

Protective Role of Zinc and Silicon in Mitigating Oxidative Stress in Swiss Chard (*Beta vulgaris* var. *cicla*) Grown under Lead-Contaminated Conditions.

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Abstract

This study aimed to assess the effect of foliar application of chelated zinc and silicon (potassium silicate) on physiological traits of Swiss chard grown under Pb-contaminated conditions. A pot experiment was conducted using a Randomized Complete Block Design (RCBD). The experiment included two lead concentrations (0 and 150 mg kg⁻¹ soil), three concentrations of chelated zinc (0, 0.1, and 0.3 g L⁻¹), and three concentrations of silicon (0, 1, and 3 g L⁻¹), resulting in 18 treatment combinations. Each treatment was replicated three times, giving a total of 54 experimental units. The results revealed that lead contamination significantly reduced leaf chlorophyll, nitrogen, potassium, and phosphorus contents, while significantly increasing leaf proline and lead concentrations. Foliar application of chelated zinc significantly improved chlorophyll content and the studied nutrient elements, while reducing the accumulation of proline and lead in the leaves. Likewise, silicon application enhanced the investigated physiological and nutritional characteristics by increasing leaf chlorophyll, nitrogen, potassium, and phosphorus contents and reducing proline and lead accumulation. Furthermore, significant effects were observed for both the two-way and three-way interactions among the experimental factors for most of the studied traits. The combined treatment of 150 mg kg⁻¹ lead + 0.3 g L⁻¹ chelated zinc + 3 g L⁻¹ silicon produced the highest mean values of leaf chlorophyll, nitrogen, potassium, and phosphorus contents, while recording the lowest values of leaf proline and lead contents. Based on the obtained results, it can be concluded that the foliar application of zinc and silicon represents an effective strategy for mitigating the toxic effect of lead contamination and enhancing the physiological performance and nutritional status of Swiss chard plants under environmental stress conditions.

Keywords: pollution, zinc, Silicon, Pb, Swiss chard.

Introduction:

The Swiss chard plant, belonging to the Amaranthaceae family, is one of the most important leafy vegetable cultivated all over the world. It is used for culinary purposes in

addition to its nutritional and medicinal value. Swiss chard is distinguished by its high content of minerals, vitamins, fibers, amino acids, as well as carbohydrates [14, 29]. The

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protective effects of this plant against oxidative stress and diseases are due to its high mineral content, such as calcium, magnesium, potassium, and iron, as well as to its antioxidant compounds. Different parts of Swiss chard contain a diverse range of flavonoids and phenolic acids, which play an important role in scavenging free radicals [21]. Regular consumption of leafy vegetables, including Swiss chard, has been linked to reduced body weight, lower cholesterol and the levels of blood pressure [40].

Contamination of soil with heavy metals represents a main environmental challenge, as heavy metals such as lead, mercury, arsenic, nickel, cadmium, and chromium do not play any important role in plants. Although these elements naturally occur in soil, their concentrations will be increased due to human activities such as agriculture and the excessive use of chemical fertilizers, posing a serious threat to living organisms [7, 13, 36].

Lead is a toxic heavy metal and a continuous pollutant commonly found in soil and hydrological systems. Its danger lies in its non-degradable nature and long-term accumulation in soils. It is absorbed by plants and transferred to humans through the food chain, causing soil fertility degradation, inhibition of microbial activity, and critical health risks such as cancer, kidney failure, and nervous system damage [30].

Zinc is one of the important micronutrients in plants due to its multiple roles. It enhances root growth and enhances cell division by influencing IAA synthesis. It also plays a very important role in chlorophyll synthesis, increasing photosynthetic efficiency, improving protein and hormone synthesis, as well as enhancing the antioxidant activity of enzymes. Moreover, zinc improves plant tolerance to stresses such as salinity, drought, and the contamination with heavy metal [39, 32, 12].

Chelated zinc is more effective than non-chelated forms, especially in calcareous soils with high pH, due to its greater stability and reduced precipitation [10]. In a study carried out on spinach plants grown in soil contaminated with lead, the application of zinc significantly improved plant growth and physiological status, reduced lead concentration, and enhanced plant tolerance to oxidative stress induced by lead exposure [42]. Another study on lettuce and spinach plants grown under lead contamination demonstrated that zinc improves plant growth by rivaling with lead for uptake sites, and reducing its concentration in plant tissues [41].

Silicon is one of the most plentiful elements in the Earth's crust after oxygen (O_2) and is considered a beneficial or quasi-essential element in order to its multiple advantages for plants, specially under environmental stress conditions [11]. Silicon enhances plant tolerance to the heavy metal stress by reducing their availability in the soil and limiting plant root uptake. It also contributes to their immobilization in less toxic forms. At the molecular and physiological levels, silicon is involved in regulating internal metal transport, activating antioxidant systems, in addition to facilitating the sequestration of metal ions into vacuoles, thereby reducing their accumulation in tissues and mitigating toxicity effects [4].

Results from a study conducted by [31] indicated a significant improvement in growth and biomass of some leafy plants exposed to Pb contamination when treated with silicon, and a significant reduction in lead concentration in plant tissues has been obtained. The study recommended the use of silicon as an effective approach to enhance the tolerance of leafy vegetables to abiotic stresses caused by heavy metals.

This study aims to evaluate the effect of treating Swiss chard plants with zinc and silicon on improving their physiological

characteristics and enhancing their nutrient content, as well as reducing the absorption and accumulation of lead in their tissues under polluted conditions. This is due to the high nutritional importance of this plant and its wide distribution, which necessitates further studies to understand its stress tolerance mechanisms and to improve its productivity and quality.

Materials and Methods:

A pot experiment was conducted in one of the agricultural nurseries التابعة to the city of Baqubah, the center of Diyala Governorate, approximately 90 km northeast of the capital, Baghdad, during the period from February to April 2026 on Swiss chard (*Beta vulgaris* var. *cicla*). Before planting, a composite random

soil sample was taken to the Diyala Agriculture Directorate for a series of physical and chemical analyses, as shown in Table (1).

Experimental design:

A factorial experiment was conducted according to a Randomized Complete Block Design (RCBD). The experiment included two concentrations of PbCl₂ (0 and 150 mg kg⁻¹ soil), three concentrations of chelated zinc Zn-EDTA (0, 0.1, 0.3 g L⁻¹), and three concentrations of potassium silicate (K₂SiO₃) (0, 1, 3 g L⁻¹). The total number of treatments was 18, as shown in Table (2), and each treatment was replicated three times, giving a total of 54 experimental units.

Table (1): Some chemical and physical properties of the study soil

Unit	Value	Property
-	7.1	pH
dS m ⁻¹	0.8	Electrical conductivity (EC)
cmol kg ⁻¹	22.77	Cation exchange capacity (CEC)
%	0.9	Organic matter
mg kg ⁻¹	63.0	Total nitrogen
mg kg ⁻¹	60.1	Available phosphorus
mg kg ⁻¹	67.1	Available potassium
%	61.48	Sand
%	13.76	Clay
%	24.76	Silt
-	Sandy loam	Soil texture

Table (2): Experimental treatments

Treatments	No. of Treatment
Pb 0 mg kg ⁻¹ + Z 0 g L ⁻¹ + SI 0 g L ⁻¹	T1
Pb 0 mg kg ⁻¹ + Z 0 g L ⁻¹ + SI 1 g L ⁻¹	T2
Pb 0 mg kg ⁻¹ + Z 0 g L ⁻¹ + SI 3 g L ⁻¹	T3
Pb 0 mg kg ⁻¹ + Z 0.1 g L ⁻¹ + SI 0 g L ⁻¹	T4
Pb 0 mg kg ⁻¹ + Z 0.1 g L ⁻¹ + SI 1 g L ⁻¹	T5
Pb 0 mg kg ⁻¹ + Z 0.1 g L ⁻¹ + SI 3 g L ⁻¹	T6
Pb 0 mg kg ⁻¹ + Z 0.3 g L ⁻¹ + SI 0 g L ⁻¹	T7
Pb 0 mg kg ⁻¹ + Z 0.3 g L ⁻¹ + SI 1 g L ⁻¹	T8
Pb 0 mg kg ⁻¹ + Z 0.3 g L ⁻¹ + SI 3 g L ⁻¹	T9
Pb 150 mg kg ⁻¹ + Z 0 g L ⁻¹ + SI 0 g L ⁻¹	T10
Pb 150 mg kg ⁻¹ + Z 0 g L ⁻¹ + SI 1 g L ⁻¹	T11
Pb 150 mg kg ⁻¹ + Z 0 g L ⁻¹ + SI 3 g L ⁻¹	T12
Pb 150 mg kg ⁻¹ + Z 0.1 g L ⁻¹ + SI 0 g L ⁻¹	T13
Pb 150 mg kg ⁻¹ + Z 0.1 g L ⁻¹ + SI 1 g L ⁻¹	T14
Pb 150 mg kg ⁻¹ + Z 0.1 g L ⁻¹ + SI 3 g L ⁻¹	T15
Pb 150 mg kg ⁻¹ + Z 0.3 g L ⁻¹ + SI 0 g L ⁻¹	T16
Pb 150 mg kg ⁻¹ + Z 0.3 g L ⁻¹ + SI 1 g L ⁻¹	T17
Pb 150 mg kg ⁻¹ + Z 0.3 g L ⁻¹ + SI 3 g L ⁻¹	T18

Soil contamination:

To contaminate the soil with lead chloride at a concentration of 150 mg kg⁻¹ soil, the soil was air-dried, crushed, and sieved using a 2 mm mesh sieve. The soil was then spread on a nylon-covered surface and sprayed with lead chloride solution using a 1-liter hand sprayer with continuous mixing to ensure uniform distribution. The soil was left to dry before

being transferred into plastic pots. After one month of contamination, Swiss chard seedlings at the two-leaf stage were obtained from a nursery in Baqubah. When they reached the 3–4 leaf stage, they were transplanted into pots, one seedling per pot.

Experimental treatments:

Seedlings were treated with chelated zinc and potassium silicate at the previously mentioned concentrations after dissolving them in distilled water. Foliar application was carried out in two stages: the first at the 4–5 leaf stage, and the second one month after the first application. Zinc was applied first, followed three days later by potassium silicate, with the addition of 2–3 drops of liquid soap as a surfactant.

Measured parameters:

Two weeks after the last treatment, leaf samples were collected and analyzed for several physiological traits, including total chlorophyll ($\text{mg } 100 \text{ g}^{-1}$), proline ($\text{mg } 100 \text{ g}^{-1}$), nitrogen (%), phosphorus (%), potassium (%), and lead (ppm). The analyses were conducted in the laboratories of the Ministry of Science and Technology in Baghdad..

Determination of mineral content in leaves:

- 1- Sample preparation: Leaves were washed thoroughly to remove dust, then oven-dried at $68\text{--}72^{\circ}\text{C}$ to constant weight and ground into a fine homogeneous powder.
- 2- Digestion of samples : 0.2 g of plant powder was digested by using a mixture of sulfuric and perchloric acid (3:1) with gradual heating until obtaining a clear solution.
- 3- Determination: The measured of nutrient contents has been done using standard methods: phosphorus by spectrophotometry, nitrogen by Kjeldahl method, , potassium by flame photometer, and lead by using atomic absorption spectrophotometry (AAS).

Chlorophyll determination: Chlorophyll has been extracted using 85% acetone, and absorbance was measured at 645 and 663 nm, then standard equations was used for calculation.

Proline determination: Proline was measured according to the spectrophotometric method at 520 nm.

Statistical analysis:

Data were analyzed using analysis of variance (ANOVA) and means were compared using Duncan's Multiple Range Test at a 5% significance level. SPSS software was used in this analysis.

Results and Discussion:

1. Effect of foliar spraying with zinc and silicon on the total chlorophyll content ($\text{mg}/100 \text{ g}$) under the conditions of lead pollution.

The results that presented in Table (3) indicate significant differences among the mean values of total chlorophyll content in Swiss Chard leaves due to lead treatment. A significant reduction has been observed in this trait under lead contamination at a concentration of 150 mg kg^{-1} soil, where this treatment recorded the lowest mean value of $93.11 \text{ mg } 100 \text{ g}^{-1}$, representing an 8.211% decrease compared with the highest mean value of $101.44 \text{ mg } 100 \text{ g}^{-1}$ obtained from the non-lead treatment (0 mg kg^{-1} soil).

This reduction may be attributed to the inhibitory effect of heavy metals on the plant's uptake of elements that involved in chlorophyll biosynthesis such as magnesium, nitrogen, as well as iron. Furthermore , lead may disrupt the structure of chloroplast and produce the reactive oxygen species , which accelerate the degradation of chlorophyll and reduce photosynthetic efficiency [19].

The results also showed significant differences among the means due to foliar application of zinc (Zn) at concentrations of 0, 0.1, and 0.3 g L^{-1} . The 0.3 g L^{-1} treatment gave the highest mean chlorophyll content of $103.94 \text{ mg } 100 \text{ g}^{-1}$, representing an 18.00% increase compared with the control treatment (0 g L^{-1}) ($88.08 \text{ mg } 100 \text{ g}^{-1}$).

This increase due to zinc's role in the metabolic enzymes activating, improving the uptake of nutrient that involved in chlorophyll biosynthesis, and protect chlorophyll molecules from degradation via enhancing antioxidant defense systems [12, 37].

The results further indicated significant differences among the means due to silicon application (potassium silicate) at concentrations of 0, 1, and 3 g L⁻¹, where the 3 g L⁻¹ treatment gave the highest mean value of 113.24 mg 100 g⁻¹, with a 36.20% increase compared with the control (83.14 mg 100 g⁻¹). This increase due to silicon's role in maintaining the cellular membrane integrity and protecting the chloroplasts from oxidative damage that caused by lead stress, in addition to the role of potassium in enhancing ionic balance and physiological activity [26, 27].

Significant differences were also observed in the interaction effects among the studied factors. The highest mean values were recorded in the combinations: (0 mg kg⁻¹ Pb + 0.1 g L⁻¹ Zn), (0 mg kg⁻¹ Pb + 3 g L⁻¹ Si), and (0.3 g L⁻¹ Zn + 3 g L⁻¹ Si), with values of 106.47, 120.43, and 128.31 mg 100 g⁻¹, respectively, compared with lower values of 82.55, 80.91, and 76.71 mg 100 g⁻¹ for the combinations (150 mg kg⁻¹ Pb + 0 g L⁻¹ Zn), (150 mg kg⁻¹ Pb + 0 g L⁻¹ Si), and (0 g L⁻¹ Zn + 0 g L⁻¹ Si), respectively.

Regarding the triple interaction, significant differences were also observed. The highest value (129.10 mg 100 g⁻¹) was recorded in the combination (150 mg kg⁻¹ Pb + 0.3 g L⁻¹ Zn + 3 g L⁻¹ Si), while the lowest value (73.8 mg 100 g⁻¹) was obtained from (150 mg kg⁻¹ Pb + 0 g L⁻¹ Zn + 0 g L⁻¹ Si).

Table (3): Effect of lead contamination and fertilization with zinc and silicon on leaf chlorophyll content (mg 100 g⁻¹).

interaction between lead and zinc	Silicon concentrations g L ⁻¹			Zinc concentrations g L ⁻¹	Lead concentrations mg kg ⁻¹ soil
	3	1	0		
95.54 c	110.38 c	96.65 e	79.60g	0	0
106.47 a	123.39 b	99.37 de	96.64 e	0.1	
104.24 ab	127.52 a	99.51 de	85.68 f	0.3	
80.62 d	86.98 f	81.07 g	73.82h	0	150
93.14 c	102.05 d	97.66 de	79.72 g	0.1	
103.64 b	129.10 a	98.40 de	83.41 fg	0.3	
97.27	113.24 a	95.44 b	83.14 c	Average effect of silicon	
interaction between lead and silicon					
Average effect of lead	Silicon concentrations g L ⁻¹			Lead concentrations mg kg ⁻¹ soil	

	3	1	0	
101.44 a	120.43 a	98.51 c	85.38 e	0
93.11 b	106.04 b	92.38 d	80.91 f	150
interaction between zinc and silicon				
Average effect of zinc	Silicon concentrations g L ⁻¹			Zinc concentrations g L ⁻¹
	3	1	0	
88.08 c	98.68 c	88.86 d	76.71 f	0
99.81 b	112.72 b	98.41 c	88.18 d	0.1
103.94	128.31 a	98.96 c	84.54 e	0.3

*Identical letters indicate that there are no significant differences among the means at the 5% probability level ($P \leq 0.05$).

2. Effect of zinc and silicon foliar application on leaf proline content (mg 100 g⁻¹) under lead contamination conditions

The results presented in Table (4) indicate significant differences in the proline content of chard leaves in response to lead (Pb) treatment. The addition of lead at a concentration of 150 mg kg⁻¹ soil resulted in a significant increase in this trait, recording the highest mean value of 104.83 mg 100 g⁻¹, with an increase of 47.31% compared with the control treatment (0 mg kg⁻¹ soil), which recorded the lowest mean value of 71.16 mg 100 g⁻¹. This increase in leaf proline content may be attributed to the role of heavy metals in inducing oxidative stress through the generation of reactive oxygen species (ROS), which subsequently leads to proline accumulation. Proline is considered one of the most important defensive compounds, as it contributes to the maintenance of cellular osmotic balance and protects cellular membranes and proteins from oxidative damage, thereby enhancing plant tolerance to heavy metal stress such as lead [16, 35].

Significant differences among mean leaf proline contents were observed in response to zinc chelate application at concentrations of 0, 0.1, and 0.3 g L⁻¹. Zinc (Zn) application caused a significant reduction in proline content of leaf, where the 0.1 g L⁻¹ treatment gave the lowest mean value of 85.33 mg 100 g⁻¹, representing a decrease of 7.12% compared with the highest mean value obtained from the control treatment (0 g L⁻¹), which was 91.88 mg 100 g⁻¹. This reduction may be due to the role of (Zn) in alleviating heavy metal-induced stress by improving antioxidant defense mechanism and reducing the free radical accumulation. Since proline accumulation is a common stress response, improved plant physiological state under zinc application reduces the need for accumulation of proline, thereby lowering its concentration in leaves [37, 34].

Similarly, significant differences were observed in leaf proline content due to silicon (Si) application at concentrations of 0, 0.1,

and 0.3 g L^{-1} . Silicon application significantly reduced proline content, where the 0.3 g L^{-1} treatment recorded the lowest mean value of $81.76 \text{ mg } 100 \text{ g}^{-1}$, with a reduction of 16.05% compared with the highest mean value recorded in the control treatment (0 g L^{-1}), which was $97.40 \text{ mg } 100 \text{ g}^{-1}$. This reduction may be attributed to the role of silicon in enhancing antioxidant enzyme activity and reducing ROS accumulation, thereby alleviating oxidative stress and decreasing the requirement for proline accumulation as a stress indicator [17].

Regarding the binary interactions among experimental factors, significant differences were observed among means. The combination of (150 mg kg^{-1} soil Pb + 0 g L^{-1} Zn) recorded the highest leaf proline content of $107.19 \text{ mg } 100 \text{ g}^{-1}$, while the combination of (150 mg kg^{-1} soil Pb + 0.3 g L^{-1} Zn) recorded a mean value of $111.35 \text{ mg } 100 \text{ g}^{-1}$.

In addition, the combination of (0 g L^{-1} Zn + 0 g L^{-1} Si) recorded the highest mean within this interaction, reaching $111.85 \text{ mg } 100 \text{ g}^{-1}$. In contrast, the lowest values of 67.01, 58.31, and $72.55 \text{ mg } 100 \text{ g}^{-1}$ were recorded for the combinations (0 mg kg^{-1} soil Pb + 0.3 g L^{-1} Zn), (0 mg kg^{-1} soil Pb + 0.3 g L^{-1} Si), and (0.1 g L^{-1} Zn + 0.3 g L^{-1} Si), respectively.

Regarding the triple interaction among the experimental factors, the results showed clear significant differences among means. The combination of (150 mg kg^{-1} soil Pb + 0 g L^{-1} Zn + 0 g L^{-1} Si) recorded the highest leaf proline content of $130.91 \text{ mg } 100 \text{ g}^{-1}$, whereas the combination of (0 mg kg^{-1} soil Pb + 0.3 g L^{-1} Zn + 0.3 g L^{-1} Si) recorded the lowest mean value of $51.48 \text{ mg } 100 \text{ g}^{-1}$, as shown in Table (4).

Table (4): Effect of lead contamination and fertilization with zinc and silicon on leaf proline content (mg/100 g-1).

interaction between lead and zinc	Silicon concentrations g L ⁻¹			Zinc concentrations g L ⁻¹	Lead concentrations mg kg ⁻¹ soil
	3	1	0		
76.57 c	65.43 j	71.49 i	92.79 ef	0	0
69.91 d	58.02 k	61.00 jk	90.71 fg	0.1	
67.01 e	51.48 l	61.72 jk	87.84 gh	0.3	
107.19 a	92.05 efg	98.61 d	130.91 a	0	150
100.75 b	121.78 b	84.11 h	96.36 de	0.1	
106.54 a	120.21 b	113.63 c	85.79 h	0.3	
87.99	84.83 b	81.76 c	97.40 a	Average effect of silicon	
interaction between lead and silicon					
Average effect of lead	Silicon concentrations g L ⁻¹			Lead concentrations mg kg ⁻¹ soil	

	3	1	0	
71.16 b	58.31 f	64.74 e	90.44 d	0
104.83 a	111.35 a	98.78 c	104.35 b	150
interaction between zinc and silicon				
Average effect of zinc	Silicon concentrations g L ⁻¹			Zinc concentrations g L ⁻¹
	3	1	0	
91.88 a	78.74 e	85.05 d	111.85 a	0
85.33 b	89.90 c	72.55 f	93.53 b	0.1
c 86.78	85.85	87.67 cd	86.81 cd	0.3

*Identical letters indicate that there are no significant differences among the means at the 5% probability level ($P \leq 0.05$).

3. Effect of zinc and silicon foliar application on leaf phosphorus content (%) under lead contamination conditions.

The results presented in Table (5) indicate significant differences among the mean values of leaf phosphorus (P) content in chard plants due to lead (Pb) treatment. Lead application at 150 mg kg⁻¹ soil caused a significant reduction in this trait, recording the lowest mean value of 0.90%, with a decrease of 10% compared with the non-lead treatment (0 mg kg⁻¹ soil), which recorded the highest mean value of 1.00%. This reduction due to the inhibitory effect of lead on the uptake of phosphorus and translocation within tissues of plant due to the competition for absorption sites. In addition, lead may form insoluble lead phosphate complexes, which reduce the absorption efficiency of root and consequently decrease the phosphorus availability in plants [16].

The results also showed significant differences among mean leaf phosphorus content due to zinc application at concentrations of 0, 0.1, and 0.3 g L⁻¹. The 0.3 g L⁻¹ treatment recorded the highest mean value of 1.04%, representing an 18.18%

increase compared with the control treatment (0 g L⁻¹), which recorded the lowest mean value of 0.88%. This increase due to the role of zinc in improving the absorption efficiency of root, increasing the permeability of membrane, activating nutrient uptake, and enhancing the translocation of nutrients within plant. Moreover, zinc may reduce lead-induced oxidative stress and, thereby inhibiting the formation of insoluble lead-phosphate complexes and increasing the availability of phosphorus in plants [37, 12].

Furthermore, the results indicated significant differences due to silicon application at concentrations of 0, 1, and 3 g L⁻¹. The 3 g L⁻¹ treatment gave the highest mean value of, 1.05%, with an increase of 25% compared with control treatment (0 g L⁻¹), which gave the lowest mean value of 0.84%. This increase may be attributed to the role of silicon in reducing phosphorus fixation in the soil, improving phosphorus uptake by roots, and enhancing ion transport efficiency. In addition, potassium in potassium silicate may

contribute to improved ionic transport and nutrient mobility within plant tissues [17, 9].

Regarding the binary interactions among the studied factors, significant differences were observed among the mean values. The combination of ($0 \text{ mg kg}^{-1} \text{ Pb} + 0.3 \text{ g L}^{-1} \text{ Zn}$) recorded the highest mean value of 1.07% in the $\text{Pb} \times \text{Zn}$ interaction, while the combination of ($0 \text{ mg kg}^{-1} \text{ Pb} + 3 \text{ g L}^{-1} \text{ Si}$) also recorded a mean value of 1.07% in the $\text{Pb} \times \text{Si}$ interaction. Moreover, the combination of ($0.3 \text{ g L}^{-1} \text{ Zn} + 3 \text{ g L}^{-1} \text{ Si}$) recorded the highest mean value of 1.22% in the $\text{Zn} \times \text{Si}$ interaction. In contrast, the

combinations ($150 \text{ mg kg}^{-1} \text{ Pb} + 0 \text{ g L}^{-1} \text{ Zn}$), ($150 \text{ mg kg}^{-1} \text{ Pb} + 0 \text{ g L}^{-1} \text{ Si}$), and ($0 \text{ g L}^{-1} \text{ Zn} + 0 \text{ g L}^{-1} \text{ Si}$) recorded the lowest mean values of 0.83%, 0.76%, and 0.80%, respectively.

Regarding the triple interaction among lead, zinc, and potassium silicate, significant differences were also observed. The combination of ($150 \text{ mg kg}^{-1} \text{ Pb} + 0.3 \text{ g L}^{-1} \text{ Zn} + 3 \text{ g L}^{-1} \text{ Si}$) recorded the highest leaf phosphorus content of 1.22%, whereas the combination of ($150 \text{ mg kg}^{-1} \text{ Pb} + 0 \text{ g L}^{-1} \text{ Zn} + 0 \text{ g L}^{-1} \text{ Si}$) recorded the lowest mean value of 0.71%.

Table (5): Effect of lead contamination and fertilization with zinc and silicon on leaf phosphorus content (%).

interaction between lead and zinc	Silicon concentrations g L ⁻¹			Zinc concentrations g L ⁻¹	Lead concentrations mg kg ⁻¹ soil
	3	1	0		
0.94 c	0.97 d	0.95 de	0.89 fg	0	0
1.01 b	1.02 c	1.08 b	0.92 def	0.1	
1.07 a	1.21 a	1.07 b	0.94 def	0.3	
0.83 e	0.93 def	0.84 gh	0.71 i	0	150
0.86 d	0.93 def	0.90 ef	0.76 i	0.1	
1.00 b	1.22 a	0.95 de	0.83 h	0.3	
0.951	1.05 a	0.97 b	0.84 c	Average effect of silicon	
interaction between lead and silicon					
Average effect of lead	Silicon concentrations g L ⁻¹			Lead concentrations mg kg ⁻¹ soil	
	3	1	0		
1.00 a	1.07 a	1.03 b	0.91 c	0	
0.90 b	1.03 b	0.90 c	0.76 d	150	
interaction between zinc and silicon					

Average effect of zinc	Silicon concentrations g L ⁻¹			Zinc concentrations g L ⁻¹
	3	1	0	
0.88 c	0.95 c	0.90 d	0.80 f	0
0.93 b	0.98 bc	0.99 b	0.84 e	0.1
1.04 a	1.22 a	1.01 b	0.88 d	0.3

*Identical letters indicate that there are no significant differences among the means at the 5% probability level ($P \leq 0.05$).

4. Effect of zinc and silicon foliar application on leaf potassium content (%) under lead contamination conditions.

The results presented in Table (6) indicate significant differences among the mean values of leaf potassium (K) content due to lead (Pb) treatment at 150 mg kg⁻¹ soil. This treatment recorded the lowest mean value of 3.20%, with a decrease of 13.27% compared with the highest mean value of 3.69% obtained from the non-lead treatment (0 mg kg⁻¹ soil). This reduction due to the inhibitory effect of lead on the mineral nutrients uptake and translocation in plants, that result from damage the root cell membranes. In addition, lead may reduce the ion transporters efficiency, thereby decreasing the uptake and movement potassium to the leaves [24].

The results of the same Table also revealed significant differences among mean potassium content due to zinc application at concentrations of 0, 0.1, and 0.3 g L⁻¹. The 0.3 g L⁻¹ treatment gave the highest mean value of 3.88%, with an increase of 31.52% compared with the control treatment (0 g L⁻¹), which gave the lowest mean value of 2.95%. This increase due to the role of zinc in enhancing uptake efficiency of ion and nutrient translocation within the plant via activation of membrane-associated enzymes. Furthermore, zinc reduce ionic imbalance caused by Pb stress, thereby improving the plant nutritional status [37].

Similarly, significant increases were observed due to silicon application at concentrations of 0, 1, and 3 g L⁻¹. The 3 g L⁻¹ treatment recorded the highest mean potassium content of, 4.05%, representing 45.16% increase compared with control (2.79%). This may be explained by the role of silicon in improving potassium uptake efficiency and reducing its loss through strengthening cell membrane integrity and regulating ion transport, particularly under stress conditions [25].

Regarding the binary interactions among the studied factors, significant differences were observed among mean values. The combinations (0 mg kg⁻¹ Pb + 0.3 g L⁻¹ Zn), (0 mg kg⁻¹ Pb + 3 g L⁻¹ Si), and (0.3 g L⁻¹ Zn + 3 g L⁻¹ Si) recorded the highest mean values of 4.27%, 4.15%, and 4.63%, respectively. In contrast, the lowest mean values of 2.87%, 2.58%, and 2.57% were recorded for the combinations (150 mg kg⁻¹ Pb + 0 g L⁻¹ Zn), (150 mg kg⁻¹ Pb + 0 g L⁻¹ Si), and (0 g L⁻¹ Zn + 0 g L⁻¹ Si), respectively.

Regarding the triple interaction among lead, zinc, and silicon treatments, significant differences were also observed. The highest mean value of 5.10% was recorded in the combination (0 mg kg⁻¹ Pb + 0.3 g L⁻¹ Zn + 3 g L⁻¹ Si), whereas the lowest mean value

of 2.14% was obtained from the combination (150 mg kg⁻¹ Pb + 0 g L⁻¹ Zn + 0 g L⁻¹ Si).

Table (6): Effect of lead contamination and fertilization with zinc and silicon on leaf potassium content (%).

interaction between lead and zinc	Silicon concentrations g L ⁻¹			Zinc concentrations g L ⁻¹	Lead concentrations mg kg ⁻¹ soil
	3	1	0		
3.04 e	3.13 g	2.97 hi	3.01 ghi	0	0
3.77 b	4.21 c	4.16 c	2.92 i	0.1	
4.27 a	5.10 a	4.65 b	3.07 gh	0.3	
2.87 f	3.73 e	2.74 j	2.14 k	0	150
3.25 d	3.94 d	3.12 g	2.70 j	0.1	
3.48 c	4.16 c	3.38 f	2.89 i	0.3	
3.44	4.05 a	3.50 b	2.79 c	Average effect of silicon	
interaction between lead and silicon					
Average effect of lead	Silicon concentrations g L ⁻¹			Lead concentrations mg kg ⁻¹ soil	
	3	1	0		
3.69 a	4.15 a	3.93 b	3.00 d	0	
3.20 b	3.95 b	3.08 c	2.58 e	150	
interaction between zinc and silicon					
Average effect of zinc	Silicon concentrations g L ⁻¹			Zinc concentrations g L ⁻¹	
	3	1	0		
2.95 c	3.43 d	2.85 f	2.57 g	0	
3.51 b	4.08 b	3.64 c	2.81 f	0.1	
3.88 a	4.63 a	4.01 b	2.98 e	0.3	

*Identical letters indicate that there are no significant differences among the means at the 5% probability level ($P \leq 0.05$).

5. Effect of zinc and silicon foliar application on leaf nitrogen content (%) under lead contamination conditions.

The results presented in Table (7) indicate significant differences among the mean values of leaf nitrogen (N) content in chard plants due to lead (Pb) treatment at 150 mg kg^{-1} soil. This treatment recorded the lowest mean value of 3.45%, with a decrease of 7.50% compared with the control treatment (0 mg kg^{-1} soil), which recorded the highest mean value of 3.73%. This reduction caused by the inhibitory effect of lead on the uptake of nitrate and ammonium from the soil, in addition to the suppression of nitrogen metabolism-related enzymes such as nitrate reductase. As well as, lead may impair the function of root, thereby reducing the absorption and translocation of nitrogen within plant tissues [19].

The results also showed significant differences among mean nitrogen content due to zinc application at concentrations of 0, 0.1 and 0.3 g L^{-1} . The 0.3 g L^{-1} treatment gave the highest mean value of 3.77% with an increase of 10.23% compared with the control treatment (0 g L^{-1}), which gave the lowest mean value of 3.42%. This increase may caused by the role of zinc in activating enzymes that involved in nitrogen metabolism, in addition to enhancing nitrate transporter activity and maintaining integrity of membrane, which supports continuous the uptake and translocation of nitrogen within plant tissues [15].

Similarly, significant increases in nitrogen content of leaf were observed as a result of

silicon application at concentrations of 0, 1, and 3 g L^{-1} . The 3 g L^{-1} treatment gave the highest mean value of 3.99% representing a 27.07% increase compared with the control treatment (0 g L^{-1}), which gave the lowest mean value of, 3.14%. This may be explained by the role of silicon in enhancing root efficiency for nutrient uptake, including nitrogen, improving nutrient utilization under stress conditions, reducing oxidative stress, and increasing the activity of enzymes associated with nitrate uptake and assimilation [1].

Regarding the binary interactions among the studied factors, significant differences were observed among the mean values. The combinations ($0 \text{ mg kg}^{-1} \text{ Pb} + 0.3 \text{ g L}^{-1} \text{ Zn}$), ($0 \text{ mg kg}^{-1} \text{ Pb} + 3 \text{ g L}^{-1} \text{ Si}$), and ($0.3 \text{ g L}^{-1} \text{ Zn} + 3 \text{ g L}^{-1} \text{ Si}$) recorded the highest values of 3.93%, 4.11%, and 4.37%, respectively. In contrast, the lowest values of 3.22%, 2.91%, and 2.90% were recorded for the combinations ($150 \text{ mg kg}^{-1} \text{ Pb} + 0 \text{ g L}^{-1} \text{ Zn}$), ($150 \text{ mg kg}^{-1} \text{ Pb} + 0 \text{ g L}^{-1} \text{ Si}$), and ($0 \text{ g L}^{-1} \text{ Zn} + 0 \text{ g L}^{-1} \text{ Si}$), respectively.

Regarding the triple interaction among lead, zinc, and silicon treatments, significant differences were also observed. The combination ($0 \text{ mg kg}^{-1} \text{ Pb} + 0.3 \text{ g L}^{-1} \text{ Zn} + 3 \text{ g L}^{-1} \text{ Si}$) recorded the highest mean value of 4.66%, whereas the combination ($150 \text{ mg kg}^{-1} \text{ Pb} + 0 \text{ g L}^{-1} \text{ Zn} + 0 \text{ g L}^{-1} \text{ Si}$) recorded the lowest mean value of 2.69%.

Table (7): Effect of lead contamination and fertilization with zinc and silicon on leaf nitrogen content (%).

interaction between lead and zinc	Silicon concentrations g L^{-1}			Zinc concentrations g L^{-1}	Lead concentrations mg kg^{-1} soil
	3	1	0		
3. 62 b	3.89 c	3.86 cd	3.10 i	0	0

3.65 b	3.77 cde	3.69 def	3.49 g	0.1	150
3.93 a	4.66 a	3.55 fg	3.56 fg	0.3	
3.22 d	3.69 def	3.28 h	2.69 j	0	
3.51 c	3.86 cd	3.63 efg	3.05 i	0.1	150
3. 62 b	4.08 b	3.81 cde	2.97 i	0.3	
3.59	3.99 a	3.64 b	3.14 c	Average effect of silicon	
interaction between lead and silicon					
Average effect of lead	Silicon concentrations g L ⁻¹			Lead concentrations mg kg ⁻¹ soil	
	3	1	0		
3.73 a	4.11 a	3.70 c	3.38 e	0	
3.45 b	3.88 b	3.57 d	2.91 f	150	
interaction between zinc and silicon					
Average effect of zinc	Silicon concentrations g L ⁻¹			Zinc concentrations g L ⁻¹	
	3	1	0		
3.42 c	3.79 bc	3.57 d	2.90 f	0	
3.58 b	3.81 b	3.66 d	3.27 e	0.1	
3.77 a	4.37 a	68 cde	3.27 e	0.3	

*Identical letters indicate that there are no significant differences among the means at the 5% probability level ($P \leq 0.05$).

6. Effect of zinc and silicon foliar application on leaf lead (Pb) content (ppm) under lead contamination conditions.

The results presented in Table (8) indicate significant differences among the mean values of leaf lead (Pb) content due to lead treatment at 0 and 150 mg kg⁻¹ soil. The application of lead at 150 mg kg⁻¹ soil resulted in a significant increase in leaf Pb content, recording the highest mean value of 86.68 ppm, with an increase of 9.36% compared with the lowest mean value of 79.26 ppm obtained from the control treatment (0 mg

kg⁻¹ soil). This increase may be caused by the external addition of lead, which improved its uptake and translocation through the vascular system with the transpiration stream, leading to its accumulation in leaves.

The results revealed a significant reduction in leaf lead content due to zinc application at concentrations of 0, 0.1, and 0.3 g L⁻¹. The highest mean value of 85.62 ppm was

obtained from the control treatment (0 g L^{-1}), whereas the lowest mean value of 80.75 ppm was obtained from 0.3 g L^{-1} treatment, representing a reduction of 5.69%. This decrease due to the antagonistic relationship between lead and zinc, where both elements compete for uptake and transport sites within the plant tissues, thereby reducing lead absorption and translocation in different parts of the plant. Moreover, zinc may enhance integrity of membrane and activate defense systems of plant, which reduces lead accumulation in shoots [2].

Similarly, the results revealed a significant decrease in leaf content due to silicon application at concentrations of 0, 1, and 3 g L^{-1} . The highest mean value of 87.03 ppm was obtained from the control treatment (0 g L^{-1}), whereas the lowest mean value of 80.33 ppm was obtained from 3 g L^{-1} treatment, representing a reduction of 7.69%. This reduction may be attributed to the role of silicon in limiting the uptake and translocation of lead from roots to shoots by immobilizing it in root tissues and forming silicon-based barriers that restrict its

movement within the plant. Furthermore, silicon enhances plant defense mechanisms against heavy metal stress, thereby reducing Pb accumulation in leaves [33].

Regarding the binary interactions among the studied factors, significant differences were observed among the mean values. The combinations ($150 \text{ mg kg}^{-1} \text{ Pb} + 0 \text{ g L}^{-1} \text{ Zn}$), ($150 \text{ mg kg}^{-1} \text{ Pb} + 0 \text{ g L}^{-1} \text{ Si}$), and ($0 \text{ g L}^{-1} \text{ Zn} + 0 \text{ g L}^{-1} \text{ Si}$) recorded the highest mean values of 91.02 ppm, 89.91 ppm, and 89.72 ppm, respectively. In contrast, the lowest mean values of 78.43 ppm, 76.54 ppm, and 77.13 ppm were recorded for the combinations ($0 \text{ mg kg}^{-1} \text{ Pb} + 0.3 \text{ g L}^{-1} \text{ Zn}$), ($0 \text{ mg kg}^{-1} \text{ Pb} + 3 \text{ g L}^{-1} \text{ Si}$), and ($0.3 \text{ g L}^{-1} \text{ Zn} + 3 \text{ g L}^{-1} \text{ Si}$), respectively.

Regarding the triple interaction among lead, zinc, and silicon treatments, significant differences were also observed. The combination ($150 \text{ mg kg}^{-1} \text{ Pb} + 0.3 \text{ g L}^{-1} \text{ Zn} + 3 \text{ g L}^{-1} \text{ Si}$) recorded the highest mean value of 97.83 ppm, whereas the combination ($0 \text{ mg kg}^{-1} \text{ Pb} + 0.3 \text{ g L}^{-1} \text{ Zn} + 3 \text{ g L}^{-1} \text{ Si}$) recorded the lowest mean value of 74.42 ppm.

Table (8): Effect of lead contamination and fertilization with zinc and silicon on leaf lead (Pb) content (ppm).

interaction between lead and zinc	Silicon concentrations g L ⁻¹			Zinc concentrations g L ⁻¹	Lead concentrations mg kg ⁻¹ soil
	3	1	0		
80.22 d	79.94 gh	77.84 hi	82.88 efg	0	0
79.13 d	75.25 i	77.04 hi	85.12 cde	0.1	
78.43 d	74.42 i	76.37 i	84.49 def	0.3	
91.02 a	87.91 bcd	88.60 b	96.56 a	0	150
85.94 b	84.61 def	88.17 bc	85.05 cde	0.1	
83.07 c	97.83 a	81 27 fg	88.10 bc	0.3	
82.97	80.33 b	81.55 b	87.03 a	Average effect of silicon	

interaction between lead and silicon				
Average effect of lead	Silicon concentrations g L ⁻¹			Lead concentrations mg kg ⁻¹ soil
	3	1	0	
79.26 b	76.54 d	77.09 d	84.16 c	0
86.68 a	84.12 c	86.02 b	89.91 a	150
interaction between zinc and silicon				
Average effect of zinc	Silicon concentrations g L ⁻¹			Zinc concentrations g L ⁻¹
	3	1	0	
85.62 a	83.92 cd	83.22 cd	89.72 a	0
82.54 b	79.93 e	82.61 d	85.08 bc	0.1
80.75 c	77.13 f	78.82 ef	86.29 b	0.3

*Identical letters indicate that there are no significant differences among the means at the 5% probability level ($P \leq 0.05$).

Conclusion:

From the present study, it can be concluded that soil contamination with lead caused a marked deterioration in most physiological traits of chard plants. In contrast, foliar application of zinc and silicon helped alleviate the harmful effects of lead and improved leaf contents of chlorophyll, nitrogen, potassium, and phosphorus, while

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reducing the accumulation of lead and proline. It can be concluded that the individual and combined applications of zinc and silicon represent successful strategies for improving plant tolerance to stress that induced by the heavy metal contamination, particularly lead.

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