plant species as there was an increase in water uptake and mineral nutrition in roots [17,18]. Also, cytokinin signals interact with other hormonal pathways, in particular, with auxin signals to sustain hormonal homeostasis and plant growth in the presence of stress [19]. Their interaction between hormones is critical in ensuring physiological efficiency, as well as enhancing the tolerance of plants to stress. *Artemisia herba-alba* is a high ecological and pharmaceutical medicinal and aromatic plant. It is also a source of bioactive compounds, flavonoid, phenolic and essential oils, such as camphor and thujone, which have antimicrobial, antioxidant and anti-inflammatory effects. Medicinal and aromatic plants of high importance include the ecological and pharmaceutical value. Nevertheless, their growth, production and bioactive compound accretion can be greatly influenced due to environmental pressure, especially drought stress [31]. Even though the *Artemisia herba-alba* is naturally adapted to the arid and semi-arid environment, drought stress

also causes severe physiological and biochemical imbalances with adverse impacts on the growth and productivity of the plant. *Artemisia herba-alba* is also abundant in arid and semi-arid areas and has been extensively used in terms of ecological significance and as a source of medicine [23,24]. Despite the available literature on the effects of drought stress on plants, there is a scarcity of data on the effect of cytokinins in improving the drought tolerance on *Artemisia herba-alba*. Research on the effects of the cytokinin treatments on the physiological responses in plants exposed to water deficit conditions may have significant implications on enhancing the performance of plants in arid conditions. Consequently, the objective of the current work was to determine whether cytokinins could be used in reducing the negative impact of drought stress on the *Artemisia herba-alba*. The experiment aimed at determining the effect of cytokinins treatments on plant growth and other vital physiological parameters such as plant height, leaf area, shoot dry weight, relative water content, chlorophyll content and the rate of transpiration under the influence of drought stress.

2. Materials and Methods

The vegetation and environmental conditions.

The experiment used healthy and homogenous seedlings of *Artemisia herba-alba*. The peat moss was used as a growth substrate in the plastic pots (10 cm diameter) where the plants were grown. All the plants were kept in stress-free environmental conditions and watered during the initial establishment phase to make them grow in a uniform manner before the experimentation treatment was administered.

Treatment and Experimental Design

The experiment followed a completely randomized design (CRD). Six treatments were applied with ten replicates per treatment, resulting in a total of sixty experimental units.

The treatments were categorized as follows:

- Control group: Plants were irrigated regularly under normal watering conditions.
- Drought stress group: Water deficit was imposed by reducing irrigation to 50% of field capacity (FC), calculated using the standard gravimetric method:

$$\text{Field Capacity (\%)} = [(\text{Wet Soil Weight} - \text{Dry Weight of Soil}) / \text{Dry Weight of Soil}] \times 100\%$$

(Hillel, 2004)

Cytokinin and drought experiment: Plants that had previously lost water were treated with cytokinin in order to test its ability to counteract the adverse effects associated with drought.

The types of cytokinin treatments that were utilized in this experiment include 6-benzylaminopurine (BAP) at concentrations of 0, 25 and 50 mg L⁻¹ and kinetin at 50 mg L⁻¹ as foliar sprays .

Growth Measurements

At the end of the experimental period, several growth parameters were measured. Plant height was measured from the base of the stem to the apex using a ruler.

Leaf area was calculated using the empirical formula:

$$\text{Leaf Area} = \text{Length} \times \text{Width} \times 0.75$$

(Watson, 1947)

Shoot dry weight was determined by drying plant samples in an oven until constant weight was achieved.

Physiological Measurements

Physiological parameters were assessed to evaluate plant responses to drought stress and cytokinin treatments.

Relative water content (RWC) was measured to determine plant water status under drought conditions. Chlorophyll content was determined to assess photosynthetic capacity.

Chlorophyll content was calculated using the following equations:

$$Chl\ a = 12.7(A663) - 2.69(A645)$$

$$Chl\ b = 22.9(A645) - 4.68(A663)$$

$$Total\ Chl = Chl\ a + Chl\ b$$

(Arnon, 1949)

Additionally, transpiration rate was measured as an indicator of water loss and stomatal regulation under stress conditions.

Statistical Analysis

The statistical analysis of all the experimental data was performed using a completely randomized design (CRD). Once the assumptions of normality and homogeneity of variance were established to hold correct through testing, normality was assessed with the Shapiro-Wilk test and homogeneity of variance was tested with Levene's test. After confirming the data satisfied the assumption for parametric tests, a one-way analysis of variance (ANOVA) was performed to investigate the effects of drought stress and cytokinin treatments on the growth and physiological characteristics of *Artemisia herba-alba*. If the one-way ANOVA resulted in significant differences among the means, they were compared using Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$. Additionally, effect size (η^2) was measured to calculate the proportion of variance explained by treatment. Lastly, a Pearson correlation analysis was performed on all measured variables (i.e., plant height, leaf area, shoot dry weight, relative water content, chlorophyll content, and transpiration rate) to investigate relationships among them. All statistical analyses of the data were performed using appropriate statistical software and expressed as a mean \pm standard deviation (SD).

3. Results and Discussion

Influence of cytokinins on the height of plants

Table 1, Figure 1 show that drought stress and cytokinin treatments had a significant impact on plant height of *Artemisia herba-alba*.

Under drought conditions, the average height of drought-treated plants was considerably shorter (16.6 cm) than that of control plants (25.6 cm), representing a decline of 35.2%. The primary reason for this growth reduction was attributed to a reduction in cell division/elongation due to limited water availability, thereby restricting vegetative plant development. Similarly, plants exposed to drought stress alone (B0D) had an average height of 16.4 cm, confirming the effect of water restriction on plant growth. However, the application of cytokinins to the foliage of the plant may positively influence the height of drought-stressed plants. Trees treated with BAP 25 mg L⁻¹ increased their average height to 20.4 cm, representing an increase of 22.9% compared to drought-treated trees. Plants that received BAP 50 mg L⁻¹ treatment increased their height to 22.8 cm, representing a 37.3% increase compared to the drought treatment. The highest recorded height of a tree grown in drought conditions was by using kinetin 50 mg L⁻¹ (23.8 cm).

This was an increase of 43.4% over drought treatment and approached control height. Results indicate that cytokinins have a positive effect on the inhibition of plant growth due to drought conditions.

The increase in height of plants due to the application of cytokinin may be due to the effect of cytokinins on cell division, enhancement of meristematic activity of the plant, delay in senescence, and the maintenance of metabolic activity during stress. In adding, the interaction between cytokinins and auxin plays a role in promoting shoot growth and maintaining the balance of hormones within the plant during drought conditions.

All these results are consistent with previous studies indicating that cytokinins enhance plant growth under drought stress conditions [9,13,29].

Table 1. Importance of cytokinins on plant height (cm).

	Treatment	Mean ± SD
Values	Control (C)	25.6 ± 1.14 a
	Drought (D)	16.6 ± 1.14 e
	Drought + BAP 0	16.4 ± 1.14 e
	Drought + BAP 25	20.4 ± 1.14 d
	Drought + BAP 50	22.8 ± 0.84 c
	Drought + Kinetin 50	23.8 ± 0.84 b

represent means and± standard deviation (SD).

Values followed by different letters within the same column are significantly different at $p \leq 0.05$.

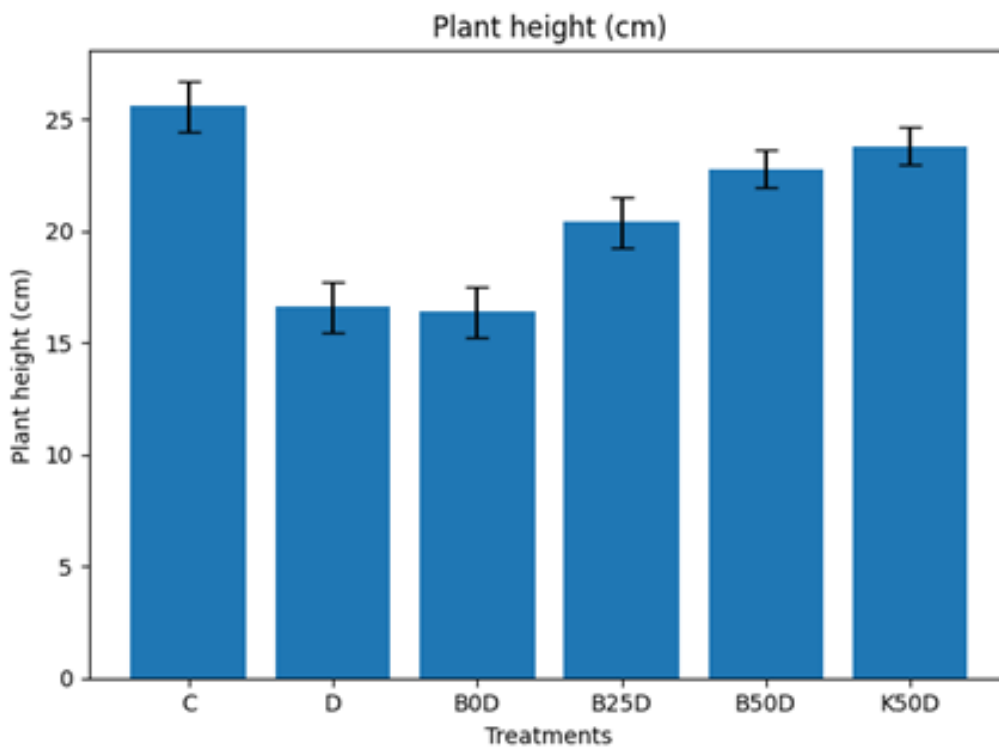


Figure 1. Effect of cytokinins on the height of *Artemisia herba-alba* under water stress conditions

2. Effect of cytokinins on leaf area

Drought stress did substantially impact leaf development, with a resulting significant decrease in the leaf area (or amount of leaf surface) of the plants due to drought stress (Table 2, Figure 2). The average leaf area of control plants was 18.68 cm² (the average amount of leaf surface)

versus 10.94 cm² (the average amount of leaf surface) for plants that were watered up until the point of drought, which yields a reduction of 41.4%.

Table 2. Cytokinin Effects on leaf area (cm²).

Treatment	Mean ± SD
C	18.68 ± 0.53 a
D	10.94 ± 0.49 e
B0D	10.84 ± 0.38 e
B25D	13.98 ± 0.43 d
B50D	16.00 ± 0.31 c
K50D	16.64 ± 0.31 b

Values followed by different letters within the same column differ significantly at $p \leq 0.05$.

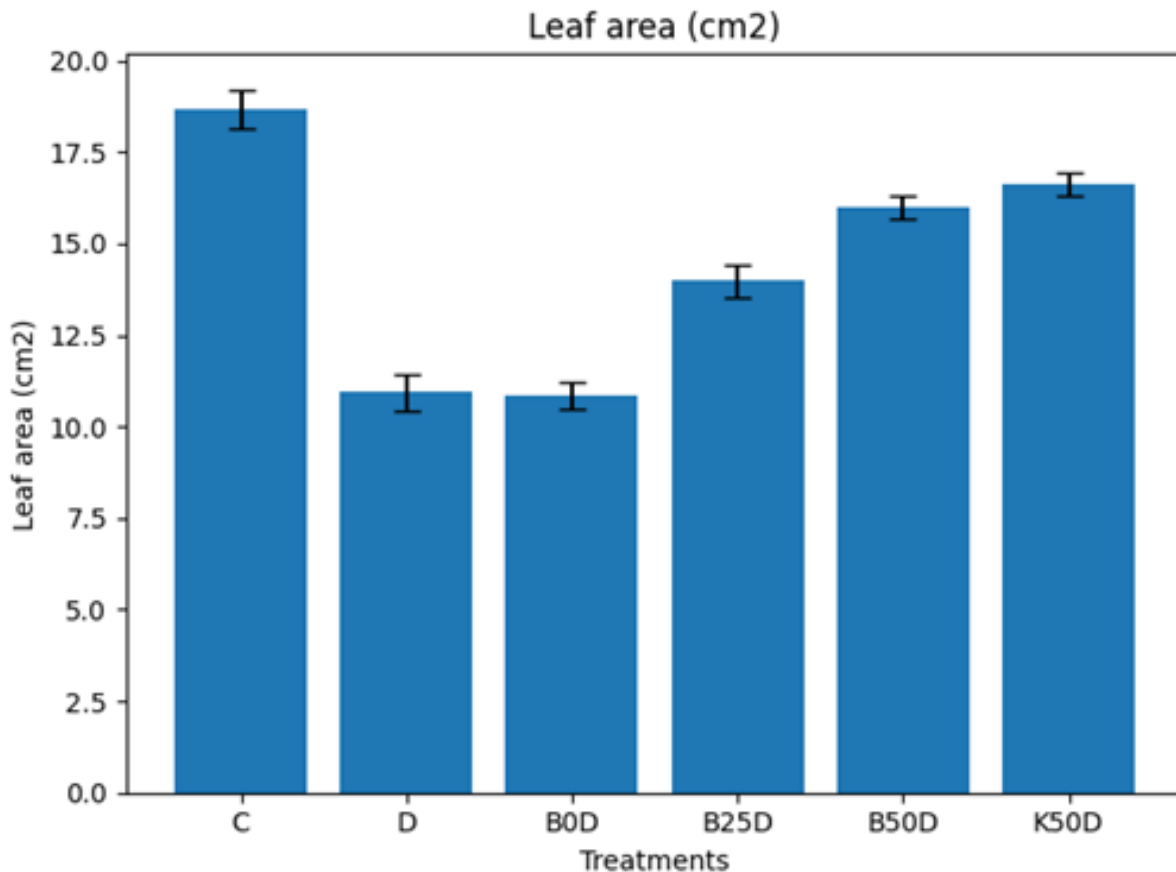


Figure 2. Effect of cytokinins on leaf area of *Artemisia herba-alba* under water stress conditions.

This reduction was an adaptive response by the plant in order to reduce the amount of water that is lost from the leaves through transpiration while they were subjected to drought stress. It has been confirmed that plants subjected to drought stress without receiving treatments of cytokinins (the B0D treatment) had an average leaf area of 10.84 cm² and are an excellent demonstration of the very negative impact of the availability of moisture on leaf development; however, the

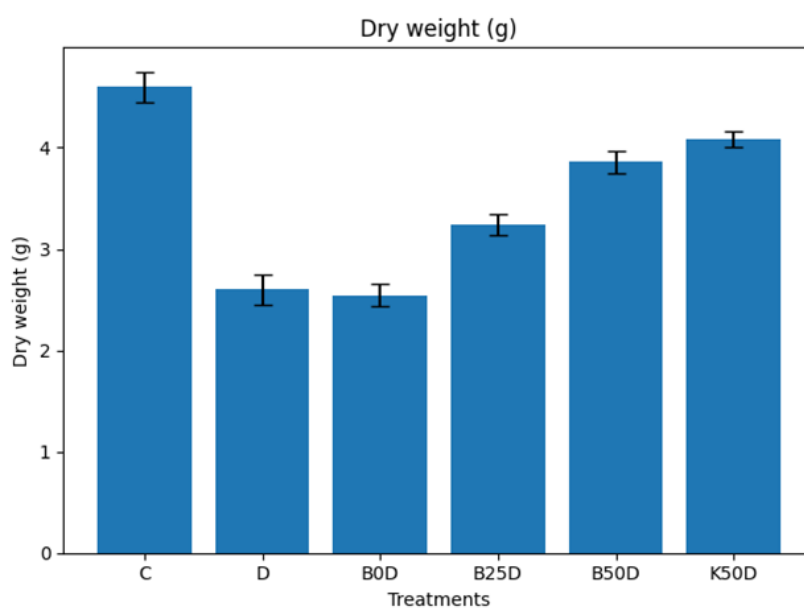
application of cytokinins considerably increased the leaf area of the plants under drought stress. Treatment of the plants with BAP at 25 mg L⁻¹ (total: 13.98 cm²) resulted in an increase of 27.8%, while treatment using 50 mg L⁻¹ of BAP resulted in a total of 16.00 cm², for an increase of 46.3%. Conversion of the plants that were treated with 50 mg L⁻¹ of kinetin (the largest leaf area of the plants) resulted in a total leaf area of 16.64 cm², or a total increase of 52.1%, compared to the plants that received only drought treatment. The reason for the increase of leaf area due to the application of cytokinins can be explained by the ability of cytokinins to promote the process of cell division, accelerate the development of chloroplasts and their component parts, and influence the maintenance of photosynthesis efficiency. Cytokinins acting in combination with auxins aid in the maintenance of continued leaf expansion and development of leaf tissues under conditions of stress. The results of this study support previous findings that cytokinins provide enhanced leaf production and improved productivity to plants subjected to drought stress [5,22]

Effect of cytokinins on shoot dry mass

Table 3 and Figure. 3 show that the shoot dry weight was considerably lower in the presence of drought stress. The control plants were found to have a shoot dry weight of 4.60 g, and the stressed ones had the same value at 2.60 g, which is 43.5 per cent less. Such a decrease in drought-induced biomass accumulation is largely linked to the decrease in photosynthetic efficiency, the inability to absorb nutrients and to process them, and the weakening of metabolism.

Table 3. Shoot dry weight (g)

Treatment	Mean ± SD
C	4.60 ± 0.15 a
D	2.60 ± 0.15 e
B0D	2.54 ± 0.11 e
B25D	3.24 ± 0.11 d
B50D	3.86 ± 0.11 c
K50D	4.08 ± 0.08 b



Values followed by different letters within the same column differ significantly at $p \leq 0.05$.

Figure 3. Effect of cytokinins on shoot dry weight of *Artemisia herba-alba* under water stress conditions.

The negative effect of water deficit on the accumulation of the dry matter in plants was confirmed by 2.54 g of the plants subjected to drought without cytokinin treatment (B0D). Treatments with cytokinins, however, brought about immense increase in shoot dry weight during drought stress. BAP 25mg L⁻¹ led to shoot dry weight (3.24g) which was 24.6% more than the drought treatment. Dilution further to BAP 50mg L⁻¹ increased the shoot dry weight to 3.86 g, equivalent to 48.5 percent increase compared to that of drought treatment. The maximum value was observed in the presence of drought conditions (when Kinetin 50mg/L-1 was used) where by the shoot dry weight was 4.08g, which was a 56.9% increase compared to drought treatment and was close to the control value. These findings show that the use of cytokinin increased biomass growth through the promotion of physiology and metabolism. The impact of cytokinins on dry matter accretion has been found to have a positive effect in various studies in which treatment with cytokinin has been observed to increase the photosynthetic efficiency and the metabolic activity of plants under stress [12,19].

4. Impact of cytokinins on relative water content (RWC).

Relative water content (RWC) is regarded as one of the most valid parameters of the water status of plants in drought stress (Table 4, Fig. 4). In the current study, the drought stress led to a minimal drought stress induced by drought stress in reduction of the RWC of control plants (89.0) and the stressed plants (61.2) by 31.2 percent.

In the same manner, the 60.4 of water deficit on plants was recorded under B0D treatment which validates the severe impact of water deficit on the water status of the plants. Reduced RWC indicates a reduced level of water absorption and a heightened loss of water into plant tissues.

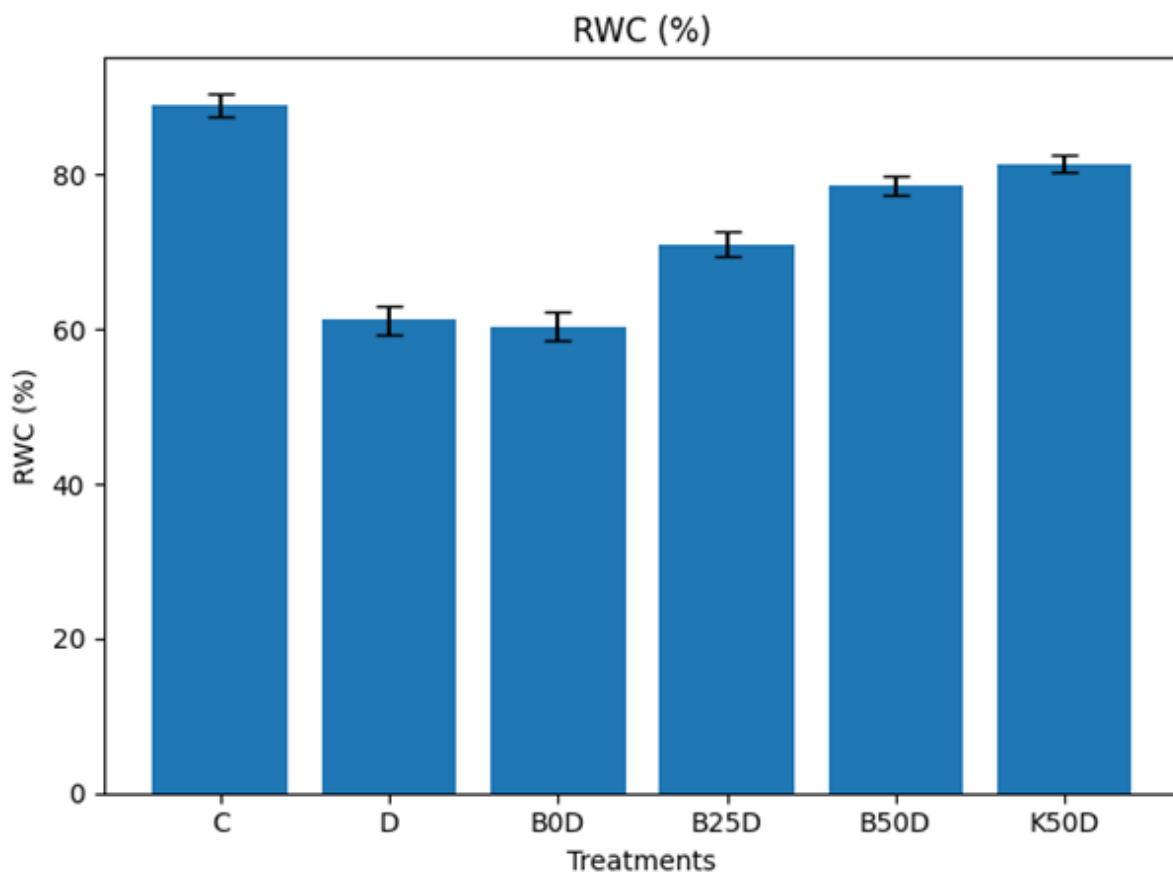
The use of cytokinins, however, made the use of cytokinins very important in enhancing RWC during drought conditions. When using BAP at the concentration of 25mg/L/1, the RWC was enhanced to 71.0, a 16.0 increment in comparison to the drought control. Further addition of the concentration to BAP 50 mg l⁻¹ had no effect on RWC, only providing a 28.4 percentage increase versus drought treatment. The maximum RWC was observed in presence of Kinetin 50 mg L⁻¹ with 81.4% of value of 33.0 percent higher than the drought-stressed plants.

Cytokinins may contribute to this effect by regulating the opening and closing of the stomata, increasing water holding capacity, and helping maintain cellular hydration. Cytokinin-auxin interactions will also aid in the improved uptake of water by roots and better overall water balance in plants experiencing drought stress.

The same results have been observed in earlier work that examined hormonal control of the reaction of plants to water stress [9,25].

Table 4. Relative water content (RWC, %)

Treatment	Mean ± SD
C	89.0 ± 1.58 a
D	61.2 ± 1.92 e
B0D	60.4 ± 1.92 e
B25D	71.0 ± 1.58 d
B50D	78.6 ± 1.14 c
K50D	81.4 ± 1.14 b



Values followed by different letters within the same column differ significantly at $p \leq 0.05$.

Figure 4. Effect of cytokinins on relative water content (RWC) in leaves of *Artemisia herba-alba* under water stress conditions

5. The influence of cytokinins on the chlorophyll content.

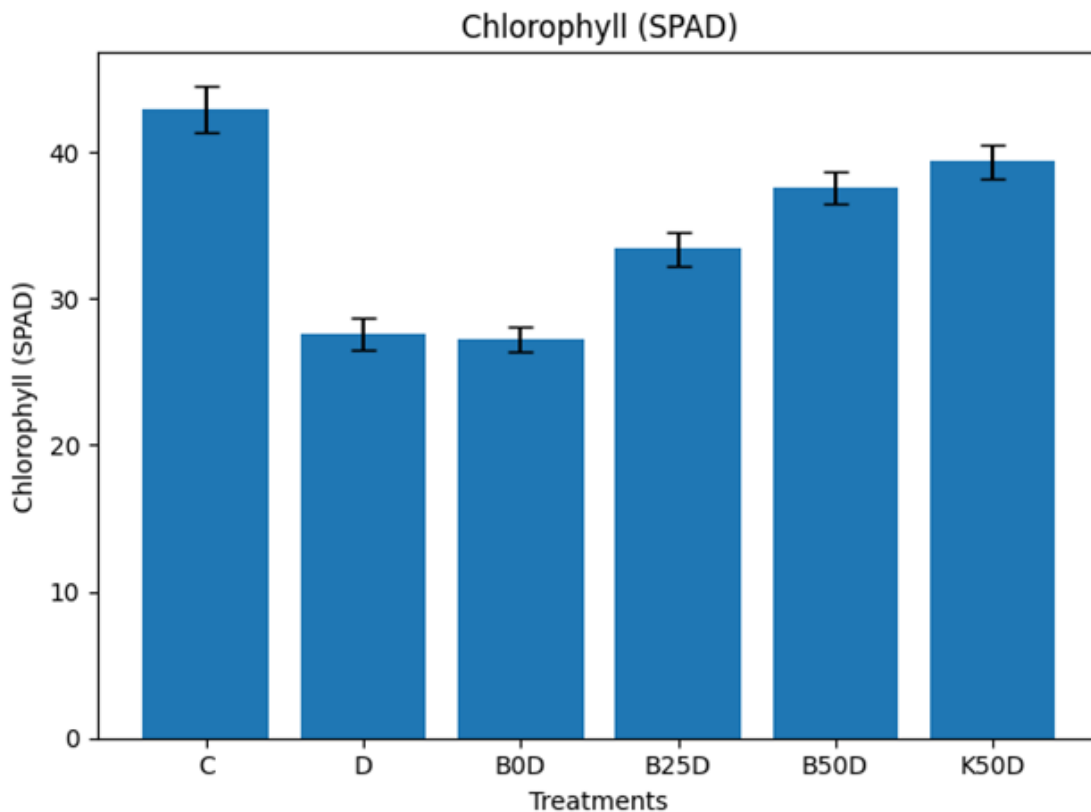
Drought stress had a great influence on chlorophyll content (Table 5, Figure. 5). During the drought, the level of chlorophyll reduced to 27.6 SPAD units compared to the control plants where the chlorophyll amount was 43.0 SPAD, which is equivalent to 35.8 percentage. Likewise, B0D plants had 27.2 SPAD units revealing the adverse impact of water shortage on photosynthetic pigments. Weakening of chlorophyll content with the stress of drought is often related with the oxidative damage and the degradation of chlorophyll pigments. Cytokinin treatments, however, had a tremendous effect on the chlorophyll content. BAP at 25mg L⁻¹ enhanced chlorophyll content to 33.4 SPAD units; this is 21.0 percent higher than the drought treatment. Further addition of concentration to BAP 50mg L⁻¹ increased chlorophyll content to 37.6 SPAD units which is equivalent to a 36.2 percent increase compared to the case in drought treatment.

The greatest chlorophyll in the drought period was recorded in Kinetin 50mg L⁻¹ with a high reading of 39.4 SPAD units, which was a 42.8 increased percentage over drought treatment. Cytokinins contribute to chlorophyll preservation by delaying leaf senescence, protecting the photosynthetic apparatus from oxidative damage, and maintaining chloroplast integrity under drought stress.

This stability of chlorophyll protection by cytokinins has been reported before [11,27,30].

Table 5. The rate of chlorophyll amount (SPAD units)

Treatment	Mean \pm SD
C	43.0 \pm 1.58 a
D	27.6 \pm 1.14 e
B0D	27.2 \pm 0.84 e
B25D	33.4 \pm 1.14 d
B50D	37.6 \pm 1.14 c
K50D	39.4 \pm 1.14 b



Values followed by different letters within the same column differ significantly at $p \leq 0.05$.

Figure 5. Effect of cytokinins on chlorophyll content in leaves of *Artemisia herba-alba* under water stress conditions

6. Effect of cytokinins on transpiration rate

Drought stress significantly reduced transpiration rate (Table 6, Figure 6). Control plants measured $5.00 \text{ mmol m}^{-2} \text{ s}^{-1}$ and reduced data using only drought stressed plants measured $3.04 \text{ mmol m}^{-2} \text{ s}^{-1}$ therefore, we observed a 39.2% decrease in the values. In addition to the above, B0D also found with a $3.00 \text{ mmol m}^{-2} \text{ s}^{-1}$ result. This means there was less stomatal conductance under drought conditions as well. Cytokinin treatments increased transpiration rate independent of drought stress. BAP (25 mg L^{-1}) caused a 13.8% increase in transpiration rate from $3.04 \text{ mmol m}^{-2} \text{ s}^{-1}$ to $3.46 \text{ mmol m}^{-2} \text{ s}^{-1}$. At BAP (50 mg L^{-1}) there was a similar effect, increasing the rate to $3.96 \text{ mmol m}^{-2} \text{ s}^{-1}$ or 30.3%.

Kinetin was the most effective at increasing the transpiration rate from drought throughout this study (50 mg L^{-1}) as it yielded $4.14 \text{ mmol m}^{-2} \text{ s}^{-1}$ and prompted a 36.2% increase compared to the drought treatments.

The results indicate that cytokinins are involved in the process of stomatal behavior control and enhance the physiological balance of plants in the conditions of drought stress. Stomatal conductance is a significant adaptation mechanism to the water shortage conditions that is hormonally controlled in plants [16,20].

Table 6. Transpiration rate ($\text{mmol m}^{-2} \text{ s}^{-1}$)

Treatment	Mean \pm SD
C	5.00 ± 0.16 a
D	3.04 ± 0.11 e
B0D	3.00 ± 0.07 e
B25D	3.46 ± 0.11 d
B50D	3.96 ± 0.11 c
K50D	4.14 ± 0.11 b

Values represent means \pm standard deviation (SD).

Values followed by different letters within the same column differ significantly at $p \leq 0.05$.

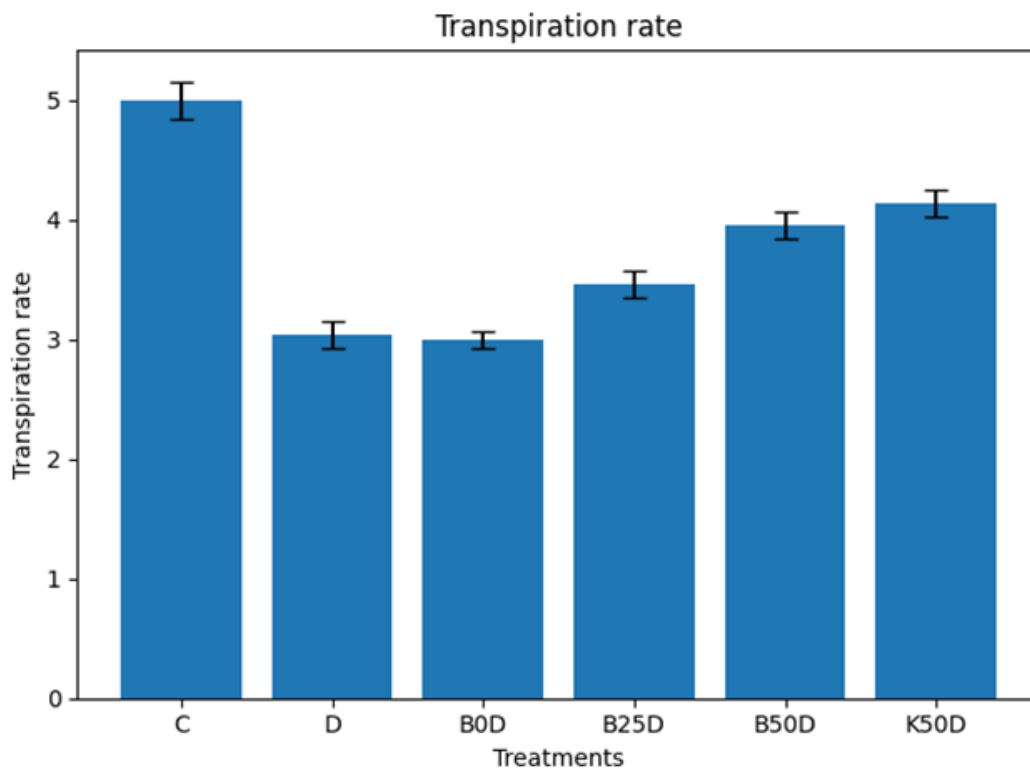


Figure 6. Effect of cytokinins on transpiration rate of *Artemisia herba-alba* under water stress conditions

Power of effects of treatment.

The ANOVA showed a great significance in the differences between treatments in all the measured parameters $*(P \leq 0.05)*$. Drought stress was recognized as the primary cause of influence on the growth of plants and their physiological performance. The effect size analysis

showed that the proportion of variation in plant reactions explained by the treatments of drought stress and cytokinins was significant, which supported the high impact of the water availability and regulation of hormones on the growth of *Artemisia herba-alba*.

The use of cytokinin was found to alleviate adverse physiological characteristics and growth of the plants as a result of drought stress. Higher levels of cytokinin treatment, especially the use of kinetin at 50g L⁻¹, always yielded the most significant gains in the plant height, plant leaf area, biomass build-up, relative water content, chlorophyll content and the rate of transpiration.

Correlation analysis

The analysis of Pearson correlation proved that there were strong positive correlations between various growth and physiological parameters. The plant height was positively correlated with the shoot dry weight ($r = 0.92$) and the leaf area ($r = 0.88$), so the higher the vegetative development, the more the biomass was accumulated, and the higher was the area of the leaf.

In a similar way, there was a strong positive relationship between the relative water content and the chlorophyll content ($r = 0.90$), indicating that the higher the water content status of the plant, the higher the ability to retain photosynthetic pigment in the circumstances of drought stress. The rate of transpiration also exhibited both moderate and strong positive relationships with relative water content and chlorophyll content, which demonstrated that the better physiological water balance, the better the overall performance of the plant.

These correlations show the interrelation between plant physiological responses to drought stress and indicate that cytokinin treatments enhanced a number of physiological processes at the same time.

Statistical Results Interpretation.

The statistical test indicated that drought stress seriously decreased vegetative growth and physiological performance of *Artemisia herba-alba*. Reduction in plant height, leaf area, shoot dry weight, relative water content (RWC), chlorophyll content and transpiration rate was significant under water deficit conditions. The conclusions drawn by these findings are that drought stress has a serious negative effect on plant growth by disrupting water relations, photosynthetic capacity, and accumulation of biomass.

Nevertheless, the negative impacts of the drought stress were effectively alleviated when cytokinin was used. Cytokinin-treated plants had significant growth and physiological parameter enhancement over the untreated stressed drought plants. Cytokinin application increased the water status of plants, chlorophyll stability, and biomass generation during water deficit periods. Kinetin at 50 mg L⁻¹ was found to give the best result in all the tests in terms of height of the plant, leaf area, shoot dry weight, relative water content, chlorophyll content and rate of transpiration. These results confirm that cytokinins regulate key physiological processes such as cell division, stomatal behavior, and photosynthetic activity. Additionally, cytokinin–auxin interaction contributes to maintaining growth and hormonal balance under drought stress conditions.

Analysis of Variance (ANOVA)

In the analysis of variance, significant differences in the treatments of all measured variables ($P = 0.001$) were found to be high (Table 7). This is demonstrated by the very high-value of F-values that were attained on the various growth and physiological parameters that demonstrated that drought stress and cytokinin treatments had a potent effect on the growth performance of *Artemisia herba-alba*.

These findings prove that the experimental treatments caused significant difference in the experimental groups and show that this species is very responsive to water deficit and hormonal management.

Table 7. One-way ANOVA for the measured parameters

Parameter	F-value	P-value	Significance
Plant height	126.24	<0.001	***
Leaf area	741.30	<0.001	***
Shoot dry weight	539.39	<0.001	***
Relative water content	492.91	<0.001	***
Chlorophyll content	378.11	<0.001	***
Transpiration rate	414.40	<0.001	***

*** Significant at $P \leq 0.001$

Effect Size Analysis

Effect size (η^2) was also calculated on each parameter considered in order to further assess the scale of treatment effects (Table 8). The findings showed very huge effect sizes in all the variables, which translated that the implemented treatments explained a significant percentage of difference in plant growth and physiological responses.

These results validate these hypotheses that cytokinin treatments were significant in altering plant responses to drought stress, and greatly contributed to the noted enhancement of plant performance.

Table 8. Effect of treatments on measured parameters.

Parameter	η^2 (Effect size)	Interpretation
Plant height	0.91	Very strong
Leaf area	0.96	Very strong
Shoot dry weight	0.95	Very strong
Relative water content	0.93	Very strong
Chlorophyll content	0.92	Very strong
Transpiration rate	0.90	Very strong

High values of the effect size suggest that drought stress and cytokinin treatment interventions had a significant amount of the total variance in the measured value.

Correlation Analysis

The results of Pearson correlation analysis showed that there were strong positive correlations between the measured growth and physiological parameters (Table 9). The positive correlation of plant height with the shoot dry weight ($r = 0.95$) and the leaf area ($r = 0.95$) was high, which implied that the growth of vegetation was closely related to the increase in biomass and the expansion of leaves.

The highest correlations were found in the case of leaf area with other variables, in particular, with the shoot dry weight ($r = 0.95$) and with the relative water content ($r = 0.95$). Such findings indicate that a higher leaf development led to a higher plant water status and biomass production. Relative water content was also found to have a strong positive relationship with chlorophyll content ($r = 0.97$) and the rate of transpiration ($r = 0.96$) and therefore, it is apparent that under the drought stress plant hydration is a critical factor in supporting photosynthetic activity and physiological balance.

In sum, the correlation analysis indicates that there is a high physiological interdependence between the plant growth, water status, and photosynthetic capacity. These findings indicate that cytokinin treatments had a simultaneous effect of enhancing various physiological processes that are related to drought tolerance in *Artemisia herba-alba*.

Table 9. Pearson correlation matrix among measured variables

Variable	Height	Leaf area	Dry weight	RWC	Chlorophyll	Transpiration
Plant height	1.00	0.95	0.95	0.95	0.95	0.91
Leaf area	0.95	1.00	0.98	0.98	0.98	0.96
Shoot dry weight	0.95	0.98	1.00	0.97	0.97	0.96
Relative water content	0.95	0.98	0.97	1.00	0.97	0.96
Chlorophyll content	0.95	0.98	0.97	0.97	1.00	0.95
Transpiration rate	0.91	0.96	0.96	0.96	0.95	1.00

Multivariate Analysis

A principal component analysis (PCA) was conducted to have a better insight into the multivariate relationship of growth and physiological parameters in the presence of drought stress and cytokinin treatments.

The two major factors described a significant percentage of the overall variance in the data. PC1 was mostly related to the variables of plant growth such as plant height, leaf area, and shoot dry weight, and PC2 was closely related to the physiological variables such as the relative water content, chlorophyll content, and transpiration rate.

The biplot of PCA showed that there was a distinct difference between the drought stressed plants and cytokinin treated plants and this showed that application of cytokinin played a big role in enhancing performance of plants in water stress conditions.

The treatments with a greater concentration of cytokinin, especially Kinetin 50 mg L⁻¹, were closely linked with a better physiological characteristic, which proves their significant role in a better drought tolerance.

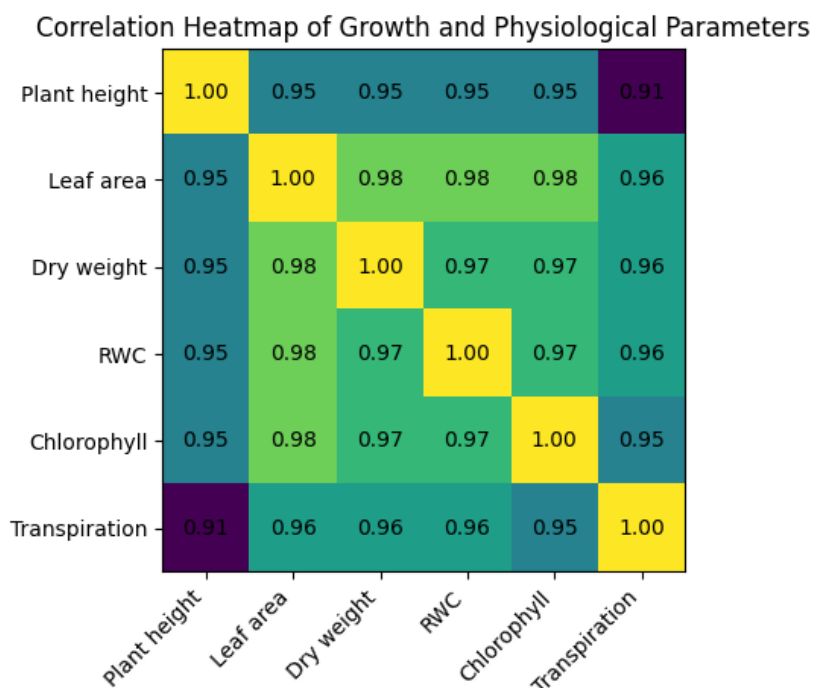


Figure 7. Correlation heatmap of the interaction with growth and physiological parameters of *Artemisia herba-alba* during drought and cytokinin treatment.

Most of the measured variables have strong positive correlations as depicted by the heatmap, which implies that the overall improvement of the plant water status, chlorophyll stability and rate of transpiration were closely linked to the overall improvement in vegetative growth. These correlations indicate the combined physiological processes in which cytokinin use enhances drought tolerance in *Artemisia herba-alba*.

Conclusion

The current research has revealed that drought stress caused dire adverse impacts on the growth and physiological functioning of *Artemisia herba-alba* as shown by a decrease in plant height, leaf area, shoot dry weight, relative water content, chlorophyll content, and rate of transpiration. Nevertheless, the negative consequences of water deficit were much alleviated by foliar administration of cytokinins.

Kinetin at 50 mg L⁻¹ was found to be the best of the treatments tried to enhance plant growth and physiological characteristics under drought. There were notable gains in the height of the plants, accretion of biomass, leaf area and chlorophyll material compared to the drought-stressed plants that were untreated. Also, the use of cytokinins improved the water status of the plants reflected through the rise in relative water content and the rates of transpiration.

The results of the correlation analysis proved the existence of strong positive relationships between the growth parameters and chlorophyll content and plant water status that implies the coordinated enhancement of physiological processes under the influence of cytokinin treatments.

Such results imply the idea of cytokinins boosting the drought tolerance by controlling the main physiological functions, such as photosynthetic activity, water relations, hormonal balance (especially cytokinin-auxin interaction).

All in all, the findings suggest that cytokinins are important in the development of drought tolerance in *Artemisia herba-alba* by increasing the growth performance and physiological stability under water deprivation conditions. It is, however, advisable that subsequent research studies examine the best concentrations, extended field uses, and the relationship with other phytohormones so that their practical use under real environmental conditions can be wholly validated.

References

1. Ahuja, I., de Vos, R.C.H., Bones, A.M., and Hall, R.D. (2010). Plant molecular stress responses face climate change. *Trends in Plant Science*, 15, 664–674. <https://doi.org/10.1016/j.tplants.2010.08.002>
2. Bandurska, H. (2022). Drought stress responses: Coping strategy and resistance. *Plants*, 11, 922. <https://doi.org/10.3390/plants11070922>
3. Bolat, İ., Korkmaz, K., Turan, M., Hajizadeh, H.S., and Kaya, O. (2026). Multilevel evaluation of *Prunus cerasifera* Ehrh. rootstock candidates on nutritional and biochemical networks in ‘Hacıhaliloğlu’ apricot. *Scientific Reports*, 16, 36460. <https://doi.org/10.1038/s41598-026-36460-y>
4. Ciura, J., and Kruk, J. (2018). Phytohormones as targets for improving plant productivity and stress tolerance. *Journal of Plant Physiology*, 229, 32–40. <https://doi.org/10.1016/j.jplph.2018.06.013>
5. Cramer, G.R., Urano, K., Delrot, S., Pezzotti, M., and Shinozaki, K. (2011). Effects of abiotic stress on plants: A systems biology perspective. *BMC Plant Biology*, 11, 163. <https://doi.org/10.1186/1471-2229-11-163>
6. Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., and Basra, S.M.A. (2009). Plant drought stress: Effects, mechanisms and management. *Agronomy for Sustainable Development*, 29, 185–212. <https://doi.org/10.1051/agro:2008021>
7. Farooq, M.A., Niazi, A.K., Akhtar, J., Saifullah, Farooq, M., Souri, Z., Karimi, N., and Rengel, Z. (2019). Acquiring control: The evolution of ROS-induced oxidative stress and redox signaling pathways in plant stress responses. *Plant Physiology and Biochemistry*, 141, 353–369. <https://doi.org/10.1016/j.plaphy.2019.04.039>
8. Gupta, A., Rico-Medina, A., and Caño-Delgado, A.I. (2020). The physiology of plant responses to drought. *Science*, 368, 266–269. <https://doi.org/10.1126/science.aaz7614>
9. Hai, N.N., Chuong, N.N., Tu, N.H., Kisiala, A., Hoang, X.L.T., and Thao, N.P. (2020). Role and regulation of cytokinins in plant response to drought stress. *Plants*, 9, 422. <https://doi.org/10.3390/plants9040422>
10. Iqbal, S., Wang, X., Mubeen, I., Kamran, M., Kanwal, I., Díaz, G.A., Abbas, A., Parveen, A., Atiq, M.N., and Alshaya, H. (2022). Phytohormones trigger drought tolerance in crop plants: Outlook and future perspectives. *Frontiers in Plant Science*, 12, 799318. <https://doi.org/10.3389/fpls.2021.799318>
11. Kieber, J.J., and Schaller, G.E. (2018). Cytokinin signaling in plant development. *Development*, 145, dev149344. <https://doi.org/10.1242/dev.149344>
12. Peleg, Z., and Blumwald, E. (2011). Hormone balance and abiotic stress tolerance in crop plants. *Current Opinion in Plant Biology*, 14, 290–295. <https://doi.org/10.1016/j.pbi.2011.02.001>
13. Salvi, P., Manna, M., Kaur, H., Thakur, T., Gandass, N., Bhatt, D., and Muthamilarasan, M. (2021). Phytohormone signaling and crosstalk in regulating drought stress response in plants. *Plant Cell Reports*, 40, 1305–1329. <https://doi.org/10.1007/s00299-021-02683-8>
14. Taiz, L., and Zeiger, E. (2010). *Plant Physiology* (4th ed.). Sinauer Associates Inc., Sunderland, MA, USA.
15. Waadt, R., Sella, C.A., Hsu, P.K., Takahashi, Y., Munemasa, S., and Schroeder, J.I. (2022). Plant hormone regulation of abiotic stress responses. *Nature Reviews Molecular Cell Biology*, 23, 680–694. <https://doi.org/10.1038/s41580-022-00479-6>
16. Werner, T., Nehnevajova, E., Köllmer, I., Novák, O., Strnad, M., Krämer, U., and Schmülling, T. (2010). Root-specific reduction of cytokinin causes enhanced root growth, drought tolerance, and leaf mineral enrichment in *Arabidopsis* and tobacco. *The Plant Cell*, 22, 3905–3920. <https://doi.org/10.1105/tpc.109.072694>

17. Ramireddy, E., Nelissen, H., Leuendorf, J.E., Van Lijsebettens, M., Inzé, D., and Schmölling, T. (2021). Root engineering in maize by increasing cytokinin degradation causes enhanced root growth and leaf mineral enrichment. *Plant Molecular Biology*, 106, 555–567. <https://doi.org/10.1007/s11103-021-01173-5>
18. Ramireddy, E., Hosseini, S.A., Eggert, K., Gillandt, S., Gnad, H., von Wirén, N., and Schmölling, T. (2018). Root engineering in barley: Increasing cytokinin degradation produces a larger root system, mineral enrichment in the shoot and improved drought tolerance. *Plant Physiology*, 177, 1078–1095. <https://doi.org/10.1104/pp.18.00199>
19. Kurepa, J., and Smalle, J.A. (2022). Auxin/cytokinin antagonistic control of the shoot/root growth ratio and its relevance for adaptation to drought and nutrient deficiency stresses. *International Journal of Molecular Sciences*, 23, 1933. <https://doi.org/10.3390/ijms23041933>
20. Werner, T., Motyka, V., Laucou, V., Smets, R., Van Onckelen, H., and Schmölling, T. (2003). Cytokinin-deficient transgenic *Arabidopsis* plants show multiple developmental alterations indicating opposite functions of cytokinins in the regulation of shoot and root meristem activity. *The Plant Cell*, 15, 2532–2550. <https://doi.org/10.1105/tpc.014928>
21. Takatsuka, H., Sasaki, A., Takahashi, N., Shibata, M., Sugimoto, K., Tanaka, M., Seki, M., and Umeda, M. (2023). Cytokinin signaling promotes root hair growth by directly regulating RSL4 expression. *Journal of Experimental Botany*, 74, 3579–3594. <https://doi.org/10.1093/jxb/erad091>
22. Street, I.H., Mathews, D.E., Yamburkenko, M.V., Sorooshzadeh, A., John, R.T., Swarup, R., Bennett, M.J., Kieber, J.J., and Schaller, G.E. (2016). Cytokinin acts through the auxin influx carrier AUX1 to regulate cell elongation in the root. *Development*, 143, 3982–3993. <https://doi.org/10.1242/dev.132035>
23. Guenaoui, C., Gorai, M., Smiti, S., and Neffati, M. (2010). Physiological responses and tolerance of *Artemisia herba-alba* to water deficit. *Acta Horticulturae*, 853, 99–106. <https://doi.org/10.17660/ActaHortic.2010.853.11>
24. Guenaoui, C., Gorai, M., Smiti, S., and Neffati, M. (2008). Biochemical and physiological changes in *Artemisia herba-alba* plants under water stress conditions. *Middle-East Journal of Scientific Research*, 3, 156–163.
25. Werner, T., and Schmölling, T. (2013). Cytokinin synthesis in response to microorganisms and stress. *Plant Physiology*, 163, 1609.
26. Skirycz, A., Vandenbroucke, K., Clauw, P., Maleux, K., De Meyer, B., Dhondt, S., et al. (2020). Survival strategy under prolonged drought may shift from stress avoidance to productivity. *Frontiers in Plant Science*, 11, 879. <https://doi.org/10.3389/fpls.2020.00879>
27. Song, J. (2024). The potential applications of cytokinins and cytokinin oxidase/dehydrogenase inhibitors for mitigating abiotic stresses in model and non-model plant species. *Current Plant Biology*, 100080. <https://doi.org/10.1016/j.cpb.2024.100080>
28. Bota, J., Medrano, H., and Flexas, J. (2004). Is photosynthesis limited by decreased Rubisco activity and RuBP content under progressive water stress? *New Phytologist*, 162, 671–681. <https://doi.org/10.1111/j.1469-8137.2004.01056.x>
29. Atkinson, N.J., and Urwin, P.E. (2012). The interaction of plant biotic and abiotic stresses: From genes to the field. *Journal of Experimental Botany*, 63, 3523–3543. <https://doi.org/10.1093/jxb/ers100>
30. Akula, R., and Ravishankar, G.A. (2011). Influence of abiotic stress signals on secondary metabolites in plants. *Plant Signaling & Behavior*, 6, 1720–1731. <https://doi.org/10.4161/psb.6.11.17613>
31. Zehra, A., Choudhary, S., Naeem, M., Khan, M.A.M., Khan, A., and Aftab, T. (2019). Medicinal and aromatic plants and their secondary metabolites under abiotic stress. *Journal of Medicinal Plants Studies*, 7, 99–106.

32. Malhi, G.S., Kaur, M., and Kaushik, P. (2021). Impact of climate change on agriculture and its mitigation strategies: A review. *Sustainability*, 13, 1318. <https://doi.org/10.3390/su13031318>
33. Sadak, M.S., Abdalla, A.M., Abd Elhamid, E.M., and Ezzo, M.I. (2020). Role of melatonin in improving growth and yield of *Moringa oleifera* under drought stress. *Bulletin of the National Research Centre*, 44, 18. <https://doi.org/10.1186/s42269-020-0275-7>
34. Wani, S.H., Kumar, V., Shriram, V., and Sah, S.K. (2016). Phytohormones and their metabolic engineering for abiotic stress tolerance in crop plants. *The Crop Journal*, 4, 162–176. <https://doi.org/10.1016/j.cj.2016.01.010>