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RESEARCH

Green Pak Choi is better in suitable environment but the purple ones more resist to drought and shading

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Abstract

Background Studying how economic vegetable adapt to stressful environment is important not only for plant biology application but also to agronomy. In this study, we selected two commonly used genotypes of pak choi, i.e., larger green pak choi (*Brassica rapa* ssp. *chinensis*) and smaller purple pak choi (*Brassica rapa* var. *chinensis*, 'Rubi F1') to examine the divergent response of the two genotypes to drought and shading in the semi-arid region of Xinjiang. We compared the differences in biomass accumulation and plant morphological traits of the two pak choi in response to the interaction effects of drought (55-70% of field water capacity) and shading (24% reduction of canopy light radiation).

Results The results showed drought and shading significantly reduced the aboveground and belowground biomass of the two pak choi, with a particularly pronounced decrease in shoot biomass under the combined effect of shading + drought. The decline in shoot biomass was mostly resulted from decreasing in the number of leaves rather than in plant height and crown width in response to drought and shading. In terms of morphological traits, green pak choi sensitively responded to increased drought and shading, with aboveground biomass mostly determined by leaf number and root mass. In contrast, purple pak choi likely more resistant to the stressful environment, as its aboveground biomass was also influenced by plant height and crown width.

Conclusions Hence it is important to consider not only the effects of drought but also the role of adequate light, which plays a key part in promoting the cultivation and growth of pak choi in stressful environments. The research and application of plant biology and agronomy in the region also need to consider the diversity of key economic plants to promote sustainability of vegetable farming in adapting to changing environmental stresses.

Keywords Xinjiang vegetables, Pak Choi, Drought, Shading, Biomass, Plant height, Leaf

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Introduction

Pak choi (*Brassica rapa* ssp. *chinensis*) is an important leafy vegetable widely cultivated and consumed in China, Japan, and Korea for thousands of years. As a member of the Brassica family [1], pak choi is not only valued for its culinary uses but also for its numerous health benefits. For example, pak choi is low in calories and and high in fiber, supporting digestive health. It is also rich in vitamins A, C, and K, as well as potassium and calcium, all of which contribute to overall health [2]. In addition to its nutritional value, pal choi has been shown to contain various anthocyanins, which contribute to the distinct color of varieties such as the purple pak choi (*Brassica rapa* var. *chinensis*, 'Rubi F1') and green pak choi (*Brassica rapa* ssp. *chinensis*). These anthocyanins have potential health benefits, both for humans and the plant itself, by enhancing stress resistance [3, 4]. Research has demonstrated significant differences in the flavonoid between green and purple pak choi, with cyanidin and its derivatives being abundant in the purple variety. Flavonoids are important precursors to anthocyanins, which play a role in improving a plants resistance to environmental stressors [5]. Given these findings, understanding how different environmental factors influence the growth and stress tolerance of pak choi is crucial, particularly in regions facing harsh climatic conditions. For example, in semi-arid regions of western China, such as Xinjiang, where both food security and agricultural productivity remain challenging, studying the adaptability of pak choi under various environmental stresses could provide valuable insights for improving crop management and yield.

Pak choi generally prefers full sun but can tolerate partial shading and thrives in moist, fertile soil [6]. Key abiotic factors that influence pak choi growth include light, water, and soil fertility. In regions like Xinjiang, which experiences a temperate continental climate with significant temperature fluctuations, prolonged sunshine, and high evaporation rates these environmental factors can severely impact the quality and yield of pak choi [7, 8]. To mitigate the effects of intense sunlight, researchers have investigated light management techniques, such as using shade shelters or spraying reflective anti-transpiration agents, particularly in areas with excessive solar radiation [9–11]. While these approaches are commonly used for fruit and vegetable crops to reduce sunburn, they also help minimize water loss, thus benefiting plant growth. However, the relationship between light intensity and growth remains complex. While excessive light can harm plants by increasing temperatures and causing solar radiation burn, insufficient light can reduce photosynthetic capacity and biomass accumulation. Studies on crops like lettuce, cucumber, and rice have shown that low light intensity can reduce total biomass and results in smaller [12–16]. Interestingly, the effects of light on the root system are less straightforward, as roots primarily respond indirectly to changes in light intensity affecting above-ground growth, often leading to changes in root-to-shoot ratio [17]. Under low light conditions, plants may also show adaptations such as increased height, elongated leaves, and reduced carbohydrate accumulation [18–22]. The root system, plant height, leaf growth rate, and total growth can be used to evaluate the drought resistant of crop varieties [23]. Pak choi, in particular, is sensitive to both light intensity and drought. Research has shown that low light and water deficiency can significantly reduce photosynthesis and biomass accumulation in pak choi [24]. Given its sensitivity to these environmental factors and the physiological differences between green and purple varieties [4], there is a critical need to investigate how these factors impact the biomass accumulation and morphological traits of pak choi, especially under combined drought and shading conditions.

This study aims to explore the impact of light intensity and water availability on pak choi's growth by simulating drought through pot-weighing methods and creating shaded environmental using black sunshade nets. By examining how these stressors affect biomass accumulation and plant morphology, we aim to uncover environmental adaptation strategies that could improve pak choi cultivation. The results could provide valuable insights into optimizing the growth conditions of pak choi, thereby enhancing the quality and cost-effectiveness of its production in regions with challenging climatic conditions.

Materials and methods

Field experiment

The experiment was conducted at the test base of Yili Normal University, located in Yili Kazak Autonomous Prefecture, Xinjiang Uygur Autonomous Region. The region has a continental climate within the northern temperate zone, with four distinct seasons, abundant sunshine, an average annual temperature ranging from 7 to 10.4 ℃, average annual precipitation about 200 mm [25], and an average annual sunshine duration of 2700–3000 h [26]. The varieties tested were green pak choi and purple pak choi (Fig. 1), both provided by the Ili Institute of Agricultural Sciences. The soil used in the experiment was black soil, with the following basic physical and chemical properties: pH 5.8, soil organic carbon 12.9 g/kg, available nitrogen (AN) 160.7 mg/kg, available phosphorus (AP) 36.9 mg/kg, and available potassium (AK) 208.8 mg/kg.

Experimental method

The experiment included 4 treatments: full water supply without shading, drought without shading, shading without drought, and both drought and shading. Two pak

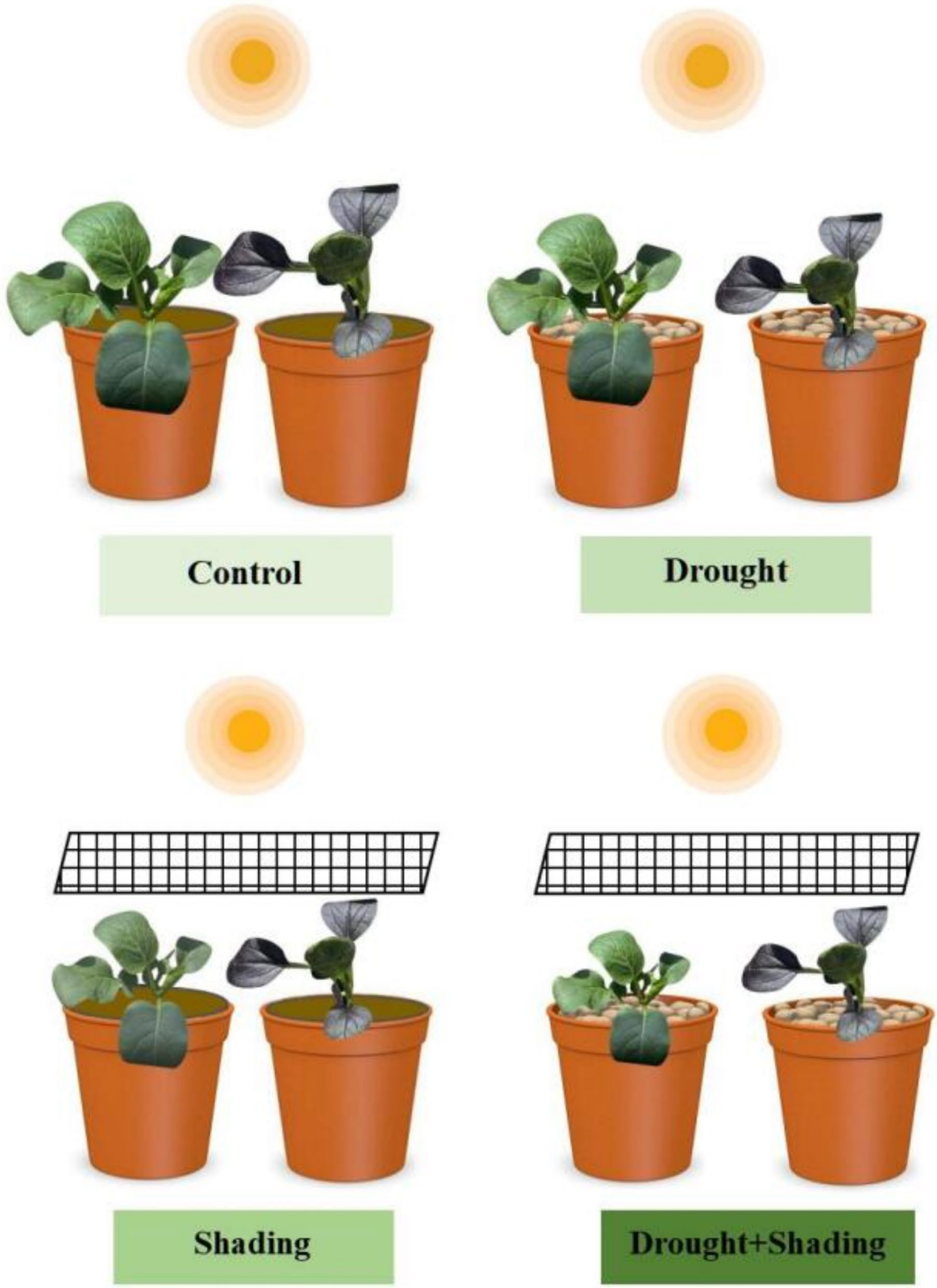

Fig. 1 Four treatments for green pak choi (left pot) and purple ones (right pot)

choi varieties were tested, with 6 replicates for each treatment. The treatment with adequate water supply and no shading served as the control group.

Light intensity was measured at a height of 40 cm from the soil surface using light intensity sensors (TOP Instruments, Zhejiang Top Instrument Co., Ltd., Hangzhou, China) [27, 28]. A black sunshade net was placed 40 cm above the pak choi canopy to reduce natural light intensity by 24%, as confirmed by preliminary tests and as described by [29]. The light reduction was verified using a light meter to ensure consistent shading levels throughout the experimental period. The saturated water-holding capacity (field capacity) of the soil was measured using the ring knife method [30]. For drought treatments, the water content in the potted plants was maintained at 55-70% of field capacity using the pot-weighing method [31, 32]. For clarity, the pot-weighing method involved determining the weight of the pot before and after watering and adjusting the irrigation to maintain the target weight. Potted plants with full water supply were kept at 80-100% of field capacity (Fig. 1). Seeds were sown on April 5, 2024, and the seedlings had reached a height of 3 cm by April 15, 2024, when the shading and water treatments were applied. The plants were harvested on June 12, 2024. Plant height, aboveground fresh biomass, aboveground dry biomass, root dry biomass, leaf number, and crown breadth of both pak choi varieties were measured in each treatment, following the standard protocols for biomass measurement [28, 33].

Data analysis

Excel 2010 was used for data sorting, while R version 4.3.1 was used for statistical analysis and visualization. A three-way analysis of variance (ANOVA) was performed for each treatment index. The least significant differences (LSD) method was applied for multiple comparisons, with different lowercase letters indicated significance differences at the $P<0.05$ level. We used a generalized canonical discriminant and correlation analyses (gCCA) to test relationships among the variation in attributes of pak choi across treatment. Additionally, linear regression was applied to assess the associations between leaf number, plant height, crown width, root dry weight, and aboveground fresh weight. The gCCA was conducted using the "candisc" package [34], and linear regression was performed using the "ggplot2" package [35].

Results

The biomass accumulation and allocation in response to drought and shading

For both green and purple pak choi, biomass accumulation was significantly affected by drought and shading (Table 1). Specifically, shoot biomass of both green and purple pak choi was significantly reduced by drought (50% and 51%, respectively) and shading (75% and 66%, respectively), whereas root biomass showed a more pronounced reduction under shading conditions, decreasing by 94% and 95% (Fig. 2). However, compared to drought alone, the shoot fresh weight of green pak choi was more sensitive to light effects than that of purple pak choi under the combined drought + shading conditions (Fig. 2a). The above-ground dry weight of green pak choi showed a significantly greater reduction under shading conditions compared to drought stress. Moreover, when light conditions were more severe, drought + shading significantly reduced the dry matter mass of the above-ground part of both green and purple pak choi compared to drought treatment alone (Fig. 2b). Drought,

Table 1 Effect of drought and shading on biomass and morphological indices of green Pak Choi and purple ones assessed by variance analysis. The * indicates a significant ($P<0.05$) difference between drought, shading, or drought + shading and the control

Treatment	Drought		Shading		Drought×Shading		Residuals
Green pak choi	**Variability (%)**	***F***	**Variability (%)**	***F***	**Variability (%)**	***F***	**Variability (%)**
Shoot fresh weight (g)	15.51	10.16*	49.10	32.19*	4.90	3.20	30.05
Shoot dry weight (g)	7.08	6.62*	68.93	64.57*	2.64	2.47	21.35
Root dry weight (g)	2.71	2.11	69.87	54.49*	1.78	1.38	25.64
Root shoot ratio	3.09	1.93	64.02	40.02*	0.90	0.56	31.99
Plant height (cm)	0.63	0.17	7.70	2.11	19.01	5.23*	72.67
Crown breadth (cm)	22.69	7.07*	10.11	3.15	3.02	0.94	64.18
Leaf number	22.81	17.39*	46.26	35.28*	4.71	3.59	26.22
Purple pak choi							
Shoot fresh weight (g)	20.76	12.07*	41.59	24.18*	6.69	3.89	30.96
Shoot dry weight (g)	14.12	9.47*	53.44	35.86*	5.63	3.78	26.82
Root dry weight (g)	52.57	3.32	14.97	9.46*	3.98	2.51	28.48
Root shoot ratio	30.32	1.70	35.17	19.74*	2.44	1.36	32.06
Plant height (cm)	28.92	8.98*	11.48	3.56	1.65	0.51	57.96
Crown breadth(cm)	17.14	4.44*	11.43	2.96	2.00	0.52	69.42
Leaf number	15.22	5.65*	33.59	12.48*	2.75	1.02	48.44

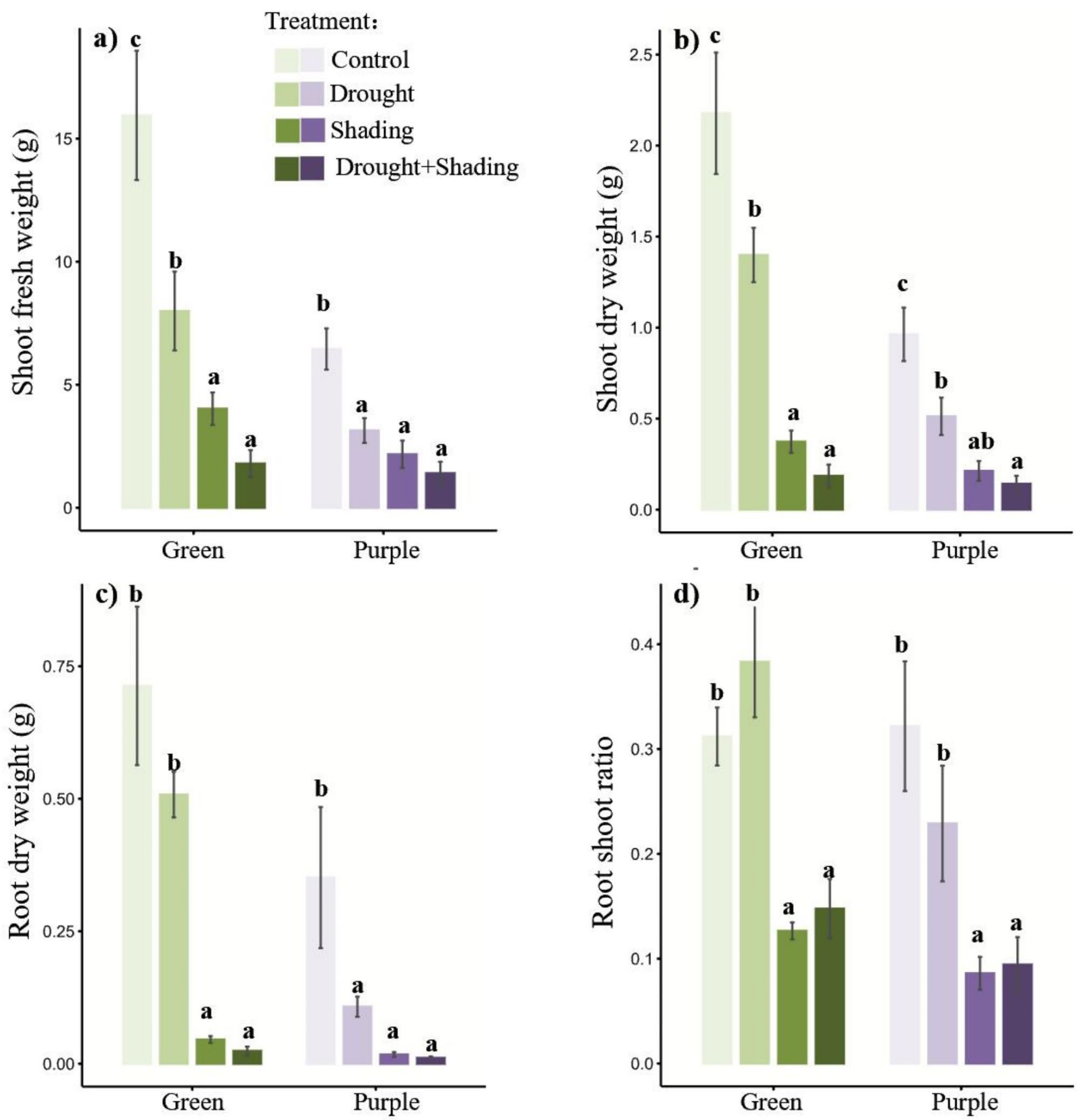

Fig. 2 Effects of drought and shading on shoot fresh weight (**a**), shoot dry weight (**b**), root dry weight (**c**) and root-to-shoot ratio (**d**) of green pak choi and purple pak choi. "Green" refers to green pak choi, and "purple" refers to purple pak choi. The treatments include Control, Drought, Shading, and Drought + Shading, representing the control group, drought, shading, and the combined drought and shading conditions, respectively. Different lowercase letters above the column indicate significant differences between treatments ($P < 0.05$)

shading, and their combined treatment (drought + shading) significantly reduced the root dry weight of purple pak choi by 69%, 95%, and 97%, respectively. For green pak choi, a significant reduction in root dry weight was observed exclusively under shading (94%) and combined drought + shading conditions (97%). Compared to drought treatment, shading resulted in a significant reduction in the root dry weight of green pak choi, whereas drought treatment showed no statistically significant effect (Fig. 2c). Drought + shading had no significant effect on the root-to-shoot ratio of either green or purple pak choi when compared with shading alone. Under shading conditions, both green and purple pak choi exhibited a reduced allocation of dry matter to their roots, with corresponding decreases in root-to-shoot ratio of 52% and 67%, respectively. In contrast, drought conditions had no effect on the root-to-shoot ratio in either variety (Fig. 2d).

The plant morphology in response to drought and shading

Drought + shading significantly decreased the plant height of green pak choi compared to drought alone. In contrast, plant height in purple pak choi demonstrated greater sensitivity to drought, shading, and their combined treatment (drought + shading), showing significant reductions of 29%, 21%, and 38% under these respective conditions. However, there was no significant difference in plant height among these affected conditions (Fig. 3a). The combined drought and shading treatment resulted in significant reductions in crown breadth for both green (50%) and purple pak choi (30%). Specifically, while the crown width of green pak choi showed a significant reduction under combined drought and shading treatment compared to shading alone, no statistically significant effect was observed in purple pak choi under the same conditions (Fig. 3b). Drought, shading, and their combined treatment (drought + shading) resulted in significant reductions in leaf number for green pak choi by 31%, 40%, and 51%, respectively. In purple pak choi, both shading and the combined drought + shading treatment significantly reduced leaf number by 24% and 31%, respectively. Notably, this cultivar demonstrated greater resistance to drought conditions compared to green pak choi (Fig. 3c).

Linking biomass allocation to plant morphology in response to drought and shading

The results showed that plant height, leaf number, crown width, above-ground biomass, above-ground dry matter mass, and root dry weight in both green and purple pak choi were negatively correlated with shading conditions. In contrast, there was a positive correlation between fresh weight, dry matter weight, root dry weight, and leaf number in both green and purple pak choi. The position of factors related to shading and water availability was significantly differentiated. As depicted in Fig. 4, shading conditions had a more negative impact on both pak choi varieties than drought conditions.

As shown in Fig. 5, the number of leaves, plant height, crown width, and root dry weight of both green and purple pak choi were directly proportional to the fresh ground weight. There was a strong correlation between leaf number and fresh weight, with $R^2 = 0.70$ for green pak choi and $R^2 = 0.68$ for purple pak choi.

Discussion

In this study, we examined the effects of drought, shading, and their combination (drought + shading) on two pak choi varieties (green pak choi and purple pak choi). Biomass analysis revealed a consistent trend across both varieties: all treatments resulted in a gradual decrease in above-ground fresh weight, above-ground dry weight, and root dry weight. Additionally, both shading and the combination of drought and shading significantly reduced the root-to-shoot ratio in both varieties. This decrease in root-to-shoot ratio under shading conditions aligns with previous research, which suggests that reduced light intensity often leads to a higher biomass allocation to above-ground parts, thus reducing the root-to-shoot ratio [36]. Interestingly, drought alone did not significantly affect the root-to-shoot ratio, highlighting that drought stress may influence other aspects of growth more directly than root-to-shoot partitioning.

Our results also indicated that drought, shading, and the combination (drought + shading) of both significantly reduced plant height in purple pak choi, but had no effect on green pak choi. This finding is consistent with research suggesting that early exposure to light control can reduce plant height, but this effect may diminish over time [37]. In purple pak choi, the reduced height under shading conditions could be attributed to its initial sensitivity to light reduction. It is well-documented that plant exhibit adaptive responses to soil water availability; deviations from optimal water levels—whether excessive or insufficient—can impair plant height growth [38]. This may explain why green pak choi, which did not show a significant change in height under drought or shading, is less sensitive to these environmental variations. Crown width, another key morphological trait, was significantly reduced only when both drought and shading were applied together, while neither drought nor shading alone had significant effects. This suggests that combined environmental stressors have a compounded effect on crown growth, which could be due to increased energy allocation to above-ground structures to cope with both light reduction and water deficit. As for leaf number, shading led to a progressive decrease in leaf count across both varieties, with shading showing a particularly strong effect. These findings corroborate earlier studies that reported shading leads to a reduction in leaf number due to limited photosynthetic activity [39]. However, the response to drought differed between the two varieties. Green pak choi showed a significant reduction in leaf number under drought conditions, while purple pak choi exhibited no significant change. This difference may be due to the higher flavonoid content in purple pak choi, which has been shown to confer better drought tolerance [4]. The ability of purple pak choi to maintain leaf number under drought stress could be linked to the photoprotective properties of anthocyanins, which may help the plant mitigate the negative effects of water scarcity [40]. Interestingly, the gCCA (generalized canonical discriminant and correlation analyses) indicated that shading had a stronger negative impact on biomass and

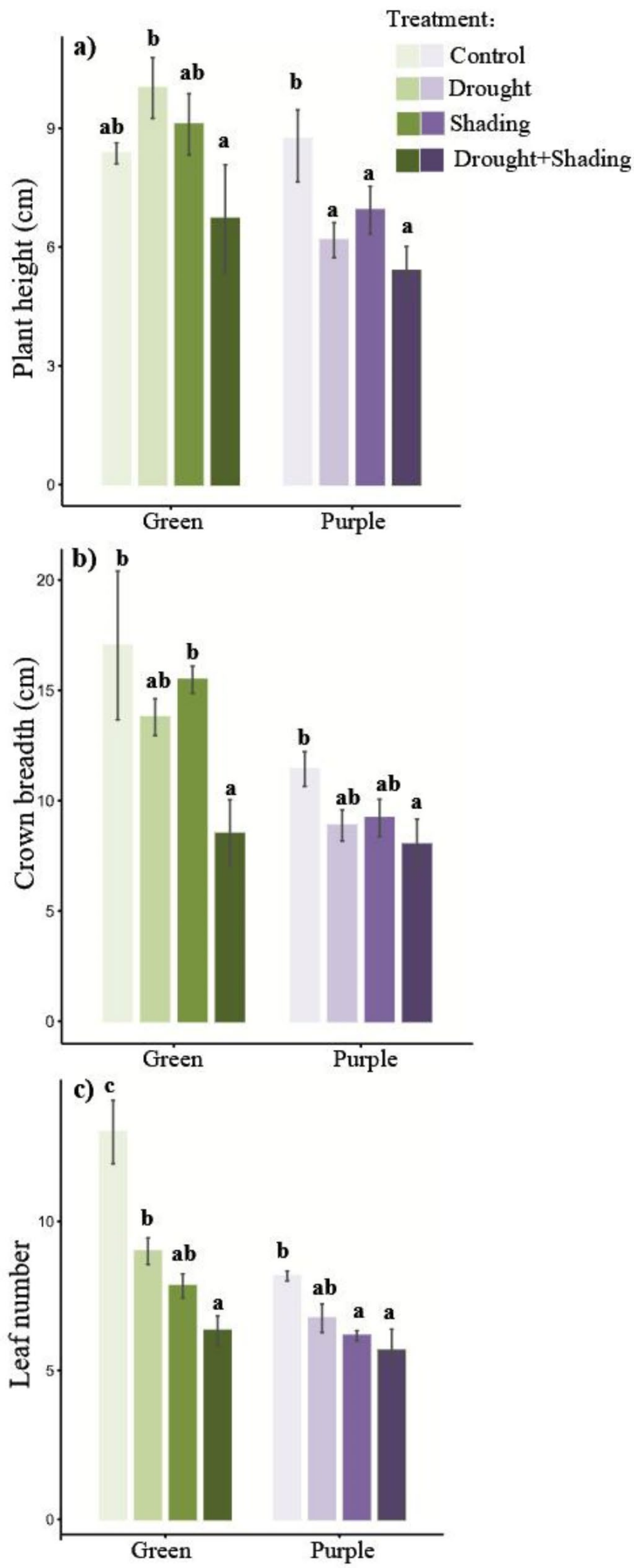

Fig. 3 Effects of drought and shading on plant height (**a**), crown breadth (**b**) and leaf number (**c**) of green pak choi and purple pak choi. "Green" refers to green pak choi, and "purple" refers to purple pak choi. The treatments include Control, Drought, Shading, and Drought + Shading, representing the control group, drought, shading, and the combined drought and shading conditions, respectively. Different lowercase letters above the column indicate significant differences between treatments ($P < 0.05$)

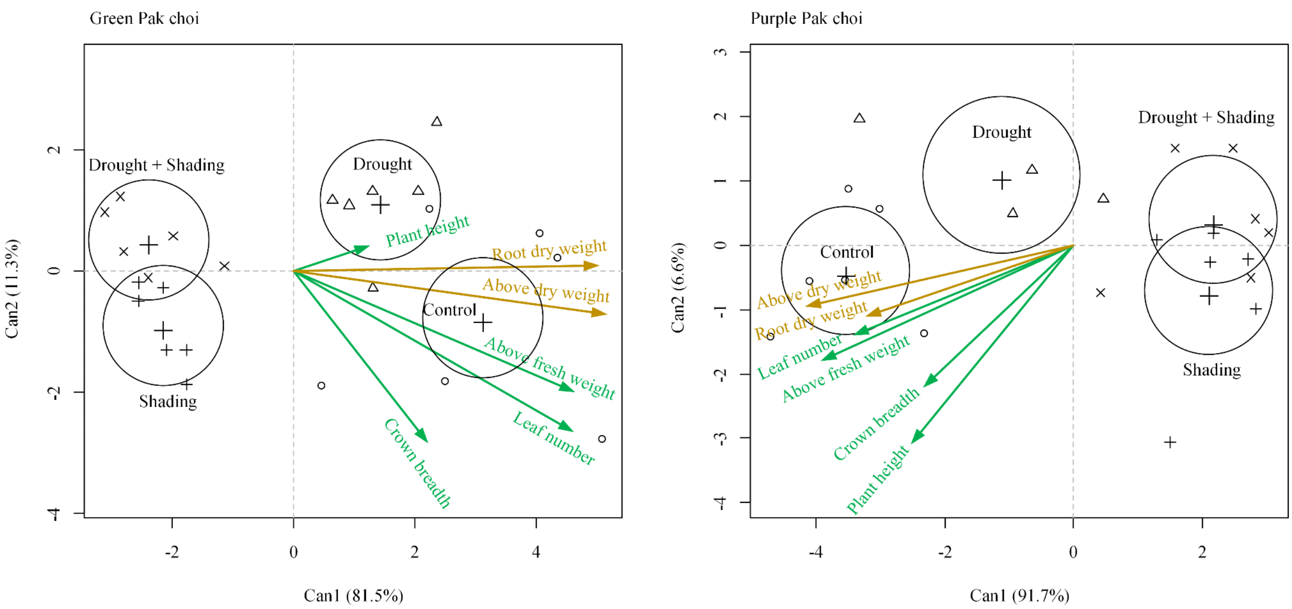

Fig. 4 Generalized canonical discriminant and correlation analyses (gCCA) illustrating the associations of measured attributes for green (**a**) and purple (**b**) pak choi across different treatments. The vectors represent the contributions of pak choi attributes in discriminating differences among treatments. The length of each vector indicates the magnitude of variation in the attributes across treatments, with longer vectors representing greater variability. The circles around the means of multiple vectors represent the 95% confidence intervals, visually indicating the reliability of the mean estimates for each treatment

morphological traits than drought in both varieties. This suggests that light stress may be a more significant factor limiting growth in pak choi compared to drought stress, especially when considering the physiological.

Purple pak choi is known to contain higher levels of anthocyanins than green pak choi, which are secondary metabolites that not only contribute to its distinctive color but also provide photoprotection [4]. Anthocyanins help protect plants from oxidative stress and DNA damage caused by high radiation flux [41]. Additionally, these compounds play a role in improcing drought resistance by enhancing antioxidant activity, promoting photosynthesis, regulating stomatal function, and supporting root growth [42–46]. In this study, purple pak choi's better drought tolerance can be attributed to its higher flavonoid content, particularly anthocyanins, which likely confer enhanced resistance to both drought and shading. This is consistent with previous research showing that flavonoid-rich plants have improved resistance to environmental stressors such as drought and UV radiation [4, 43, 46]. Shade-induced alleviation of drought stress has been observed in other crops, such as coffee and ginger, where shading helps protect photosynthetic activity and maintains higher water-use efficiency [47–49]. Shading can mitigate drought effects by reducing stomatal restriction, limiting photochemical damage to the photosystem, and enhancing antioxidant enzyme activity [50]. In our study, purple pak choi, with its higher anthocyanin content and lower light saturation point, may be better adapted to shade compared to green pak choi, which is more sensitive to light reduction [49]. The photoprotective mechanisms of flavonoids, such as scavenging reactive oxygen species (ROS) and protecting the photosynthetic apparatus, likely contribute to the observed differences in drought tolerance between the two varieties [43, 51].

It is important to note that the 24% shading used in this study did not result in a reduction in the number of leaves in purple pak choi under drought conditions. This suggest that the effects of shading on leaf growth may vary depending on the intensity of shading and the specific plant species. Future studies should explore different shading intensities to better understand the threshold beyond which shading becomes detrimental. Additionally, the limited number of pak choi varieties studied in this research restricts the generalizability of the findings. Further investigation into the physiological, molecular, and genetic mechanisms underlying the drought and shading responses of different pak choi varieties is needed to expand the applicability of these results.

Conclusion

Biomass reduction due to drought and shading in both green and purple pak choi was primarily attributed to a decrease in leaf number. Our study found that purple pak choi exhibited greater drought tolerant, with shading not further exacerbating reductions in stem fresh weight, root dry weight, or leaf number, particularly under drought conditions. These results suggest that purple pak choi may be more resilient in environments where both

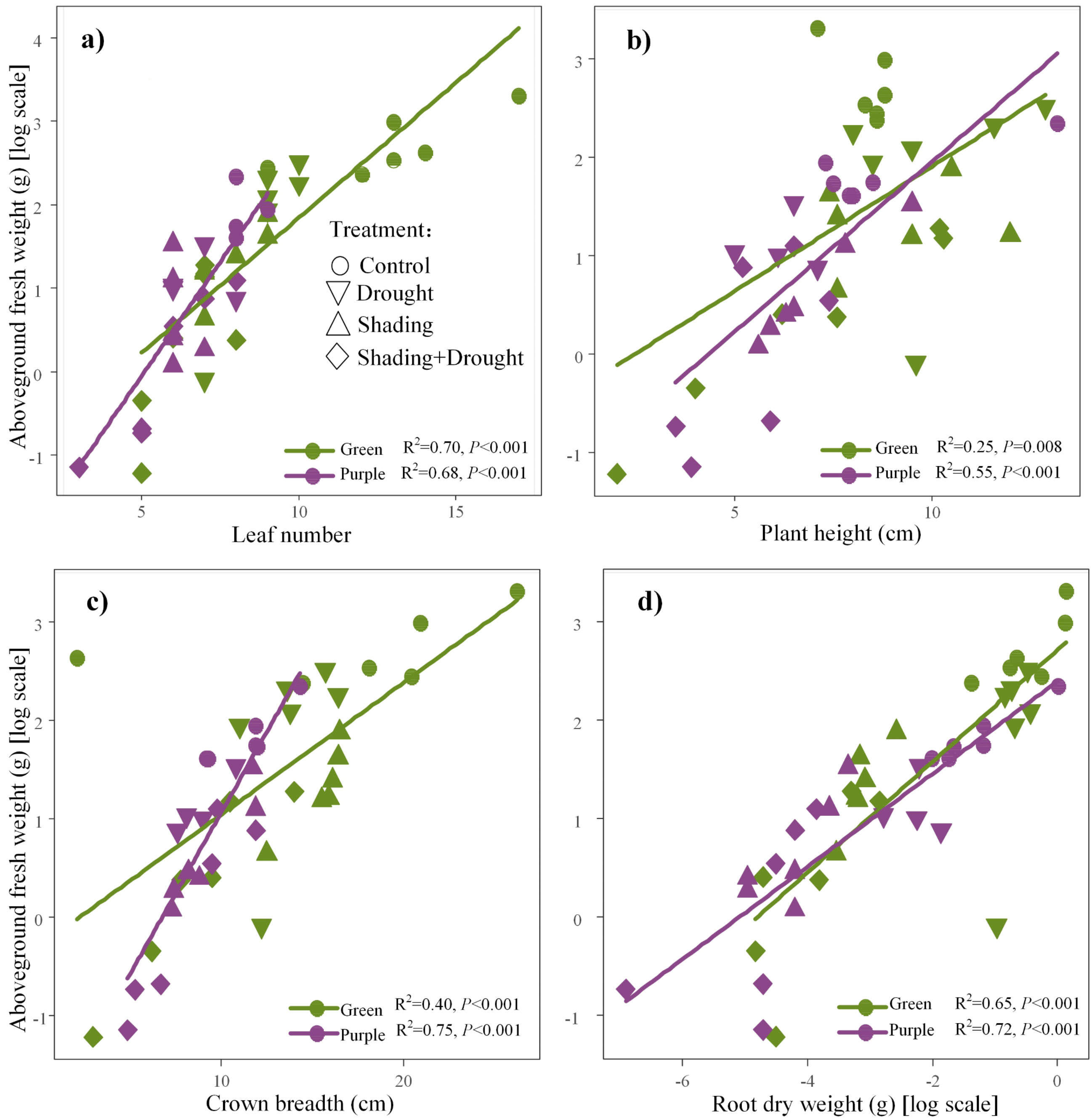

Fig. 5 Association of aboveground fresh weight of green and purple pak choi with leaf number (**a**), plant height (**b**), crown width (**c**), root dry weight (**d**) in response to drought and shading treatments

drought and shading are common, offer distinct advantages in such conditions. In contrast, green pak choi appears to perform better under optimal water, fertilizer, and light conditions, making it more suitable for regions with stable resource availability. This study highlights the differing responses of two pak choi varieties to environmental stressors and provides key insights into how these crops can be managed for improved yield and biomass accumulation. For regions like Xinjiang, which effaces challenges such as intense sunlight and drought, understanding the growth adaptability of pak choi is critical for optimizing crop production. These findings have significant implications for agricultural practices in similar environments, helping to inform strategies that can enhance the resilience, yield, and quality of pak choi cultivation under challenging climatic conditions.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12870-025-06354-8 .

Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

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On behalf of all co-authors of manuscript, I hereby confirm the submission of this manuscript only to this journal, and this manuscript has not been submitted to any other journals.

Author contributions
FW, ZKL, KCN, conceptualize the work, and wrote the draft of the manuscript. FW, CC, perform the experuimental work. All authors read and approved the final manuscript.

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Data availability
The datasets of the current study are available from the corresponding author on a reasonable request.

Declarations

Ethics approval and consent to participate
This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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