Egyptian Journal of Soil Science
http://ejss.journals.ekb.eg/

# Can foliar application of Titanium and Zeolite Soil Addition Enhance Crisphead Lettuce Production, and Reduce N-Leaching or/and Volatilization?

**Rasha A. El-Awady, Mohamed A. El-Sherpiny** and **Mohamed M. El-Kafrawy**

*Soil & Water and Environment Research Institute, Agriculture Research Center, Giza, 12619 Egypt*

EXCESSIVE NITROGEN application can lead to environmental pollution, thus improving soil properties, along with raising nitrogen fertilizer efficiency is necessary for sustainability in Egypt. Therefore, a field experiments were conducted to assess the impact of varying doses of nitrogen recommended (NR) at 100% and 75% as the main factor, different rates of soil zeolite addition (0.0, 2.5, and 5.0 tons fed$^{-1}$) as sub-plot factors, and spraying titanium at different rates (0.0, 3.0, and 6.0 mg L$^{-1}$) as sub-sub-plot factors on soil properties and growth performance of crisphead lettuce during the 2022 and 2023 seasons. Soil available nutrients, including nitrogen, phosphorus and potassium, along with other soil properties such as water holding capacity (WHC), electrical conductivity (EC), and cation exchange capacity (CEC), were determined. Additionally, plant performance and quality traits such as fresh and dry weights, relative water content, nitrogen and potassium levels, chlorophyll and carotene contents, head weight and diameter, total dissolved solids, dry matter, and vitamin C were assessed. Results revealed that the highest levels of available nitrogen, phosphorus, and potassium post-harvest were observed with the highest zeolite rate (5.0 tons fed$^{-1}$), while the lowest levels were noted in the control treatment. Soil WHC, EC and CEC increased with higher zeolite application rates, with the highest values recorded in soil treated with 5.0 tons of zeolite fed$^{-1}$, followed by 2.5 tons and the control treatment. Plant traits, including growth, leaf chemical constituents, photosynthetic pigments, head characteristics, and quality, gradually improved as the zeolite application rate increased from 0.0 to 2.5 and then 5.0 tons fed$^{-1}$. Similarly, all aforementioned plant traits exhibited gradual enhancement as the titanium application rate increased from 0.0 to 3.0 and then 6.0 mg L$^{-1}$. Overall, the most favorable results were achieved with plants treated with 100% of NR, zeolite at a rate of 5.0 tons fed$^{-1}$, and simultaneously sprayed with 6.0 mg Ti L$^{-1}$. Notably, plants treated with 75% of NR, zeolite at a rate of 5.0 tons fed$^{-1}$, and simultaneously sprayed with 6.0 mg Ti L$^{-1}$ demonstrated superior results compared to those treated with 100% of NR without zeolite and titanium.

**Keywords**: Excessive nitrogen, Zeolite, Titanium, Water holding capacity.

## 1. Introduction

Recently, crisphead lettuce (*Lactuca sativa* var. capitate, family Asteraceae) holds significant importance as an essential vegetable crop in Egypt due to its numerous benefits **(Abd El-Hady *et al*., 2024).** With its high nutritional value, including vitamins, minerals, and dietary fiber, crisphead lettuce contributes to a balanced and healthy diet for Egyptian consumers **(Lebeda *et al*., 2022).** Its crisp texture and mild flavor make it a versatile ingredient in various culinary dishes, salads, and sandwiches, catering to diverse preferences and tastes. Moreover, crisphead lettuce cultivation provides economic opportunities for farmers, contributing to agricultural livelihoods and rural development in Egypt (**Mostafa *et al*., 2023).** Additionally, as a water-efficient crop, crisphead lettuce cultivation aligns with Egypt's efforts to conserve water resources and promote sustainable agriculture in the face of water scarcity challenges. Overall, crisphead lettuce stands as a valuable vegetable crop in Egypt, offering nutritional, economic, and environmental benefits to both producers and consumers alike **(Abdel-Hakim *et al*., 2023).**

Nitrogen plays a pivotal role in the growth, development, yield, and quality of crisphead lettuce

*Corresponding author e-mail: M_Elsherpiny2010@yahoo.com
Received: 08/02/2024; Accepted: 22/02/2024
DOI: 10.21608/EJSS.2024.268791.1722

**(Ottaiano *et al.*, 2021).** Adequate nitrogen supply is essential for promoting leaf expansion, biomass accumulation, and head formation, ultimately contributing to increased marketable yield and improved crop quality **(Kılıç, 2022).** However, excessive nitrogen application can lead to environmental pollution, reduced water and nutrient use efficiency, and increased production costs **(Farouk *et al.*, 2023).** Therefore, it is imperative to adopt precise nitrogen management practices tailored to the specific needs of crisphead lettuce, considering factors such as soil fertility, crop growth stage, and environmental conditions.

Zeolite plays a significant role in enhancing the efficiency of mineral nitrogen fertilizers in agriculture through various mechanisms **(Omar *et al.*, 2020)**. Firstly, zeolite possesses a high cation exchange capacity (CEC), allowing it to adsorb and retain positively charged ions such as ammonium ($NH_4^+$) released from nitrogen fertilizers **(Soltys *et al.*, 2020)**. This retention prevents leaching of ammonium into groundwater, reducing nitrogen losses and enhancing nutrient availability for plant uptake **(Rodrigues *et al.*, 2021).** Additionally, zeolite's porous structure provides a reservoir for holding water and nutrients, facilitating gradual release to plant roots as needed, thereby improving nutrient use efficiency (**Li *et al.*, 2022).** Moreover, zeolite can mitigate nitrogen loss through volatilization by trapping ammonium ions within its lattice structure, reducing atmospheric emissions of nitrogen compounds. Furthermore, zeolite amendments can improve soil structure, aeration, and water retention, creating a favorable environment for root growth and nutrient uptake (**Ghazi *et al.*, 2023**). Overall, the incorporation of zeolite in conjunction with mineral nitrogen fertilizers offers a sustainable approach to optimize nutrient management, mitigate environmental impacts, and enhance crop productivity in agriculture **(ElGhamry *et al.*, 2024).**

Titanium dioxide ($TiO_2$) may play a role in the non-biological fixation of atmospheric nitrogen to nitrate on $TiO_2$ surfaces **(Al-Taani, 2008).** In this process, $TiO_2$ acts as a catalyst to facilitate the conversion of atmospheric nitrogen into nitrate through a series of reactions involving intermediate nitrogen oxide species **(ElGhamry *et al.*, 2022).** When titanium dioxide ($TiO_2$) is exposed to ultraviolet (UV) light, it undergoes a photochemical reaction. $TiO_2$ possesses a relatively wide bandgap energy, meaning it absorbs UV light and reflects or transmits most of the visible light **(Al-Taani, 2008**; Elsherpiny **and Faiyad, 2023)**. When UV light with energy higher than the band gap energy of $TiO_2$ is incident upon it, electron-hole pairs are generated **(Kozlova *et al.*, 2021).** Electrons from the valence band are excited to the conduction band, leaving behind positively charged holes in the valence band. These electron-hole pairs in titanium dioxide can participate in various photochemical reactions **(Wu *et al.*, 2022).** Specifically, they can interact with adsorbed nitrogen molecules on the $TiO_2$ surface, facilitating the conversion of nitrogen gas ($N_2$) into nitrogen oxides and eventually into nitrate ions ($NO^{3-}$) in the presence of water and oxygen. This process of nitrogen fixation on $TiO_2$ surfaces under UV light irradiation is a form of photocatalysis **(Elsherpiny and Faiyad, 2023)**.

The objective of this investigation was to evaluate how the addition of soil zeolite and titanium spraying influences both soil properties and the growth performance of crisphead lettuce under different levels of recommended nitrogen fertilization. Through this study, we aimed to gain valuable insights into enhancing crop productivity and fostering environmental sustainability in Egyptian agriculture by optimizing nitrogen fertilizer application methods and improving soil properties.

## 2. Material and Methods

**Location**

A field experiments were executed over two consecutive seasons, 2022 and 2023 on a private farm located at Met-Antar Village, Talkha District, El-Dakahlia Governorate, Egypt, (31°4'54"N - 31°24'4"E).

**Soil sampling**

The attributes of the initial soil (taken at a depth of 0-30 cm) were determined as routine work using standard methods as described by **Tandon (2005).** The initial soil's attributes included textural class determination by texture triangle based on the percentages of sand, silt and clay percentages which were identified by the pipette method. Additionally, measurements were taken for water-holding capacity (WHC, by saturation through the free capillary attraction method), organic matter content (by Walkley and Black method), electrical conductivity (EC, by EC meter), pH (by pH meter), cation exchange capacity (CEC, using ammonium acetate), and nutrient availability such as available nitrogen AN (through the Kjeldahl method), phosphorus AP (Olsen method using spectrophotometer) and potassium AK (flame photometer method). The initial soil exhibited a textural class of clay, with sand content at 20 %, silt content at 30.45%, and clay content at 49.55%. The soil's WHC was measured at 34.95%. It contained 1.22% organic matter. The soil's EC was recorded at 1.90 $dSm^{-1}$, and the soil pH was 8.0. Additionally, the soil's CEC was found to be 48.6 cmolc $kg^{-1}$. The soil's AN, AP and AK were recorded at 26.0, 8.0 and 230 $mgKg^{-1}$, respectively.

**Zeolite properties**

Similarly, zeolite properties were assessed following the procedures outlined by **Tandon (2005),** which may include determining characteristics like CEC (160 cmolc $kg^{-1}$), EC (3.770 $dSm^{-1}$), pH (8.0) and nutrient composition such as $P_2O_5$, (1.0%), $SiO_2$ (65.0%), $K_2O$ (5.0%), CaO (9.0%) and $Na_2O$ (1.0%). Zeolite was sourced from the Egyptian commercial market (Alex Zeolite Company ).

**Titanium**

Titanium dioxide, with a chemical formula $TiO_2$ and a titanium content of 59.93%, was sourced from the Faculty of Agriculture at Mansoura University in Egypt. This compound was derived from ilmenite mineral ($FeTiO_3$). Its properties include a molar mass of 79.866 g/mol, a white solid appearance, a density of 4.17 g/mL at 25°C and a melting point ranging from 1830 to 3000°C. For the standard solution preparation, a specific concentration was achieved by dissolving a precise quantity of $TiO_2$ in water. Subsequently, various concentrations were prepared following methodologies outlined by **Doklega *et al.* (2022).**

**Experimental design and treatments**

This investigation was conducted under experimental design of split-split plot with three replicates to assess the impact of varying doses of nitrogen recommended (NR, 50 units N $fed^{-1}$) at 100% and 75% as the main factor, different rates of soil zeolite addition (0.0, 2.5, and 5.0 tons $fed^{-1}$ ) as sub-main factors, and spraying titanium at different rates (0.0, 3.0, and 6.0 mg $L^{-1}$) as sub-sub-main factors on soil properties and growth performance of crisphead lettuce.

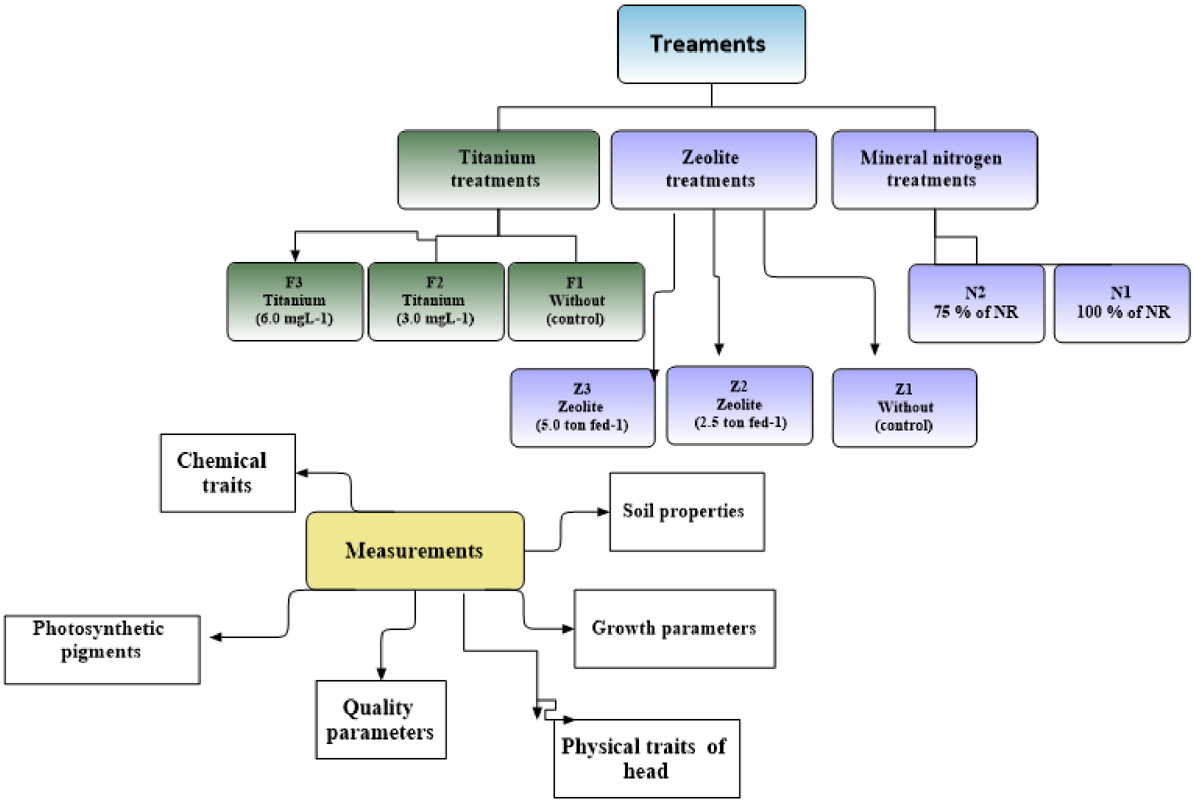


**Fig. 1. The flowchart of the current experiment.**

**Experimental set up**

The sub-sub plot area for this investigation was 9.0 $m^2$ (3.0 m x 3.0 m). The row length was 6.0 m and the width was 0.80 m, while the number of rows in the plot was 3.0. Crisphead lettuce seedlings "cv Kharga, age of 20 days" were transplanted on the 17th of October in both investigated seasons. The transplantation was carried out in the middle of the ridges, maintaining a plant spacing of 40 cm. Prior to the immediate transplanting of seedlings, zeolite was incorporated into the soil in accordance with the studied rates. Additionally, prior to plowing, all plots received calcium superphosphate (6.6% P) at a rate of 30 units of phosphorus per feddan. According to the recommendations of the Ministry of Agriculture and soil reclamation for the production of different types of lettuce and vegetable crops in Egypt. Nitrogen fertilization was applied at two intervals, each with two equal doses corresponding to the studied treatments, utilizing ammonium sulfate (21% N). Concurrently, potassium sulfate, containing 48% $K_2O$, was administered alongside nitrogen, at a rate of 25 units of $K_2O$ per feddan. Titanium spraying was conducted at three intervals: on days 25, 40, and 55 post-transplant.

**Plant sampling**

After the 80 days following transplanting, crisphead lettuce plants as well as soil samples were selected from each replicate to assess the traits outlined in Table 1.

**Statistical Analyses**

The data obtained underwent statistical analysis through analysis of variance (ANOVA) using **Co-State software (version 6.303, copyright 1998-2004)** to determine the LSD at a significance level of 0.05, as outlined by **Gomez** and **Gomez (1984).**

**Table 1. Methods and references of measurements.**

| Parameters | Methods and formula | References |
|---|---|---|
| **Soil properties after harvest [Available N, P and K as well as WHC, EC , CEC]** | The same methods used with initial soil, which were mentioned above | |
| **Fresh and dry weights (including the weight of the head and outer leaves), leaf area, relative water content and the number of outer leaves** | Manually and visually | |
| **Digested plant samples** | Mixed of $HClO_4 + H_2SO_4$ | **Peterburgski (1968)** |
| **N, P, K%** | Micro-Kjeldahl, Spectrophotometrically and flame photometer, respectively | **Walinga *et al.* (2013)** |
| **Chlorophyll, SPAD value** | SPAD reading (SPAD-502, Soil-Plant Analysis Development (SPAD) Section, Minolta Camera, Osaka, Japan) | **Balasubramanian *et al*. (2000)** |
| **Carotene levels** | Using acetone through a spectrophotometer | **Dere, (1998).** |
| **Physical traits [head weight, head diameter and head height** | Manually and visually | |
| **Quality traits [carbohydrates, protein, total sugar, fiber, dry matter and vitamin C and total dissolved solid]** | | **A.O.A.C (2000)** |

**3. Results**

**Post-harvest soil analyses**

Table 2 outlines the impact of different doses of nitrogen recommended (NR), soil addition of zeolite and spraying titanium on soil available nutrients, specifically nitrogen, phosphorus and potassium (mg $kg^{-1}$) after harvest of crisphead lettuce during the seasons of 2022 and 2023. Additionally, Fig. 1 represents the individual effects of the zeolite rates on soil water holding capacity (WHC, %), electrical conductivity (EC, $dSm^{-1}$), and cation exchange capacity (CEC, cmolc $kg^{-1}$) during the same periods.

The data in Table 2 indicate that applying 100% of the recommended nitrogen dose resulted in decreased soil nutrient levels post-harvest compared to plants treated with 75% of the recommended dose. This trend suggests that plants receiving 100% of the recommended nitrogen may have enhanced nutrient absorption abilities, leading to reduced nutrient residues in the soil.

**Table 2. Impact of different doses of nitrogen recommended (NR), soil addition of zeolite and spraying titanium on soil properties (available nitrogen, phosphorus and potassium) after harvest of crisphead lettuce during seasons of 2022 and 2023.**

| Treatments | | | Available-N, mg kg$^{-1}$ | | Available-P, mg kg$^{-1}$ | | Available-K, mg kg$^{-1}$ | |
|---|---|---|---|---|---|---|---|---|
| | | | 1$^{st}$ season | 2$^{nd}$ season | 1$^{st}$ season | 2$^{nd}$ season | 1$^{st}$ season | 2$^{nd}$ season |
| **Main factor: Mineral nitrogen treatments** | | | | | | | | |
| **$N_1$: 100 % of NR** | | | 42.78b | 44.08b | 10.37b | 10.57b | 225.64b | 228.45b |
| **$N_2$:75 % of NR** | | | 43.95a | 45.39a | 11.08a | 11.31a | 231.95a | 234.91a |
| **LSD at 5%** | | | **1.37** | **0.69** | **0.20** | **0.15** | **1.17** | **1.19** |
| **Sub main factor: Zeolite treatments** | | | | | | | | |
| **$Z_1$: Without(control)** | | | 41.30c | 42.60c | 9.79c | 9.99c | 213.95c | 216.55c |
| **$Z_2$: Zeolite (2.5 ton fed$^{-1}$)** | | | 43.10b | 44.47b | 10.82b | 11.03b | 229.17b | 232.30b |
| **$Z_3$: Zeolite (5.0 ton fed$^{-1}$)** | | | 45.70a | 47.15a | 11.57a | 11.80a | 243.26a | 246.18a |
| **LSD at 5%** | | | **0.34** | **0.30** | **0.06** | **0.06** | **0.68** | **0.68** |
| **Sub-sub main factor: Titanium treatments** | | | | | | | | |
| **$F_1$: Without(control)** | | | 43.69a | 45.05a | 10.86a | 11.08a | 230.34a | 233.45a |
| **$F_2$: Titanium (3.0 mgL$^{-1}$)** | | | 43.35ab | 44.72ab | 10.72b | 10.93b | 228.77b | 231.56b |
| **$F_3$: Titanium (6.0 mgL$^{-1}$)** | | | 43.06b | 44.44b | 10.60c | 10.81c | 227.26c | 230.02c |
| **LSD at 5%** | | | **0.40** | **0.43** | **0.09** | **0.11** | **0.65** | **0.66** |
| **Interaction** | | | | | | | | |
| **$N_1$** | **$Z_1$** | **$F_1$** | 41.19 | 42.55 | 10.09 | 10.30 | 212.81 | 215.15 |
| | | **$F_2$** | 40.82 | 42.01 | 9.99 | 10.19 | 212.12 | 214.45 |
| | | **$F_3$** | 40.59 | 41.75 | 9.90 | 10.08 | 211.15 | 214.10 |
| | **$Z_2$** | **$F_1$** | 42.94 | 44.30 | 10.40 | 10.62 | 226.41 | 229.81 |
| | | **$F_2$** | 42.56 | 43.78 | 10.29 | 10.47 | 224.63 | 227.33 |
| | | **$F_3$** | 42.36 | 43.67 | 10.19 | 10.38 | 223.28 | 226.18 |
| | **$Z_3$** | **$F_1$** | 45.20 | 46.65 | 10.93 | 11.16 | 242.02 | 245.16 |
| | | **$F_2$** | 44.88 | 46.25 | 10.80 | 10.98 | 240.05 | 242.92 |
| | | **$F_3$** | 44.47 | 45.75 | 10.73 | 10.94 | 238.29 | 240.90 |
| **$N_2$** | **$Z_1$** | **$F_1$** | 42.08 | 43.30 | 9.69 | 9.85 | 217.65 | 220.91 |
| | | **$F_2$** | 41.67 | 43.10 | 9.59 | 9.83 | 215.90 | 218.28 |
| | | **$F_3$** | 41.46 | 42.85 | 9.48 | 9.68 | 214.06 | 216.42 |
| | **$Z_2$** | **$F_1$** | 43.89 | 45.21 | 11.57 | 11.82 | 235.48 | 239.01 |
| | | **$F_2$** | 43.60 | 45.09 | 11.29 | 11.53 | 233.50 | 237.00 |
| | | **$F_3$** | 43.24 | 44.74 | 11.16 | 11.37 | 231.69 | 234.47 |
| | **$Z_3$** | **$F_1$** | 46.82 | 48.28 | 12.46 | 12.70 | 247.68 | 250.65 |
| | | **$F_2$** | 46.57 | 48.08 | 12.36 | 12.61 | 246.44 | 249.39 |
| | | **$F_3$** | 46.26 | 47.89 | 12.12 | 12.40 | 245.12 | 248.06 |
| **LSD at 5%** | | | **0.96** | **1.06** | **0.23** | **0.26** | **1.60** | **1.62** |

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

On the other hand, the highest levels of available nitrogen, phosphorus, and potassium post-harvest were observed with the highest zeolite rate (5.0 tons fed$^{-1}$), while the lowest levels were noted in the control treatment. In other words, the values increased as the zeolite added rate increased. This suggests that increasing the zeolite application rate led to higher nutrient retention in the soil, particularly nitrogen, which tends to be lost rapidly after nitrogen fertilizer application due to leaching or volatilization, as will discuss in the following section.

Regarding foliar application of titanium, soil nutrient levels post-harvest decreased as the titanium rate increased gradually from 0.0 to 3.0 and then 6.0 mg L$^{-1}$. This suggests that plants sprayed with titanium may have improved nutrient absorption abilities, resulting in reduced nutrient residues in the soil.

Fig 1 illustrates that soil WHC (%), EC (dSm$^{-1}$), and CEC (cmolc kg$^{-1}$) increased during both studied seasons under all zeolite treatments compared to the initial soil, likely due to root zone activity. Moreover, the values of these soil properties increased with increasing zeolite application rate, with the highest values observed in soil treated with 5.0 tons of zeolite fed$^{-1}$, followed by 2.5 tons and then the control treatment. This trend was consistent across both studied seasons.

**Plant growth analysis**

Table 3 illustrates the impact of varied nitrogen doses, zeolite soil addition and titanium spraying on crisphead lettuce growth criteria across the 2022 and 2023 seasons, including fresh and dry weights (g plant$^{-1}$), leaf area (cm$^2$ plant$^{-1}$), relative water content (%) and No. of outer leaves. Additionally, Table 4 displays the effect of these treatments on the chemical constituents of leaves (N, P and K %) as well as photosynthetic pigments (chlorophyll content - SPAD reading, and carotene - mg g$^{-1}$) at harvest time. The data show that the treatment of 100% of NR caused the maximum values compared to the treatment of 75% of NR, which possessed the lowest values of all aforementioned traits, except relative water content (%) in the first season which had no significantly affected due to nitrogen treatments.

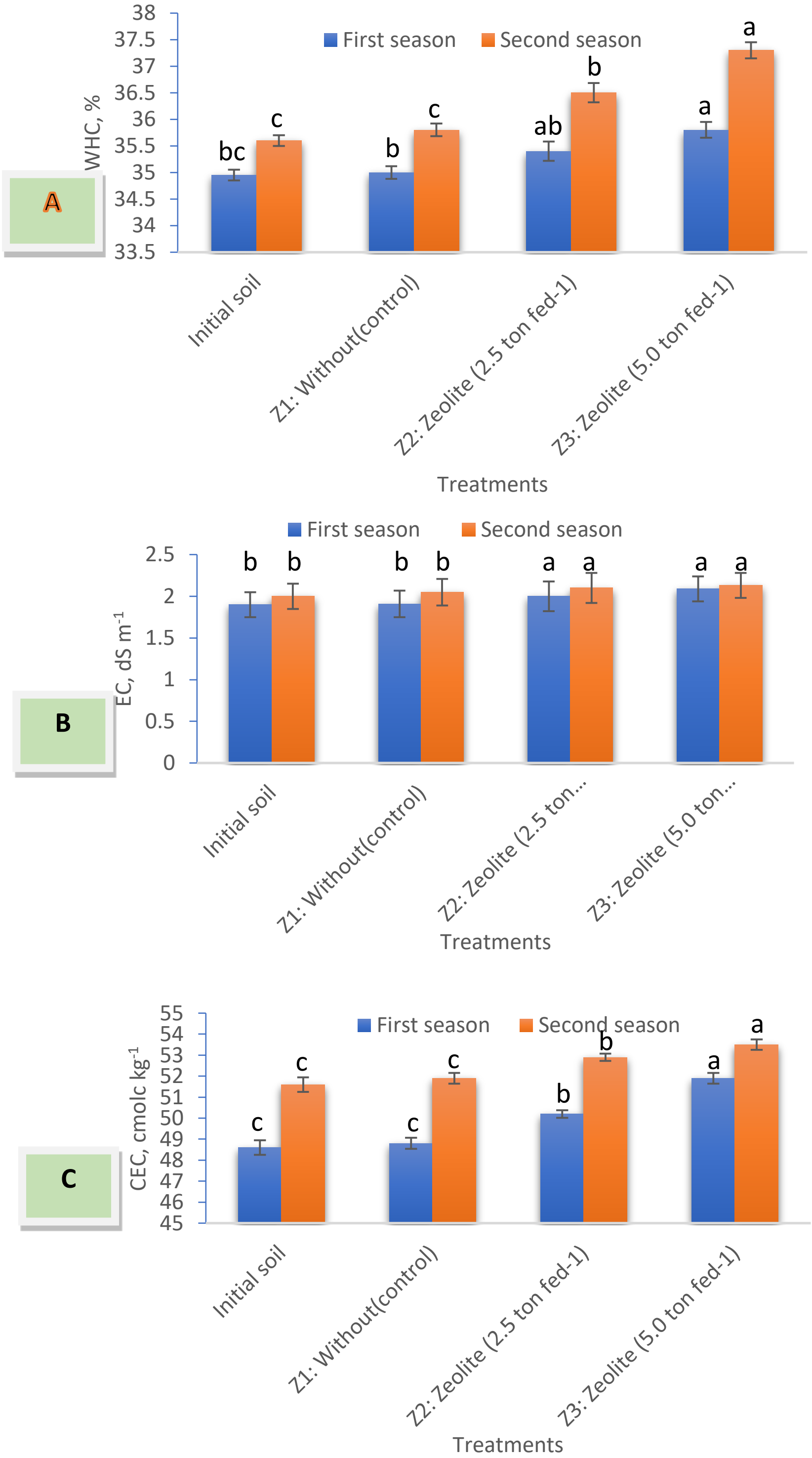


**Fig. 1. Individual effect of zeolite rates on soil WHC (A), EC (B) and CEC (C) after harvest during seasons of 2022 and 2023.**

**Table 3. Impact of different doses of nitrogen recommended (NR), soil addition of zeolite and spraying titanium on growth performance of crisphead lettuce during seasons of 2022 and 2023.**

| Treatments | | | Fresh weight, g plant$^{-1}$ | | Dry weight, g plant$^{-1}$ | | Leaf area, cm$^2$ plant$^{-1}$ | |
|---|---|---|---|---|---|---|---|---|
| | | | 1$^{st}$ season | 2$^{nd}$ season | 1$^{st}$ season | 2$^{nd}$season | 1$^{st}$ season | 2$^{nd}$ season |
| **Main factor: Mineral nitrogen treatments** | | | | | | | | |
| **$N_1$: 100 % of NR** | | | 1352.19a | 1370.48a | 106.00a | 107.88a | 2469.85a | 2511.33a |
| **$N_2$:75 % of NR** | | | 1161.81b | 1176.48b | 83.78**b** | 85.44b | 2061.78b | 2092.59b |
| **LSD at 5%** | | | **50.93** | **2.80** | **4.60** | **3.98** | **100.19** | **4.46** |
| **Sub main factor: Zeolite treatments** | | | | | | | | |
| **$Z_1$: Without(control)** | | | 1094.83c | 1110.56c | 79.47c | 80.82c | 1944.22c | 1974.61c |
| **$Z_2$: Zeolite (2.5 ton fed$^{-1}$)** | | | 1289.83b | 1305.17b | 97.79b | 99.44b | 2299.94b | 2339.44b |
| **$Z_3$: Zeolite (5.0 ton fed$^{-1}$)** | | | 1386.33a | 1404.72a | 107.42a | 109.71a | 2553.28a | 2591.83a |
| **LSD at 5%** | | | **11.17** | **3.50** | **1.80** | **0.89** | **19.74** | **6.22** |
| **Sub-sub main factor: Titanium treatments** | | | | | | | | |
| **$F_1$: Without(control)** | | | 1236.72b | 1253.67c | 92.55c | 94.22c | 2223.83c | 2257.94c |
| **$F_2$: Titanium (3.0 mg L$^{-1}$)** | | | 1263.00a | 1278.61b | 94.75b | 96.59b | 2259.83b | 2294.89b |
| **$F_3$: Titanium (6.0 mg L$^{-1}$)** | | | 1271.28a | 1288.17a | 97.37a | 99.16a | 2313.78a | 2353.06a |
| **LSD at 5%** | | | **11.14** | **3.73** | **1.97** | **0.85** | **17.19** | **6.87** |
| **Interaction** | | | | | | | | |
| **$N_1$** | **$Z_1$** | **$F_1$** | 1194.00 | 1212.33 | 85.38 | 86.67 | 2020.67 | 2054.00 |
| | | **$F_2$** | 1203.00 | 1217.33 | 88.02 | 89.71 | 2093.33 | 2129.33 |
| | | **$F_3$** | 1208.33 | 1225.00 | 90.43 | 91.92 | 2168.33 | 2201.33 |
| | **$Z_2$** | **$F_1$** | 1367.00 | 1383.00 | 108.88 | 110.65 | 2554.33 | 2599.00 |
| | | **$F_2$** | 1404.67 | 1419.33 | 110.95 | 112.91 | 2575.67 | 2625.67 |
| | | **$F_3$** | 1420.33 | 1437.33 | 113.67 | 115.88 | 2629.33 | 2687.00 |
| | **$Z_3$** | **$F_1$** | 1430.33 | 1454.00 | 116.58 | 118.59 | 2683.67 | 2722.67 |
| | | **$F_2$** | 1468.00 | 1492.67 | 118.84 | 121.10 | 2737.33 | 2772.33 |
| | | **$F_3$** | 1474.00 | 1493.33 | 121.24 | 123.44 | 2766.00 | 2810.67 |
| **$N_2$** | **$Z_1$** | **$F_1$** | 984.00 | 999.67 | 68.13 | 69.17 | 1753.00 | 1775.00 |
| | | **$F_2$** | 986.67 | 1000.00 | 70.00 | 71.21 | 1761.00 | 1787.33 |
| | | **$F_3$** | 993.00 | 1009.00 | 74.85 | 76.23 | 1869.00 | 1900.67 |
| | **$Z_2$** | **$F_1$** | 1177.00 | 1191.33 | 83.88 | 85.54 | 2010.33 | 2039.00 |
| | | **$F_2$** | 1180.00 | 1193.00 | 84.55 | 85.84 | 2011.67 | 2039.33 |
| | | **$F_3$** | 1190.00 | 1207.00 | 84.79 | 85.86 | 2018.33 | 2046.67 |
| | **$Z_3$** | **$F_1$** | 1268.00 | 1281.67 | 92.47 | 94.73 | 2321.00 | 2358.00 |
| | | **$F_2$** | 1335.67 | 1349.33 | 96.14 | 98.80 | 2380.00 | 2415.33 |
| | | **$F_3$** | 1342.00 | 1357.33 | 99.22 | 101.61 | 2431.67 | 2472.00 |
| **LSD at 5%** | | | **27.28** | **9.14** | **4.84** | **2.08** | **42.11** | **16.81** |

| Treatments | | | Relative water content, % | | No. of outer leaves | |
|---|---|---|---|---|---|---|
| | | | 1$^{st}$ season | 2$^{nd}$ season | 1$^{st}$ season | 2$^{nd}$ season |
| **Main factor: Mineral nitrogen treatments** | | | | | | |
| **$N_1$: 100 % of NR** | | | 87.93a | 90.00a | 5.26b | 5.59b |
| **$N_2$:75 % of NR** | | | 84.16a | 86.05b | 7.67a | 8.00a |
| **LSD at 5%** | | | ***NS** | **2.68** | **1.59** | **1.83** |
| **Sub main factor: Zeolite treatments** | | | | | | |
| **$Z_1$: Without(control)** | | | 83.39c | 85.36c | 5.72b | 6.06b |
| **$Z_2$: Zeolite (2.5 ton fed$^{-1}$)** | | | 86.28b | 88.15b | 6.33b | 6.67b |
| **$Z_3$: Zeolite (5.0 ton fed$^{-1}$)** | | | 88.47a | 90.57a | 7.33a | 7.67a |
| **LSD at 5%** | | | **1.24** | **0.66** | **0.73** | **0.86** |
| **Sub-sub main factor: Titanium treatments** | | | | | | |
| **$F_1$: Without(control)** | | | 85.68a | 87.68a | 6.28a | 6.61a |
| **$F_2$: Titanium (3.0 mg L$^{-1}$)** | | | 86.00a | 87.96a | 6.44a | 6.78a |
| **$F_3$: Titanium (6.0 mg L$^{-1}$)** | | | 86.46a | 88.44a | 6.67a | 7.00a |
| **LSD at 5%** | | | ***NS** | ***NS** | ***NS** | ***NS** |
| **Interaction** | | | | | | |
| **$N_1$** | **$Z_1$** | **$F_1$** | 84.13 | 86.12 | 4.33 | 4.67 |
| | | **$F_2$** | 84.34 | 86.22 | 4.67 | 5.00 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | **$F_3$** | 84.87 | 86.95 | 5.00 | 5.33 |
| | **$Z_2$** | **$F_1$** | 87.71 | 89.44 | 5.00 | 5.33 |
| | | **$F_2$** | 88.43 | 90.55 | 5.00 | 5.33 |
| | | **$F_3$** | 89.39 | 91.18 | 5.33 | 5.67 |
| | **$Z_3$** | **$F_1$** | 90.05 | 92.48 | 5.67 | 6.00 |
| | | **$F_2$** | 90.82 | 93.16 | 6.00 | 6.33 |
| | | **$F_3$** | 91.62 | 93.94 | 6.33 | 6.67 |
| **$N_2$** | **$Z_1$** | **$F_1$** | 82.23 | 84.26 | 6.67 | 7.00 |
| | | **$F_2$** | 82.34 | 84.02 | 6.67 | 7.00 |
| | | **$F_3$** | 82.42 | 84.62 | 7.00 | 7.33 |
| | **$Z_2$** | **$F_1$** | 84.06 | 85.93 | 7.33 | 7.67 |
| | | **$F_2$** | 84.01 | 85.90 | 7.67 | 8.00 |
| | | **$F_3$** | 84.09 | 85.89 | 7.67 | 8.00 |
| | **$Z_3$** | **$F_1$** | 85.91 | 87.85 | 8.67 | 9.00 |
| | | **$F_2$** | 86.05 | 87.92 | 8.67 | 9.00 |
| | | **$F_3$** | 86.36 | 88.09 | 8.67 | 9.00 |
| | | **LSD at 5%** | **4.41** | **2.01** | **2.12** | **2.35** |

Means within a row followed by a different letter (s) are statistically different at a 0.05 level
*NS= non-significant

On the other side, zeolite treatments, the values of fresh and dry weights, leaf area, relative water content, No. of outer leaves, chemical constituents of leaves (N, P and K) and photosynthetic pigments (chlorophyll and carotene) gradually increased as the added rate of zeolite increased from 0.0 to 2.5 then 5.0 ton fed$^{-1}$.

Except relative water content (%) and No. of outer leaves, all aforementioned traits gradually increased as added rate of titanium increased from 0.0 to 3.0 then 6.0 mg L-$^{1}$. In terms of relative water content (%), the effect of titanium treatment was non-significant under both studied season.

Generally, it can be noticed that the best results were achieved with plants treated with 100% of NR and zeolite at rate of 5.0 ton fed$^{-1}$ and simultaneously sprayed with 6.0 mg Ti L$^{-1}$. But also, it can be noticed that plants treated with 75% of NR and zeolite at rate of 5.0 ton fed$^{-1}$ and simultaneously sprayed with 6.0 mg Ti L$^{-1}$ possessed the results better than those of plants treated with 100% of NR without both zeolite and titanium. Similar trend was found under both studied seasons.

**Head traits (physical traits and quality)**

Table 5 outlines the influence of different nitrogen doses, zeolite soil addition, and titanium spraying on the physical characteristics of crisphead lettuce heads, such as head weight (g), head diameter (cm) and head height (cm). Meanwhile, Tables 6 and 7 show the impacts of these treatments on quality attributes, encompassing carbohydrates, protein, total sugars, fibers, dry matter (DM %), vitamin C (mg 100g$^{-1}$), and total dissolved solid (TDS, %) during the 2022 and 2023 seasons. The data show that the treatment of 100% of NR caused the maximum values compared to the treatment of 75% of NR, which possessed the lowest values of all aforementioned traits, except No. of outer leaves.

Regarding zeolite treatments, the values of head traits and quality gradually increased as the added rate of zeolite increased from 0.0 to 2.5 then 5.0 ton fed$^{-1}$.

Concerning titanium treatments, all aforementioned traits gradually increased as added rate of titanium increased from 0.0 to 3.0 then 6.0 mg L-$^{1}$.

Regarding interaction effect, the highest values of head traits and quality parameters were realized with plants treated with 100% of NR and zeolite at rate of 5.0 ton fed$^{-1}$ and simultaneously sprayed with 6.0 mg Ti L$^{-1}$. But also, it can be noticed that plants treated with 75%of NR and zeolite at rate of 5.0 ton fed$^{-1}$ and simultaneously sprayed with 6.0 mg Ti L$^{-1}$ possessed the head traits and quality better than those of plants treated with 100% of NR without both zeolite and titanium. Similar trend was found under both studied seasons.

**Table 4. Impact of different doses of nitrogen recommended (NR), soil addition of zeolite and spraying titanium on chemical constituents in dry leaves and photosynthetic pigment contents in fresh leaves of crisphead lettuce during seasons of 2022 and 2023.**

| Treatments | | | Leaves chemical constituents | | | | | | Photosynthetic pigment | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | N, % | | P, % | | K, % | | Chlorophyll, SPAD reading | | Carotene, mg $g^{-1}$ | |
| | | | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season |
| **Main factor: Mineral nitrogen treatments** | | | | | | | | | | | | |
| **$N_1$: 100 % of NR** | | | 3.26a | 3.36a | 0.364a | 0.379a | 2.98a | 3.04a | 45.83a | 46.40a | 0.367a | 0.383a |
| **$N_2$:75 % of NR** | | | 2.92b | 3.01b | 0.323b | 0.336b | 2.68b | 2.73b | 42.71b | 43.25b | 0.305b | 0.318b |
| **LSD at 5%** | | | **0.04** | **0.01** | **0.006** | **0.008** | **0.06** | **0.13** | **0.61** | **0.62** | **0.013** | **0.006** |
| **Sub main factor: Zeolite treatments** | | | | | | | | | | | | |
| **$Z_1$: Without(control)** | | | 2.85c | 2.94c | 0.314c | 0.327c | 2.62c | 2.67c | 41.86c | 42.37c | 0.295c | 0.308c |
| **$Z_2$: Zeolite (2.5 ton $fed^{-1}$)** | | | 3.14b | 3.23b | 0.347b | 0.362b | 2.85b | 2.91b | 44.51b | 45.12b | 0.341b | 0.356b |
| **$Z_3$: Zeolite (5.0 ton $fed^{-1}$)** | | | 3.28a | 3.38a | 0.368a | 0.383a | 3.02a | 3.08a | 46.43a | 46.99a | 0.373a | 0.388a |
| **LSD at 5%** | | | **0.02** | **0.02** | **0.004** | **0.005** | **0.02** | **0.05** | **0.29** | **0.30** | **0.001** | **0.004** |
| **Sub-sub main factor: Titanium treatments** | | | | | | | | | | | | |
| **$F_1$: Without(control)** | | | 3.06b | 3.15b | 0.338c | 0.352c | 2.79c | 2.85b | 43.95b | 44.54b | 0.328c | 0.342c |
| **$F_2$**: Titanium (3.0 mg $L^{-1}$) | | | 3.08b | 3.18b | 0.344b | 0.358b | 2.83b | 2.89ab | 44.3ab | 44.8ab | 0.337b | 0.350b |
| **$F_3$**: Titanium (6.0 mg $L^{-1}$) | | | 3.13a | 3.23a | 0.348a | 0.362a | 2.87a | 2.93a | 44.59a | 45.13a | 0.345a | 0.359a |
| **LSD at 5%** | | | **0.03** | **0.03** | **0.002** | **0.002** | **0.02** | **0.06** | **0.43** | **0.44** | **0.003** | **0.003** |
| **Interaction** | | | | | | | | | | | | |
| **$N_1$** | **$Z_1$** | **$F_1$** | 2.98 | 3.08 | 0.326 | 0.339 | 2.71 | 2.76 | 42.42 | 42.89 | 0.310 | 0.323 |
| | | **$F_2$** | 3.01 | 3.10 | 0.331 | 0.346 | 2.75 | 2.81 | 42.73 | 43.20 | 0.316 | 0.330 |
| | | **$F_3$** | 3.03 | 3.12 | 0.337 | 0.351 | 2.80 | 2.84 | 43.09 | 43.69 | 0.322 | 0.336 |
| | **$Z_2$** | **$F_1$** | 3.34 | 3.44 | 0.370 | 0.386 | 2.99 | 3.05 | 46.54 | 47.24 | 0.370 | 0.386 |
| | | **$F_2$** | 3.36 | 3.44 | 0.374 | 0.389 | 3.03 | 3.09 | 46.69 | 47.25 | 0.379 | 0.394 |
| | | **$F_3$** | 3.37 | 3.47 | 0.377 | 0.394 | 3.08 | 3.13 | 47.31 | 47.91 | 0.386 | 0.404 |
| | **$Z_3$** | **$F_1$** | 3.39 | 3.50 | 0.381 | 0.397 | 3.13 | 3.20 | 47.57 | 48.19 | 0.398 | 0.415 |
| | | **$F_2$** | 3.40 | 3.49 | 0.387 | 0.402 | 3.16 | 3.23 | 48.02 | 48.60 | 0.410 | 0.426 |
| | | **$F_3$** | 3.47 | 3.57 | 0.393 | 0.408 | 3.20 | 3.28 | 48.07 | 48.59 | 0.418 | 0.434 |
| **$N_2$** | **$Z_1$** | **$F_1$** | 2.65 | 2.73 | 0.292 | 0.303 | 2.45 | 2.50 | 40.67 | 41.28 | 0.267 | 0.277 |
| | | **$F_2$** | 2.68 | 2.77 | 0.299 | 0.311 | 2.48 | 2.53 | 41.06 | 41.51 | 0.273 | 0.284 |
| | | **$F_3$** | 2.76 | 2.86 | 0.303 | 0.315 | 2.54 | 2.60 | 41.18 | 41.63 | 0.285 | 0.297 |
| | **$Z_2$** | **$F_1$** | 2.90 | 2.98 | 0.318 | 0.331 | 2.65 | 2.70 | 42.07 | 42.70 | 0.298 | 0.310 |
| | | **$F_2$** | 2.93 | 3.03 | 0.321 | 0.333 | 2.68 | 2.73 | 42.18 | 42.81 | 0.305 | 0.318 |
| | | **$F_3$** | 2.95 | 3.05 | 0.323 | 0.337 | 2.70 | 2.74 | 42.27 | 42.78 | 0.308 | 0.322 |
| | **$Z_3$** | **$F_1$** | 3.08 | 3.18 | 0.343 | 0.358 | 2.83 | 2.89 | 44.42 | 44.95 | 0.326 | 0.340 |
| | | **$F_2$** | 3.14 | 3.24 | 0.351 | 0.366 | 2.88 | 2.94 | 44.92 | 45.46 | 0.338 | 0.352 |
| | | **$F_3$** | 3.19 | 3.30 | 0.354 | 0.368 | 2.90 | 2.96 | 45.59 | 46.14 | 0.349 | 0.363 |
| **LSD at 5%** | | | **0.07** | **0.08** | **0.006** | **0.006** | **0.05** | **0.15** | **1.06** | **1.07** | **0.007** | **0.006** |

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

**Table 5. Impact of different doses of nitrogen recommended (NR), soil addition of zeolite and spraying titanium on growth performance of crisphead lettuce during seasons of 2022and 2023.**

| Treatments | | | Head weight, g plant$^{-1}$ | | Head diameter, cm | | Head height, cm | |
|---|---|---|---|---|---|---|---|---|
| | | | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season |
| **Main factor: Mineral nitrogen treatments** | | | | | | | | |
| **$N_1$: 100 % of NR** | | | 1165.74a | 1193.15a | 19.08a | 20.03a | 17.38a | 18.24a |
| **$N_2$:75 % of NR** | | | 991.22b | 1013.11b | 16.40b | 17.21b | 14.94b | 15.69b |
| **LSD at 5%** | | | **29.12** | **44.71** | **0.11** | **0.21** | **0.40** | **0.15** |
| **Sub main factor: Zeolite treatments** | | | | | | | | |
| **$Z_1$: Without(control)** | | | 950.50c | 972.06c | 15.70c | 16.48c | 14.39c | 15.15c |
| **$Z_2$: Zeolite (2.5 ton fed$^{-1}$)** | | | 1103.11b | 1127.22b | 17.99b | 18.86b | 16.32b | 17.12b |
| **$Z_3$: Zeolite (5.0 ton fed$^{-1}$)** | | | 1181.83a | 1210.11a | 19.53a | 20.53a | 17.76a | 18.62a |
| **LSD at 5%** | | | **5.72** | **9.73** | **0.13** | **0.10** | **0.15** | **0.13** |
| **Sub-sub main factor: Titanium treatments** | | | | | | | | |
| **$F_1$: Without(control)** | | | 1050.56c | 1075.00c | 17.42c | 18.29c | 15.89c | 16.69c |
| **$F_2$: Titanium (3.0 mg L$^{-1}$)** | | | 1081.83b | 1105.89b | 17.76b | 18.63b | 16.18b | 16.98b |
| **$F_3$: Titanium (6.0 mg L$^{-1}$)** | | | 1103.06a | 1128.50a | 18.04a | 18.95a | 16.41a | 17.22a |
| **LSD at 5%** | | | **9.27** | **9.78** | **0.14** | **0.17** | **0.09** | **0.13** |
| **Interaction** | | | | | | | | |
| **$N_1$** | **$Z_1$** | **$F_1$** | 1027.33 | 1051.33 | 16.50 | 17.40 | 15.07 | 15.80 |
| | | **$F_2$** | 1034.00 | 1055.00 | 16.50 | 17.27 | 15.50 | 16.40 |
| | | **$F_3$** | 1053.00 | 1077.67 | 17.00 | 17.80 | 15.60 | 16.40 |
| | **$Z_2$** | **$F_1$** | 1122.67 | 1145.33 | 19.47 | 20.40 | 17.67 | 18.57 |
| | | **$F_2$** | 1176.00 | 1203.67 | 19.93 | 20.90 | 17.80 | 18.60 |
| | | **$F_3$** | 1258.00 | 1281.33 | 20.10 | 21.10 | 18.17 | 19.10 |
| | **$Z_3$** | **$F_1$** | 1268.00 | 1303.00 | 20.40 | 21.40 | 18.70 | 19.60 |
| | | **$F_2$** | 1275.67 | 1308.00 | 20.83 | 21.90 | 18.80 | 19.70 |
| | | **$F_3$** | 1277.00 | 1313.00 | 21.00 | 22.10 | 19.10 | 19.97 |
| **$N_2$** | **$Z_1$** | **$F_1$** | 800.00 | 817.33 | 14.50 | 15.20 | 13.00 | 13.70 |
| | | **$F_2$** | 888.67 | 908.00 | 14.70 | 15.40 | 13.50 | 14.20 |
| | | **$F_3$** | 900.00 | 923.00 | 15.00 | 15.80 | 13.70 | 14.40 |
| | **$Z_2$** | **$F_1$** | 1017.33 | 1042.00 | 15.97 | 16.77 | 14.50 | 15.17 |
| | | **$F_2$** | 1020.33 | 1043.00 | 16.20 | 16.90 | 14.80 | 15.50 |
| | | **$F_3$** | 1024.33 | 1048.00 | 16.30 | 17.10 | 15.00 | 15.80 |
| | **$Z_3$** | **$F_1$** | 1068.00 | 1091.00 | 17.70 | 18.57 | 16.40 | 17.30 |
| | | **$F_2$** | 1096.33 | 1117.67 | 18.37 | 19.40 | 16.67 | 17.47 |
| | | **$F_3$** | 1106.00 | 1128.00 | 18.87 | 19.80 | 16.87 | 17.67 |
| | | **LSD at 5%** | **22.70** | **23.95** | **0.34** | **0.43** | **0.22** | **0.33** |

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

**Table 6. Impact of different doses of nitrogen recommended (NR), soil addition of zeolite and spraying titanium on quality characteristics of crisphead lettuce (carbohydrates, protein, T. Sugars, fibers) during seasons of 2022 and 2023.**

| Treatments | | | Carbohydrates, % | | Protein, % | | T. Sugars, % | | Fibers, % | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season |
| **Main factor: Mineral nitrogen treatments** | | | | | | | | | | |
| **$N_1$: 100 % of NR** | | | 1.92a | 1.98a | 2.79a | 2.83a | 0.87a | 0.91a | 1.43a | 1.50a |
| **$N_2$:75 % of NR** | | | 1.52b | 1.57b | 2.24b | 2.27b | 0.45b | 0.48b | 0.89b | 0.93b |
| **LSD at 5%** | | | **0.01** | **0.01** | **0.06** | **0.12** | **0.05** | **0.01** | **0.08** | **0.01** |
| **Sub main factor: Zeolite treatments** | | | | | | | | | | |
| **$Z_1$: Without(control)** | | | 1.42c | 1.46c | 2.12c | 2.16c | 0.35c | 0.37c | 0.75c | 0.79c |
| **$Z_2$: Zeolite (2.5 ton fed$^{-1}$)** | | | 1.74b | 1.80b | 2.57b | 2.61b | 0.68b | 0.72b | 1.21b | 1.27b |
| **$Z_3$: Zeolite (5.0 ton fed$^{-1}$)** | | | 2.00a | 2.06a | 2.85a | 2.89a | 0.95a | 0.99a | 1.53a | 1.60a |
| **LSD at 5%** | | | **0.01** | **0.02** | **0.02** | **0.05** | **0.02** | **0.02** | **0.02** | **0.01** |
| **Sub-sub main factor: Titanium treatments** | | | | | | | | | | |
| **$F_1$: Without(control)** | | | 1.68c | 1.73c | 2.45c | 2.49c | 0.61c | 0.64c | 1.11c | 1.16c |
| **$F_2$**: Titanium (3.0 mg L$^{-1}$) | | | 1.72b | 1.77b | 2.51b | 2.55b | 0.66b | 0.69b | 1.16b | 1.22b |
| **$F_3$**: Titanium (6.0 mg L$^{-1}$) | | | 1.77a | 1.83a | 2.57a | 2.61a | 0.72a | 0.75a | 1.21a | 1.27a |
| **LSD at 5%** | | | **0.01** | **0.02** | **0.02** | **0.05** | **0.02** | **0.02** | **0.02** | **0.01** |
| **Interaction** | | | | | | | | | | |
| **$N_1$** | **$Z_1$** | **$F_1$** | 1.48 | 1.54 | 2.30 | 2.34 | 0.42 | 0.44 | 0.82 | 0.86 |
| | | **$F_2$** | 1.53 | 1.58 | 2.35 | 2.39 | 0.47 | 0.49 | 0.88 | 0.93 |
| | | **$F_3$** | 1.58 | 1.63 | 2.43 | 2.47 | 0.51 | 0.53 | 0.96 | 1.01 |
| | **$Z_2$** | **$F_1$** | 2.01 | 2.07 | 2.82 | 2.87 | 0.93 | 0.97 | 1.57 | 1.65 |
| | | **$F_2$** | 2.05 | 2.11 | 2.89 | 2.94 | 0.98 | 1.03 | 1.62 | 1.69 |
| | | **$F_3$** | 2.09 | 2.15 | 2.95 | 3.01 | 1.07 | 1.13 | 1.68 | 1.77 |
| | **$Z_3$** | **$F_1$** | 2.13 | 2.20 | 3.03 | 3.07 | 1.09 | 1.15 | 1.73 | 1.82 |
| | | **$F_2$** | 2.18 | 2.24 | 3.11 | 3.15 | 1.14 | 1.20 | 1.80 | 1.88 |
| | | **$F_3$** | 2.24 | 2.30 | 3.21 | 3.26 | 1.21 | 1.27 | 1.84 | 1.93 |
| **$N_2$** | **$Z_1$** | **$F_1$** | 1.26 | 1.30 | 1.84 | 1.86 | 0.21 | 0.22 | 0.56 | 0.59 |
| | | **$F_2$** | 1.27 | 1.31 | 1.90 | 1.93 | 0.24 | 0.25 | 0.61 | 0.64 |
| | | **$F_3$** | 1.38 | 1.43 | 1.93 | 1.96 | 0.27 | 0.28 | 0.65 | 0.68 |
| | **$Z_2$** | **$F_1$** | 1.40 | 1.44 | 2.21 | 2.24 | 0.35 | 0.37 | 0.77 | 0.81 |
| | | **$F_2$** | 1.45 | 1.50 | 2.25 | 2.28 | 0.37 | 0.39 | 0.80 | 0.84 |
| | | **$F_3$** | 1.47 | 1.52 | 2.28 | 2.31 | 0.40 | 0.42 | 0.80 | 0.84 |
| | **$Z_3$** | **$F_1$** | 1.77 | 1.82 | 2.50 | 2.54 | 0.64 | 0.67 | 1.19 | 1.25 |
| | | **$F_2$** | 1.82 | 1.88 | 2.59 | 2.63 | 0.77 | 0.81 | 1.27 | 1.33 |
| | | **$F_3$** | 1.88 | 1.95 | 2.65 | 2.69 | 0.83 | 0.87 | 1.34 | 1.41 |
| **LSD at 5%** | | | **0.02** | **0.04** | **0.05** | **0.13** | **0.04** | **0.06** | **0.06** | **0.03** |

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

**Table 7. Impact of different doses of nitrogen recommended (NR), soil addition of zeolite and spraying titanium on quality characteristics of crisphead lettuce [dry matter (DM), vitamin C (VC) total dissolved solid (TDS)] during seasons of 2022 and 2023.**

| Treatments | | | DM, % | | VC, mg100g$^{-1}$ | | TDS, % | |
|---|---|---|---|---|---|---|---|---|
| | | | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season |
| **Main factor: Mineral nitrogen treatments** | | | | | | | | |
| **$N_1$: 100 % of NR** | | | 6.28a | 6.55a | 3.12a | 3.18a | 5.66a | 5.78a |
| **$N_2$:75 % of NR** | | | 5.02b | 5.23b | 2.29b | 2.33b | 4.38b | 4.47b |
| **LSD at 5%** | | | **0.26** | **0.02** | **0.04** | **0.06** | **0.21** | **0.06** |
| **Sub main factor: Zeolite treatments** | | | | | | | | |
| **$Z_1$: Without(control)** | | | 4.74c | 4.93c | 2.14c | 2.18c | 4.00c | 4.08c |
| **$Z_2$: Zeolite (2.5 ton fed$^{-1}$)** | | | 5.81b | 6.06b | 2.76b | 2.81b | 5.15b | 5.26b |
| **$Z_3$: Zeolite (5.0 ton fed$^{-1}$)** | | | 6.41a | 6.68a | 3.21a | 3.29a | 5.91a | 6.04a |
| **LSD at 5%** | | | **0.05** | **0.04** | **0.03** | **0.03** | **0.05** | **0.04** |
| **Sub-sub main factor: Titanium treatments** | | | | | | | | |
| **$F_1$: Without(control)** | | | 5.56c | 5.80c | 2.62c | 2.67c | 4.92c | 5.02c |
| **$F_2$: Titanium (3.0 mg L$^{-1}$)** | | | 5.64b | 5.87b | 2.69b | 2.75b | 5.01b | 5.12b |
| **$F_3$: Titanium (6.0 mg L$^{-1}$)** | | | 5.76a | 6.00a | 2.80a | 2.86a | 5.13a | 5.24a |
| **LSD at 5%** | | | **0.05** | **0.06** | **0.03** | **0.02** | **0.04** | **0.05** |
| **Interaction** | | | | | | | | |
| **$N_1$** | **$Z_1$** | **$F_1$** | 4.91 | 5.11 | 2.20 | 2.24 | 4.34 | 4.43 |
| | | **$F_2$** | 5.03 | 5.25 | 2.28 | 2.33 | 4.53 | 4.62 |
| | | **$F_3$** | 5.16 | 5.38 | 2.39 | 2.43 | 4.74 | 4.83 |
| | **$Z_2$** | **$F_1$** | 6.61 | 6.90 | 3.25 | 3.33 | 5.88 | 6.00 |
| | | **$F_2$** | 6.75 | 7.02 | 3.37 | 3.43 | 6.02 | 6.14 |
| | | **$F_3$** | 6.88 | 7.19 | 3.48 | 3.55 | 6.18 | 6.32 |
| | **$Z_3$** | **$F_1$** | 7.03 | 7.34 | 3.60 | 3.68 | 6.38 | 6.51 |
| | | **$F_2$** | 7.06 | 7.34 | 3.68 | 3.77 | 6.42 | 6.57 |
| | | **$F_3$** | 7.11 | 7.39 | 3.81 | 3.91 | 6.44 | 6.60 |
| **$N_2$** | **$Z_1$** | **$F_1$** | 4.34 | 4.52 | 1.95 | 1.99 | 3.37 | 3.43 |
| | | **$F_2$** | 4.39 | 4.56 | 1.99 | 2.03 | 3.42 | 3.50 |
| | | **$F_3$** | 4.60 | 4.79 | 2.02 | 2.06 | 3.61 | 3.69 |
| | **$Z_2$** | **$F_1$** | 4.85 | 5.04 | 2.11 | 2.16 | 4.25 | 4.34 |
| | | **$F_2$** | 4.85 | 5.06 | 2.15 | 2.19 | 4.28 | 4.37 |
| | | **$F_3$** | 4.89 | 5.12 | 2.18 | 2.22 | 4.32 | 4.40 |
| | **$Z_3$** | **$F_1$** | 5.60 | 5.85 | 2.60 | 2.65 | 5.29 | 5.41 |
| | | **$F_2$** | 5.74 | 5.99 | 2.69 | 2.75 | 5.39 | 5.51 |
| | | **$F_3$** | 5.91 | 6.16 | 2.91 | 2.97 | 5.51 | 5.61 |
| | **LSD at 5%** | | **0.11** | **0.15** | **0.07** | **0.06** | **0.11** | **0.13** |

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

## Economic feasibility

Table 8 presents the comprehensive economic feasibility analysis combining data from both studied seasons. Each feddan corresponds to 20,000 plants. The market value of a single plant, weighing 1.0 kg, is set at 5 pounds. Ammonium sulfate is priced at 67 pounds per kilogram, with a total of 300 kilograms feddan as recommended dose. The cost of one ton of zeolite stands at 2000 pounds. Additionally, it's worth noting that the combined cost of all titanium treatments does not surpass 100 pounds. The economic feasibility in Table 8 shows the ability of zeolite as a partial substitute for 25% of nitrogen fertilizer without pronouncedly affecting the net return. Moreover, a clear net return was achieved due to titanium treatments.

Where 100% of the recommended nitrogen fertilizer is used without zeolite, the total cost was 20100 LE and net return was 83833 LE. However, soil properties may not be as improved without zeolite, and there is an increased risk of environmental pollution due to the higher nitrogen dosage.

Where 75% of the recommended nitrogen fertilizer is used, under titanium treatments, along with zeolite at rates of 2.5 and 5 ton fed$^{-1}$, the total cost was 20175 (with the first-rate of zeolite) and 25175LE (with the second rate of zeolite), respectively, while the net return was from 82891.5 to 86525 LE. With zeolite, soil properties are improved, and there is a reduced risk of environmental pollution due to the lower nitrogen dosage and zeolite's ability to mitigate nitrogen loss.

Considering both economic and environmental factors, treating 75% of the recommended nitrogen fertilizers with zeolite and titanium is preferable to using 100% of the recommended nitrogen fertilizers. This approach provides a similar net return while improving soil properties and reducing the risk of environmental pollution.

**Table 8. Economic feasibility.**

| Treatments | | | Total Cost (LE/fed) | Mean head weight (ton fed$^{-1}$) | Revenue Generated (LE/fed) | Net profit (LE/fed) |
|---|---|---|---|---|---|---|
| **$N_1$: 100 % of NR** | **$Z_1$: Without (control)** | **$F_1$: Without (control)** | 20100 | 20.7866 | 103933 | 83833 |
| | | **$F_2$:Titanium (3.0 mgL$^{-1}$)** | 20200 | 20.89 | 104450 | 84250 |
| | | **$F_3$: Titanium (6.0 mgL$^{-1}$)** | 20200 | 21.3067 | 106533.5 | 86333.5 |
| | **$Z_2$: Zeolite (2.5 ton fed$^{-1}$)** | **$F_1$: Without(control)** | 25100 | 22.68 | 113400 | 88300 |
| | | **$F_2$:Titanium (3.0 mgL$^{-1}$)** | 25200 | 23.7967 | 118983.5 | 93783.5 |
| | | **$F_3$: Titanium (6.0 mgL$^{-1}$)** | 25200 | 25.3933 | 126966.5 | 101766.5 |
| | **$Z_3$: Zeolite (5.0 ton fed$^{-1}$)** | **$F_1$: Without(control)** | 30100 | 25.71 | 128550 | 98450 |
| | | **$F_2$:Titanium (3.0 mgL$^{-1}$)** | 30200 | 25.8367 | 129183.5 | 98983.5 |
| | | **$F_3$: Titanium (6.0 mgL$^{-1}$)** | 30200 | 25.9 | 129500 | 99300 |
| **$N_2$:75 % of NR** | **$Z_1$: Without (control)** | **$F_1$: Without(control)** | 15075 | 16.1733 | 80866.5 | 65791.5 |
| | | **$F_2$:Titanium (3.0 mgL$^{-1}$)** | 15175 | 17.9667 | 89833.5 | 74658.5 |
| | | **$F_3$: Titanium (6.0 mgL$^{-1}$)** | 15175 | 18.23 | 91150 | 75975 |
| | **$Z_2$: Zeolite (2.5 ton fed$^{-1}$)** | **$F_1$: Without(control)** | 20075 | 20.5933 | 102966.5 | 82891.5 |
| | | **$F_2$:Titanium (3.0 mgL$^{-1}$)** | 20175 | 20.6333 | 103166.5 | 82991.5 |
| | | **$F_3$: Titanium (6.0 mgL$^{-1}$)** | 20175 | 20.7233 | 103616.5 | 83441.5 |
| | **$Z_3$: Zeolite (5.0 ton fed$^{-1}$)** | **$F_1$: Without(control)** | 25075 | 21.59 | 107950 | 82875 |
| | | **$F_2$:Titanium (3.0 mgL$^{-1}$)** | 25175 | 22.14 | 110700 | 85525 |
| | | **$F_3$: Titanium (6.0 mgL$^{-1}$)** | 25175 | 22.34 | 111700 | 86525 |

## 4. Discussion

### Post-harvest soil analyses

Plants receiving 100% of the recommended nitrogen dose likely exhibited higher absorption efficiency due to sufficient nitrogen availability, leading to reduced residual nitrogen in the soil post-harvest. This enhanced absorption could be attributed to the optimized nitrogen levels, promoting vigorous root growth and nutrient uptake **(Ottaiano *et al.*, 2021)**. Higher nitrogen doses may have stimulated plant growth, leading to increased nutrient utilization for biomass production rather than leaving excess nutrients in the soil. This efficient nutrient utilization can result in lower residual soil nutrient levels after harvest **(Kılıç, 2022).**

Zeolite has a high cation exchange capacity (CEC) and adsorption capacity, allowing it to retain nutrients such as nitrogen, phosphorus, and potassium in the soil. The observed increase in soil nutrient levels with higher zeolite application rates suggests that zeolite effectively retained these nutrients in the root zone, making them available for plant uptake **(Omar *et al*. 2020; Soltys *et al*. 2020)**. Zeolite's porous structure enables it to retain water and nutrients, reducing the risk of nutrient leaching below the root zone. This retention helps maintain nutrient availability in the root zone for longer periods, thereby enhancing plant nutrient uptake and reducing nutrient losses from the soil. Zeolite's porous structure enhances soil water retention by absorbing and holding water molecules within its structure (**Li, *et al*. 2022).** This increased WHC promotes better soil moisture retention, which is beneficial for plant growth and root development. Zeolite's high CEC allows it to exchange cations with the soil, improving nutrient retention and availability for plant uptake. This enhanced CEC contributes to better soil fertility and nutrient management (**Ghazi *et al.*, 2023)**. Zeolite amendments can improve soil structure by promoting aggregation and reducing compaction. This improved soil structure enhances root penetration and facilitates better air and water movement within the soil, creating a more favorable environment for plant growth and nutrient uptake **(ElGhamry *et al.*, 2024).**

Titanium spraying may have enhanced nutrient uptake efficiency in plants, leading to increased nutrient absorption from the soil and consequently lower residual soil nutrient levels post-harvest. Titanium is known to enhance plant physiological processes, including nutrient assimilation and translocation within the plant, which could contribute to improved nutrient uptake efficiency **(ElGhamry *et al.*, 2022)**. Moreover, its ability in non-biological nitrogen fixation. Titanium treatments may have stimulated root growth and development, resulting in increased root surface area for nutrient absorption. This enhanced root system can facilitate greater exploration of the soil volume, leading to improved nutrient uptake and reduced residual soil nutrients **(Elsherpiny and Faiyad, 2023)**.

### Plant growth analysis

Plants treated with 100% of the recommended nitrogen dose showed maximum values for most growth criteria, chemical constituents of leaves and photosynthetic pigments compared to those treated with 75% of the recommended dose. This suggests that adequate nitrogen supply promotes plant growth and development, leading to higher biomass accumulation and leaf area expansion **(Farouk *et al.*, 2023)**.

Relative water content (%) was not significantly affected by nitrogen treatments in the first season, indicating that nitrogen doses may not directly influence water retention in plant tissues.

Increasing zeolite application rates led to gradual improvements in all growth criteria, relative water content, chemical constituents of leaves and photosynthetic pigments. This is likely due to zeolite's ability to improve soil structure, enhance nutrient retention, and promote water and nutrient availability for plant uptake. The highest values were observed with zeolite at a rate of 5.0 tons $fed^{-1}$, indicating the effectiveness of higher zeolite doses in promoting plant growth and physiological processes **(Omar *et al*., 2020; Soltys *et al*., 2020**.

Titanium spraying may enhance nutrient uptake efficiency and photosynthetic activity, leading to increased biomass production and chlorophyll synthesis **(ElGhamry *et al.*, 2022)**. The best results were achieved with plants treated with 6.0 mg Ti $L^{-1}$, indicating the beneficial effects of higher titanium concentrations on plant growth and pigment synthesis. Moreover, titanium dioxide ($TiO_2$) may play a role in the non-biological fixation of atmospheric nitrogen to nitrate on $TiO_2$ surfaces **(Al-Taani, 2008).** In this process, $TiO_2$ acts as a catalyst to facilitate the conversion of atmospheric nitrogen into nitrate through a series of reactions involving intermediate nitrogen oxide specie**s (ElGhamry *et al.*, 2022; (Elsherpiny and Faiyad, 2023)**. When UV light with energy higher than the band gap energy of $TiO_2$ is incident upon it, electron-hole pairs are generated **(Kozlova, *et al.*, 2021).** Electrons from the valence band are excited to the conduction band, leaving behind positively charged holes in the valence band. These electron-hole pairs in titanium dioxide can participate in various photochemical reactions **(Wu *et al.*, 2022).** Specifically, they can interact with adsorbed nitrogen molecules on the $TiO_2$ surface, facilitating the conversion of nitrogen gas ($N_2$) into nitrogen oxides and eventually into nitrate ions ($NO^{3-}$) in the presence of water and oxygen. This process of nitrogen fixation on $TiO_2$ surfaces under UV light irradiation is a form of photocatalysis **(Elsherpiny and Faiyad, 2023)**.

Plants treated with 100% of the recommended nitrogen dose, zeolite at a rate of 5.0 tons $fed^{-1}$, and simultaneously sprayed with 6.0 mg Ti $L^{-1}$ exhibited the highest growth performance. This suggests synergistic effects between nitrogen, zeolite, and titanium treatments in promoting plant growth and physiological processes. Even plants treated with 75% of the recommended nitrogen dose, zeolite at a rate of 5.0 tons $fed^{-1}$, and simultaneously sprayed with 6.0 mg Ti $L^{-1}$ showed better results than those treated with 100% of the recommended nitrogen dose without zeolite and titanium. This highlights the importance of combined nutrient management strategies for optimizing plant growth and productivity.

Overall, the results indicate that proper nutrient management, including nitrogen supplementation, zeolite soil addition, and titanium spraying, can significantly improve crisphead lettuce growth and physiological performance, with synergistic effects observed with combined treatments.

**Head traits (physical traits and quality)**

Regarding head traits (physical characteristics and quality parameters) of crisphead lettuce, the plants treated with 100% of the recommended nitrogen dose exhibited the best performance compared to those treated with 75% of the recommended dose and this indicates the importance of adequate nitrogen supply for achieving optimal head traits and quality parameters in crisphead lettuce. Nitrogen is crucial for the growth and development of crisphead lettuce due to its essential roles in protein synthesis, leaf expansion, biomass accumulation, yield and quality **(Ottaiano *et al.*, 2021).** As a key component of chlorophyll, nitrogen promotes photosynthesis and enhances leaf development, leading to larger and healthier foliage **(Kılıç, 2022).** Adequate nitrogen supply supports head formation, increases head size and weight, and improves overall yield and marketability. Furthermore, nitrogen plays a vital role in enhancing plant resilience to environmental stresses and maintaining overall plant health. Optimal nitrogen management is therefore essential for maximizing crop productivity, quality, and profitability in crisphead lettuce production **(Farouk *et al.*, 2023).**

Increasing zeolite application rates led to gradual improvements in head traits and quality parameters. This suggests that zeolite soil addition enhances soil fertility, nutrient availability, and water retention, resulting in improved plant growth and nutritional content of lettuce heads **(Omar *et al***. **2020; Soltys *et al***. **2020)**. Zeolite plays a significant role in enhancing the efficiency of mineral nitrogen fertilizers in agriculture through various mechanisms. Firstly, zeolite possesses a high cation exchange capacity (CEC), allowing it to adsorb and retain positively charged ions such as ammonium ($NH_4^+$) released from nitrogen fertilizers **(Rodrigues *et al*. 2021).** This retention prevents leaching of ammonium into groundwater, reducing nitrogen losses and enhancing nutrient availability for plant uptake. Additionally, zeolite's porous structure provides a reservoir for holding water and nutrients, facilitating gradual release to plant roots as needed, thereby improving nutrient use efficiency (**Li *et al*. 2022)**. Moreover, zeolite can mitigate nitrogen loss through volatilization by trapping ammonium ions within its lattice structure, reducing atmospheric emissions of nitrogen compounds (**Ghazi *et al.* 2023)**.

Similarly, increasing titanium application rates resulted in gradual improvements in head traits and quality parameters. Titanium spraying may enhance nutrient uptake efficiency, photosynthetic activity, and overall physiological performance of lettuce plants, leading to improved head characteristics and nutritional quality **(Al-Taani, 2008; Kozlova *et al.*, 2021; ElGhamry *et al.*, 2022; Wu *et al*., 2022; Elsherpiny, and Faiyad, 2023)**.

## 5. Conclusion

The current study highlights the critical importance of optimizing nitrogen fertilizer application to ensure environmental sustainability in Egyptian agriculture.

According to the obtained results, it can be concluded that zeolite amendments, particularly at higher rates (5.0 ton $fed^{-1}$), positively influence soil nutrient availability and properties, leading to improved plant growth and quality traits. Additionally, titanium spraying (especially at rate of 6.0 mg Ti $L^{-1}$) enhances plant performance, further contributing to enhanced crop productivity.

Generally, the recommendations for sustainable agricultural practices include precise nitrogen management, incorporating zeolite amendments, and utilizing titanium spraying techniques to optimize crop growth while minimizing environmental impacts. Furthermore, the study underscores the importance of integrated nutrient management strategies tailored to local agricultural conditions to achieve optimal results and ensure long-term sustainability in Egyptian agriculture.

**Conflicts of interest**

Authors have declared that no competing interests exist.

**Formatting of funding sources:** The research was funded by the personal efforts of the authors.

## 6. References

**Abd El-Hady, M.A., Shehata, M. N., & Abd ELhamied, A.S (2024).** Effect of mineral and organic fertilization rates under magnetized water irrigation on growth, yield, and quality of crisphead lettuce. Egyptian Journal of Soil Science, 64(1):275-286.

**Abdel-Hakim, S. G., Shehata, A. S., Moghannem, S. A., Qadri, M., El-Ghany, M. F. A., Abdeldaym, E. A., & Darwish, O. S. (2023).** Nanoparticulate fertilizers increase nutrient absorption efficiency and agro-physiological properties of lettuce plant. Agronomy, 13(3), 691.

**Al-Taani, A. A. (2008).** Non-biological fixation of atmospheric nitrogen to nitrate on titanium dioxide and desert soil surfaces. University of Nevada, Reno.

**AOAC, (2000).**˝Official Methods of Analysis˵. 18th Ed. Association of Official Analytical Chemists, Inc., Gaithersburg, MD, Method 04.

**Balasubramanian, V., Morales, A. C., Cruz, R. T., Thiyagarajan, T. M., Nagarajan, R., Babu, M., ... & Hai, L. H. (2000).** Adaptation of the chlorophyll meter (SPAD) technology for real-time N management in rice: a review. International Rice Research Notes, 25(1): 4-8.

**CoStat version 6.303 copyright (1998-2004).** CoHort Software 798 Lighthouse Ave. PMB 320, Monterey, CA, 93940, USA.

**Dere, Ş., Güneş, T., & Sivaci, R. (1998).** Spectrophotometric determination of chlorophyll-A, B and totalcarotenoid contents of some algae species using different solvents. Turkish Journal of Botany, 22(1), 13-18.

**Doklega, S. M., El-Ezz, S. F. A., Mostafa, N. A., Dessoky, E. S., Abdulmajeed, A. M., Darwish, D. B. E., ... & Abd El-Hady, M. A. (2022).** Effect of titanium and vanadium on antioxidants content and productivity of red cabbage. Horticulturae, 8(6), 481.

**ElGhamry, A., Ghazi, D. A., Elsherpiny, M. A., Soliman, M., & Helmy, A. (2022).** Titanium: An element of non-biological atmospheric nitrogen fixation and a regulator of sugar beet plant tolerance to salinity. Egyptian Journal of Soil Science, 62(4):, 373-381.

**ElGhamry, A., Ghazi, D. A., Elsherpiny, M. A., Kassem, M. A., Kassem, A., & Helmy, A. A. (2024).** Enhancing onion growth and yield quality via soil amendments and foliar nutrition under deficit irrigation. Egyptian Journal of Soil Science, 64(2):, 523-542.

**Elsherpiny, M. A., & Faiyad, R. M. N. (2023).** Effect of titanium as a stimulant of atmospheric nitrogen fixation on faba bean plants. Egyptian Journal of Soil Science, 63(4), 465-474.

**Farouk, S., El-Hady, M. A. A., El-Sherpiny, M. A., Hassan, M. M., Alamer, K. H., Al-Robai, S. A., ... & El-Bauome, H. A. (2023).** Effect of Dopamine on Growth, Some Biochemical Attributes, and the Yield of Crisphead Lettuce under Nitrogen Deficiency. Horticulturae, 9(8), 945.

**Ghazi, D., Hafez, S., & Elsherpiny, M. A. (2023).** Rice cultivation adaption to water resources shortage in Egypt. Egyptian Journal of Soil Science, 63(1): 113-126.

**Gomez; K. A and Gomez, A.A (1984).** "Statistical Procedures for Agricultural Research". John Wiley and Sons, Inc., New York.pp:680.

**Kılıç, C. C. (2022).** Effect of nitrogen and planting dates on yield and yield components of head lettuce grown in soilless culture. Journal of Plant Nutrition, 45(20): 3159-3173.

**Kozlova, E. A., Lyulyukin, M. N., Kozlov, D. V., & Parmon, V. N. (2021).** Semiconductor photocatalysts and mechanisms of carbon dioxide reduction and nitrogen fixation under UV and visible light. Russian Chemical Reviews, 90(12), 1520.

**Lebeda, A., Křístková, E., Kitner, M., Widrlechner, M. P., Maras, M., & El-Esawi, M. A. (2022).** Egypt as one of the centers of lettuce domestication: morphological and genetic evidence. Euphytica, 218(1), 10.

**Li, Y., Xia, G., Wu, Q., Chen, W., Lin, W., Zhang, Z., ... & Chi, D. (2022).** Zeolite increases grain yield and potassium balance in paddy fields. Geoderma, 405, 115397.

**Mostafa, N. A., El-Sherpiny, M. A., Elmakarm, A., & Amira, A. (2023).** Impact of organic fertilization and some beneficial elements on the performance and storability of Salt-Stressed Crisphead Lettuce (*Lactuca sativa* L.). Journal of Plant Production, 14(12):, 403-409.

**Omar, L., Ahmed, O. H., Jalloh, M. B., & Nik Muhamad, A. M. (2020).** Soil nitrogen fractions, nitrogen use efficiency and yield of *Zea mays* L. grown on a tropical acid soil treated with composts and clinoptilolite zeolite. Applied Sciences, 10(12), 4139.

**Ottaiano, L., Di Mola, I., Cozzolino, E., El-Nakhel, C., Rouphael, Y., & Mori, M. (2021).** Biostimulant application under different nitrogen fertilization levels: Assessment of yield, leaf quality, and nitrogen metabolism of tunnel-grown lettuce. Agronomy, 11(8), 1613.

**Peterburgski, A. V. (1968)."**Handbook of Agronomic Chemistry". Kolos Puplishing House, Moscow, (in Russian, pp. 29-86).

**Rodrigues, M. Â., Torres, L. D. N. D., Damo, L., Raimundo, S., Sartor, L., Cassol, L. C., & Arrobas, M. (2021).** Nitrogen use efficiency and crop yield in four successive crops following application of biochar and zeolites. Journal of Soil Science and Plant Nutrition, 21:, 1053-1065.

**Soltys, L., Myronyuk, I., Tatarchuk, T., & Tsinurchyn, V. (2020).** Zeolite-based composites as slow release fertilizers. Physics and Chemistry of Solid State, 21(1):, 89-104.

**Tandon, H. L. S. (2005).** Methods of analysis of soils, plants, waters, fertilisers & organic manures. Fertilizer Development and Consultation Organization.

**Walinga, I., Van Der Lee, J. J., Houba, V. J., Van Vark, W., & Novozamsky, I. (2013).** Plant analysis manual. Springer Science & Business Media.

**Wu, S., He, C., Wang, L., & Zhang, J. (2022).** High-efficiency electron tandem flow mode on carbon nitride/titanium dioxide heterojunction for visible light nitrogen photofixation. Chemical Engineering Journal, 443, 136425.