



# Enhancing drought resistance in grass pea: The positive regulatory role of plant-smoke solution

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## ABSTRACT

Drought stress poses a significant challenge to agricultural productivity as a primary consequence of climate change. This study aimed to investigate the potential of plant-derived smoke solutions as a novel, natural, and environmentally friendly factor for enhancing drought resistance in grass pea (*Lathyrus sativus* L.). For this, two varieties of grass pea were independently assessed under three different drought stress (control, moderate and severe) after priming with smoke solution. Drought stress was modulated by water deficiency as the last 4 days in moderate and 8 days in severe drought. Grass pea seeds primed with smoke solution derived from poppy (*Papaver somniferum* L.) at doses of 1 %, 10 % and with distilled water as control. Biometric measurements, chlorophyll pigments, secondary metabolite levels, and biochemical parameters were analyzed in the experiments. The results indicated that grass pea was sensitive to drought, with no discernible differences between the two varieties. The application of smoke solutions resulted in increased fresh and dry weight for plants grown under both control and drought conditions. While 1 % of smoke solution had a notable impact on leaf relative water content (LRWC), 10 % primarily influenced chlorophyll pigments and malondialdehyde (MDA) levels. Additionally, smoke solutions resulted in increased anthocyanin and secondary metabolite levels. These findings suggest that smoke solutions enhanced the defense mechanisms against drought stress in grass pea, but this improvement varies depending on the solution doses. In conclusion, our study demonstrates that poppy derived smoke solutions have the potential to offer a novel and natural approach for enhancing drought resistance in plants. It also encourages new studies to examine the interaction of different smoke solutions and plants against drought stress.

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## 1. Introduction

Animal-based foods play a crucial role in maintaining a balanced and healthy diet, and the quality of these products is inherently tied to the quality of forage. Grass pea (*Lathyrus sativus* L.) stands out as a rich source of protein, iron, potassium, and calcium, available in both grain and hay forms. Also, grass pea is particularly resistant to drought stress, but not under severe drought conditions. Severe drought significantly disrupts the morphological, physiological, and biochemical functions of plants, thereby compromising both the quality and yield, as seen in grass peas. Water scarcity-induced drought stress tends to hinder cell growth more than cellular structure (Jaleel et al., 2008), thus exerting profound impacts on overall plant development. 2021 drought report issued by the Union of Chambers of Agriculture of Turkey (TZOB) reveals a concerning reality, with 22.5w% of Turkey's land area experiencing high desertification and 50.9 % facing moderate desertification. Offering

opportunities for cultivating high-quality plants like a grass pea in these regions represents a promising strategy to mitigate future drought-related concerns. Drought, stemming from both human activities and climate change, is an abiotic stressor posing a significant threat to agricultural productivity. It leads to alterations in leaf photosynthetic pigments, respiration rates, secondary metabolism, root growth, nutrient metabolism, and the biochemical equilibrium of plants (Bano et al., 2012; Sezer et al., 2021). Plants respond to shifting environmental conditions by developing defense mechanisms through various parameters, including anthocyanins, chlorophyll pigments, secondary metabolites, and morphological adaptations (Hura et al., 2015). Plant responses to drought stress significantly vary based on the stress level and plant species, necessitating a deep understanding of these reactions for effective stress resilience.

The recurring nature and increasing trend of the drought threat necessitates focusing on new approaches and practices in agriculture for sustainability. Several methods have been employed to mitigate drought stress, the development of drought-tolerant crops (Nuccio et al., 2018), the use of nanoparticles (Saxena et al., 2016), and the application of superabsorbents, hydrogels, and biochar (Saha et al.,

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2020; Zhang et al., 2020). Additionally, the utilization of plant growth-promoting rhizobacteria has shown promise (Chiappero et al., 2019). In addition to these methods, plant-derived smoke solutions, as a relatively new and underexplored approach, may offer a noteworthy strategy within the realm of agricultural mitigation. Plant-derived smoke solutions are obtained by burning crop residues and capturing the smoke in water, and it may be applied directly to seeds as priming or to the soil. Direct application to the seed is usually in the form of priming to ensure that chemicals in solution enter the seed and stimulate the system. These solutions include recycling agricultural waste and can thus contribute to the development of environmentally friendly solutions for drought stress relief and sustainability in agriculture. These solutions have shown significant positive effects on germination and seedling growth, depending on the plant material burned (Jefferson et al., 2008; Dixon et al., 2009). Plant-derived smoke, containing compounds like karrikin, has demonstrated the ability to enhance plant stress resilience (Li et al., 2017; Bose et al., 2020). Smoke solutions have been found to bolster plant tolerance against various abiotic stresses, including drought (Li et al., 2017), floods (Shah et al., 2021), cold (Shah et al., 2021), cadmium (Shah et al., 2020), and salt (Khan et al., 2017). The efficacy of smoke solutions varies based on factors such as the type and quantity of plant material burned, solution concentration, and the specific plant genotype (Dogrusoz et al., 2022). When we look at the studies conducted in this context, it can be seen that it's mostly focus on the effect of smoke solutions on germination, seedling development and quality parameters. However, it seems that the number of studies involving the interaction of smoke solutions and abiotic stress is quite low. Therefore, in this study, it was investigated how smoke solutions affect the drought resistance of plants with reference to grass pea.

In this study, the effect of poppy-derived smoke solution on the response of grass pea to different drought levels was investigated based on biochemical determinations under laboratory conditions. For this purpose, two grass pea genotypes and three levels of drought stress and two deses of smoke solution were used. Thus, it has been revealed how both the response of grass pea to drought stress and how smoke solutions support the defense mechanism.

## 2. Materials and methods

This study included two Turkish origin grass pea (*Lathyrus sativus* L.) as plant material, one registered variety 'Karadağ' and one population. The seeds were first primed with smoke solutions and distilled water (as control), and then grown under conditions with different drought levels. The response of the plant to treatments is revealed based on the analysis of stress-sensitive biochemical contents. Germination and seedling development were carried out in a light, temperature and humidity controlled climate room within the Agriculture Faculty of Yozgat Bozok University.

### 2.1. Preparation of the smoke solutions and priming

Smoke solutions were created by combusting poppy (*Papaver somniferum* L.) residues. A quantity of 1 kg of poppy straw was subjected to burning, and the ensuing smoke was collected by passing it through 4 L of distilled water, employing a specialized system (Ghebrehiwot et al., 2009; Başaran et al., 2019). This stock solution was then diluted to concentrations of 1 % and 10 % using distilled water. Subsequently, grass pea seeds were primed by immersing them in either smoke solutions or tap water (control) for 18 h at 22 °C.

### 2.2. Adjusting drought stress and growth environment

The study was structured around three distinct applications: severe drought, moderate drought, and normal irrigation (control). Initially, all treatments were irrigated to field capacity. For sub-

irrigation, the amount of water that would reach the field capacity in each pot was determined, and the water required was given for the following 20 days. Drought stress was formed with last 8 days water scarcity for severe drought stress and last 4 days for moderate drought stress. The primed seeds were sown in 8 L pots filled with an even mixture of peat and soil (50 % and 50 %, v/v). The experiment followed a randomized block design with three replications, each containing 10 plants. Grass peas were grown under conditions maintained at 25 ± 2 °C with 12:12 h light/dark period and 75 % humidity. The treatments receiving smoke solution under non-drought condition were used as controls. At the end of the 28th day, the experiment was completed and the following characteristics were examined in the harvested seedlings.

## 3. The parameters examined in grass pea seedlings

### 3.1. Biometric parameters

Ten plants within each pot were harvested and weighed, allowing us to calculate their fresh weight (FW;gr). Subsequently, the same samples were subjected to a 48-hour drying period at 65 °C until a constant weight was achieved, and their dry weight (DW;gr) was determined. To assess leaf relative water content (LRWC) for each plant, young leaves were utilized. After determining fresh weight (FW), the leaves were immersed in distilled water for 6 h at room temperature and their turgid weight (TW) was recorded. Then the leaves were subjected to oven drying at 65 °C until they reached a constant weight, allowing us to determine their dry weight (DW). LRWC for three randomly selected leaves from each replication was calculated using the equation developed by Smart and Bingham (1974):

$$\text{LRWC}(\%) = [(FW - DW)/(TW - DW)] \times 100$$

### 3.2. Photosynthetic pigment content

Chlorophyll a, chlorophyll b, the sum of chlorophyll a and b (a + b), a/b ratio, and carotenoid concentration were quantified following the procedure outlined by Corte-Real et al. (2017). To achieve this, 0.5 g of fresh leaf samples were ground and combined with 10 mL of 80 % acetone solution, after which the mixture was stored in darkness at a temperature of 25 °C for 24 h. Subsequently, the samples were filtered, and their absorbance was measured at 470, 645, and 663 nanometers using a spectrophotometer.

For the determination of total anthocyanin content, fresh leaves (1 g) from three plants per replicate were homogenized in methanol containing 1 % HCl (v/v) at 4 °C and allowed to incubate for 24 h. Following centrifugation, the absorbance of the supernatant was recorded at 530 and 657 nanometers, and the total anthocyanin content was calculated using the method described by Mita et al. (1997).

### 3.3. Anthocyanins, malondialdehyde contents

To determine the total anthocyanin content, fresh leaves were blended in methanol with 1 % HCl (v/v) at 4 °C and left to incubate for 24 h. After centrifugation, the supernatant's absorbance was measured at wavelengths of 530 and 657 nm, and the total anthocyanin content was calculated using the formula established by Mita et al. (1997).

Lipid peroxidation was assessed by quantifying the malondialdehyde (MDA) content in the leaves, following the method described by Madhava Rao and Sresty (2000). Membrane permeability was determined using an electrical conductivity meter. Leaf samples measuring 1 cm x 1 cm were immersed in 10 mL of distilled water and shaken at room temperature (25 °C) for 24 h. The initial electrical conductivity (EC1) was recorded. Subsequently, the samples were

autoclaved at 120 °C for 20 min, and the second measurement (EC2) was conducted. Membrane permeability was calculated using the formula  $(EC1/EC2) \times 100$ , as outlined by Lutts et al. (1996).

### 3.4. Secondary metabolic

The total phenolic content (TP) of the samples was determined following a modified method based on Singleton et al. (1999). In this method, 200  $\mu$ L of samples were mixed with 200  $\mu$ L of Folin-Ciocalteu reagent and 200  $\mu$ L of sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) solution. The mixture was then incubated in darkness for 120 min at room temperature. Subsequently, the absorbance of the extracts was measured at 760 nm using a PeakInstruments (E-1000V-USA) spectrophotometer. The total phenolic contents were expressed as milligrams equivalent to gallic acid (GAE) per gram of dry weight (DW) based on the equation derived from the standard gallic acid graph and calculated from the calibration curve ( $R^2 = 0.9994$ ). For the quantification of total phenols, methanol was used for extraction. Total phenolic content was assayed by measuring A765 with Folin-Ciocalteu reagent (Singleton and Rossi, 1965). The results were expressed as micrograms of p-hydroxycinnamic acid per gram of fresh weight.

Total flavonoid (TF) determination followed the method of Arvouet-Grand et al. (1994) with slight modifications. Each sample (200  $\mu$ L) was mixed with 100  $\mu$ L of 10 % aluminum nitrate and 100  $\mu$ L of 1 M potassium acetate. The total volume was adjusted to 5 mL with ethanol. After a 40-minute incubation at room temperature in darkness, absorbance was measured at 417 nm using a Peak Instruments (E-1000V-USA) spectrophotometer. TF content was expressed as milligrams of quercetin equivalents (QE) per gram of dry weight, calculated from the standard quercetin graph and the calibration curve ( $R^2 = 0.9994$ ).

The measurement of DPPH radical scavenging activity followed the methodology described by Gezer et al. (2006). A solution was prepared by adding 4 mg of DPPH to 100 mL of the solvent (methanol/ethanol). The extracts, dissolved in methanol and ethanol, were used. Main stock solutions of 8 mg mL<sup>-1</sup> were prepared from which different concentrations (100, 200, 400, 600, 800, and 1000  $\mu$ g mL<sup>-1</sup>) were derived. In each test tube, 200  $\mu$ L of extract solutions at varying concentrations were added to 3.2 mL of DPPH solution. The solvent quantities in each test tube were adjusted to 200  $\mu$ L of ethanol and 3.2 mL of methanol. After 30-minute incubation at room temperature in the dark, the absorbance at 517 nm was recorded using a Peak Instruments (E-1000V-USA) spectrophotometer.

Condensed tannin analysis was carried out according to the method by Bate-Smith (1975). In this process, 6 mL of tannin solution was added to 0.01 g of ground sample, mixed on a vortex, and placed in a tube. The tubes were securely capped and heated to 100 °C for 1 h, followed by cooling. Absorbance was then measured at 550 nm using a spectrophotometer. Condensed tannins (CT) were calculated using the formula:  $\text{Absorbance (550 nm)} \times 156.5 \times \text{dilution factor} / \text{Dry weight (\%)}$ .

### 3.5. Data analysis

Statistical analyses were conducted using SPSS software, version 20.0. Data underwent two-way ANOVA and were separated using Duncan's test with a significance level of  $p < 0.05$ . Principal component analysis (PCA) was applied to all data parameters. To interpret the results, biplot graphs were generated based on the principal components (PC1) and (PC2) obtained from PCA, separately for each variety. These biplot figures were produced using XLSTAT Software to reduce the dimensionality of multivariate data (Goodacre et al., 2000). The heat map graphic was created with SRplot (A free online platform for data visualization and graphing, <http://www.bioinformatics.com.cn>), separately for each variety.

## 4. Results

Applied drought levels had a significant impact on the biometric parameters and chemical content investigated of grass pea plants. As expected, severe drought levels had a more devastating effect on grass pea. Nonetheless, the utilization of the smoke solution contributed to alleviating these adverse impacts. Both fresh weight (FW) and dry weight (DW) decreased in both genotypes under drought stress conditions. However, both smoke solutions counteracted these reductions. Interestingly, while the fresh weight of the population had the highest value with SD-10 % application, the gain was approximately 90 %. Generally, FW and DW values of both genotypes increased in priming with 1 and 10 % smoke solutions in MD and 10 % in SD. The highest FW and DW for both species were achieved when 10 % smoke solution was applied under control. Under normal irrigation conditions, smoke solutions partially increased FW and DW. In particular, the fresh weight of the population had the highest value.

Drought led to a decrease in LRWC in both genotypes (Fig. 1). The loss in this reduction was 22 % and 3 % in the MD conditions and 40 % and 32 % in the SD conditions, respectively, variety and population. However, positive effect of smoke solutions against drought was observed in both genotypes. However, values above the control LRWC value were obtained from Cont1–10 %, MD-1 % and SD-1 % only in the population.

The content of photosynthetic pigments (Chl a, Chl b, and Chl a/b) in the grass pea variety exhibited a decline corresponding to the severity of drought stress, as indicated in Table 1. Nonetheless, priming with smoke solutions, particularly at the 10 % concentration, effectively mitigated the adverse impacts of both drought levels. The highest chlorophyll yield (Chl a + b) of variety was achieved with the 10 % smoke solution treatment (163.96  $\mu$ g g<sup>-1</sup> fw), representing an approximately 28 % increase compared to the control group. Notably, drought stress and smoke solution treatments did not significantly affect the photosynthetic pigment content of the grass pea population, suggesting that this population demonstrates a higher degree of resilience to drought stress concerning chlorophyll parameters.

There were significant differences in carotenoid and MDA between the control and smoke solution doses in grass pea variety, but in only anthocyanin in grass pea population (Table 2). Drought stress led to an increase in anthocyanin concentration and declines in carotenoid concentration in both genotypes. Smoke solution increased anthocyanin of population, and the most effective dose was 10 % in drought conditions. Membrane permeability increased as a result of water deficiency in grass pea. These increments were decreased with smoke solutions in grass pea variety but did not reach the control level.

Secondary metabolites content were significantly induced by drought stress and smoke solutions in both population and variety of grass pea (Table 3). An increase in these parameters was observed in parallel with drought stress. Except tannin, these increases were supported by the smoke solution and the highest values were determined in the 1 % solution of severe drought. Condensed tannin decreased with the smoke solution severe drought conditions. Although the grass pea population and variety showed similar responses, the variety was more affected by drought stress and achieved better recovery with smoke solutions.

A heat map was created for both genotypes separately, in order to express the relationships between features and applications, as well as how the applications and features are distributed in the context of these relationships (Fig. 2). The color distribution on the map clearly shows the role of the growing environment and the effect of drought in terms of the characteristics examined in grass pea genotypes. The effect and positive results of priming with smoke solution in terms of environment and properties are also seen. This distinction was especially evident in the variety, which is expected due to its genetic

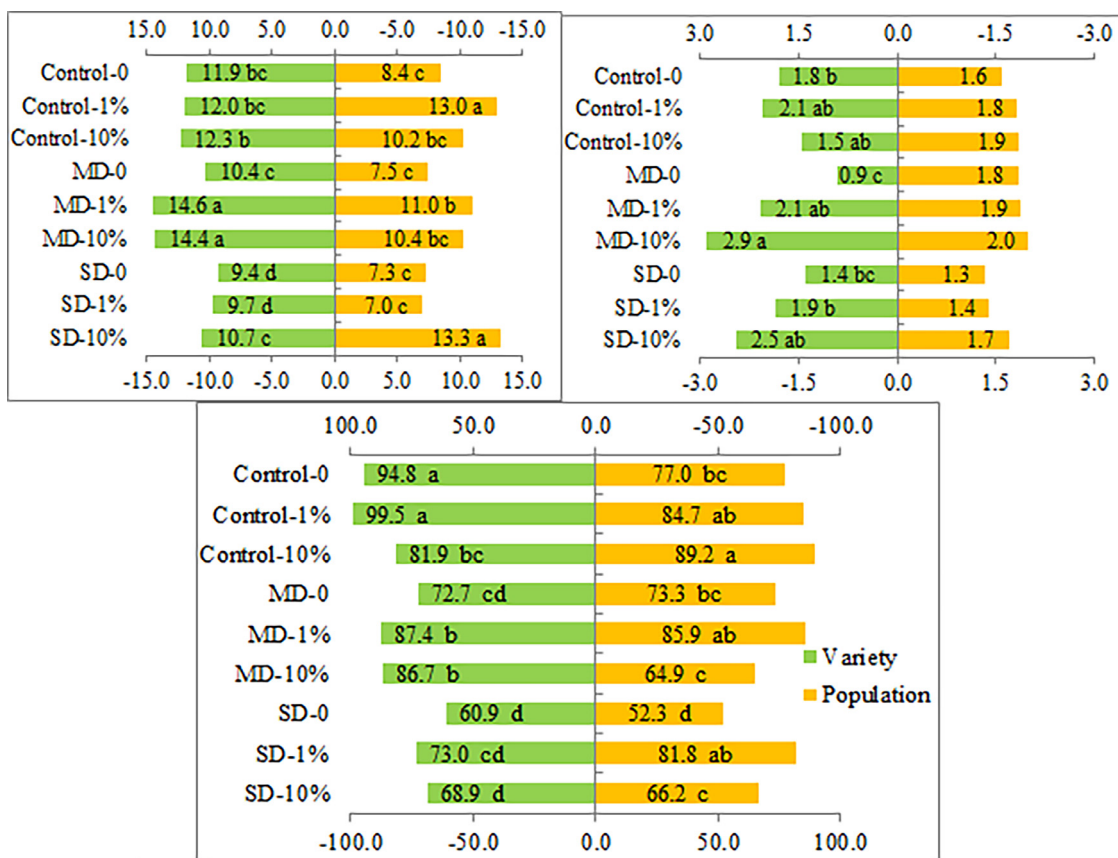


Fig. 1. Changes in biometric parameters of smoke solution applied in grass pea under drought stress; Different letters significant differences at  $p \leq 0.05$  within one parameter. (FW; gr; top left graphic, DW; gr; top right graphic and LRWC; subgraph).

Table 1  
Content of chlorophyll and precursors of smoke solution primed grass pea leaves under drought stress

Treatments	Chlorophyll a ( $\mu\text{g g}^{-1}$ fw)		Chlorophyll b ( $\mu\text{g g}^{-1}$ fw)		Chlorophyll b ( $\mu\text{g g}^{-1}$ fw)		Chlorophyll a/b	
	Variety	Variety	Variety	Population	Variety	Population	Population	Variety
Control-0	62.76 abc	63.31	64.85 c	57.15	127.61 cd	120.46	1.08 bc	1.12
Control-1%	64.27 abc	62.87	66.69 bc	71.79	130.96 bc	134.67	0.98 c	0.88
Control-10%	66.39 ab	62.47	88.42 ab	58.24	154.81 ab	120.71	0.76 c	1.07
MD-0	59.13 cd	62.38	36.90 d	54.82	96.03 e	117.21	1.64 a	1.16
MD-1%	62.56 bc	62.21	53.92 cd	50.57	116.48 cde	112.78	1.16 abc	1.23
MD-10%	63.73 abc	62.76	66.17 bc	59.06	129.90 bc	121.83	0.96 c	1.07
SD-0	56.3 d	63.04	36.65 d	43.63	93.04 e	106.66	1.65 a	2.14
SD-1%	60.21 cd	62.18	42.00 d	70.97	102.21 de	133.15	1.49 ab	0.88
SD-10%	68.53 a	61.41	95.43 a	68.49	163.96 a	129.89	0.72 c	0.94

Different letters significant differences at  $p \leq 0.05$  within one parameter.

Table 2  
Carotenoid, anthocyanin and Malondialdehyde (MDA) content of grass pea primed smoke solution under drought stress

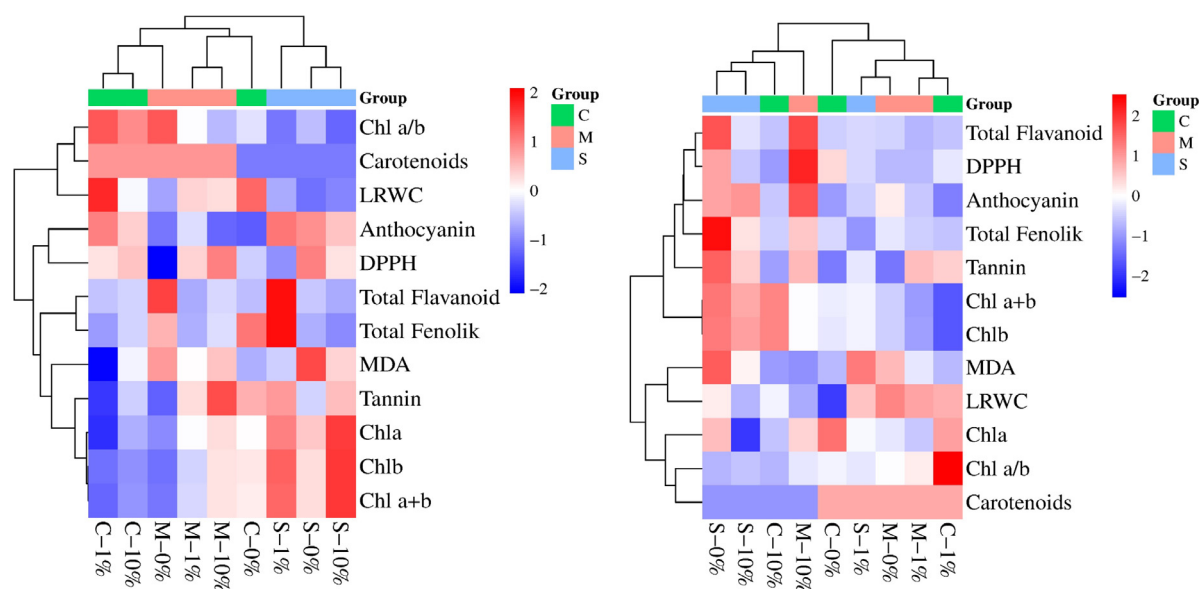
Treatments	Anthocyanin ( $\text{mg L}^{-1}$ )		Carotenoid ( $\text{mg L}^{-1}$ )		MDA $\mu\text{mol g}^{-1}$ FW	
	Variety	Population	Variety	Population	Variety	Population
Control-0	0.53	0.56 c	0.0042 bc	0.0059	1.53 b	1.59
Control-1%	2.29	0.48 c	0.0053 ab	0.0075	1.30 c	1.59
Control-10%	1.81	0.73 bc	0.0067 a	0.0078	1.67 bc	1.55
MD-0	0.68	0.73 bc	0.0034 b	0.0047	1.77 ab	1.77
MD-1%	1.32	0.99 abc	0.0060 ab	0.0061	1.62 bc	1.65
MD-10%	0.58	1.55 a	0.0062 ab	0.0058	1.61 bc	1.53
SD-0	2.19	0.76 bc	0.0014 d	0.0039	1.88 a	1.89
SD-1%	2.35	1.25 ab	0.0020 cd	0.0045	1.57 b	1.75
SD-10%	1.86	1.30 ab	0.0044 ab	0.0051	1.69 b	1.70

Different letters significant differences at  $p \leq 0.05$  within one parameter.

**Table 3**  
Secondary metabolites of smoke solution primed grass pea under drought stress

Treatments	Total phenolic (mg GA g <sup>-1</sup> )		Total flavonoid (mg QEg <sup>-1</sup> )		DPPH free radical scavenging activity (%)		Condensed tannin (%)	
	Variety	Population	Variety	Population	Variety	Population	Variety	Population
Control-0	4.51 e	4.43 e	0.30 e	0.34 ef	40.82 d	38.22 h	1.53 bc	1.14 de
Control-1%	4.23 ef	4.74 de	0.32 de	0.32 ef	44.22 c	43.68 d	0.99 g	1.41 b
Control-10%	4.02 f	4.59 de	0.35 c	0.31 f	45.55 b	47.95 c	1.28 e	1.19 d
MD-0	4.46 e	4.19 e	0.89 b	0.35 de	31.75 f	40.48 fg	1.07 f	1.13 e
MD-1%	5.10 d	4.59 de	0.26 f	0.27 g	44.88bc	40.28 g	1.44 d	1.43 b
MD-10%	6.45 c	6.02 b	0.36 c	0.37 cd	38.05 e	42.65 e	1.29 e	1.44 b
SD-0	4.98 d	4.95 d	0.33 cd	0.44 bc	48.45 a	51.52 b	1.72 a	1.57 a
SD-1%	8.56 a	8.59 a	0.96 a	0.98 a	48.48 a	60.55 a	1.57 b	1.41 b
SD-10%	7.21 b	5.62 c	0.25 f	0.40 c	44.05 c	41.25 f	1.50 c	1.30 c

Different letters significant differences at  $p \leq 0.05$  within one parameter.



**Fig. 2.** Representation with a heat map of the relationship between responses of smoke solution applied to grass pea under water deficiency conditions (*The heat map on the left is for the species, the one on the right is for the population.*) (*The heat map was created with SRplot: A free online platform for data visualization and graphing, <http://www.bioinformatics.com.cn>.*)

homogeneity. Therefore, the variability between groups in the population can be attributed to intra-genetic differences.

Principal Component Analysis (PCA) is a frequently used technique to understand relationships between variables in multivariate datasets and to reduce the dataset to more meaningful dimensions. In this study, PCA analysis was chosen to better understand the complexity of 12 variables and to determine their fundamental characteristics. PCA helps reduce noise in the analysis and achieve more meaningful results by identifying the fundamental components representing the dataset. In this context, additionally, PCA was applied to see the effects of all transactions simultaneously on the graph for each genotype by using first two components (Table 4). PCA biplots have offered a comprehensive overview the biochemical responses of grass pea to water deficiency and smoke solutions. PCA biplots

including all the investigated traits were created separately for the population and variety of grass pea. Biplot graphs for variety explained 69.63 % of the cumulative variance, with F1 and F2 contributing 48.16 % and 21.47 % of the cumulative variance, respectively. In contrast, the population variety exhibited principal components F1 and F2, which represented 45.07 % and 23.14 % of the cumulative variance, respectively (Fig. 2). According to vector contributions in the biplot for variety, first component mainly loaded by chlorophyll related traits, condensed tannins and MDA while second component by total phenolic, total flavonoid and DPPH. As for the biplots of the population, first component highly loaded by about all the traits and second component too, but with the exception of LRWC, MDA and total anthocyanin. It can be said that there are 4 main groups in both biplots, as can be seen in the heat map. In both genotypes, Control-0 was in a group by itself. Similarly, it is seen that Control-0, MD-0 and SD-0 processes are placed in different groups. With the priming, especially with smoke solution, this basic distinction decreased and different treatments were located in the same groups. But that genetics and solution dosage are also important in this regard. In variety, the SD-1 % treatment was positioned in positive quadrants of both F1 and F2. Conversely, the SD-0 and MD-10 % treatments in the population were similarly situated. These treatments, highlighting the remarkable efficacy of the poppy smoke solution in enhancing drought stress tolerance. Additionally, it was evident that the response mechanism to drought stress in the variety was associated

**Table 4**  
Eigenvalues and variance of the first two components used

	Variety		Population	
	F1	F2	F1	F2
Eigenvalue	5.78	2.58	5.41	2.78
Variability (%)	48.16	21.47	45.07	23.14
Cumulative %	48.16	69.63	45.07	68.21



et al. (2022) observed a decrease in chlorophyll a and b levels due to flooding stress in wheat; however, these levels were subsequently restored with the application of a plant-derived smoke solution.

Carotenoids play a crucial role in shielding cell membranes from environmental stresses and are generally anticipated to be adversely affected by drought stress, as reported by Nisar et al. (2015). In our study, we observed a similar negative impact of drought stress on carotenoid levels; however, this adverse effect was mitigated by the application of 1 % and 10 % smoke solutions. Numerous studies have highlighted the capacity of anthocyanins to scavenge reactive oxygen species (ROS), as documented by Aras et al. (2021) and Sperdouli and Moustakas (2012). Interestingly, drought stress induced a notable increase in anthocyanin content, particularly at the moderate drought (MD) level. This suggests that grass pea employs anthocyanins as a defense mechanism in response to drought conditions. Remarkably, even under drought stress, the application of 1–10 % smoke solutions led to an increase in anthocyanin content across the genotypes. Li et al. (2017) identified a reduction in anthocyanin production in response to Kai2-derived smoke solutions during drought, potentially rendering plants more susceptible to drought sensitivity. This finding aligns with previous research demonstrating a positive correlation between drought resistance and anthocyanin levels in plants. This positive relationship is attributed to the ROS-scavenging antioxidant properties of anthocyanins, which serve as a protective shield against the detrimental effects of drought. Insufficient water availability triggers the generation of reactive oxygen species (ROS), which can exacerbate cellular membrane damage, as elucidated by Kaya et al. (2019). In our study, we assessed cell membrane damage by quantifying malondialdehyde (MDA) levels, a byproduct of lipid peroxidation. Drought conditions led to a reduction in MDA levels, a trend that was notably reversed by the application of a 1 % smoke solution under severe drought conditions.

High levels of antioxidative activity are vital for sustaining growth, promoting high-quality crop yields, and serving as an indicator of a plant's defense mechanism against drought stress, as emphasized by Jaleel et al. (2008). Additionally, these antioxidants can have a positive impact on the productivity and overall health of animals, as demonstrated by studies conducted by Seradj et al. (2014) and Paula et al. (2016). In our study, we observed an increase in antioxidative activities, including phenolic and flavonoid content, as well as DPPH scavenging activity, in response to drought stress, particularly under severe drought conditions. Zhang et al. (2021) reported a decrease in antioxidant activity and MDA content in *A. lancea* after more than four days of exposure to drought stress. Conversely, Zhou et al. (2008) noted that short-term drought stress could enhance the activities of antioxidant enzymes (SOD, CAT, etc.) in *A. lancea* seedlings, reducing oxidative damage. This phenomenon may be attributed to the reallocation of carbon, fixed during photosynthesis, towards the formation of secondary metabolites as a result of reduced plant growth under drought stress, as proposed by Hale et al. (2005). Interestingly, the positive effects of smoke solutions on antioxidant levels and drought stress tolerance were consistent across genotypes in our study. Singh et al. (2023) also supported this finding, suggesting that karrikin present in plant-derived smoke acts as a bioactivator, affecting various compounds including the cell's antioxidant mechanisms, anthocyanins, and phytohormones. Notably, the application of a 1 % smoke solution yielded promising results in both genotypes. Wang et al. (2022) similarly reported a reduction in MDA levels and an increase in antioxidant activity in response to drought stress in *Lolium perenne* and *Medicago sativa*. Furthermore, they demonstrated that melatonin application effectively alleviated the inhibitory effects of drought stress on these species.

Tannins, specifically condensed tannins or proanthocyanidins, are a group of polymeric flavan-3-ols that are recognized for their ability to bind with proteins. In the hierarchy of plant tissue biochemicals, they rank as the fourth most abundant, trailing behind cellulose,

hemicellulose, and lignin. Their prevalence in plant tissues significantly contributes to the overall carbon-nutrient balance, as elucidated by Hernes and Hedges (2000). The production of vegetable tannins is a complex outcome of the dynamic interaction between plants and their surrounding environments. This intricate process is notably influenced by a multitude of abiotic factors, including drought and salinity, among others, as highlighted by Hernes et al. (2001). Condensed tannins play a crucial role in various ecological and forage quality aspects. For instance, in forages like sainfoin, they regulate rumen microbial activity, reducing the risk of foaming and bloat, as noted by Waghorn and McNabb (2003). Hence, condensed tannins hold practical importance in both ecological and forage quality contexts. According to Onal Asci and Acar (2018), the ideal amount of condensed tannins in high-quality forage should not exceed 3 %, as an excess amount can lead to degradation of proteins and enzyme activity. In our study, we found that the condensed tannin content of all processes remained below the 3 % threshold. Interestingly, while condensed tannin content decreased under moderate drought conditions, it increased in response to severe drought stress for both species. However, the elevated tannin levels induced by severe drought were mitigated by the application of a 1–10 % dose of smoke solution. Gourlay et al. (2022) emphasized that condensed tannins serve as antioxidants that protect poplar trees against oxidative stress caused by drought. They further demonstrated that drought stress could influence the condensed tannin levels in these trees.

Based on the findings and insights obtained from the study, several future recommendations can be proposed: -Investigate of smoke solution concentrations on plant based to identify the most effective level in enhancing drought resistance mechanisms without causing any adverse effects. -Explore the use of different plant materials to produce smoke solutions. Because, various plant sources may have unique compositions that could impact their effectiveness in inducing stress resistance. -Conduct experiments in diverse geographic locations and soil types to ensure the practical applicability and effectiveness of the poppy-smoke solution across different agricultural settings. -Investigate the potential synergistic effects of combining poppy-smoke priming with other stress mitigation techniques. -Evaluate the economic feasibility of integrating poppy-smoke priming into existing agricultural practices. -Disseminate the findings and knowledge gained from the study to local farmers and agricultural practitioners. These recommendations can further enhance the practical applicability and impact of poppy-smoke priming in mitigating drought stress and improving crop resilience.

## 6. Conclusion

Based on the examined parameters and PCA biplot analysis, it is evident that grass pea is more susceptible to severe drought stress, and the variety exhibits greater stress sensitivity. Furthermore, the application of smoke solution was found to enhance the drought resistance mechanisms of grass pea genotypes by enhancing the activity of protective enzymes (SOD, CAD etc.), thereby reducing stress-induced damage. This observation can be elaborated as follows: Under drought stress conditions, chlorophyll pigment levels decreased, impacting the assimilation process. Severe drought stress led to decreased tolerance due to inhibition of the antioxidative enzyme system. Consequently, priming with poppy-smoke solution initiated a defense mechanism against drought stress in grass pea. However, it's important to note that the efficacy of plant-derived smoke solutions may vary depending on the dosage and the specific plant material used. Therefore, evaluating plant-based smoke solutions against various abiotic stresses, such as drought, is crucial for understanding their potential benefits.

## Declaration of competing interest

The authors have no conflicts of interest to declare.

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