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Article

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Interactive Effects of Nutrient Solution Concentration and Wind Hardening on Cabbage (*Brassica oleracea* var. *capitata*) Transplant Quality

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Abstract

Transplant hardening is considered a determining factor in the success of producing various vegetables, including cabbage, so a factorial experiment was designed and implemented to achieve the production of high-quality and resistant cabbage transplants. The first factor was feeding with a special cabbage nutrient solution called SANRU in four concentrations of 25, 50, 75 and 100 percent, and the second factor was wind treatment at two levels (with and without wind) to harden cabbage transplants. The results of this study showed that increasing the nutrient solution concentration had a positive and significant effect on the vegetative growth of cabbage transplants, such that the highest plant height (8.65 cm) and the highest fresh weight (0.91 g) and dry weight of shoots (0.10 g) were observed at a concentration of 100 percent nutrient solution, and with a decrease in the concentration to 25 percent, these traits showed a significant decrease. The ratio of root to shoot dry weight was at its maximum in the 25% nutrient solution with wind treatment, but the other combined treatments did not differ significantly from each other. In the dilute nutrient solution (25 and 50%), wind treatment caused a significant decrease in the concentration of phosphorus and potassium in the leaves, but this negative effect was not observed in the concentrations of 75 and 100% nutrient solution. The highest value of the SPAD index was observed in the concentration of 100% nutrient solution with wind treatment, which was not significantly different from the concentration of 75% nutrient solution (regardless of wind treatment). The highest amount of total phenol (15.6 mg/g fresh weight) was observed in the treatment of 25% nutrient solution without wind treatment, which was not significantly different from the treatments of 75 and 100% nutrient solution with wind treatment. The amount of proline was at its highest in the treatments of 75 and 100% nutrient solution with wind treatment. The lowest stomatal area was recorded in the 75 and 100% nutrient solution treatments with wind treatment. Since the 75% nutrient solution alongside wind treatment showed a favorable condition in many transplant resistance indices, such as SPAD, leaf phosphorus concentration, total phenol, proline content, and low stomatal area, this treatment can be recommended for the hardening of cabbage transplants.

Keywords: Brassica, nutrients, proline, stomata

Introduction

One of the most important plant groups with high nutritional and medicinal value is the genus Brassica, which is known for its high levels of minerals, vitamin C, glucosinolates, and carotenoids. In addition to these bioactive constituents, cole crops contain considerable amounts of complex carbohydrates and dietary fiber, further enhancing their nutritional quality and health-promoting potential (Zhang et al., 2025). Among the species in this genus, cabbage (*Brassica oleracea* var. *capitata*) holds significant nutritional and economical value. It is typically grown from transplants.

Success in vegetable cultivation largely depends on high-quality transplants, which are influenced by various factors, particularly nutrient management. Adequate nutrient supply during the transplant production stage is essential for achieving uniform growth, enhancing seedling vigor, and improving transplant quality, thereby influencing subsequent crop performance in the field (Liptay and Nicholls, 2019). Increasing the concentration of the nutrient solution during purple cabbage microgreen cultivation increased shoot fresh and dry weight as well as plant height, while reducing total carotenoid content and total soluble solids (Wieth et al., 2019). The results of a study on lettuce and Chinese cabbage transplants showed that the application of nutrient solutions at different concentrations had a significant effect on fresh weight, morphological characteristics, chlorophyll content, and stomatal conductance (Michelon et al., 2021). In another study, different nutrient solution concentrations altered morphological and biochemical traits, including plant height, leaf number, root weight and volume, total soluble solids, total sugar, and ascorbic acid content in white cabbage (Blagorodova et al., 2021).

The adaptation of plant cells to stressful environments by increasing the concentration of solutes, mainly by the accumulation of various minerals and organic substances, which leads to a decrease in osmotic potential and an increase in the plant's ability to retain water, is known as osmoregulation. For example, under drought conditions, leaves of the Naked fruitwood species can reduce their osmotic potential by accumulating proline, soluble sugars, and soluble proteins, thereby providing relative resistance to drought (Zhang et al., 2023). Although wind can strongly affect the growth, development, and physiology of terrestrial plants, plant responses to wind and their underlying mechanisms are still not well understood. This is because plant responses to mechanical motion are inherently complex and wind not only involves mechanical effects but also alters gas and heat exchange in leaves. The plant response to mechanical stress, known as thigmomorphogenesis, is often thought to involve the production of thicker and stronger structures to enable the plant to withstand greater forces. Reduced height growth is the most common response of plants to mechanical stimuli because shorter plants have both greater mechanical resistance (by allocating biomass to diametric growth rather than longitudinal growth) and less exposure to drag force (Onoda & Anten, 2011).

Xylem development in California and eastern spruce trees was affected by mechanical stresses induced by wind in the greenhouse, with results showing that wind stress increased radial growth and stem stiffness, while height, leaf area, and total biomass growth were reduced (Kern et al., 2005). Plantain (*Plantago major*) exposed to wind treatment showed reduced growth and altered plant structure (Anten et al., 2010). It has been reported that constant unidirectional wind in *Arabidopsis thaliana* induced a positive anemotropic response, with major changes in

morphology, mechanical properties, and anatomical tissue organization (Zhdanov et al., 2021). In an experiment with four species of steppe dicots, wind reduced plant height and projected crown area, while increasing root length and stem base diameter (Zhang et al., 2021). Wind stress, as one of the most important environmental mechanical stresses, plays a decisive role in crop production by affecting vegetative growth, nutrient balance, and physiological performance of plants (Gardiner et al., 2016). Strong winds, by increasing transpiration, changing stomatal conductance, and damaging aerial organs, can disrupt the absorption and transport of nutrients from roots to shoots and lead to a decrease in leaf nutrient concentrations (Telewski, 2012).

The importance of transplant health and its resistance to successful vegetable production, including cabbage, is absolutely accepted. In this regard, the present study aimed to evaluate the possibility of producing high-quality and resistant cabbage transplants by optimizing the nutrient solution concentration and using wind treatment.

Materials and Methods

Planting and Treatments Application

Cabbage seeds of the RUBY KING variety produced by the seed company Taki and Partners from Japan were sown in a plastic cultivation tray containing a substrate of 80% cocopeat and 20% perlite (V/V). The average temperature in the greenhouse was 21 degrees Celsius during the day and 16 degrees Celsius at night.

This experiment was carried out as a factorial experiment with two factors in a completely randomized design, hydroponically in a transplant tray in the greenhouse of the Horticulture Department of Sari Agricultural Sciences and Natural Resources University. The first factor was the concentration of a special nutrient solution for cole crops called SANRU, with four dilution levels (100,75, 50, and 25 percent of SANRU concentration), and the second factor was the hardening of transplants by wind treatment in two levels: control and wind treatment. After the seedlings had four leaves, SANRU nutrient solution (Table 1) was used weekly to feed the plants at a rate of approximately 4 ml per plug plant. Wind treatment was also applied for 5 minutes every day using a pump set at a speed of 5 m/s during the last ten days of the experiment.

Table 1. Nutrients concentration in SANRU solution used for transplants feeding

Elements	N	P	K	Mg	Ca	S	Fe	B	Mn	Zn	Cu	Mo
Concentration ($mg.L^{-1}$)	153	70	144	61	170	82	5	0.7	2	0.25	0.08	0.05

Trait Measurements

Morphological traits including transplant length (cm), root length (cm), aerial fresh and dry weight (g), and root fresh and dry weight were measured at the end of the experiment.

In order to measure the nutrients, the samples collected from each treatment were washed with distilled water and turned into ash at 70°C. The samples were digested using sulfuric acid, salicylic acid and hydrogen peroxide in special tubes. The plant phosphorus at a wavelength of 470 nm with a spectrophotometer, the plant potassium by a flame photometer and magnesium by the dry ash method using a Varian-Spectr AA-10 atomic absorption spectrometer were measured according to the methods described by Emami (1996).

Methanolic solvent was used for the extraction of photosynthetic pigments (Carter & Knapp, 2001). The absorbance of the extract was read at wavelengths of 665, 652 and 470 nm, then the content of chlorophyll a, chlorophyll b and carotenoid were calculated using the equation presented by Lichtenthaler and Buschmann (2001). Also, the SPAD device (Spad-502 plus-Konica-JAPAN), which is a non-destructive and rapid tool for measuring the amount of leaf chlorophyll, was used to determine the SPAD index (Markwell et al., 1995).

Total antioxidant activity was measured by the DPPH (DiPhenyl Picryl Hydrazyl) method and its absorbance was read at a wavelength of 517 nm by a spectrophotometer. Finally, the antioxidant activity was expressed as a percentage of DPPH free radical scavenging (Brand-Williams et al., 1995). Total phenolic content was determined by the Folin-Ciocaltio and calcium carbonate method and after keeping the extract solution for 15 minutes in the dark, its absorbance was read at a wavelength of 765 nm (Slinkard and Singleton, 1977).

To measure proline, first, two grams of fresh leaf tissue was ground in a porcelain mortar containing 5 ml of 3% sulfosalicylic acid solution and a uniform mixture was obtained. The obtained extract was centrifuged for 5 minutes at 10,000 rpm and the supernatant was used for proline measurement. 2 ml of the supernatant was mixed with 2 ml of ninhydrin reagent and 2 ml of glacial acetic acid and placed in a hot water bath at 100°C for 1 hour. Then, it was placed in a cold-water bath and 4 ml of toluene was added to the mixture and the tubes were vortexed well. The upper phase absorbance was determined at a wavelength of 520 nm and the amount of proline in each sample was calculated (Bates, 1973).

To examine stomatal cells, circular samples were first prepared from the leaves using a punch, then the sections were placed in a solution of ethanol, acetone, formaldehyde in a ratio of (18:1:1) and placed in a 7.5% NaOH solution for seven to nine days to completely decolorize the sample. For staining, the prepared samples were immersed in 1% safranin solution for 5 min and subsequently dehydrated through a graded ethanol series (30, 50, 70, 96, and 100%) to remove excess stain. The stained samples were then mounted on glass slides and photographed under a light microscope at ×10 and ×40 magnifications. Stomatal characteristics, including stomatal number, width, area, and density per unit leaf area, were quantified from the captured images using Digimizer® v.6.4.3 software (Ouyang et al., 2017; Zhang et al., 2024).

Statistical Data Analysis

The data obtained from this experiment were analyzed using SAS 9.4 software for variance analysis and then means were compared using Duncan's multiple range test at the 5% probability level. To explore relationships among measured traits, a correlation based on Pearson coefficients was generated using the *ggraph* package (Osku et al., 2026).

Results

Transplant morphology

The highest cabbage transplants were observed in plants fed with 100% nutrient solution, and gradually with decreasing nutrient solution concentration to 25%, plant height also showed a decreasing trend (Figure 1 and 2). The main effect of wind also showed that the wind treatment used in this experiment significantly reduced the height of cabbage plants (Figure 2). The highest root length was obtained in 75% nutrient solution without wind treatment; however, this treatment was statistically superior only to the same nutrient treatment that had been subjected to wind stress and was not significantly superior to other combined treatments (Figure 3).



Figure 1. Comparison of the height of cabbage transplants treated by different nutrient solution concentrations (S1: 25%, S2: 50%, S3: 75%, and S4: 100% of SANRU nutrient solution)

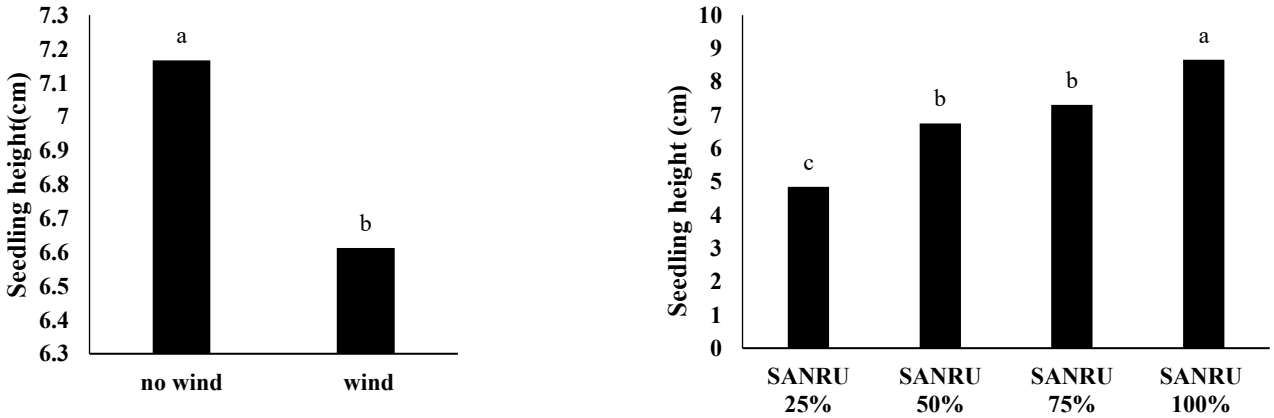


Figure 2. Effect of nutrient solution concentration (right) and wind treatment (left) on cabbage transplant height. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

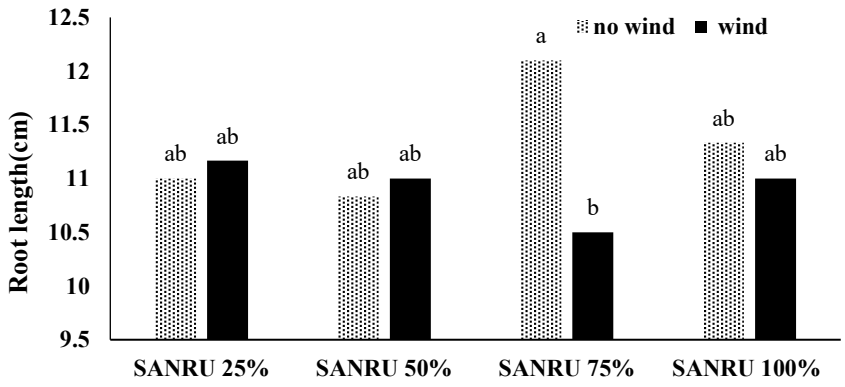


Figure 3. Effect of nutrient solution concentration and wind treatment on root length of cabbage transplant. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

Transplant biomass

The highest fresh weight of shoot was obtained in 100% nutrient solution, which was significantly higher than other nutrient solution concentrations (Figure 4). A similar trend was observed in the dry weight of shoot; although, the difference between 100 and 75 nutrient solutions was not statistically significant (Figure 4). However, it can be clearly seen that the fresh and dry weight of cabbage transplants increased with increasing nutrient solution concentration. The fresh weight of the shoot was more strongly affected by the nutrient solution concentration, such that the highest fresh weight of shoot was obtained in 100% nutrient solution concentration and gradually decreased significantly with decreasing nutrient solution concentration (Figure 4). The dry weight of shoot also followed a similar trend, but the difference between the dry weight of shoot in 100 and 75% nutrient solution concentrations was not statistically significant (Figure 4).

The highest root fresh weight was obtained in the 75% nutrient solution, which was not significantly different from the 100% concentration, but was higher compared to other concentrations (Figure 4). The highest root dry weight was obtained in the 100% nutrient solution treatment, but was statistically significantly different only from the 25% nutrient solution (Figure 4). The highest root to aerial dry weight ratio was obtained in the 25% nutrient solution plus wind treatment, which was not significantly different from the 50% concentration plus wind treatment and was higher compared to other concentrations (Figure 5).

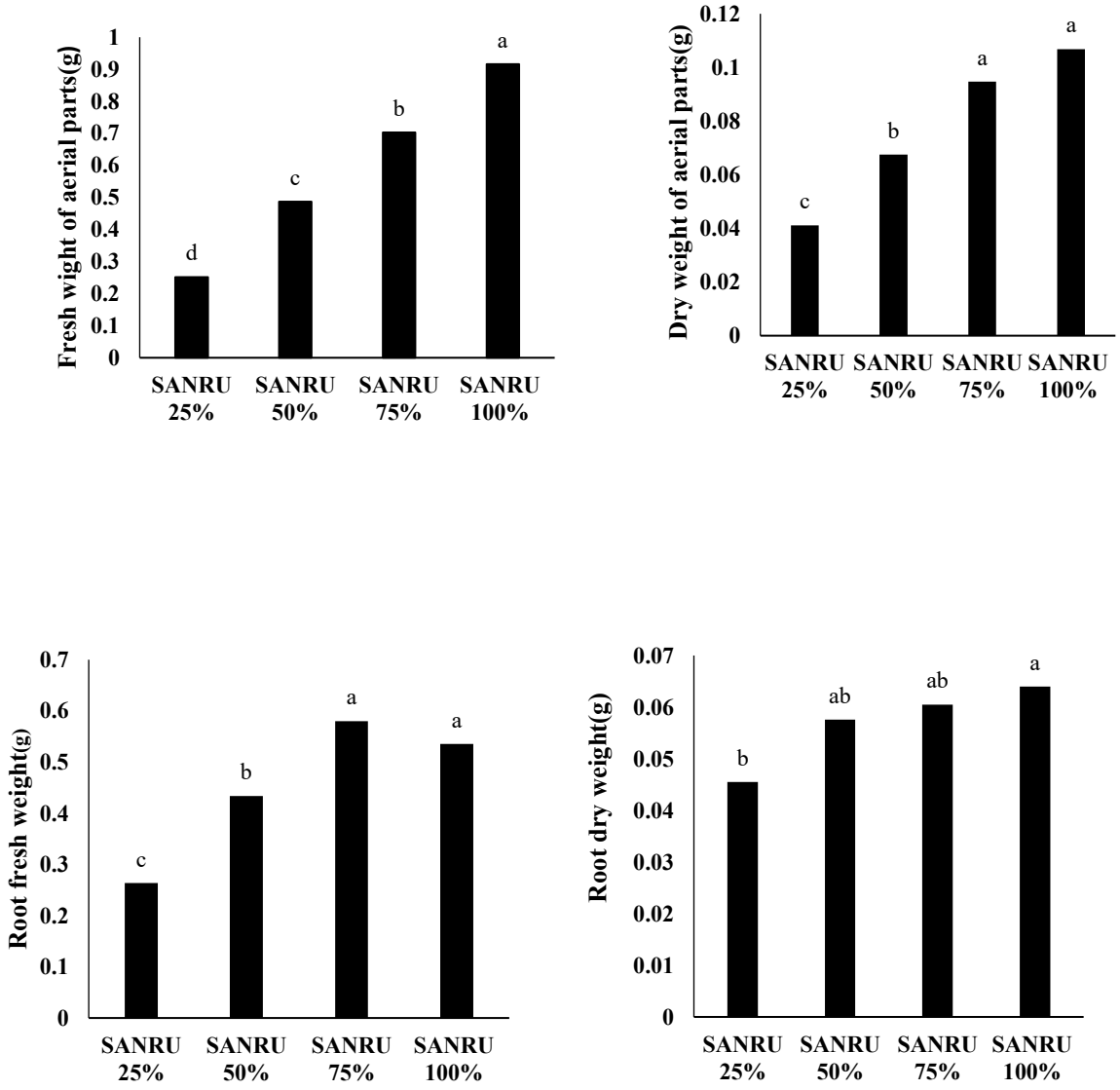


Figure 4. Effect of nutrient solution concentration on fresh and dry weight of shoots and roots of cabbage transplants. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

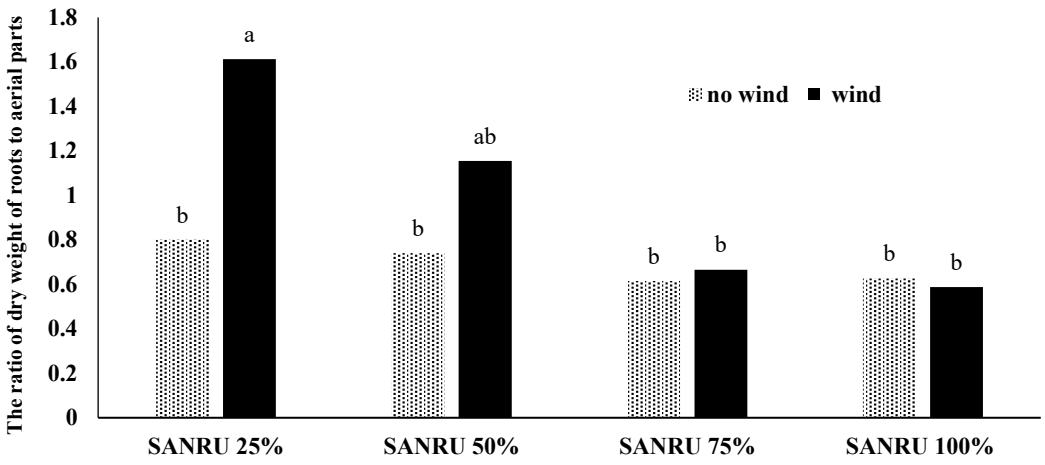


Figure 5. Effect of nutrient solution concentration and wind treatment on the root to shoot dry weight ratio of cabbage transplants. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

Leaf nutrients concentration

The phosphorus concentration in the 25% nutrient solution was strongly affected by wind treatment, such that in this nutrient solution, plants under wind treatment showed significantly lower phosphorus concentration than control plants (no exposure to wind). This is while in other nutrient solution treatments, no difference was seen between control and wind stressed plants (Figure 6). Results almost similar to those seen for phosphorus were seen for leaf potassium of cabbage transplants. When dilute nutrient solution treatments (25 and 50%) were used, wind treatment caused a significant decrease in leaf potassium concentration compared to control plants, while in concentrated nutrient solutions (75 and 100%) this negative impact was not seen, such that the difference between stressed and control plants was not significant (Figure 7). The leaf magnesium concentration of cabbages fed with 100 and 75% nutrient solution was at the highest level, which was significantly higher than that of 50 and 25% concentrations (Figure 8).

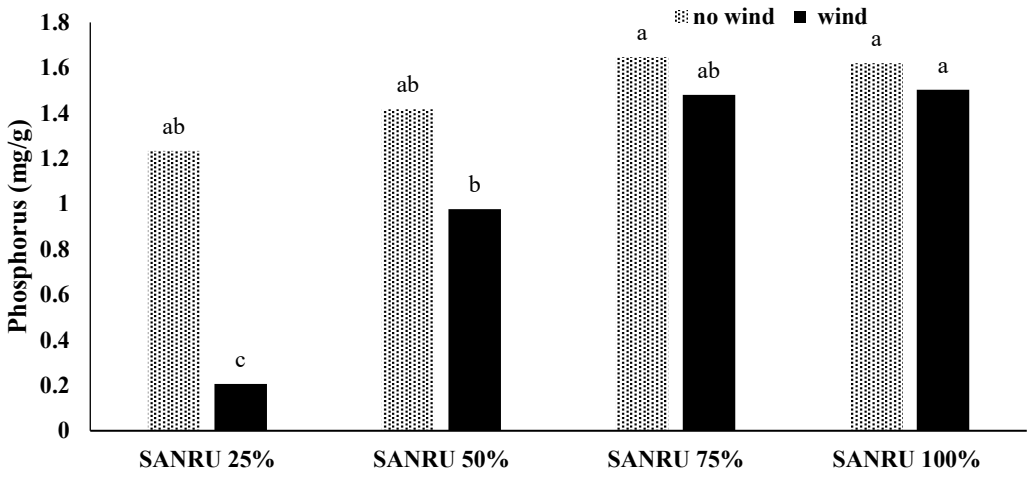


Figure 6. Effect of nutrient solution concentration and wind treatment on phosphorus concentration in leaves of cabbage transplants. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

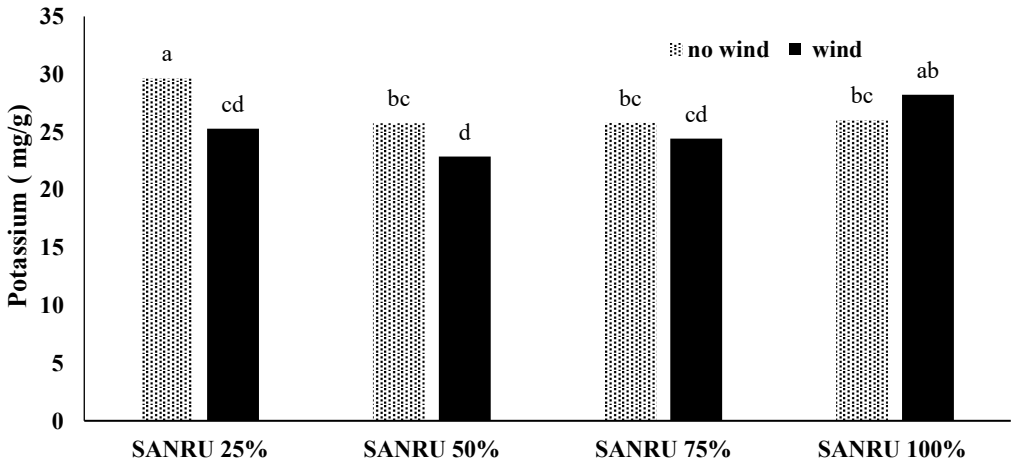


Figure 7. Effect of nutrient solution concentration and wind treatment on potassium concentration in leaves of cabbage transplants. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

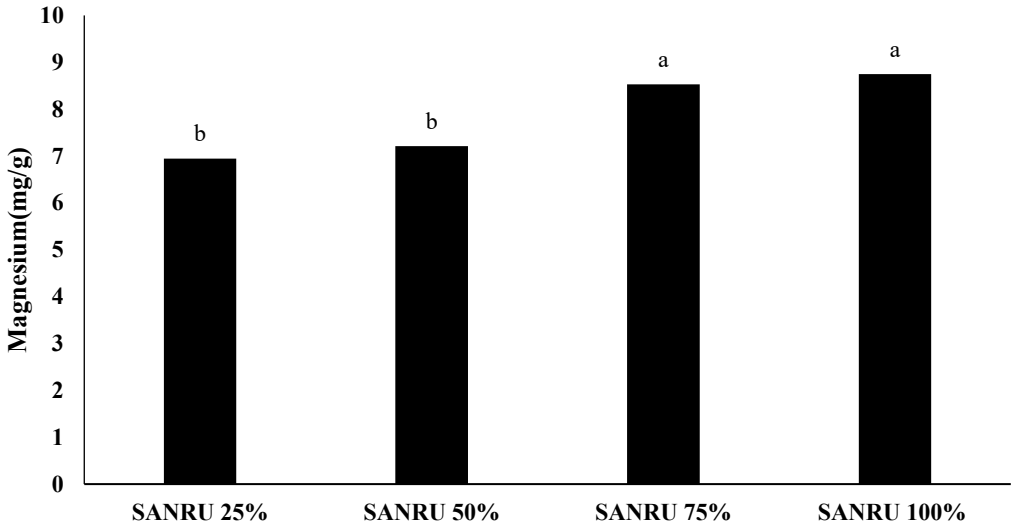
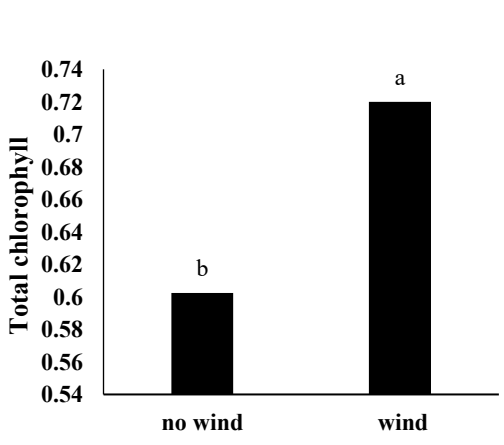


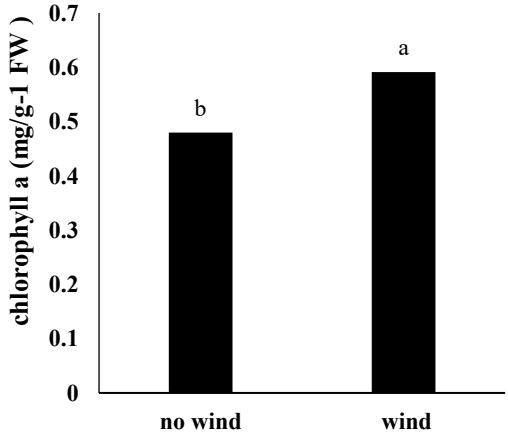
Figure 8. Effect of nutrient solution concentration on magnesium concentration in leaves of cabbage transplants. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

Photosynthetic pigments

Chlorophyll a and total chlorophyll in wind-treated plants were significantly higher than in control plants (Figure 9). The ratio of chlorophyll a to b and the content of leaf carotenoids also showed a significant increase in wind-treated plants (Figure 9). In terms of the SPAD index, the highest value was related to the 100% nutrient solution with wind treatment. However, the difference between this treatment and the 25% nutrient solution without wind treatment and the 75% solution with and without wind treatment was not significant (Figure 10).



(a)



(b)

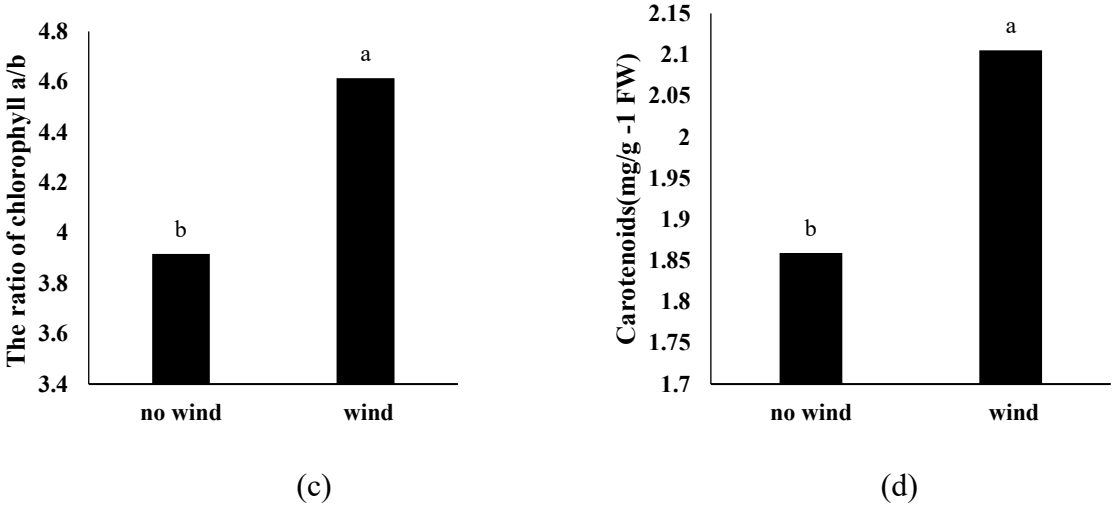


Figure 9. Effect of wind treatment on total chlorophyll (a), chlorophyll a (b), ratio of chlorophyll a to b (c), and carotenoid (d) in leaves of cabbage transplant. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

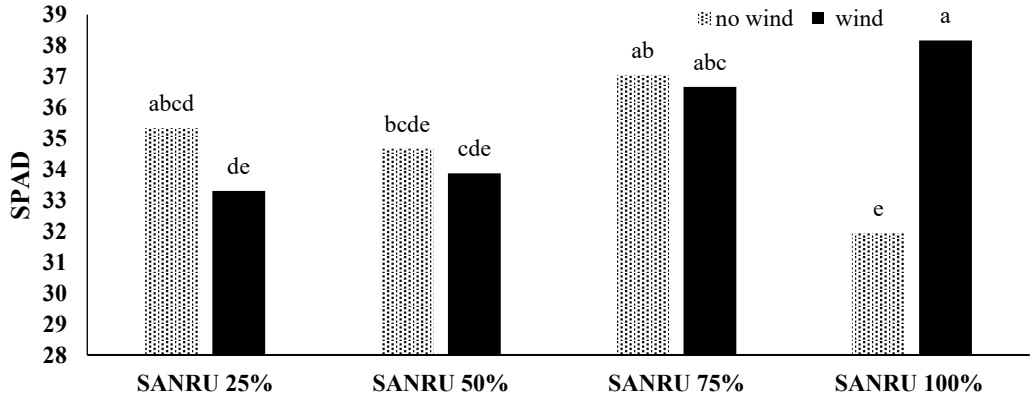


Figure 10. Effect of nutrient solution concentration and wind treatment on the SPAD index in leaves of cabbage transplant. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

Biochemical properties

The total antioxidant activity in the 50% nutrient solution without wind stress showed the maximum value with an inhibition percentage of 78.21%, which was not significantly different from the 25% nutrient solution with and without wind treatment (Figure 11). The total phenol content in the 25% nutrient solution without wind treatment had the highest value, but its

difference with the 75% and 100% nutrient solutions with wind treatment was not significant (Figure 12). The proline content of cabbage transplants in the two treatments of 75% and 100% nutrient solutions with wind stress showed the highest value, which was significantly higher than other combined treatments (Figure 13).

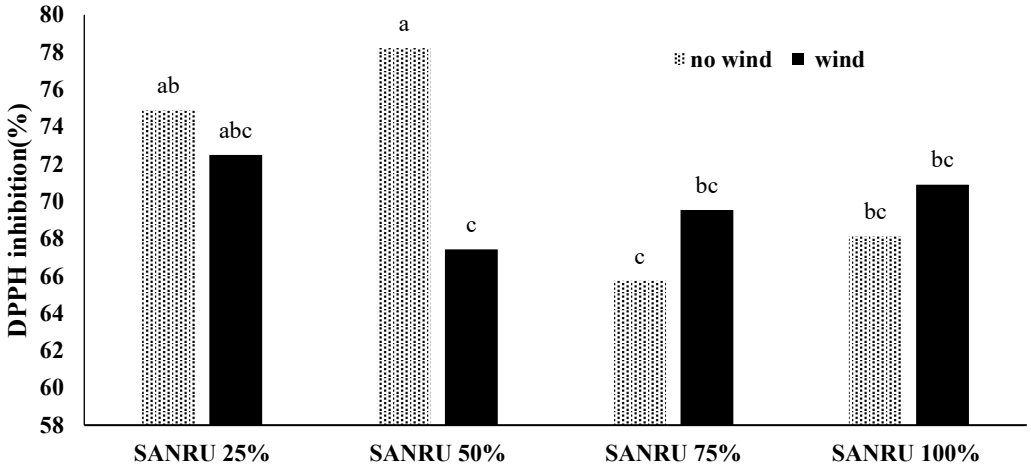


Figure 11. Effect of nutrient solution concentration and wind treatment on total antioxidant activity of cabbage transplants. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

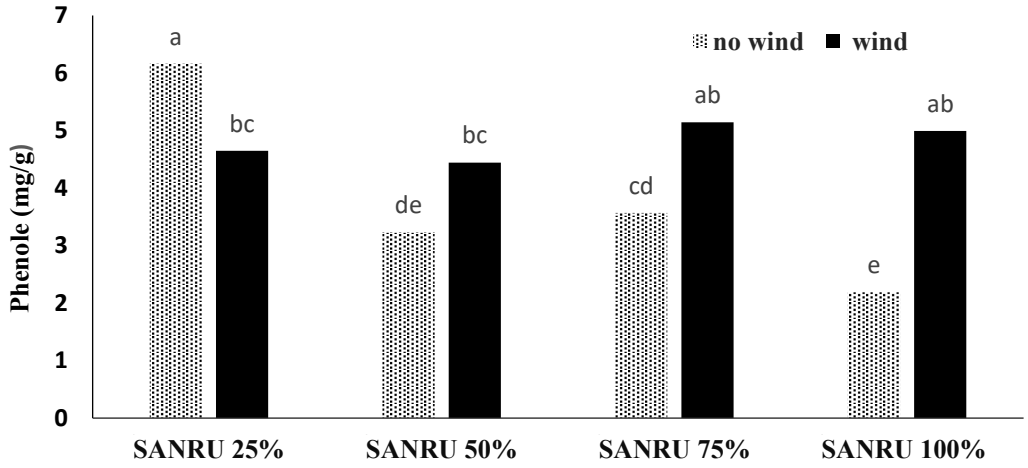


Figure 12. Effect of nutrient solution and wind treatment on total phenolic content of cabbage transplants. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

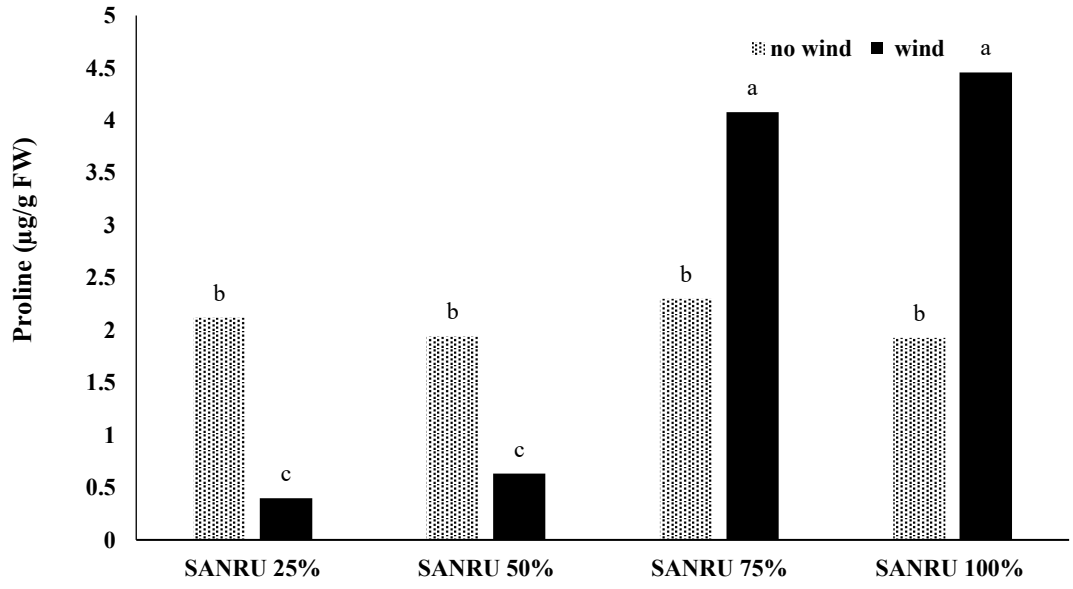


Figure 13. Effect of nutrient solution concentration and wind treatment on proline content of cabbage transplants. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

Stomata characteristics

The shortest stoma length was observed in the 25 and 50% nutrient solution treatments without wind treatment, which was not significantly different from the 75 and 100% nutrient solution with wind treatment (Figure 14). The shortest stoma width was observed in the two treatments of 75 and 100% nutrient solution with wind treatment, which was significantly less than all other applied treatments (Figure 15).

The shortest stoma area was observed in the 75% treatment with wind treatment, which was not significantly different from the two treatments of 100% nutrient solution alongside wind treatment and 50% nutrient solution without wind treatment (Figure 16). The highest stoma density was observed in the 100% nutrient solution treatment without wind treatment, which was significantly higher than all other combined treatments. In the next step, three treatments of nutrient solution 100 with wind treatment and nutrient solution 75 with and without wind treatment were placed (Figure 17). The overall morphology of the stomata in the nutrient solution 75 with and without wind treatment is shown in Figure 18.

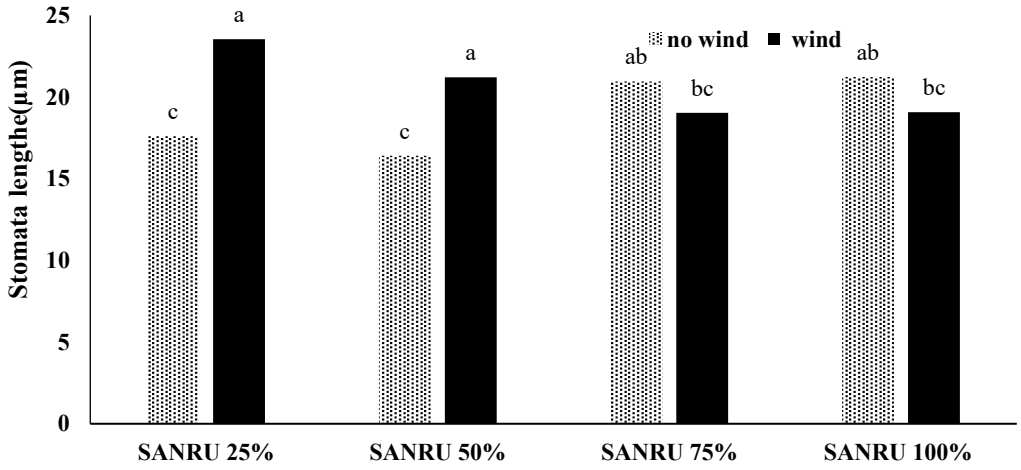


Figure 14. Effect of nutrient solution concentration and wind treatment on the stomata length in leaves of cabbage transplants. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

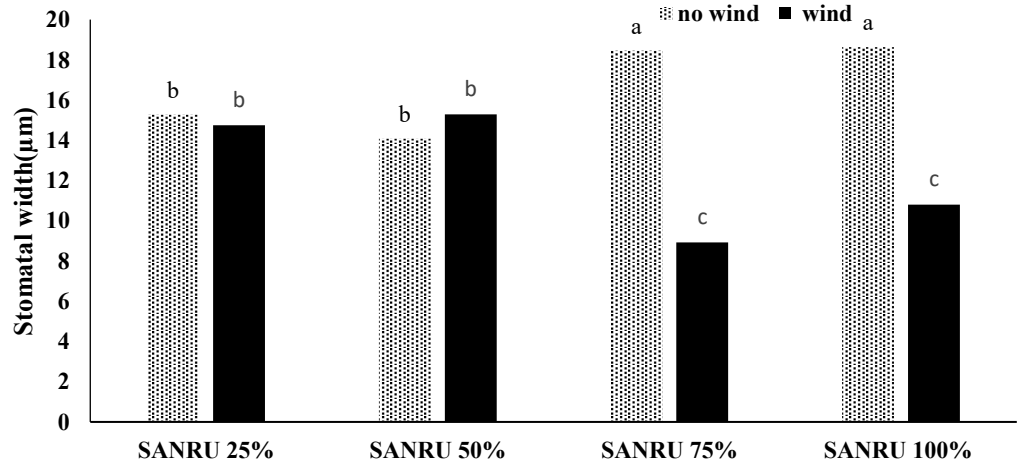


Figure 15. Effect of nutrient solution concentration and wind treatment on the stomata width in leaves of cabbage transplants. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

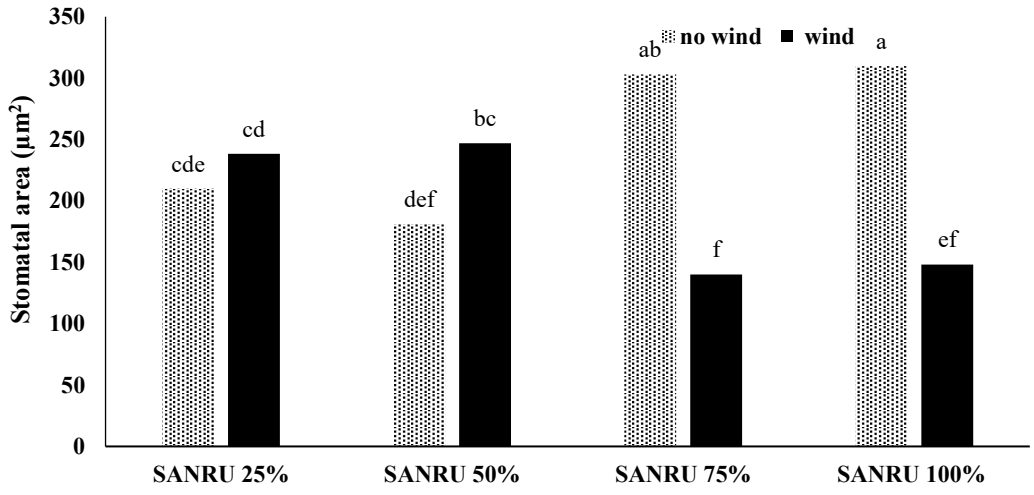


Figure 16. Effect of nutrient solution concentration and wind treatment on the stomata area in leaves of cabbage transplants. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

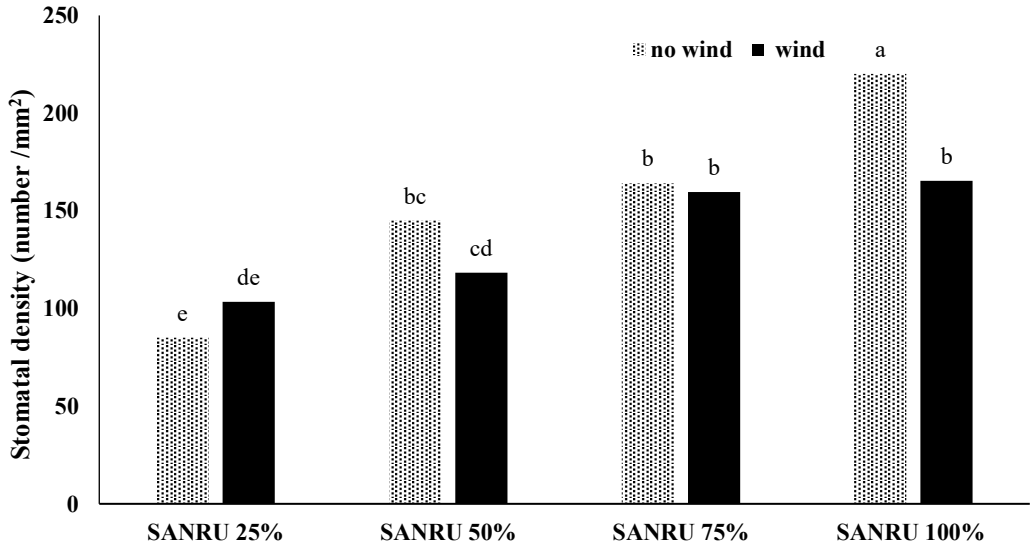


Figure 17. Effect of nutrient solution concentration and wind treatment on the stomata density in leaves of cabbage transplants. Different letters indicate significant differences among treatments according to Duncan's test at $P < 0.05$; treatments sharing at least one common letter are not significantly different.

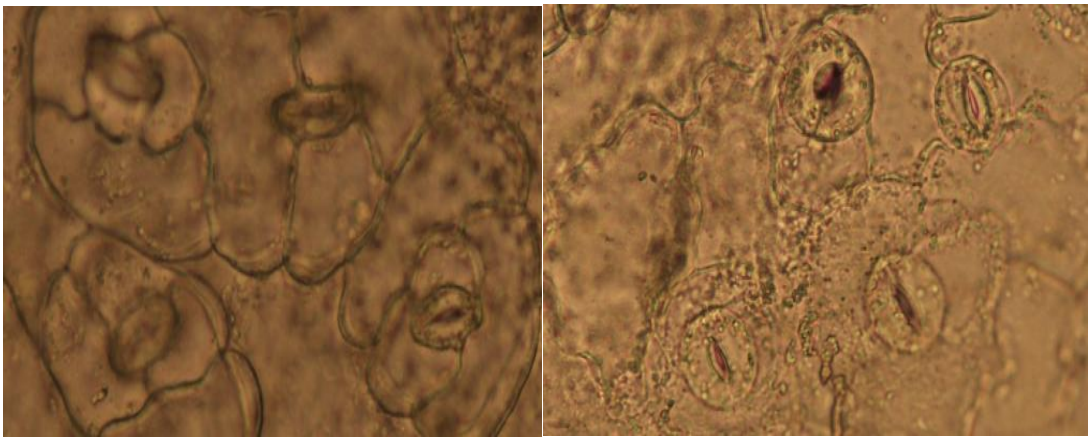


Figure 18. Stomata morphology with 75% nutrient solution without wind treatment (right) and with 75% nutrient solution with wind treatment (left) in leaves of cabbage transplants

Correlation analysis

Pearson's correlation analysis revealed several significant associations among the measured physiological and growth traits (Fig. 19). Among the photosynthetic pigments, chlorophyll a showed an almost perfect positive correlation with total chlorophyll (chlorophyll a+b) ($r = 0.992^{***}$), while chlorophyll a+b was also strongly correlated with carotenoids ($r = 0.943$). Likewise, chlorophyll a was highly associated with carotenoids ($r = 0.905^{***}$), and chlorophyll b exhibited strong positive correlations with carotenoids ($r = 0.890^{***}$) and chlorophyll a+b ($r = 0.778^{***}$). Stomatal density was positively associated with fresh weight of aerial parts (AFW; $r = 0.917^{***}$) and aerial dry weight (ADW; $r = 0.828^{***}$), indicating that higher stomatal density was accompanied by greater biomass accumulation. Fresh weight of aerial parts also showed a very strong positive correlation with aerial dry weight ($r = 0.912^{***}$), root fresh weight ($r = 0.746^{***}$), magnesium content ($r = 0.739^{***}$). In addition, phosphorus was strongly correlated with aerial dry weight ($r = 0.744^{***}$). Among stomatal traits, aperture width exhibited a very strong positive relationship with aperture area ($r = 0.921^{***}$). In contrast, phenolic content displayed negative correlations with root length ($r = -0.521^{***}$), aperture area ($r = -0.495^{***}$), chlorophyll b ($r = -0.470^{***}$), and carotenoids ($r = -0.464^{***}$).

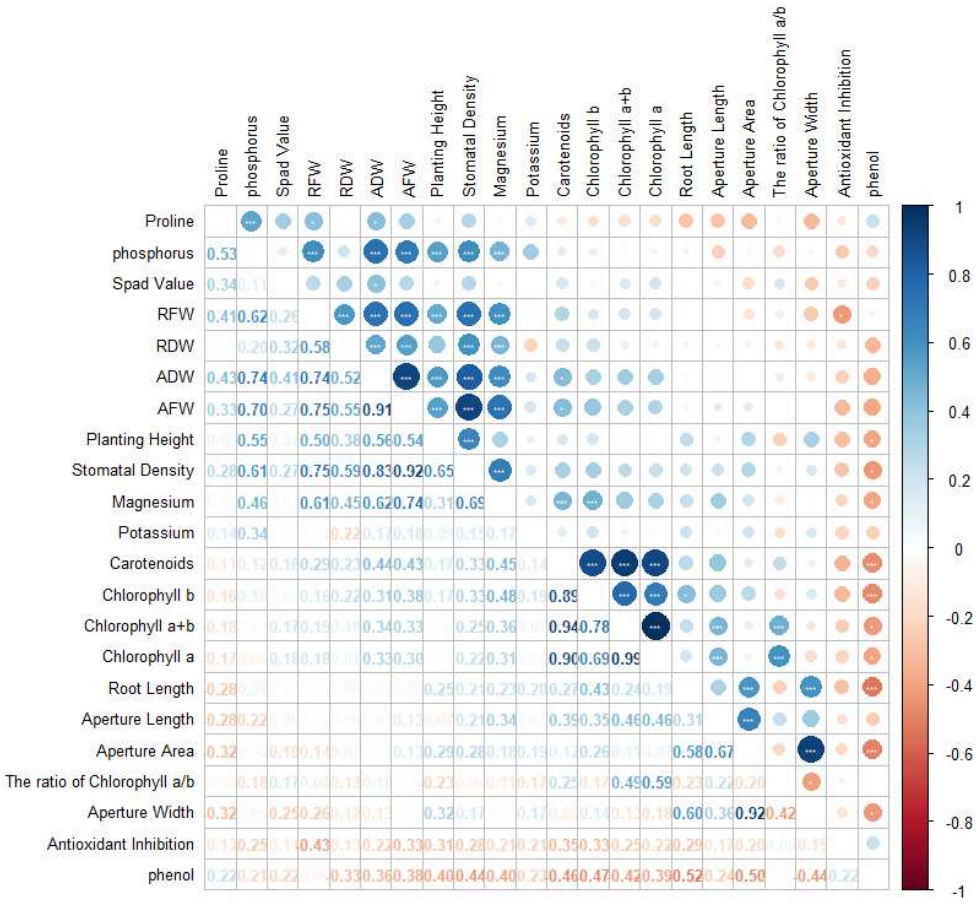


Figure 19**.** Pearson's correlation matrix among the physiological, biochemical, and growth traits measured in the studied plants. Circle color and size indicate the direction and strength of the correlation coefficients, with dark blue and dark red representing strong positive and strong negative correlations, respectively. Asterisks denote the significance levels of the correlations (*$P \leq 0.05$, **$P \leq 0.01$, and ***$P \leq 0.001$).

Discussion

The results of this study showed that wind treatment significantly reduced the height of cabbage transplant. The reduction in height observed in the wind treatment indicates the sensitivity of cabbage vegetative growth to mechanical stress caused by wind. In addition, wind can limit cell growth and cell elongation by increasing transpiration rate and reducing plant water potential. Reduced cell turgor pressure is one of the main factors in reducing longitudinal growth in plants under environmental stresses, including wind stress (Taiz et al., 2022). Previous studies have also reported similar results, for example, researchers showed that wind caused mechanical stress to reduce the height of plantain (*Plantago major*) and change biomass allocation (Anten et al. 2010). They also reported that strong and continuous wind can reduce the vertical growth of crop plants and lead to their stunting. In leafy vegetables of the Brassica family, height reduction under physical stresses has been interpreted as an adaptive response to reduce the risk of lodging (Gardiner et al. 2016). From an ecophysiological perspective, plant height reduction under windy conditions could be an adaptive mechanism that increases the mechanical stability of the plant and reduces the probability of stem breakage (Niklas, 1998).

The combined treatment of 75% nutrient solution alongside wind stress recorded the shortest root length. Since the interaction of examined factors was not significant in fresh and dry weight of root, the shorter root length in the 75% nutrient solution with wind stress can be considered an advantage, because it only reduced the length without reducing the root biomass. This feature can prevent damage to the roots of the transplants during transfer from the nursery to the field. The results of this study showed that nutrition and wind stress had a interaction effect on the root length of cabbage. In general, improving the nutritional status increased the root length, while wind stress had different effects on root growth depending on the level of nutrition. These results indicate that the response of the cabbage root system to environmental stresses is highly dependent on the nutritional conditions of the plant. The increase in root length at higher nutrition levels can be attributed to the greater availability of essential nutrients, which increases the division and elongation of meristem cells in the root tip region. Nutrients, especially nitrogen, phosphorus, and potassium, play a key role in the development of the root system, and their deficiency is usually associated with limited root growth (Marschner, 2011). In cabbage, which has rapid vegetative growth, proper nutrition can lead to better root development and increase water and nutrient absorption capacity. On the other hand, wind stress, as a mechanical stress, can indirectly affect root growth. By stimulating the phenomenon of thigmomorphogenesis, wind changes the allocation pattern of photo-assimilates and directs carbohydrates towards the aerial organs for strengthening them; as a result, fewer resources will be available for root development (Telewski, 2006). This can lead to a decrease in root length under wind stress conditions, especially at low nutrition levels. However, at higher levels of nutrition, the negative effect of wind on root length was reduced or even compensated in some cases. This phenomenon suggests that appropriate nutrition can play a moderating role in wind stress. Adequate supply of nutrients increases photosynthetic capacity and dry matter production, allowing simultaneous allocation of resources to both aerial and underground organs. In contrast, low levels of nutrients stimulate root growth. So, regardless of wind stress, longitudinal root growth occurs in the acquisition of nutrients under nutrient-poor conditions.

The fresh and dry weights of the shoot were strongly affected by the concentration of the nutrient solution, whereas the fresh and dry weights of the root were less responsive to this factor. In general, the further a plant organ is from the limiting source, the less it is influenced by that limitation. For example, under light limitation, root growth is often more restricted, whereas under water and nutrient limitations, shoot growth is more adversely affected. The enhanced shoot biomass observed in cabbage transplants under higher nutrient concentrations suggests that adequate nutrient availability promoted vegetative development by supporting essential physiological processes, including cell expansion, leaf formation, and biomass accumulation (Blagorodova et al., 2021; Siahaan et al., 2024). Recent studies have shown that adequate nutrient supply increases chlorophyll levels, enhances photosynthetic activity, and consequently promotes the accumulation of photosynthates in plant shoots (Zhao et al., 2021). The enhanced growth observed under higher nutrient availability may be associated with improved physiological performance and more efficient biomass accumulation. Consistent with our results, previous studies have shown that increased nutrient supply improves vegetative growth, leaf area, and shoot biomass in Brassica species(Li et al., 1999).

The highest root fresh weight was observed at 75% nutrient solution, indicating that this level was probably close to the optimal nutritional level for growth of cabbage transplants root. The

lack of significant increase in root fresh weight at 100% nutrient solution compared to 75% could indicate a decrease in nutrient utilization efficiency or even the onset of nutritional stress due to excessive accumulation of some elements. Such a pattern has been reported in many plants, where excessive nutrition does not necessarily lead to greater growth (Taiz et al., 2022). The increase in root dry weight in response to higher nutrient solution levels indicates that nutrition plays a decisive role in increasing the actual root biomass of cabbage. Unlike fresh weight, which is affected by water content, root dry weight reflects the accumulation of carbohydrates, proteins, and structural compounds and is a more accurate indicator for assessing root growth (Poorter et al., 2012). Physiologically, proper nutrition increases root apical meristem activity, improves protein and lignin synthesis, and increases the development of xylem vessels, all of which contribute to increased root dry weight (Lynch, 2019). Using a nutrient solution with the optimum concentration can increase root growth, weight and volume, and can also increase the accumulation of phosphorus in the plant, an element that is often deficient during seedling growth (Blagorodova et al., 2021). Also, increasing root biomass can increase the plant's ability to absorb water and nutrients and strengthen its resistance to environmental stresses after transplanting. Recent studies have shown that a stronger root system is one of the most important mechanisms for plant adaptation to mechanical and environmental stresses, and balanced nutrition can enhance this adaptive response (Ristova & Busch, 2014). Therefore, increasing root dry weight at high nutrient solution levels can be considered a positive change for keeping the stability of cabbage growth under field stress conditions.

The root to shoot dry weight ratio is one of the important indicators in studying the plant biomass allocation pattern and its adaptation strategies against environmental stresses. The results of this study showed that wind stress caused a significant increase in this ratio only at the low level of 25% nutrient solution, while at higher levels of nutrition, the effect of wind was neutralized. The increase in the root-to-shoot ratio under the conditions of 25% nutrient solution with wind can be interpreted as an adaptive response of the plant to mechanical stress and nutritional limitation. Under such conditions, the plant tries to increase mechanical stability and water and nutrient absorption capacity by reducing shoot growth and increasing the relative size of the root system. This response can be explained within the framework of the thigmomorphogenesis phenomenon, during which mechanical stimulation leads to changes in carbon partitioning and growth pattern (Telewski, 2006). In contrast, the lack of significant difference between wind and control plants at 50, 75, and 100% nutrient solution levels suggests that appropriate nutrition can counteract or moderating effects of wind stress. The decrease in root-to-shoot ratio at higher nutrient solution levels (regardless of wind) may indicate that shoot growth is prioritized under nutrient-rich conditions.

Wind stress can reduce leaf nutrient concentrations by limiting nutrient uptake under mechanical stress conditions, suggesting that adequate nutrient supply may help maintain leaf nutritional status and sustain metabolic activity under wind stress (Zhang et al., 2022). The reduction of nutrients under wind stress conditions is usually associated with a decrease in leaf growth, photosynthetic rate, and dry matter production (Taiz et al., 2022). In these conditions, the nutritional status of the plant plays an important role in moderating the negative effects of wind stress, such that a balanced supply of nutrients can maintain the stability of the plant's cellular structure and metabolic function (Marschner, 2011).

Adequate phosphorus levels in transplants are essential because this nutrient promotes root initiation, regeneration, and development following transplanting. In the present study, wind stress markedly reduced leaf phosphorus concentration in cabbage transplants receiving the 25% nutrient solution, indicating greater susceptibility of nutrient-deficient plants to wind-induced stress. Because successful transplant establishment depends on rapid root regeneration, adequate phosphorus availability is critical during the early stages after transplanting. Therefore, maintaining a balanced nutrient supply, particularly sufficient phosphorus availability, may mitigate the adverse effects of wind stress by preserving leaf nutrient status, supporting root establishment, and improving transplant tolerance to environmental stress (Khan et al., 2023; Zeng et al., 2025). Overall, the interaction of wind stress and nutrition plays a key role in determining the state of leaf elements, plant growth and stability, and simultaneous management of these two factors seems essential to achieve high quality transplants.

Wind stress, as a mechanical abiotic stress, can increase the production of reactive oxygen species (ROS) and induce oxidative stress in plant tissues. Under these conditions, activation of the phenylpropanoid pathway enhances the accumulation of phenolic compounds (Zeng et al., 2025). In the present study, the significant increase in total phenolic content under wind stress is consistent with previous studies reporting enhanced phenolic accumulation in plants exposed to mechanical stress. This response likely reflects an adaptive antioxidant mechanism that helps protect plant tissues against oxidative damage (Sharma et al., 2019).

High levels of proline are a very important indicator in assessing the success of transplant hardening, as they can increase the resilience of transplants to the shock of transfer to the field. In stressed plants, proline acts as an adaptive osmolyte and non-enzymatic antioxidant, maintaining the structure of proteins and the stability of membranes (Taiz et al., 2022). Researchers have introduced the increase in proline as an indicator of the severity of mechanical stress and the plant's adaptive response (Hosseinifard et al., 2022). In this regard, 75 and 100 percent nutrient solutions along with wind stress showed excellent results. As these treatments had high total phenols as well, so overall they showed a favorable result in terms of biochemical compounds.

High stomatal density and smaller stomatal size can be so important property for resistance to extre-transpiration in the field, as small stomata respond more quickly to drought stress and close quickly. On the other hand, a high number of stomata per unit area allows for adequate gas exchange when conditions are available (Aliniaeifard & Meeteren, 2016). Regarding these considerations, the combined treatment of 75% nutrient solution alongside wind stress seems to be favorable in terms of stomatal characteristics of transplants. The aforementioned treatment had the lowest stomatal area and ranked second in terms of stomatal density. Under mild wind conditions, some plant species show an increase in stomatal density per unit area by reducing leaf area and keeping the number of stomata constant. This mechanism can help maintain gas exchange under conditions of increased transpiration. In contrast, severe and persistent wind stress usually leads to a decrease in stomatal density or a decrease in their size to prevent the plant from losing too much water (Grace, 1988). These findings are consistent with previous studies showing that wind stress induces structural and anatomical adaptations in leaves, including changes in stomatal characteristics, as part of the plant's protective response to environmental stress (Bano et al., 2019). In nutrient deficiency conditions, reduced leaf growth and limited epidermal cell division lead to reduced stomatal density (Taiz et al., 2022).

Conclusion

High leaf phosphorus concentration and SPAD index were observed in the 75% nutrient solution alongside wind treatment, which are considered an important feature for plant resistance to transplanting. In the combined treatment of 75% nutrient solution with wind treatment, short root length was recorded without negative impacts on the fresh and dry weight of roots, potentially reducing mechanical damage during transplanting. Additionally, other important transplant resistance indices, such as proline level and stomatal properties, showed favorable performance in the 75% nutrient solution alongside wind treatment. Therefore, overall, this treatment (75% nutrient solution + wind) could be recommended for enhancing the resistance of cabbage transplants while maintaining high transplant quality.

Author contributions

ATA conducted tests, KG designed the experiment and wrote the manuscript, HM revised and finalized the article.

Competing interests

The authors declare no competing interests.

Data availability

All data generated or analyzed during this study are included in this published article.

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