PLANT SCIENCE TODAY
Vol 12(3): 1-7
https://doi.org/10.14719/pst.8736

eISSN 2348-1900

RESEARCH ARTICLE

Leaf physiological attributes and root productivity of two radish cultivars as influenced via low tunnel plastic sheeting and silicon foliar application under cold stress

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Received: 08 April 2025; Accepted: 30 June 2025; Available online: Version 1.0: 07 September 2025; Version 2.0: 28 September 2025

Cite this article: Ammar Sami A, Nasser JRA . Leaf physiological attributes and root productivity of two radish cultivars as influenced via low tunnel plastic sheeting and silicon foliar application under cold stress. Plant Science Today. 2025; 12(3): 1-7. https://doi.org/10.14719/pst.8736

Abstract

This study aimed to assess the impact of low plastic tunnels integrated with potassium silicate spraying on the physiological traits and root productivity of two radish cultivars under cold stress conditions. A field experiment was performed on a private sector farm in Albuhidari, Al-Najaf governorate, Iraq, during the autumn season of 2023. The experiment was conducted in a split-split plot design using Randomized Complete Block Design (RCBD) with three replicates, testing the effects of three factors: growth conditions (open field versus plastic tunnels) designated as the main plots, cultivars (red versus white) assigned as subplots and doses of silicon spraying (0, 400, 600 mg L^{-1}) assigned as sub-subplots. The results showed that plastic sheeting significantly improved total chlorophyll in leaves, nitrogen and potassium percentages in the leaves, total plant dry matter and root yield compared to the open field. The red cultivar outperformed the white cultivar in chlorophyll content, potassium percent, total plant dry matter and yield. Furthermore, silicon spraying enhanced the studied traits, as total chlorophyll, total dry matter and root yield gradually increased with higher silicon concentrations. Moreover, the triple interaction of plastic tunnels, red cultivar and silicon at 600 mg L^{-1} was the best regarding all attributes except phosphorus percentage in leaves. These results suggest that plastic sheeting combined with silicon spraying represents an effective strategy for improving radish productivity under cold stress.

Keywords: cold stress; growing environment; nutrient; productivity; radish; silicon

Introduction

Radish (*Raphanus sativus* L.) represents a prominent root vegetable crop that is classified within the Brassicaceae family, distinguished by its high nutritional value and medicinal properties. Radishes are widely cultivated in many countries of the world, particularly in temperate and cool climates, where they are consumed either fresh or cooked. They represent a rich source of vitamins (such as vitamins C and B6), minerals (including potassium, phosphorus and calcium) and antioxidants (1). Radish is considered a fast-growing crop that can be cultivated in various agricultural systems; however, the observed decline in radish productivity, which can be attributed to unfavorable climatic conditions, particularly characterized by increased soil salinity, water deficiencies and extremely cold temperatures, has necessitated the exploration of modern agricultural strategies to augment crop production and quality under harsh environmental conditions (2).

The practice of low tunnels of plastic material is an efficient agricultural technique for improving growth conditions under environmental stress, particularly in areas that experience low temperatures during planting seasons. These miniature frames additionally serve to shield plants from extreme precipitation and coldness, as well as from strong gales and frost. Furthermore, low tunnels have been utilized in protecting many crops, including peppers, tomatoes, beans, cucumbers and radishes thereby reducing the impact of cold stress on the plant and enhancing both quality and productivity (3).

The genetic variability between varieties can also be exploited, as it is a vital strategy to enhance production through the implementation of various treatments, including the foliar application of components abundant in specific elements. Silicon (Si) is considered a beneficial element for plants, as various studies have shown that Si spray improves plant resistance to environmental stresses such as cold, drought, nutritional imbalance, metal toxicity and salinity (4, 5). Most of these advantages are attributed to the accumulation of silicon in plant tissues, especially in the cell walls of stems, leaves and roots, which function as a physical barrier against abiotic stressors (6, 7). Further, Si improves chlorophyll formation thus increasing photosynthetic efficiency, as well as augments absorption of nitrogen and potassium, contributing to the enhancement of metabolic processes within the plant and increased dry matter content and productivity (8, 9).

This research aims to evaluate the effectiveness of low plastic tunnels in improving nutrient uptake and root productivity in two cultivars of radish under cold stress conditions. In addition, determines the influence of Si foliar application on crop quality and quantity based on enhancing environmental growth conditions that contribute to sustainable agricultural techniques.

Materials and Methods

Location and field management

The field trial was carried out in one of the farms adjacent to the Faculty of Agriculture at the University of Kufa known as Albuhidari during the autumn season of 2023. The field site was sampled for soil test, as indicated in Table 1. The experimental field was subdivided into plots measuring 1 m^2, wherein radish seeds were sown directly in the plots with an inter-row spacing of 25 cm, comprising three rows per plot and a seed spacing of 10 cm, resulting in a total of 30 plants per plot. Field management related to the planting of radish cultivars was performed throughout the whole growing season.

Growing conditions and foliar application

Two distinct growing conditions of plots cultivated with radishes were designated for this experiment: low tunnel plastic sheets were set up over hoops for certain plots to create a controlled microenvironment, while the other plots were maintained as an open field condition. Both growing conditions were subjected to identical environmental conditions to facilitate a comparison between the two growing conditions under cold stress. White and red radish plants were treated with a silicon solution in the form of potassium silicate (K_2SiO_3), which contains 37 % (K_2O) and 48 % (SiO_2). The application of the foliar spray was conducted after the emergence of the true leaves of the plant. The foliar application was repeated thrice with intervals of seven days between each successive spray (10).

Table 1. Some physicochemical analysis of the experimentation soil

Properties	Unit	Value	Properties	Percent
Soil pH	---	8.10	O. M.	0.28
Soil Ec	dS.m^{-1}	0.76	Clay	25
Total N	%	1.90	Silt	61
Available P	%	0.13	Sand	14
Available K	%	0.79	Soil texture	Silty loam

Experimental layout and data analysis

The field trial comprised three factors and each treatment was triplicated, obtaining a total of 12 plots per block. Two distinct growing conditions were represented as the first factor (tunnel plastic sheets vs open field as a control). Two distinct local cultivars of radish represented the second factor (white vs red radish), which were selected for their contrasting characteristics and potential responses to the experimental conditions. The third factor comprised three concentrations of silicon (0, 400, 600 mg L^{-1}) denoted by (Si 0, Si 1, Si 2) that were sprayed on the radish canopy. The control plots were treated with distilled water only to serve as a baseline for comparison.

The experimental layout was performed in a split-split plot system following a Completely Randomized Block Design (CRBD). The growing conditions were assigned to the whole plots and the radish cultivars were assigned to the subplots, while the applications of silicon were assigned to the sub-subplots. Following data acquisition, the ANOVA procedure was employed using the Statistix 10 software program (11). Furthermore, the Least Significant Difference (LSD) test was adopted for mean comparison at a probability level of $p < 0.05$.

Physiological and yield attributes

In each experimental unit, three plants were selected randomly for the following attributes: Total chlorophyll in leaves using SPAD (%), percentages of nitrogen, phosphorus and potassium in leaves (12, 13), total plant dry matter percentage (14) and root yield (kg m^{-2}).

Results and Discussion

Simple effects of growing conditions

The results of Table 2 revealed that the cultivation of radishes under plastic tunnels provided a significant improvement in most physiological and productive traits in comparison with the open field plots. Radish plants grown under tunnel plastic sheets revealed a significant improvement in the total chlorophyll of leaves, leaf N, leaf K, total plant dry matter and root productivity by (49.14 %, 3.13 %, 3.03 %, 24.36 % and 3.23 kg m^{-2}), respectively. Contrarily, radish plants grown in

Table 2. Simple effects of growing conditions and silicon foliar spray on leaf physiological contents, dry matter and root yield of two radish cultivars under cold stress

Treatments	Total leaf chlorophyll (%)	Leaf nitrogen (%)	Leaf phosphorus (%)	Leaf potassium (%)	Total plant dry matter (%)	Root yield (kg m^{-2})
			Simple effect of growing conditions			
Open field	47.44	2.72	0.38	2.61	22.98	2.94
Plastic tunnels	49.14	3.13	0.37	3.03	24.36	3.23
LSD 0.05	**0.970**	**0.131**	**N S**	**0.014**	**0.035**	**0.036**
			Simple effect of radish cultivar			
White cultivar	46.47	2.86	0.38	2.60	22.33	1.91
Red cultivar	50.11	2.98	0.37	3.05	25.00	4.26
LSD 0.05	**0.350**	**N S**	**N S**	**0.036**	**0.113**	**0.014**
			Simple effect of silicon spray			
Si 0 (control)	47.50	2.73	0.36	2.68	22.93	2.93
Si 1 (400 mg L^{-1})	48.33	2.96	0.37	2.83	23.81	3.10
Si 2 (600 mg L^{-1})	49.04	3.08	0.40	2.97	24.27	3.22
LSD 0.05	**0.390**	**0.158**	**0.017**	**0.038**	**0.223**	**0.047**

N S indicates a non-significant effect at $p > 0.05$

the open field gave the minimal averages for the same attributes abovementioned (47.44 %, 2.72 %, 2.61 %, 22.98 % and 2.94 kg m^{-2}). These differences between the two growing conditions may be attributed to the role of plastic tunnels in reducing the impact of low thermal stress by improving the microclimatic environment around the plant, thereby contributing to enhanced photosynthetic efficiency (15). This improvement can be explained by the fact that plastic cover provides a stable growth environment that enhances photosynthesis and the efficiency of water and nutrient absorption, increasing the deposition of organic matter in plant tissues, as well as the role of potassium helps in boosting the plant's resistance to cold stress and improving cell membrane stability (4). Moreover, the enhanced traits may be related to the stimulation of nutrient absorption because of increased photosynthetic rates and reduced environmental stress (16, 17). As for the phosphorus percent, no significant differences were observed between treatments, suggesting that the effect of plastic covering on phosphorus absorption may be less pronounced compared to other nutrients. On the other hand, cold stress reduces the water potential, which consequently hinders cellular expansion while inducing stomatal closure, resulting in a reduction in photosynthetic efficiency. In addition to the growth inhibition caused by cold exposure, a significant portion of respiratory energy is expended in the essential osmotic adjustment process rather than being allocated to growth activities. Cold stress also leads to the obstruction of cytosolic movement, an elevation in membrane permeability and the efflux of solutes from cells, alongside the potential accumulation of toxic substances within plant cells. Additionally, it may disrupt transport mechanisms and alter the composition of membrane-constructing lipids (18, 19).

Simple effects of radish cultivars

The findings exhibited that the red radish outperformed the white radish in most of the studied traits (Table 2). The red radish recorded the highest averages for chlorophyll rate (50.11 %), leaf K (3.05 %), total dry matter (25 %) and root yield (4.26 kg m^{-2}). In comparison, the white radish cultivar gave total chlorophyll (46.47 %), leaf K (2.60 %), total dry matter (22.33 %) and root yield (1.91 kg m^{-2}). The observed variations in the examined traits may be attributable to variations in their physiological processes, which could stem from the genetic makeup inherent to the different varieties, or the red variety may have exhibited greater adaptability to the climatic conditions prevalent in the research locale. Meanwhile, the red radish showed a clear superiority in these traits compared to the white radish enhancing its ability to adapt to low temperatures. This superiority may be attributed to the red radish's ability to have a greater capacity for photosynthesis under cold environmental conditions compared to white radish. The increased plant productivity may result from the red radish's ability to direct more carbohydrate resources toward root growth rather than leaf growth under low-temperature conditions (20). These findings align with the results documented when investigating the cultivation of two distinct radish varieties (21).

There was no significant variation in leaf N and P between the two cultivars, suggesting a similar response concerning the absorption of both nutrients.

Simple effects of silicon

The findings in Table 2 exhibited that the application of silicon enhanced most physiological and productive traits of radish. The total chlorophyll content gradually increased with rising silicon concentration from 0 to 600 mg L^{-1}, with values recorded at (47.50 %, 48.33 % and 49.04 %) respectively. This positive effect is attributed to the role of silicon in enhancing photosynthetic efficiency by reducing oxidative stress and increasing cellular membrane stability (9).

Similarly, nitrogen percent in the leaves significantly increased with higher silicon concentrations, with plants treated with 600 mg L^{-1} showing the highest percentage (3.08 %) compared to untreated plants (2.73 %). This is attributed to silicon's role in improving nitrogen absorption from the soil and enhancing its utilization efficiency in biological processes (8). As for leaf phosphorus, there was a slight but significant improvement, with its content rising from (0.36 %) in the control to (0.40 %) at a concentration of 600 mg L^{-1} of silicon. This is associated with silicon's role in improving phosphorus availability by reducing fixation reactions in the soil (22).

Leaf potassium percent gradually improved from (2.68 %) in the control to (2.97 %) with the highest silicon concentration treatment, confirming the role of silicon in enhancing potassium absorption and improving plant resistance to environmental stress (23). The content of dry matter increased with the concentration of silicon, rising from (22.93 %) in the control to (24.27 %) when using 600 mg L^{-1}. This effect confirms the role of silicon in enhancing the stabilization of organic materials and improving the plant's resistance to harsh environmental conditions (8).

The root productivity gradually increased with higher silicon concentrations, starting from (2.93 kg m^{-2}) in the control to (3.22 kg m^{-2}) at 600 mg L^{-1}, reflecting the effect of silicon in enhancing root growth by improving nutrient absorption and promoting cell wall formation (24). It is evident that the function of silicon in mitigating cold-induced deterioration is attributable to the influence of this component in augmenting the efficacy of the root architecture while concurrently diminishing the transpiration ratio. Silicon additionally enhances the functionality of proteins involved in ion transfer and various substances, as well as supporting the integrity of vacuole membranes and plasma (25). Cold stress has been documented to diminish the concentrations of essential phytohormonal regulators including gibberellic acid, indole acetic acid and zeatin, within both root and shoot tissues. Nevertheless, the administration of silicon has been demonstrated to restore hormonal equilibrium in a manner analogous to that observed in plants not subjected to stress. Moreover, it has been established that silicon can indeed promote the synthesis of phytohormones that enable adaptation to stress conditions, such as abscisic, salicylic and jasmonic acids (26). Consequently, this would enhance the root yield of the radish crop.

Two-way interaction effects of growing conditions x cultivars

The dual interactions between growing conditions (open field versus plastic tunnels) and cultivars (white versus red) had a significant effect on most physiological traits and root yield of radish plants (Table 3). Consequently, the red radish grown under plastic tunnels had the highest chlorophyll of leaves, leaf N, leaf K, total dry matter and root productivity (51.29 %, 3.17 %, 3.32 %, 26.07 % and 4.45 kg m^{-2}), respectively. Conversely, white radish plants grown in the open field gave the lowest averages for the same attributes above mentioned (45.96 %, 2.63 %, 2.45 %, 22.01 % and 1.80 kg m^{-2}).

These results confirm that red radish is more efficient in photosynthesis compared to white radish, particularly under plastic cover, which enhances the growth environment by increasing ambient temperatures and reducing cold stress (4). Further, the plastic tunnels enhance nitrogen and potassium absorption due to an increase in the accumulation of carbohydrates and dry matter which in turn augment root activity and increase nutrient uptake efficiency (16). Besides the role of potassium in improving cold stress resistance by maintaining water balance in cells and enhancing membrane stability (4).

Interestingly, the yield of white radishes was significantly lower in both cases, indicating that red radishes have a greater ability to adapt to lower temperatures and benefit from improved climatic conditions under plastic cover. Furthermore, similar findings have been previously reported who noted that crops cultivated under tunnel conditions with mulching displayed markedly superior increases in vegetative characteristics relative to the control treatment (27). Consequently, the implementation of low-cost plastic tunnels may serve as a viable strategy for promoting crop growth and development. Comparable results have been documented by (28, 29), who have documented that polyethylene tunnels considerably augmented plant yield and leaf nutrients, owing to the optimal thermal conditions afforded within the protected conditions.

Meanwhile, there was no significant effect of the interaction between growing conditions and cultivars on phosphorus percent, indicating that phosphorus absorption may be relatively independent of these factors, or that the environmental effects were not sufficient to cause clear differences.

Two-way interaction effects of growing conditions x silicon

It is obvious from the data in Table 3 that the dual interaction between the growing conditions and silicon doses has a substantial impact on some of the studied physiological and productivity attributes. Accordingly, chlorophyll content gradually increased with higher silicon concentration, with the highest recorded content at the treatment of 600 mg L^{-1} of silicon under plastic tunnels (50.03 %), while the lowest content was observed with no silicon applied in the open field (46.75 %). This effect reflects the role of silicon in enhancing chlorophyll stability and protecting the photosystem from oxidative stress (24). Similarly, the nitrogen percent increased with higher doses of silicon, with plants treated with 600 mg L^{-1} of silicon under plastic tunnels recording the highest percentage (3.23 %) compared to the control in the open field (2.40 %). This indicates that silicon may enhance nitrogen absorption efficiency and reduce losses due to environmental stress (8). However, there were no significant differences in this interaction on leaf phosphorus percent, confirming that silicon does not significantly affect phosphorus absorption under different environmental conditions (22). Nonetheless, the highest values were recorded in the interaction between plastic tunnels and treatment with a silicon concentration at 600 mg L^{-1} (3.23 %), indicating the role of silicon in improving potassium absorption, which is a key element in resistance to thermal and cold stress (23).

When using 600 mg L^{-1} of silicon, the total dry matter of the plants increased to (25.02 %) under plastic tunnels, compared to (23.51 %) in the open field. This indicates that plastic covering enhances the absorption of silicon, which contributes to strengthening plant tissue development and increasing the stability of plant cells (9).

Table 3. Two-way interaction effects of growing conditions and silicon foliar spray on leaf physiological contents, dry matter and root yield of two radish cultivars under cold stress

Treatments		Total leaf chlorophyll (%)	Leaf nitrogen (%)	Leaf phosphorus (%)	Leaf potassium (%)	Total plant dry matter (%)	Root yield (kg m²)
Growing conditions x Cultivar interaction							
Open field	White	45.96	2.63	0.39	2.45	22.01	1.80
	Red	48.94	2.80	0.38	2.78	23.94	4.07
Plastic tunnels	White	46.99	3.09	0.37	2.75	22.65	2.02
	Red	51.29	3.17	0.37	3.32	26.07	4.45
LSD 0.05		**0.499**	**0.213**	**N S**	**0.050**	**0.160**	**0.019**
Growing conditions x Silicon interaction							
Open field	Si 0	46.75	2.40	0.37	2.52	22.33	2.75
	Si 1	47.55	2.81	0.38	2.61	23.09	2.97
	Si 2	48.05	2.94	0.40	2.71	23.51	3.09
Plastic tunnels	Si 0	48.27	3.06	0.35	2.83	23.53	3.11
	Si 1	49.12	3.11	0.36	3.05	24.53	3.24
	Si 2	50.03	3.23	0.40	3.23	25.02	3.36
LSD 0.05		**0.556**	**0.224**	**N S**	**0.054**	**N S**	**0.067**
Cultivar x Silicon interaction							
White cultivar	Si 0	45.78	2.70	0.36	2.45	21.67	1.76
	Si 1	46.64	2.86	0.37	2.61	22.41	1.93
	Si 2	47.00	3.02	0.40	2.74	22.91	2.05
Red cultivar	Si 0	49.24	2.75	0.36	2.91	24.19	4.11
	Si 1	50.03	3.05	0.37	3.04	25.20	4.28
	Si 2	51.07	3.15	0.40	3.20	25.62	4.40
LSD 0.05		**0.556**	**N S**	**N S**	**0.054**	**N S**	**0.067**

N S indicates a non-significant effect at $p > 0.05$

The highest root yield was observed in the interaction between red radish and treatment with 600 mg L^{-1} of silicon (4.40 kg m^{-2}), while the lowest production was recorded for white radish without silicon treatment (1.76 kg m^{-2}).

Two-way interaction effects of cultivars x silicon

The red radish showed a greater response to silicon spraying at 600 mg L^{-1}, achieving the highest averages for chlorophyll content (51.07 %), leaf K (3.20 %) and root yield (4.40 kg m^{-2}), compared to the white radishes that unsprayed, giving the lowest averages (45.78 %), (2.45 %) and (1.76 kg m^{-2}), respectively (Table 3).

This may be linked to the red radish's ability to interact better with silicon, resulting in a greater benefit in enhancing photosynthetic activity. These results reveal that the red radish is more efficient in utilizing silicon to enhance growth and productivity under cold stress.

The findings reveal that red radish demonstrates a superior capacity for the effective utilization of silicon, which plays a crucial role in boosting nutrient status and overall productivity under conditions characterized by cold stress (30).

Meanwhile, the interaction effect of radish cultivars and silicon application did not reach significant effects, indicating that red radish is more responsive to silicon treatments as compared to white radish (24).

Three-way interaction effects of growing conditions x cultivars x silicon

It seems from the findings in Table 4 that most of the leaf and root attributes have increased significantly regarding the triple interaction. It presented that the highest chlorophyll content was recorded in the red radish grown under plastic tunnels with a spray of 600 mg L^{-1} of silicon (52.68 %), reflecting the synergistic effect of the plastic cover and silicon in enhancing photosynthetic activity and protecting chlorophyll from oxidative degradation under cold stress conditions (4). Conversely, the lowest chlorophyll content was recorded in the white radish grown in the open field with unsprayed silicon (45.02 %), indicating that the plants were subjected to greater stress due to lower temperatures and the absence of the protective effect of silicon and plastic cover (22). These results suggest that silicon contributes to the stabilization of chlorophyll by enhancing the plant's response to oxidative stress and improving stomatal regulation, thus increasing photosynthetic efficiency (9).

The interaction in the same table showed that the highest nitrogen percent in red radish grown under plastic tunnels with a silicon spray at 600 mg L^{-1} was found to be 3.23 %, indicating that silicon enhances nitrogen absorption by promoting root activity and increasing its utilization efficiency in metabolic processes (18). In contrast, the lowest nitrogen percent was recorded in white radish grown in the open field with no silicon application (2.37 %), reflecting the impact of cold stress in reducing nitrogen absorption due to decreased activity of the enzymes responsible for nitrogen assimilation within plant tissues (31). These results support the hypothesis that silicon plays a role in enhancing nutrient absorption efficiency by strengthening root cell walls and reducing nitrogen loss through transpiration (8).

The three-way interaction (Table 4) had no significant effect on the phosphorus percent in the leaves, indicating that phosphorus absorption may be less affected by environmental factors compared to other elements such as nitrogen and potassium. This result is consistent with previous studies that indicated silicon may not directly influence phosphorus absorption, but it can improve its efficiency by enhancing root growth and increasing its ability to extract nutrients from the soil (22). Nevertheless, the interaction among the three factors may indirectly affect phosphorus utilization by improving the physiological processes associated with nutrient transport within the plant (24).

The highest potassium percent was recorded in red radish grown under plastic tunnels with a silicon spray at 600 mg L^{-1} of (3.56 %), indicating that this treatment enhanced potassium absorption due to improved permeability of cell membranes and increased activity of ion transport channels in the roots (23). In contrast, the minimum potassium percent was recorded in white radish grown in the open field with no spray (2.31 %), reflecting the negative impact of coldness on the efficiency of potassium absorption and its translocation within the plant (19). This effect reinforces the known role of silicon in enhancing plant tolerance to cold stress by reducing potassium loss from plant cells, thereby improving ionic balance regulation and increasing the plant's resistance to harsh environmental conditions (4).

Table 4. Three-way interaction effects of growing conditions and silicon foliar spray on leaf physiological contents, dry matter and root yield of two radish cultivars under cold stress

Treatments			Total leaf chlorophyll (%)	Leaf nitrogen (%)	Leaf phosphorus (%)	Leaf potassium (%)	Total plant dry matter (%)	Root yield (kg m²)
Growing conditions x Cultivar x Silicon interaction								
Open field	White cultivar	Si 0	45.02	2.37	0.38	2.31	21.13	1.66
		Si 1	46.23	2.72	0.38	2.45	22.17	1.83
		Si 2	46.63	2.81	0.40	2.58	22.74	1.93
	Red cultivar	Si 0	46.55	2.43	0.36	2.73	23.53	3.85
		Si 1	47.05	2.89	0.38	2.76	24.00	4.11
		Si 2	47.37	3.08	0.39	2.85	24.28	4.25
Plastic tunnels	White cultivar	Si 0	48.48	3.03	0.34	2.58	22.21	1.86
		Si 1	48.87	3.01	0.36	2.77	22.65	2.03
		Si 2	49.46	3.22	0.39	2.90	23.08	2.16
	Red cultivar	Si 0	49.99	3.08	0.35	3.08	24.84	4.36
		Si 1	51.20	3.20	0.36	3.32	26.41	4.44
		Si 2	52.68	3.23	0.40	3.56	26.97	4.55
LSD 0.05			**0.787**	**0.317**	**N S**	**0.077**	**0.446**	**0.095**

N S indicates a non-significant effect at $p > 0.05$

The highest dry matter percent (26.97 %) was recorded under the interaction between red radish, plastic sheets and silicon application at 600 mg L^{-1}. Contrarily, the minimum dry matter percent (21.13 %) was observed under the interaction between white radish, open field and no silicon spray. This effect demonstrates that plastic covering enhances silicon absorption, improving carbon utilization efficiency within the plant and leading to an increase in the dry matter stored in plant tissues (22).

The effect of the triple interaction on root productivity was evident, as the results showed that the best root productivity was recorded when combining plastic tunnels and silicon at 600 mg L^{-1} on red radish by (4.55 kg m^{-2}). This can be explained by the fact that silicon enhances nutrient absorption efficiency, increases the rigidity of root tissues and improves the plant's resistance to cold stress, leading to increased root formation and improved productivity (9, 20). Conversely, the lower root productivity was recorded in white radish grown in the open field with no spray (1.66 kg m^{-2}), indicating that this cultivar is less capable of withstanding environmental stress compared to red radish.

Conclusion

We can conclude that this study suggests a synergistic influence of the experimental factors on enhancing leaf tissue nutrients and plant yield, in addition to improving resilience against environmental stresses. Specifically, our findings indicate that plastic cover and silicon spraying are effective strategies for improving radish growth and productivity under cold-stress conditions. The plastic cover has proven effective in enhancing the thermal environment of the plant, leading to increased photosynthetic efficiency and nutrient absorption. Furthermore, the superiority of the red radish variety compared to the white variety demonstrates its higher adaptability to low temperatures, making it a suitable agricultural choice for cold environments. Moreover, the positive impact of silicon on radish growth and productivity underscores its importance in agricultural management programs to improve crop resilience to environmental stress. On the other hand, silicon has played an important role in enhancing radish resistance to cold stress by improving nutrient absorption, enhancing cellular membrane stability and reducing cellular oxidation.

Acknowledgements

The authors gratefully acknowledge the staff of the Department of Horticulture, Faculty of Agriculture, University of Kufa, Iraq for their valuable help and technical assistance in conducting this research.

Authors' contributions

Methodology, writing original draft, review and editing was done by ASAB and NJRA. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare no conflict of interest.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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