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The Effect of Silica Fertilizer on the Yield and Shelf Life of Arugula (Eruca sativa)

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Abstract. Nutrition is one of the factors affecting the quality and durability of products. Silica element is considered as one of the useful nutritional elements for plants. Therefore, in the present study, this element was used to feed before harvesting Arugula vegetable (Eruca sativa (Mill.) Thell.) and to investigate its effects after harvesting. The seeds were cultivated in June, 2021 in boxes (10 x 25 x 35) containing a mixture of perlite (50%) and cocopeat (50%) and in the research greenhouse of the Faculty of Agriculture, University of Kurdistan, so that 15 plants were grown in each box in 3 rows. The experiment was carried out as a completely randomized design before harvesting and factorial after harvesting with two factors and in three repetitions. The first factor was silica at three levels (0, 5 and 10 mM), the second factor was storage times in cold storage at four levels (harvest time, 4, 7 and 10 days after storage). Applying silica (potassium silicate) treatments in the amount of (0, 5 and 10 mM) was added to Hoagland's nutrient solution and after the establishment of plants (ten days after seed cultivation) on a daily basis until the end of the experiment. Weighing and drying traits of roots and shoots, total yield, leaf nitrate content before harvest and weight loss traits, total soluble carbohydrate, total phenol, flavonoid and vitamin C after harvesting Arugula. became The results showed that silica (10 mM) had a greater effect on the growth rate of roots, stems and leaves and their wet and dry weight in Arugula plant. The increase of silica decreased the accumulation of nitrate in the leaves. The effect of this fertilizer on the plant after harvest was investigated and it was observed that the treatment of 10 mM silica had a positive effect compared to the treatment of 5 mM silica and the control. Arugula treated with silica was kept at 4 degrees Celsius for 0, 4, 7 and 10 days and it was observed that soluble carbohydrates, chlorophyll content, weight, vitamin C and other measured factors which are marketable factors of the product in the application of this Fertilizers were well preserved during the storage period. In general, the use of silica fertilizers as pre-harvest nutrition can be used to increase the shelf life of Arugula after harvesting.

***Keywords:** Post-Harvest Waste; Vegetable Quality; Nitrate; Rocket Leaves*

1. Introduction

Arugula (*Eruca sativa* (Mill.) Thell.) is a biennial plant from the Brassicaceae family. The distribution of Arugula is mainly in southern Europe, northern Africa, Iran, Syria, Pakistan, Afghanistan, and India (Garg and Sharma *et al.*, 2014). Due to its various applications, including medicinal and forage uses, as well as its valuable traits such as genetic diversity, rapid vegetative growth, and high resistance to various stresses, it has gained significant attention in recent years (Nezhadhasan *et al.*, 2015).

Arugula, as a leafy vegetable, is highly sensitive to water loss and wilting in the post-harvest stages. The main issue after harvesting this vegetable is its premature aging. Aging in

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Arugula primarily appears as yellowing accompanied by chlorophyll degradation, but wilting and weight loss are also serious problems (Siomos and Koukounaras *et al.,* 2007).

Leafy vegetables such as lettuce, spinach, beet greens, and Arugula are considered key species for nitrate accumulation. Despite the relatively non-destructive effects of nitrates, their reactions and metabolites, including nitric oxide and N-nitroso compounds and nitrites, can pose a serious threat to human health. Additionally, increased nitrate levels and high nitrogen consumption can reduce the shelf life of leafy products like Arugula and lettuce (Hall *et al.,* 2013). Research on leafy plants indicates that silicon treatment is associated with increased yield, improved quality, and reduced nitrate concentration in edible tissues (Gottardi *et al.,* 2012).

Many researchers believe that plant growth may be stimulated by increased silicon availability (Ma et al., 2007). In fact, the application of silicon-containing fertilizers may help reduce stress caused by global environmental changes (Ali *et al.,* 2008).

The various beneficial effects of silicon in plants include delaying the aging process, improving water use efficiency, and reducing various abiotic stresses (Zhu and Gong, 2014).

Isa and colleagues (2010) reported that the application of silicon in plants increases the stiffness and resistance of cell walls through the deposition of silicon in the form of amorphous silica (SiO2 ·nH2O). The application of silicon has been reported to affect the activity of certain enzymes, antioxidant capacity, plant water relations, photosynthesis, ion mobility within plant tissues, nutrient and non-nutrient anion uptake, and gene expression (Zhu and Gong, 2014).

A study on the application of silicon revealed that silicon can also enhance photosynthesis by increasing stomatal conductance (Savvas and Ntatsi, 2015).

In a study conducted in Brazil on lettuce treated with silicon (on the twentieth day after planting), both yield and post-harvest lifespan were increased. The aim of this research was to determine the effect of using silicon and manganese on the shelf life of lettuce. It was reported that the fresh and dry weights of the treated plants were greater compared to the control, leading to a delay in leaf aging during storage compared to the control samples (Artyszak et *al.,* 2018).

Previous studies have shown that the application of silicon reduces nitrate concentration in the plant Valerianella locusta due to changes in the plant's metabolism (such as the nitrate assimilation pathway) or alterations in root structure related to nitrate uptake (Gottardi *et al.,* 2012). Additionally, the use of silicon led to a decrease in the expression of the polyphenol oxidase gene at harvest and post-harvest stages, which ultimately resulted in reduced chlorophyll degradation, delayed leaf aging, and increased shelf life of this product (Siomos and Koukounaras, 2007).

A study investigated the effect of silicon application on the physiology and growth of two cucumber varieties in the presence of high levels of ammonium and nitrate. The results showed that the application of silicon, when nitrogen is supplied as ammonium, can enhance growth traits and physiological characteristics of the plants, as well as help mitigate ammonium toxicity (Campos *et al.,* 2016). Additionally, examining the effect of silicon on cucumber growth under salt stress conditions indicated that using silicon along with nutrient solutions can improve plant growth, photosynthesis, reduce nitrate accumulation, and increase the activity of enzymes involved in the nitrogen assimilation pathway in the leaves (Gou *et al.,* 2020).

Therefore, the use of silica fertilizer may provide a way to enhance plant performance during stress periods. Additionally, the application of silica can increase the shelf life of plants (Carpenter *et al.*, 2000). This research, considering the importance of silica and its impact on yield and post-harvest longevity, was conducted to achieve an understanding of the role and effect of silica in reducing nitrate accumulation in the leaves and extending the post-harvest shelf life of Arugula greens using soilless cultivation methods

This research also contributes to global sustainability objectives by aligning with key United Nations Sustainable Development Goals (SDGs). Improving arugula yield and reducing post-harvest losses through pre-harvest silicon application directly support SDG 2 (Zero Hunger), particularly Target 2.3, which aims to enhance agricultural productivity and efficiency. Furthermore, the reduction of nitrate accumulation and the preservation of nutritional quality during storage contribute to SDG 3 (Good Health and Well-being) by improving food safety and nutritional value of leafy vegetables. Therefore, the findings of this study provide practical insights for sustainable horticultural production systems with both agronomic and public health benefits.

2. Methods

The experiment was conducted as a completely randomized design before harvest and a factorial design after harvest with two factors and three replications. The first factor was silicon at three levels (0, 5, and 10 millimolar), and the second factor was storage times in cold storage at four levels (0, 4, 7, and 10 days after storage). For the experiment, Arugula seeds were obtained from the Research Institute of Seed and Seedling Improvement in Karaj. The seeds were sown in June 2021 in boxes (35*25*10) containing a mixture of perlite (50%) and coco peat (50%) in the greenhouse of the Agricultural Faculty at the University of Kurdistan, with 15 plants grown in three rows per box. Plant nutrient solution was applied based on half the concentration of the Hoagland nutrient formula. Silicon treatments were applied by adding to the Hoagland nutrient solution daily after the plants had established (ten days after sowing) until the end of the experiment. At the end of the growth period, growth traits including fresh and dry weight of leaves and roots, yield and nitrate content were measured. During the storage period, traits such as weight loss, phenol content, vitamin C, and carbohydrate content were also measured.

3. Results and Discussion

3.1 Fresh and dry weight of the root

The results of the analysis of variance for the fresh and dry weight of the root showed that the application of silicon significantly affected the fresh and dry weight of the root in Arugula plants at the 5 percent level (Table 1).

Based on the comparison chart of means, the application of silica fertilizer increased the fresh root weight, with the highest increase observed in the treatments with 10 mM silica (Figure 1). Additionally, according to the comparison chart for root dry weight, the application of 10 mM silica led to an increase in the dry root weight in the Arugula plant (Figure 2).

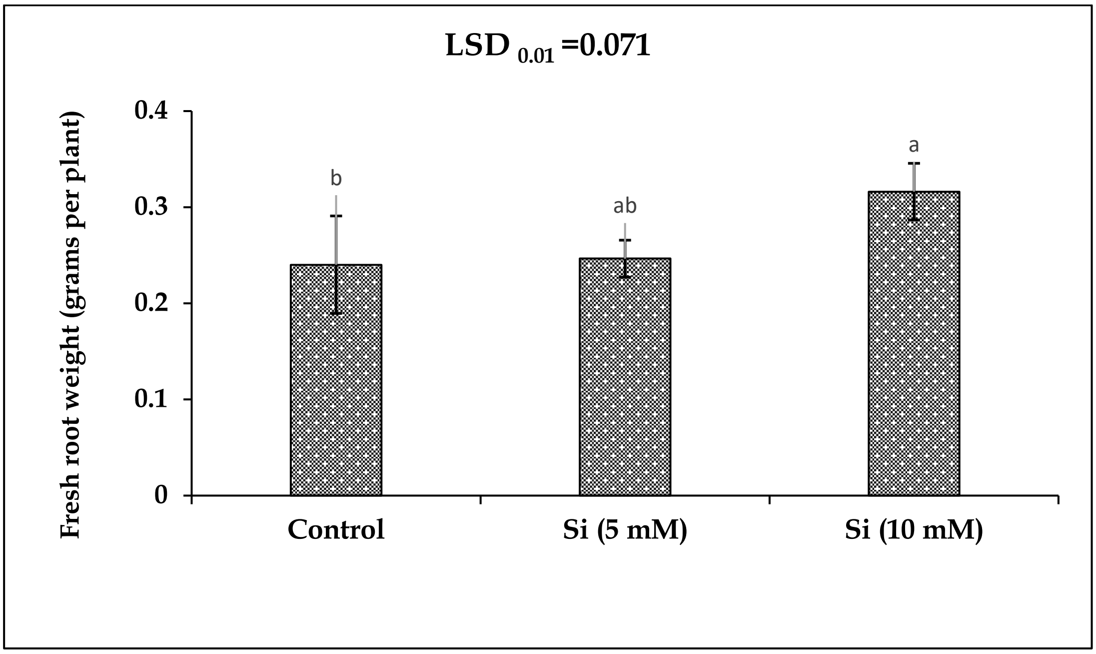

Figure 1. Effect of silica on fresh root weight of arugula (*Eruca sativa*) at harvest.

Figure 1 illustrate Fresh root weight of mustard greens at harvest time in control samples and those treated pre-harvest with 5 and 10 mM concentrations of silica. Data are presented as mean ± standard error (n = 3). Different letters indicate significant differences based on the LSD test at the 5% probability level.

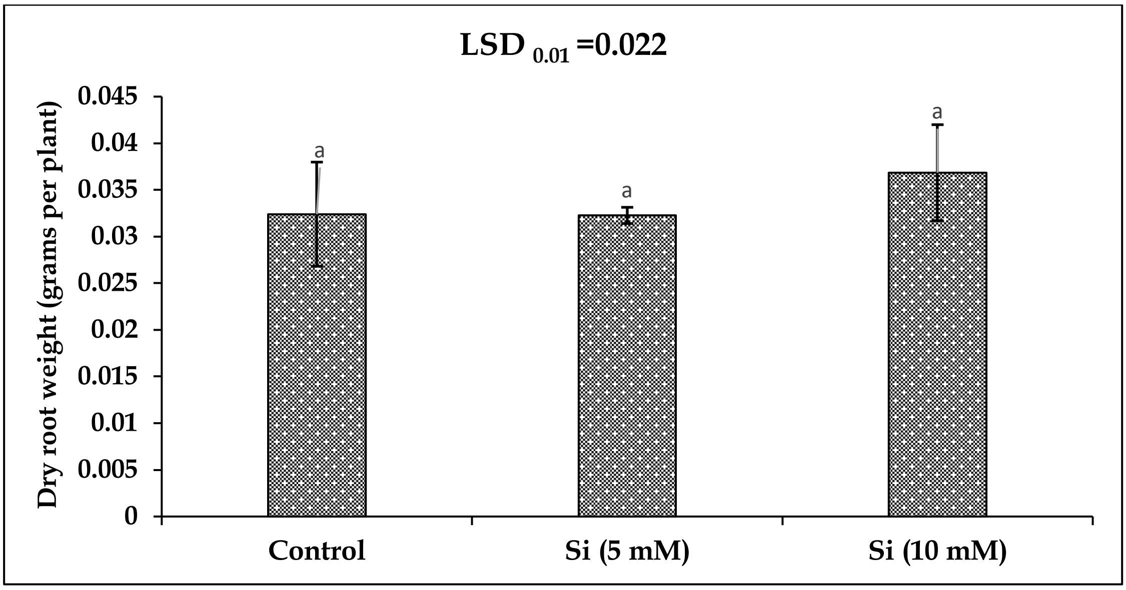

Figure 2. Effect of silica on dry root weight of arugula (*Eruca sativa*) at harvest.

Figure 2 shows, Dry root weight of mustard greens at harvest time in control samples and those treated pre-harvest with 5 and 10 mM concentrations of silica. Data are presented as mean ± standard error (n = 3). Different letters indicate significant differences based on the LSD test at the 5% probability level.

3.2 Leaf Nitrate Content

The results obtained from the analysis of variance showed that leaf nitrate content was significantly affected by silica application at the 1% probability level (Table 3).

Based on the results obtained from the mean comparison chart, nitrate accumulation increased with the application of silica. However, the 5 mM silica treatment did not show a significant difference compared to the control, while increasing the silica concentration to 10 mM resulted in a considerable reduction in nitrate accumulation (Figure 3).

The highest nitrate content in the present study corresponds to the control sample (2000 mg per kg of fresh weight), whereas in the 10 millimolar treatment, it has decreased to 1000 mg per kg of fresh weight.

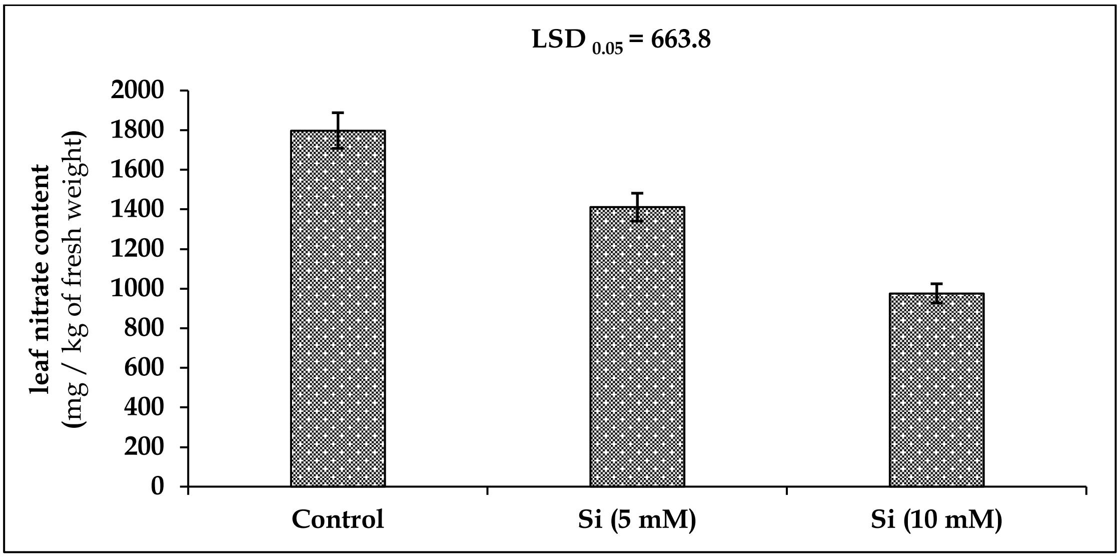

Figure 3. Effect of silica on leaf nitrate content of arugula (*Eruca sativa*) before harvest.

Figure 3 depicts Mean comparison chart of leaf nitrate content before harvest in control samples and pre-harvest treatments with 5 and 10 mM silica concentrations, mean ± standard error (replicates = 3). Different letters indicate significant differences based on the LSD test at the 5% probability level.

Based on the results obtained from the mean comparison chart, with increasing silica concentration, nitrate accumulation in Arugula (Eruca sativa) leaves decreased. The application of 10 mM silica had a greater effect compared to 5 mM silica and the control (Figure 3). In a study on the effect of silica nanoparticles on cucumber under hydroponic conditions, researchers reported that, in addition to increasing photosynthesis, chlorophyll, fresh and dry weight, and yield, nitrate content also increased in both fruit and leaves (Shakari *et al*., 2022). The reduction of nitrate in plant storage organs is directly related to harvest time, as nitrate levels are naturally low in the storage organs of plants at the early vegetative stage (Maynard *et al*., 1976). Therefore, to reduce nitrate content in leafy vegetables, the optimal physiological age for harvesting each plant should be selected according to the plant species.

The results obtained from the analysis of variance showed that leaf nitrate content was significantly affected by silica application at the 1% probability level (Table 3).

Based on the results of the mean comparison, nitrate accumulation in Arugula leaves decreased with increasing silica concentration. While the 5 mM silica treatment did not show a statistically significant difference compared to the control, the 10 mM silica treatment resulted in a substantial reduction in nitrate accumulation (Figure 3).

In the present study, the highest nitrate content was observed in the control treatment (approximately 2000 mg kg^{-1} fresh weight), whereas nitrate concentration decreased to about 1000 mg kg^{-1} fresh weight in plants treated with 10 mM silica. These findings clearly indicate that silica application, particularly at higher concentrations, effectively reduces nitrate accumulation in Arugula leaves prior to harvest.

Table 1. Results of the analysis of variance for the effect of silicon treatment on the fresh and dry weight of Arugula.

Sources of Variation	**Mean Squares**			
	Degrees of Freedom	Fresh Weight of the Root	Dry Weight of the Root	Leaf Nitrate
Replication	2	0.01^{ns}	0.0001^{ns}	31437.23^{ns}
Treatment	2	0.005*	0.0001*	507761/47**
Error	4	0.001	0.000	85738/42
Coefficient of Variation(%)		10.85	17.32	20.99

^{ns} , *and ** indicate non-significant, significant at the 5% and significant at the 1% probability level, respectively.

3.3 Performance of Aerial Organs

The results obtained from the analysis of variance of the data related to the fresh and dry weight of aerial organs and the total performance of aerial organs showed that the effect of silica in Arugula (*Eruca sativa*) on these traits was significant at the 1% level (Table 2).

Table 2. Effect of pre-harvest silica on fresh and dry leaf weight and total yield of arugula (*Eruca sativa*).

Sources of Variation	**Mean Squares**			
	Degrees of Freedom	Fresh Weight of the leaf	Dry Weight of the leaf	Yeild
Replication	2	0.011^{ns}	0.621^{ns}	0.486^{ns}
Treatment	2	0.480**	3.58**	20.87**
Error	4	0.032	0.137	1.37
Coefficient of Variation(%)		6.06	3.61	6.07

^{ns} and ** indicate non-significant and significant at the 1% probability level, respectively.

The results obtained from the analysis of variance of the data related to the fresh weight, dry weight, and performance of aerial organs showed that the effect of silica in Arugula (*Eruca sativa*) on these traits was significant at the 1% level (Table 2). According to the comparison of means, the fresh weight of aerial organs increased with the application of 10 mM silica compared to the 5 mM silica treatment and the control (Figure 4).

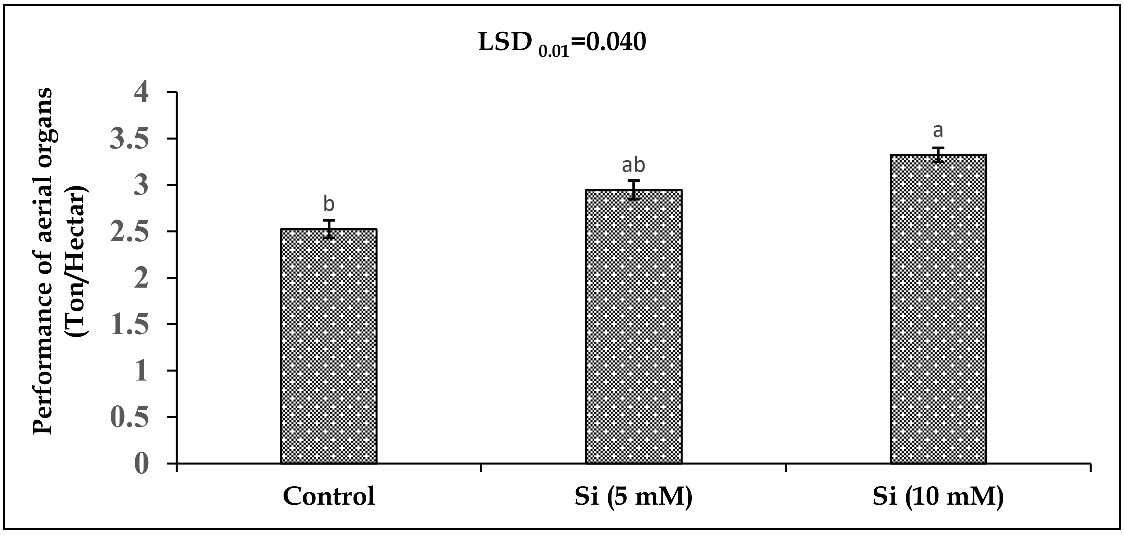

Figure 4. Effect of pre-harvest silica on fresh and dry weight of aerial organs of arugula (*Eruca sativa*) at harvest.

Figure 4 depict Performance of aerial organs of arugula (Eruca sativa) at harvest time in control samples and pre-harvest treatments with 5 and 10 mM silica concentrations, mean ± standard error (replicates = 3). Different letters indicate significant differences based on the LSD test at the 1% probability level.

Silica increases root biomass by enhancing the mechanism of nutrient transfer. Nutritional supplementation with silica can lead to an increase in root volume as well as improved rooting (Azizi *et al.,* 2016). Additionally, feeding with silica fertilizers creates a strong complex with compounds in the cell wall, enhancing the strength of xylem vessels and preventing physiological disorders (Bandani and Abdolazadeh, 2007). Silica penetrates the cell wall, resulting in increased thickness and diameter of the stem (Zhao *et al.,* 2013). Based on the results from the variance analysis table (1) and mean comparison charts, it can be concluded that silica improves the resistance of aerial organs and stems and enhances nutrient and water absorption in the roots, leading to increased growth and yield in the studied plant. This increase was more pronounced at a concentration of 10 millimolar silica compared to 5 millimolar. In a study on the application of silica fertilizer on cucumber in a hydroponic culture, it was observed that the fresh and dry weight of roots and aerial organs in plants treated with silica fertilizer significantly increased compared to the control group, attributed to the effect of silica fertilizer on water and nutrient absorption. In that research, different concentrations of silica were used at three levels (zero, 200, and 500 mg per liter), which showed that with increasing silica concentration, the fresh and dry weight of roots and aerial organs significantly increased (Moghadam *et al.,* 2010). The application of silica fertilizer at a concentration of 5 millimolar increased the fresh and dry weight of leaves in the Parous strawberry variety (Seydlar Fatemi *et al.,* 2010). The application of silica has also increased dry matter in wheat (Gong *et al.,* 2003). The improvement in performance under silica nutrition conditions is due to the increased surface area for the absorption of elements and nutrients (Pulz *et al.,* 2008).

3.4 Leaf Phenol, Flavonoid, and Vitamin C Content

The results obtained from the analysis of variance showed that the application of silica fertilizer had a significant effect on leaf phenol, flavonoid, and vitamin C content at the 1% probability level (Table 3).

Phenol content

The highest phenol content was observed in the 5 mM silica treatment with 7 days of storage, while the lowest phenol content was recorded in the control with 10 days of storage. The application of 5 mM silica increased phenol content during the storage period compared to the control. The 10 mM silica treatment did not show a significant difference from the 5 mM treatment at 0 and 4 days of storage; however, phenol content decreased at 7 and 10 days of storage.

Table 3. Results of analysis of variance for phenol, flavonoid, and vitamin C content in Arugula (*Eruca sativa*) under the effect of silica application

	Mean Squares					
Sources of Variation	Degrees of Freedom	Fenol	Flovonoeid	Vit C	Wieght loss	Corbohydrate
Storage Time	3	789.4**	81.19**	0.270**	586.21**	196.70**
Silica Treatment	2	373.3**	39.56**	0.195**	48.97*	120.99**
Storage Time × Silica Treatment	6	122.6**	112.47**	0.80**	9.53**	8.41**
Error	24	55.30	12.56	0.004	22.09	1.04
Coefficient of Variation(%)		13.33	14.96	0.53	45.30	9.06

significant at the 1% probability level, respectively.

Flavonoid content

The highest flavonoid content was observed in the control at 0 days of storage. The lowest flavonoid content was recorded in the 10 mM silica treatment after 10 days of storage. The application of 5 mM silica, except at 4 and 7 days of storage, caused a decrease in flavonoid content compared to the control. The 10 mM silica treatment increased flavonoid content at 4 and 7 days of storage.

Vitamin C content

The highest vitamin C content was observed in the control at 0 days of storage. The application of 5 mM silica resulted in a decrease in vitamin C up to 7 days of storage, followed by a slight increase at 10 days compared to the control. The 10 mM silica treatment showed a lower vitamin C content compared to the previous treatments; however, vitamin C levels remained stable and unchanged throughout the storage period.

Vitamin C is considered a commercial index for defining the nutritional value of fruits and vegetables. The amount of vitamin C, or ascorbic acid, is typically influenced by factors such as genotype, climatic variations and environmental conditions, cultivation methods, maturity, harvest time, post-harvest techniques, and storage conditions. This vitamin is highly sensitive to oxidation and has low stability (Akhtar et al., 2010). Silica and nano-silica have been shown to preserve fruit quality and vitamin C content in strawberries (Stamatakis *et al*., 2003).

The results obtained from the analysis of variance showed that the application of silica fertilizer had a significant effect on weight loss and carbohydrate content during the storage period at the 1% probability level (Table 3).

Weight Loss Control

The highest weight loss was observed in the control after 10 days of storage. The application of 5 mM silica caused an increase in weight changes during the storage period, but this increase was lower than that of the control. In the 10 mM silica treatment, the highest weight changes were observed after 10 days of storage, which was not significantly different from the 10-day storage of leaves treated with 5 mM silica.

One of the important goals in post-harvest stages is the control of product weight loss. When a product loses weight during storage, its marketability decreases. If the plant's nutritional conditions are not optimal, its post-harvest lifespan is significantly reduced (Koushesh Saba and Ramazanian, 2015). The application of potassium silicate in lettuce reduced weight loss during the storage period after harvest (Mattiuz *et al.,* 2015). Researchers believe that silica and nano-silica help retain water in the product, resulting in a lower rate of weight loss after harvest. The effect of silica fertilizer on maintaining product weight post-harvest may be due to increased cell wall strength (Weerahewa and David, 2015). In the present study, it seems that weight loss in the samples during storage is due to differences in water vapor pressure between the samples and their surrounding environment, which leads to the movement of intercellular water to the surrounding space.

Total Carbohydrate Content

Based on the findings from the analysis of variance, total carbohydrate content in Arugula (Eruca sativa) was significantly affected by silica application, storage duration, and the interaction of silica and storage duration at the 1% probability level. The comparison of mean carbohydrate data under the effect of silica showed that the application of 10 mM silica can increase total carbohydrate content during storage, with the highest carbohydrate content observed in samples stored for 10 days under the 10 mM silica treatment.

Carbohydrates play a protective role in regulating the osmotic balance of cells. Soluble sugars usually accumulate under stress conditions. The increase in carbohydrates during storage can be attributed to the mechanism of osmotic pressure enhancement (Ghaderi and Siosemardeh, 2011). The application of silica enhances water and nutrient uptake in the plant, leading to increased growth; as a result, photosynthesis is enhanced and carbohydrate accumulation during product storage is affected (Abu-Muriefah, 2015). The increase in carbohydrates observed in this study may be attributed to the conversion of starch into sugars or the hydrolysis of polysaccharides in the cell wall.

Table 4. Interaction effect of silica concentration and storage time on total phenol, flavonoid, and vitamin C content in Arugula (Eruca sativa)

Silica (mM)	Storage Time (days)	Total Phenol (mg GAE g^{-1} FW)	Flavonoid (mg QE g^{-1} FW)	Vitamin C (mg 100 g^{-1} FW)
0	0	X_1 ± SE	Y_1 ± SE	Z_1 ± SE
0	4	X_2 ± SE	Y_2 ± SE	Z_2 ± SE
0	7	X_3 ± SE	Y_3 ± SE	Z_3 ± SE
0	10	X_4 ± SE	Y_4 ± SE	Z_4 ± SE
5	0	X_5 ± SE	Y_5 ± SE	Z_5 ± SE
5	4	X_6 ± SE	Y_6 ± SE	Z_6 ± SE
5	7	**X_7 ± SE**	Y_7 ± SE	Z_7 ± SE
5	10	X_8 ± SE	Y_8 ± SE	Z_8 ± SE
10	0	X_9 ± SE	Y_9 ± SE	Z_9 ± SE
10	4	X_{10} ± SE	Y_{10} ± SE	Z_{10} ± SE
10	7	X_{11} ± SE	Y_{11} ± SE	Z_{11} ± SE
10	10	X_{12} ± SE	**Y_{12} ± SE**	Z_{12} ± SE

Phenol, Flavonoid, and Vitamin C Content

The results of the analysis of variance indicated that storage time, silica treatment, and their interaction had significant effects ($p \leq 0.01$) on total phenol, flavonoid, and vitamin C content in Arugula leaves (Table 3). To better illustrate these interaction effects, the mean values of these metabolites under different silica concentrations and storage durations are presented in Table 4.

Total phenol content was influenced by both silica concentration and storage time. The highest phenol content was observed in plants treated with 5 mM silica after 7 days of storage, whereas the lowest phenol content occurred in the control treatment after 10 days of storage. Application of 5 mM silica generally increased phenol accumulation during storage compared to the control. In contrast, although the 10 mM silica treatment maintained phenol levels during early storage (0 and 4 days), a gradual decline was observed at 7 and 10 days of storage.

Flavonoid content showed a decreasing trend with prolonged storage across all treatments. The highest flavonoid content was recorded in the control at harvest time (0 days), while the lowest content was observed in the 10 mM silica treatment after 10 days of storage. However, plants treated with 10 mM silica exhibited relatively higher flavonoid levels at 4 and 7 days of storage compared to the control, indicating a temporary protective effect of silica during mid-storage.

Vitamin C content was significantly affected by both silica application and storage duration. The highest vitamin C content was observed in freshly harvested control samples, while a general decline was noted with increasing storage time. Although silica treatments, particularly 10 mM, showed lower absolute vitamin C values compared to the control, vitamin C levels remained more stable throughout the storage period, suggesting that silica application may contribute to maintaining vitamin C stability during post-harvest storage.

Conclusions

The present study demonstrated that pre-harvest application of silica through its incorporation into the Hoagland nutrient solution plays a significant role in improving the growth, yield, and post-harvest quality of arugula (*Eruca sativa*). Among the evaluated treatments, silica applied at a concentration of 10 mM showed the most pronounced positive effects on plant performance. This treatment significantly enhanced root and shoot development, as reflected by increased fresh and dry weights of roots and aerial organs, ultimately leading to improved total yield compared with the 5 mM silica treatment and the control.

In addition to promoting vegetative growth, silica application markedly influenced nitrogen-related traits in arugula leaves before harvest. Importantly, the results confirmed that increasing silica concentration, particularly at 10 mM, reduced nitrate accumulation in leaf tissues, which is a critical quality and food safety parameter for leafy vegetables. This reduction in nitrate content suggests that silica enhances nitrogen assimilation efficiency rather than increasing nitrate storage in plant tissues. Therefore, the observed effects of silica on nitrogen metabolism should be interpreted as improvements in nitrogen utilization and metabolic regulation, rather than an increase in leaf nitrate concentration.

Post-harvest evaluations further highlighted the beneficial role of silica nutrition in extending the shelf life of arugula. During cold storage at 4°C for 0, 4, 7, and 10 days, plants treated with silica—particularly at 10 mM—exhibited lower weight loss and better preservation of physiological and biochemical quality attributes compared to untreated plants. Key marketability indicators, including chlorophyll and carotenoid content, color index, total soluble carbohydrates, total phenolic compounds, flavonoids, and vitamin C, were maintained at higher levels in silica-treated samples throughout the storage period. These effects indicate a delay in senescence and a reduction in post-harvest deterioration.

The ability of silica to enhance cell wall strength, improve water retention, and regulate metabolic processes likely contributed to the observed improvements in both pre- and post-harvest performance. Although elevated nitrate levels are often associated with accelerated senescence in leafy vegetables, the application of silica successfully mitigated this risk by lowering nitrate accumulation while simultaneously maintaining overall plant vigor and storage quality.

The results of this study also have broader sustainability implications. By increasing arugula yield, reducing post-harvest losses, and improving nutritional quality, pre-harvest silica application contributes to SDG 2 (Zero Hunger) and SDG 3 (Good Health and Well-being), highlighting its potential role in promoting sustainable and nutritious food production systems.

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Conflicts of Interest

The authors declare no conflict of interest.

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