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Exploring the Potential Nutritional Benefits of Elements in the Periodic Table for Plants

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IN OUR QUEST to understand the intricate relationship between elements and plant nutrition, we delve into the intriguing question: "Can all elements in the periodic table be beneficial for plant nutrition?" This inquiry is pivotal in unlocking some of nutrients available to plants, potentially revolutionizing agricultural practices and fostering sustainable cultivation methods. Two plants have been chosen for this study: crisphead lettuce and red cabbage. These selected specimens represent a range of botanical species, enabling us to investigate how various plants respond to elemental supplementation with diverse perspectives. A field experiment was conducted during the 2023/2024 season at the Agricultural Faculty Farm, Mansoura University, Egypt. The tested elements from the periodic table included titanium (Ti), zirconium (Zr), chromium (Cr) and iodine (I). These elements were administered at two concentrations, 5.0 and 10 mgL^{-1} *via* foliar application on the selected plants, alongside a control group with no elemental foliar application. The study identified multiple parameters to evaluate the response of the tested plants to the studied elements. These parameters encompassed various aspects of plant growth, physiology, and biochemical composition. They included fresh and dry weights ($g plant^{-1}$), plant height (cm), No. of leaves, leaf area (cm^2 plant), head weight (g), head diameter (cm), chlorophyll (SPAD), carotene (mg 100 g^{-1}), ascorbic acid (mg 100 g^{-1}), total phenol (mg g^{-1}) and catalase activity (mgH_2O_2/g). All elements studied exhibited significant positive effects on the growth traits and productivity of both crisphead lettuce and red cabbage. Titanium showed the most pronounced impact, followed by iodine, chromium, zirconium, and finally the control group. Additionally, the enhancement in performance and productivity of both tested plants increased with higher element concentration levels from 5.0 to 10 mg L^{-1}. Based on the results obtained, it is recommended that agricultural practitioners consider foliar application of Ti, Zr, Cr and I to enhance the growth and productivity of crisphead lettuce and red cabbage. However, further research is warranted to optimize the application methods and determine the ideal concentration levels for different environmental conditions and plant varieties. Additionally, exploring the mechanisms underlying the observed enhancements could provide valuable insights for developing more efficient and sustainable agricultural practices.

Keywords: Plant nutrition, Element supplementation, Titanium (Ti), zirconium (Zr), chromium (Cr), iodine (I).

1. Introduction

In the realm of agricultural science, continual advancements are vital to meet the ever-growing demand for sustainable food production. A key avenue for achieving this goal lies in the exploration of novel nutritional elements from the periodic table that have the potential to enhance plant performance and productivity. Such endeavors are imperative in the face of mounting challenges posed by climate change, soil degradation and the burgeoning global population (Elsherpiny and Faiyad 2023; ElGhamry *et al*. 2024).

Titanium, known for its biocompatibility and catalytic properties, holds promise for enhancing plant growth and stress tolerance (Ghazi *et al*. 2022a). Zirconium, with its potential role in enzyme activation and nutrient uptake, presents an intriguing avenue for improving plant nutrition (Masalem *et al*.

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2010; Shahid *et al.* 2012). Chromium, a trace element involved in carbohydrate metabolism and oxidative stress response, offers prospects for bolstering plant health and productivity (Shahid *et al.,* 2017; López-Bucio *et al.* 2022). Similarly, iodine, crucial for thyroid function in humans, may exert beneficial effects on plant growth and nutrient content (Kumar and Hemantaranjan 2017; Kiferle *et al.* 2021).

Furthermore, the choice to study crisphead lettuce (*Lactuca sativa* L, family Asteraceae) and red cabbage (*Brassica oleracea* L, family Brassicaceae) is deliberate. Crisphead lettuce, renowned for its culinary versatility and rich nutrient profile, represents a staple crop in many cuisines worldwide (Abd El-Hady *et al.* 2024; El-Sherpiny *et al.* 2024). Red cabbage, prized for its vibrant color and health-promoting compounds, holds significance both as a culinary ingredient and a functional food (Ghazi *et al.* 2022b).

In light of the aforementioned considerations, the overarching goal of this research investigation is to assess the impact of introducing selected elements from the periodic table on the growth, productivity, and biochemical composition of crisphead lettuce and red cabbage. By subjecting these crops to elemental supplementation, this study aims to elucidate the potential benefits of titanium, zirconium, chromium, and iodine on their growth, nutritional quality, and antioxidant capacity. Through a systematic examination of various parameters, this study endeavors to contribute valuable insights to the field of agricultural science, thereby facilitating the development of innovative strategies for sustainable crop production and nutritional enhancement. The selection of these crops is strategic, considering their widespread cultivation, nutritional value, and economic significance in various regions worldwide.

2. Materials and Methods

Location site

This investigation was conducted during the 2023/2024 season at the Agricultural Faculty Farm, Mansoura University, Egypt, located at coordinates 31°03′00″N 31°22′9″E in the El-Dakahlia Governorate, Egypt.

Initial soil characteristics

Before transplantation, a soil sample was obtained from a depth of 0.0 to 30 cm for routine soil physical and chemical analysis. The standard methods outlined by Tandon (2005) were followed for this analysis. The properties of the soil before transplantation are detailed in Table 1.

Table 1. Initial soil properties.

Characteristics and unit	Values
Silt, g $100g^{-1}$	35. 3
Sand, g $100g^{-1}$	15.0
Clay, g $100g^{-1}$	49.7
Textural class	Clay
EC, dSm^{-1}	3.00
pH	8.00
Organic matter, %	1.19
Availability of macronutrients, $mgKg^{-1}$	
Available nitrogen	40.02
Available phosphorus	6.000
Available potassium	201.6

Plant tested

The plants examined in this study were crisphead lettuce and red cabbage. Seedlings of crisphead lettuce (cv Kharga, 20 days old) and red cabbage (cv Nadine, 45 days old) were procured from private nurseries for experimentation.

Periodic elements used

The elements selected from the periodic table included titanium (Ti), obtained in the form of titanium dioxide (TiO_2); zirconium (Zr), sourced as zirconium oxide (ZrO_2); chromium (Cr), acquired as chromium sulfate [$Cr_2(SO4)_3$]; and iodine (I), obtained as iodine pentoxide (I_2O_5). These elements were all procured from the Chemistry Department at the Faculty of Agriculture, Mansoura University in Egypt (sourced Sigma Company). Solutions of each element were meticulously prepared at concentrations of 5.0 and 10.0 mg L^{-1}. To attain the desired concentrations for standard solutions, precise quantities of each salt were dissolved in water.

Experimental design and flowchart

The tested elements from the periodic table were administered at two concentrations, 5.0 and 10 mgL^{-1} *via* foliar application on the selected plants, alongside a control group with no elemental foliar application. The experimental design followed a completely randomized block design with three replicates. Fig. 1 depicts the experimental flowchart.

Experimental setup and transplanting

Each studied plant occupied a plot area of 46.2 m² (7.70 m x 6.0 m), with rows extending 6.0 m in length and 0.85 m in width. Within each plot, there were 9 rows representing different treatments. Each row was subdivided into three replicates, each 2.0 m in length.

Transplantation of both crisphead lettuce and red cabbage seedlings occurred on October 20th, with plants spaced 50 cm apart in the middle of the ridges.

Before transplanting, organic fertilizer (plant compost) was mixed into the soil for both crisphead lettuce and red cabbage. The plant compost being utilized possesses a pH level of 8.14, an EC value of 4.0 dSm^{-1}, a C/N ratio (carbon-to-nitrogen) ratio of 13.4, and an organic matter content of 55%. Additionally, before plowing, calcium superphosphate (6.6% P) was applied to all plots at a rate equivalent to 72 units ha^{-1}. Nitrogen fertilization was applied in two equal doses using urea (46% N) at a rate of 120 units ha^{-1}. Potassium sulfate, containing 39.84% K, was administered alongside the second dose of nitrogen at a rate of 49.8 ha^{-1}.Titanium (Ti), zirconium (Zr), chromium (Cr), and iodine (I) were sprayed three times, with the first application initiated 25 days after transplanting, followed by subsequent applications at 10-day intervals.

Irrigation

The irrigation water utilized for the experiment was drawn from the Nile River. The prescribed irrigation requirements were approximately set at 3000 m³ per hectare for both crisphead lettuce and red cabbage.

Harvest time and plant sampling

On 13th of January, the harvest process was executed for both studied plants. At the 83-day mark from transplanting, three plants each of crisphead lettuce and red cabbage were sampled from every replicate for the measurement of various growth parameters, yield attributes, and quality, as detailed in Table 2.

Statistical Analyses

The statistical analysis of the data followed the methodology described by Gomez and Gomez (1984), utilizing CoStat version 6.303 copyright (1998-2004). Treatment means were compared using the least significant difference (LSD) at a significance level of 0.05 probability. To facilitate the comparison of means across different treatments, Duncan's Multiple Range (Duncan 1955).

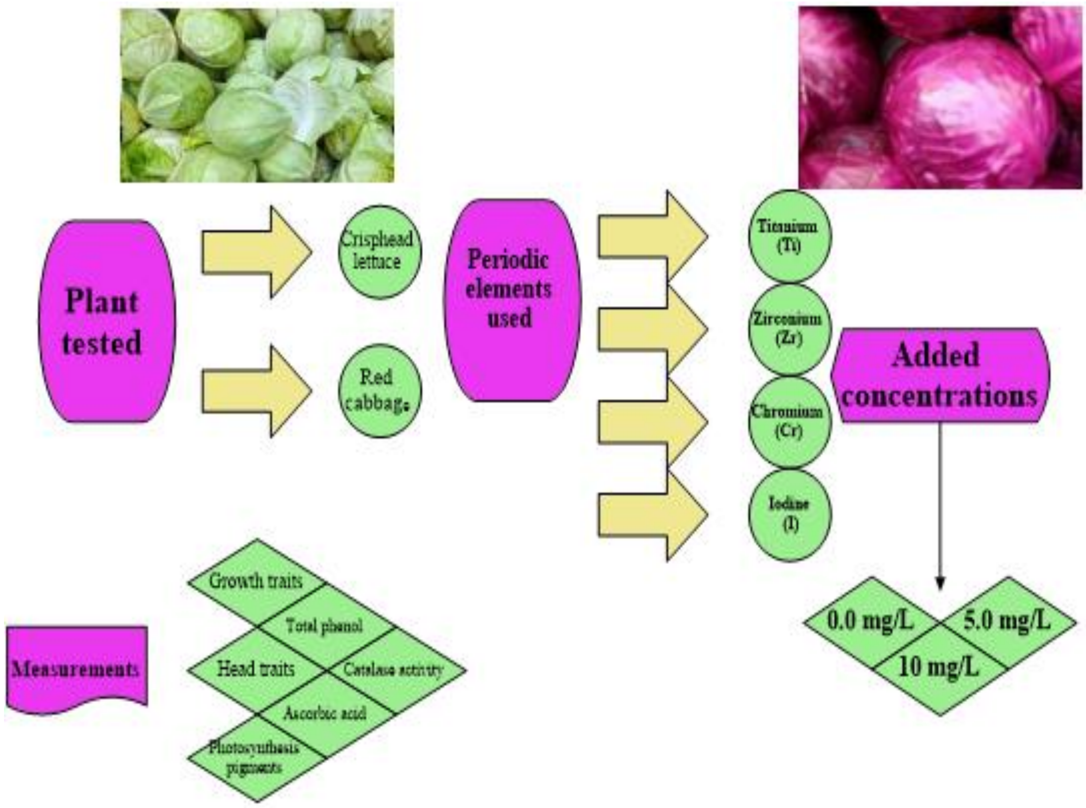

Fig. 1. The flowchart of the studied treatments and measurements.

Table 2. Measurements in each plant, methods and references.

Measurements		Plant	Methods	Refs.
Fresh and dry weights, g plant^{-1} **Plant height, cm** **No. of leaves** **Leaf area, cm^2 plant** **Head weight, g plant^{-1}** **Head diameter, cm**		In both studied plants	Manually	
Head length, cm **No. of outer leaves** **Weight of outer leaves, g plant^{-1}**		In red cabbage only		
Photosynthetic pigments, in fresh weight	**Chlorophyll content**	In both studied plants	Measuring *via* a SPAD meter (SPAD-502, Minolta Camera, Osaka, Japan),	[1]
	Carotene content		Determining using acetone through a spectrophotometer	
Digesting the dry samples to determine the chemical composition (nitrogen, phosphorus, potassium and iron)		In both studied plants	Using $H_2SO_4/HClO_3$	[2]
Nitrogen,%			*Via* Micro-Kjeldahl method	[3]
Phosphorus, %			*Via* Olsen method using spectrophotometer	
Potassium, %			Using flam photometer	
Iron, mg kg^{-1}			Using atomic adsorption	
Catalase activity (mgH_2O_2/g)		In both studied plants	Spectrophotometric determination	[4]
Anthocyanin, mg 100g^{-1}		In red cabbage only		[5]
Ascorbic acid, mg 100 g^{-1} **Total phenol, mg g^{-1} DM** **Total carbohydrates, %** **Total dissolved solid**		In both studied plants	Stander methods	[6]

List of refs: [1] Dere, (1998), [2] Peterburgski, (1968), [3] Walinga *et al.* (2013), [4] Elavarthi and Martin (2010), [5] Mazza, *et al.* (2004), [6] AOAC, (2000).

3. Results

Growth criteria and head traits

Table 3 depicts the data showing the effect of spraying titanium (Ti), zirconium (Zr), chromium (Cr) and iodine (I) at different rates on growth performance and head traits of crisphead lettuce, including fresh and dry weights (g plant^{-1}), plant height (cm), No. of leaves, leaf area (cm^2 plant), head weight (g plant^{-1}) and head diameter (cm). On the other hand, Tables 4 and 5 present the effects of the same treatments on red cabbage plants. In addition to the aforementioned traits, these tables also provide data on head length (cm), number of outer leaves, and weight of outer leaves (g plant^{-1}) of red cabbage.

Analysis of the data presented in Tables 3, 4 and 5 reveals significant positive effects of all studied elements on the growth criteria and head traits of both crisphead lettuce and red cabbage. Among the elements, titanium demonstrated the most substantial effect, followed by iodine, chromium, zirconium, and the control group, in decreasing order of effectiveness. Moreover, the enhancement in growth criteria and head traits of both plant species was observed to increase with higher concentrations of the elements, ranging from 5.0 to 10 mg L^{-1}. This trend was consistent across both tested plants, indicating a dose-dependent response to elemental supplementation.

Table 3. Effect of spraying some periodic table elements [titanium (Ti), zirconium (Zr), chromium (Cr) and iodine (I)] on growth performance of crisphead lettuce and head traits.

Treatments	Fresh weight, g plant^{-1}	Dry weight, g plant^{-1}	Plant height, cm	No. of leaves	Leaf area, cm^2 plant	Head weight, g plant^{-1}	Head diameter, cm
Control	516.67f	53.67h	20.10f	21.33f	952.33f	347.00i	14.73d
Zr (5.0 mgL^{-1})	608.00e	66.00g	20.40f	24.67ef	963.00f	389.67h	15.17cd
Zr (10.0 mgL^{-1})	655.00d	82.00f	23.27e	27.67e	967.33f	403.67g	15.30cd
Cr (5.0 mgL^{-1})	695.00c	88.00e	24.30e	32.33d	1025.67e	438.67f	15.77bcd
Cr (10.0 mgL^{-1})	719.00c	90.67e	27.37d	35.67cd	1055.00de	458.00e	15.93bcd
I (5.0 mgL^{-1})	784.67b	95.00d	28.23d	37.67c	1080.00cd	489.33d	16.30abc
I (10.0 mgL^{-1})	891.00a	113.00c	32.40c	44.67b	1110.00bc	502.33c	17.10ab
Ti (5.0 mgL^{-1})	895.33a	117.00b	35.97b	50.67a	1151.00ab	515.67b	17.57a
Ti (10.0 mgL^{-1})	903.00a	126.00a	37.67a	53.67a	1192.00a	577.67a	17.63a
LSD at 5%	**31.26**	**3.99**	**1.49**	**3.64**	**44.11**	**12.98**	**1.53**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level.

Table 4. Effect of spraying some periodic table elements [titanium (Ti), zirconium (Zr), chromium (Cr) and iodine (I)] on growth performance of red cabbage and head traits.

Treatments	Fresh weight, g plant^{-1}	Dry weight, g	Plant height,	No. of leaves	Leaf area, cm^2 plant
Control	808.67i	72.67i	35.40f	31.00f	986.37g
Zr (5.0 mgL^{-1})	871.33h	92.00h	35.97ef	32.00ef	995.30fg
Zr (10.0 mgL^{-1})	963.33g	109.00g	36.43def	35.00de	1007.57efg
Cr (5.0 mgL^{-1})	1083.00f	130.00f	37.60cde	36.00d	1014.67def
Cr (10.0 mgL^{-1})	1190.33e	145.00e	37.97cd	37.00d	1027.40cde
I (5.0 mgL^{-1})	1289.67d	156.67d	38.27bc	43.00c	1033.50bcd
I (10.0 mgL^{-1})	1396.00c	175.00c	39.80ab	49.33b	1046.50abc
Ti (5.0 mgL^{-1})	1479.67b	187.67b	40.13a	50.33b	1055.00ab
Ti (10.0 mgL^{-1})	1573.33a	204.00a	40.43a	55.67a	1069.80a
LSD at 5%	**8.19**	**7.82**	**1.77**	**3.50**	**23.57**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level.

Table 5. Effect of spraying some periodic table elements [titanium (Ti), zirconium (Zr), chromium (Cr) and iodine (I)] on head traits of red cabbage.

Treatments	Head weight, g plant^{-1}	Head diameter, cm	Head length, cm	No. of outer leaves	Weight of outer leaves, g
Control	775.33e	15.80f	18.57h	13.00f	146.32i
Zr (5.0 mgL^{-1})	794.33de	16.00f	19.10g	13.67ef	163.22h
Zr (10.0 mgL^{-1})	811.00d	16.50e	19.47fg	14.33ef	179.71g
Cr (5.0 mgL^{-1})	832.33c	16.77de	19.83ef	15.00e	191.48f
Cr (10.0 mgL^{-1})	848.00c	17.00cd	20.20de	16.67d	205.12e
I (5.0 mgL^{-1})	930.67b	17.27c	20.60cd	17.33cd	217.28d
I (10.0 mgL^{-1})	945.33b	17.70b	20.90bc	18.67bc	226.92c
Ti (5.0 mgL^{-1})	967.00a	18.10a	21.30ab	20.00ab	239.57b
Ti (10.0 mgL^{-1})	982.33a	18.37a	21.60a	20.67a	250.59a
LSD at 5%	**19.06**	**0.38**	**0.43**	**1.62**	**3.49**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level.

Photosynthetic pigments and leaves chemical constituents

Table 6 illustrates the effect of spraying titanium (Ti), zirconium (Zr), chromium (Cr) and iodine (I) at different rates on photosynthetic pigments [chlorophyll (SPAD reading), carotene (mg 100g^{-1})] and leaves chemical constituents [N, P, K (%) and Fe (mg kg^{-1})] of crisphead lettuce. Conversely, Table 7 provides insights into the effects of the same treatments on the aforementioned traits but on red cabbage plants.

The results indicate that all studied elements significantly increased the values of the mentioned traits in both crisphead lettuce and red cabbage compared to the control treatment. Titanium exhibited the most pronounced effect, followed by iodine, chromium, zirconium, and the control group. The most effective treatment was the spraying of titanium at a rate of 10 mg L^{-1}, resulting in the highest values of photosynthetic pigments (chlorophyll measured *via* SPAD reading, carotene content in mg $100g^{-1}$) and leaf chemical constituents (nitrogen, phosphorus, potassium percentages, and iron concentration in mg kg^{-1}) for both plants. Additionally, it was observed that the values increased with increasing element concentration levels from 5.0 to 10 mg L^{-1} for both tested plants.

Table 6. Effect of spraying some periodic table elements [titanium (Ti), zirconium (Zr), chromium (Cr) and iodine (I)] on photosynthetic pigments and leaves chemical constituents of crisphead lettuce.

Treatments	Photosynthetic pigments		Leaves chemical constituents			
	Chlorophyll, SPAD reading	Carotene, mg $100g^{-1}$	N, %	P, %	K ,%	Fe, mg kg^{-1}
Control	6.00e	0.029g	1.01g	0.302f	0.94g	72.10f
Zr (5.0 mgL^{-1})	6.13e	0.035f	1.06g	0.309f	1.10f	72.20f
Zr (10.0 mgL^{-1})	6.30de	0.039ef	1.18f	0.331e	1.14f	73.06ef
Cr (5.0 mgL^{-1})	6.90d	0.041e	1.25f	0.342d	1.22ef	74.92e
Cr (10.0 mgL^{-1})	8.67c	0.049d	1.42e	0.353c	1.34de	78.11d
I (5.0 mgL^{-1})	9.63b	0.054c	1.55d	0.355c	1.41cd	82.04c
I (10.0 mgL^{-1})	9.87b	0.057c	1.69c	0.387b	1.51c	82.96c
Ti (5.0 mgL^{-1})	10.30b	0.061b	1.79b	0.391b	1.72b	86.90b
Ti (10.0 mgL^{-1})	11.40a	0.076a	1.93a	0.415a	1.94a	89.82a
LSD at 5%	**0.75**	**0.004**	**0.08**	**0.009**	**0.12**	**1.94**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level.

Table 7. Effect of spraying some periodic table elements [titanium (Ti), zirconium (Zr), chromium (Cr) and iodine (I)] on photosynthetic pigments and leaves chemical constituents of red cabbage.

Treatments	Photosynthetic pigments		Leaves chemical constituents			
	Chlorophyll, SPAD reading	Carotene, mg $100g^{-1}$	N, %	P, %	K ,%	Fe, mg kg^{-1}
Control	2.00f	0.630h	1.45f	0.204h	1.50f	705.00h
Zr (5.0 mgL^{-1})	2.40e	0.766g	1.54ef	0.218g	1.61ef	717.67g
Zr (10.0 mgL^{-1})	2.40e	0.981f	1.60def	0.221g	1.70def	730.13f
Cr (5.0 mgL^{-1})	2.60de	1.117e	1.65def	0.256f	1.77cde	746.97e
Cr (10.0 mgL^{-1})	2.90cd	1.187d	1.68de	0.326e	1.87bcd	772.57d
I (5.0 mgL^{-1})	3.00c	1.699c	1.79cd	0.355d	1.93bc	778.00d
I (10.0 mgL^{-1})	3.17bc	1.710c	1.90bc	0.384c	2.04ab	808.83c
Ti (5.0 mgL^{-1})	3.40ab	1.921b	2.00ab	0.407b	2.21a	823.90b
Ti (10.0 mgL^{-1})	3.50a	2.107a	2.12a	0.416a	2.25a	839.90a
LSD at 5%	**0.33**	**0.035**	**0.20**	**0.007**	**0.22**	**5.56**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level.

Enzymatic antioxidants (catalase)

Figure 2 illustrates the effect of spraying titanium (Ti), zirconium (Zr), chromium (Cr), and iodine (I) at varying concentrations on catalase activity (mgH_2O_2/g) in the leaves of both crisphead lettuce and red cabbage. Interestingly, the highest catalase activity values for both plant species were observed in the control group, indicating a potential suppressive effect of the studied elements on catalase activity. The order sequence, from the highest to the lowest catalase activity values in leaves of crisphead lettuce and red cabbage, is as follows: Control > Zr (5 mgL^{-1}) > Zr (10 mgL^{-1}) > Cr (5 mgL^{-1}) > Cr (10 mgL^{-1}) > Ti (5 mgL^{-1}) > Ti (10 mgL^{-1}).This sequence suggests differential effects of the studied elements on catalase activity, with zirconium demonstrating the most significant impact at both concentrations, followed by chromium and titanium.

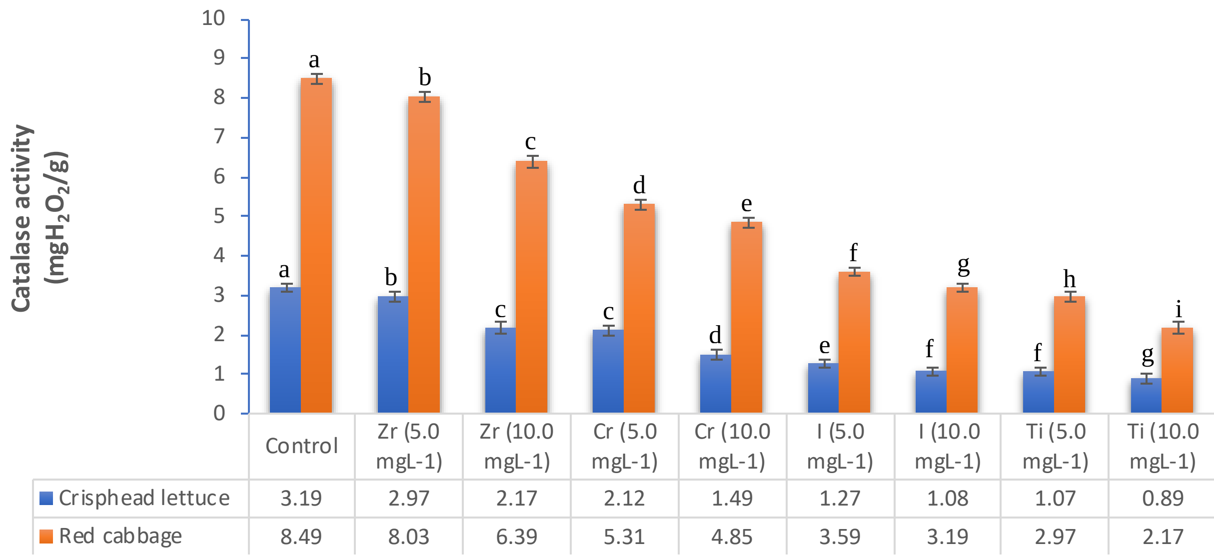

Fig. 2. Effect of spraying some periodic table elements [titanium (Ti), zirconium (Zr), chromium (Cr) and iodine (I)] on catalase activity in leaves of crisphead lettuce and red cabbage.

Quality traits

Table 8 shows the effect of spraying titanium (Ti), zirconium (Zr), chromium (Cr) and iodine (I) at different rates on quality traits of crisphead lettuce, including ascorbic acid (mg $100g^{-1}$), total phenol (mg g^{-1} DM), total carbohydrates (%) and total dissolved solid (TDS,%). On the other hand, Table 9 presents the effects of the same treatments on red cabbage plants. In addition to the aforementioned traits, these tables also provide data on anthocyanin pigment in red cabbage (mg $100g^{-1}$). The data reveal a significant positive effect of all studied elements on all quality traits of both crisphead lettuce and red cabbage. Among the elements, titanium demonstrated the most substantial effect, followed by iodine, chromium, zirconium, and the control group, in decreasing order of effectiveness. Moreover, the enhancement in quality traits of both plant species was observed to increase with higher concentrations of the elements, ranging from 5.0 to 10 mg L^{-1}. This trend was found with both studied plant species.

Table 8. Effect of spraying some periodic table elements [titanium (Ti), zirconium (Zr), chromium (Cr) and iodine (I)] on quality traits of crisphead lettuce.

Treatments	Ascorbic acid, mg $100g^{-1}$	Total phenol, mg g^{-1} DM	Total carbohydrates, %	*TDS,%
Control	3.81h	0.22g	26.94f	19.04d
Zr (5.0 mgL^{-1})	4.18g	0.31f	28.79e	19.39d
Zr (10.0 mgL^{-1})	4.44f	0.38e	29.04de	19.94c
Cr (5.0 mgL^{-1})	4.61e	0.40de	29.48cde	19.94c
Cr (10.0 mgL^{-1})	4.64e	0.42d	29.76cd	20.08bc
I (5.0 mgL^{-1})	4.85d	0.47c	30.05c	20.14bc
I (10.0 mgL^{-1})	5.01c	0.52b	30.96b	20.23abc
Ti (5.0 mgL^{-1})	5.23b	0.60a	31.31b	20.48ab
Ti (10.0 mgL^{-1})	5.46a	0.63a	33.17a	20.66a
LSD at 5%	**0.12**	**0.04**	**0.76**	**0.51**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level.
*TDS=Total dissolved solid.

Table 9. Effect of spraying some periodic table elements [titanium (Ti), zirconium (Zr), chromium (Cr) and iodine (I)] on quality traits of red cabbage.

Treatments	Anthocyanin, mg 100g^{-1}	Ascorbic acid, mg 100g^{-1}	Total phenol, mg g^{-1} DM	Total carbohydrates, %	*TDS,%
Control	0.394e	20.46h	3.26f	33.50g	18.65d
Zr (5.0 mgL^{-1})	0.416d	23.63g	3.30f	34.19g	18.80cd
Zr (10.0 mgL^{-1})	0.418cd	25.73f	3.32f	36.59f	19.01bcd
Cr (5.0 mgL^{-1})	0.420bcd	26.47e	3.49e	37.35f	19.16bc
Cr (10.0 mgL^{-1})	0.421ab	26.46e	3.78d	39.94e	19.34ab
I (5.0 mgL^{-1})	0.421ab	30.54d	3.83d	42.59d	19.37ab
I (10.0 mgL^{-1})	0.426abc	32.58c	5.58c	44.72c	19.39ab
Ti (5.0 mgL^{-1})	0.429ab	34.65b	6.05b	48.82b	19.41ab
Ti (10.0 mgL^{-1})	0.430a	36.55a	6.29a	50.42a	19.63a
LSD at 5%	**0.010**	**0.71**	**0.10**	**1.06**	**0.46**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level.
*TDS=Total dissolved solid.

4. Discussion

The observed improvements in growth performance, head traits and quality of both crisphead lettuce and red cabbage with the supplementation of each studied element may be attributed to the vital role of each studied element and its role in plant nutrition.

Titanium (Ti) came in the first order, as it is known to play a crucial role in various physiological processes in plants, including photosynthesis, enzyme activation, and nutrient uptake (Ghazi *et al*. 2022a). It acts as a cofactor for certain enzymes involved in chlorophyll synthesis and carbon fixation, thereby enhancing photosynthetic efficiency and overall plant growth. Additionally, titanium has been shown to improve plant resilience to environmental stressors, such as drought and disease, leading to increased yield and quality (Elsherpiny and Faiyad 2023).

Iodine (I) came in the second order, as it is an essential micronutrient for plants, primarily involved in the synthesis of growth hormones and regulation of metabolic processes. It facilitates the conversion of starches to sugars, promoting carbohydrate accumulation and root development (Kumar and Hemantaranjan 2017). Iodine also enhances chlorophyll synthesis and photosynthetic activity, leading to increased biomass production and improved leaf area expansion. Moreover, iodine has been linked to enhanced nutrient uptake and translocation within the plant, resulting in improved nutrient assimilation and overall plant vigor (Kiferle *et al*. 2021).

Chromium (Cr) came in the third order, as it plays a vital role in plant metabolism, particularly in carbohydrate and lipid metabolism. It acts as a cofactor for various enzymes involved in energy production and storage, facilitating the conversion of sugars into energy-rich compounds (Shahid *et al*. 2017). Chromium also enhances the efficiency of nutrient uptake and utilization, leading to improved plant growth and development. Additionally, chromium has been shown to enhance plant tolerance to biotic and abiotic stressors, such as pests, pathogens, and environmental extremes, contributing to increased yield and quality of produce (López-Bucio *et al*. 2022).

Zirconium (Zr) came in the fourth order, as it is known to stimulate plant growth and development through its role in enhancing nutrient uptake and translocation. It improves root development and nutrient absorption efficiency, leading to increased nutrient availability for plant growth (Masalem *et al*. 2010). Zirconium also enhances plant resistance to various stress factors, such as salinity, heavy metals, and drought, by regulating antioxidant activity and osmotic balance. Moreover, zirconium has been shown to promote cell division and elongation, resulting in increased biomass production and improved head traits, such as size and weight (Shahid *et al*. 2012).

The trend of increased improvements with higher application rates can be attributed to a combination of factors. Firstly, higher application rates result in greater availability of the supplemented elements, ensuring plants have access to the studied elements necessary for optimal growth. Secondly, increased rates facilitate enhanced uptake and utilization of these elements by plants, leading to more efficient incorporation into metabolic processes crucial for growth and development. Additionally, certain elements, such as iodine and titanium, exert hormonal effects that stimulate growth processes more strongly at higher concentrations (Hu *et al*. 2020; Sahin *et al*. 2021). Furthermore, higher application rates may confer greater resilience to environmental stressors, helping plants withstand adverse conditions and maintain vigorous growth. Finally, some elements may exhibit threshold effects, with optimal responses only achieved at higher rates. Overall, these factors collectively contribute to the observed trend of increased improvements in plant growth, head traits and quality with higher application rates of supplemented elements.

The observed decrease in catalase concentration, an enzymatic antioxidant, within both selected plants following foliar spraying of the studied elements suggests a potential modulation of antioxidant activity. This phenomenon may indicate that these elements, to varying extents, aided the plants in coping with environmental stresses, thereby reducing the necessity for self-production of catalase. The stimulatory role played by these elements, albeit to differing degrees, likely contributed to this effect. It's plausible that the supplemented elements bolstered the plants' defense mechanisms, mitigating oxidative stress and alleviating the demand for endogenous catalase production (ElGhamry *et al*. 2024). The degree of influence on catalase concentration varied among the elements, reflecting their diverse impacts on plant physiology and stress response pathways.

Overall, the supplementation of titanium, iodine, chromium, and zirconium has been shown to positively influence the growth and head traits of both crisphead lettuce and red cabbage by enhancing various physiological processes essential for plant development and productivity.

5. Conclusion

Finally, the findings of this study demonstrate that foliar application of titanium, zirconium, chromium, and iodine positively influences the growth traits and productivity of both crisphead lettuce and red cabbage. Among these elements, titanium exhibited the most significant enhancement, followed by iodine, chromium, and zirconium. Moreover, the performance and productivity of the tested plants showed improvement with increasing concentration levels of the applied elements.

Based on the results obtained, it is recommended that farmers and agricultural practitioners consider foliar application of titanium, iodine, chromium, and zirconium at rate of 10.0 mgL^{-1} to enhance the growth and productivity of crisphead lettuce and red cabbage. However, further research is warranted to optimize the application methods and determine the ideal concentration levels for different environmental conditions and plant varieties. Additionally, exploring the mechanisms underlying the observed enhancements could provide valuable insights for developing more efficient and sustainable agricultural practices.

Conflicts of interest

The authors have declared that no competing interests exist.

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