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Indonesian Journal of Agricultural Research
Journal homepage: https://injar.usu.ac.id

Effects of zeolite-amended sandy soil on moisture, ash, and protein content of Swiss Chard

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ARTICLE INFO

Article history:
Received 18-10-2024
Revised 20-04-2025
Accepted 21-06-2025
Available online 22-07-2025

E-ISSN: 2615-5842
P-ISSN: 2622-7681

How to cite:
O. A. Sindesi, B. Ncube, M. N. Lewu, A. R. Mulidzi, and F. B. Lewu, "Effects of zeolite-amended sandy soil on moisture, ash, and protein content of Swiss Chard", *Indonesian J. Agric. Res*, vol. 8, no. 2, pp. 85–91, Jul. 2025.

https://doi.org/10.32734/injar.v8i2.18592

ABSTRACT

Soil degradation and water scarcity are major challenges affecting crop productivity in sandy soils. Zeolite, a naturally occurring aluminosilicate mineral, has been explored as a soil amendment to improve soil properties and enhance plant growth for various crops. However, limited information on the influence of zeolite soil amendment on Swiss chard nutritional content. A greenhouse pot experiment was conducted at the Agricultural Research Council, Infruitec-Nietvoorbij, Stellenbosch, South Africa, from late autumn to late spring. The study accessed the effects of zeolite soil amendment on dry matter yield, moisture content, crude ash, and crude protein of Swiss Chard (*Beta vulgaris* var. *cicla* cv. Ford Hook Giant) over five harvests. The experiment was laid out in a completely randomised block design with four treatments 0; 10; 20 and 30% zeolite application to sandy soil, all at 12 kg sandy soil or sandy soil and zeolite mixture. Data were analysed using analysis of variance (ANOVA), and treatment means were compared using Fisher's least significant difference test at a 5% probability level. The results of this study show that zeolite through its porous nature, high cation exchange capacity and alkalinity may be used to improve water availability to plants (moisture content) while at the same time improving dry matter yields and mineral accumulation (crude ash content). However, zeolite did not improve the crude protein contents of Swiss chard, which is a function of nitrogen assimilation. Nevertheless, 20–30% zeolite application levels can be used as an effective method to combat soil degradation and mitigate drought-related challenges. These rates improved dry matter yields, enhanced crop moisture content, and promoted crude ash and/or mineral accumulation in Swiss chard.
Keyword: *Beta vulgaris var. cicla*, leafy vegetables, plant nutrition, soil amendment

1. Introduction

Africa faces numerous challenges in its cropping systems, part of these challenges are drought and soil degradation [1]. Many parts of Africa experience periodic droughts, mostly climate change-led droughts, leading to crop failures and water shortages [2]; [3]. Additionally, arable lands tend to experience soil nutrient depletion primarily due to improper land management practices. Nutrient depletion in agricultural land is normally solved with the use of inorganic fertilisers which tend to acidify soils in the long term [4]. Historically, fallowing and organic matter applications were used to combat soil degradation, while reductions in land area used for crop production were done to reduce irrigation needs. Due to current limitations in arable land and optimal fallow lengths, fallowing cannot be practised. In addition, organic amendments in soils quickly decompose leaving the soil vulnerable again [5]; [6]. However, the ever-growing food demand due to the growing population prohibits a reduction in food production. therefore, a need to research innovative approaches to ameliorate these challenges, without compromising food production.

Zeolite is gaining popularity as a stable soil amendment that can improve crop growth and yields [7]; [8]. Zeolites are porous hydrated aluminosilicate minerals with a three-dimensional structure formed by bonded silicon and aluminium tetrahedra [9]; [10] Due to their alkaline nature, high cation exchange capacity (CEC), strong affinity to cations (NH_4^+ and K^+) and porous nature. Zeolite can ameliorate soil acidity, improve nutrient retention and prolong availability while increasing the soil water holding capacity [11]; [12]. This allows conducive plant growth conditions leading to improved crop yields. There is, however, limited information on the influence of zeolite soil amendment on crop nutritional content, especially vegetables. Leafy vegetables such as Swiss chard (*Beta vulgaris* var. *cicla*) supply significant amounts of essential nutrients throughout Africa, particularly in South Africa where it is wrongfully known as spinach [13]. Zeolite soil amendment did not improve micromineral composition of Swiss chard [12], lettuce [14], and cabbage [15]. However, [15] observed an increase in macro-mineral concentration of cabbage with increased zeolite application. This study investigated the influence of zeolite soil application on the dry matter yield, moisture, ash, and protein content (%) in Swiss chard grown in zeolite-amended sandy soils.

2. Methods

2.1. Research design and site

A greenhouse pot experiment was conducted at the Agricultural Research Council (ARC), Infruitec-Nietvoorbij, Stellenbosch, South Africa, from late autumn to late spring of 2018. The study assessed the influence of natural clinoptilolite zeolite soil amendment on Swiss chard (*Beta vulgaris* var. *cicla* cv. Ford Hook Giant) yield, moisture content, crude ash and crude protein. The experiment comprised three zeolite soil amended treatments, at 0; 10; 20 and 30% zeolite-to-sandy soil *w/w*, and a non-amended control. Each pot had 12 kg of soil or soil and zeolite mixture. The pots were arranged in a randomised complete block design, with six (6) replicates. Each replicate comprised three (3) potted Swiss chard plants. Previous research [12] has reported fertiliser, irrigation, and pest control strategies. Irrigation was maintained between 50% and 70% of pot capacity throughout the study to ensure that there was no nutrient leaching. Weeds were controlled manually, while insect pests were managed using Makhro Cyper® (active ingredient: cypermethrin, 200 g L^{-1}).

2.2. Observed variables

The study assessed the following variables: (i) dry matter yield (g/3 plants), (ii) moisture content (%), (iii) crude ash content (%), and (iv) crude protein content (%) of Swiss chard grown in zeolite-amended sandy soils. Swiss chard harvesting commenced four weeks after transplanting and was done every 21 days for four more harvests. In total, 5 harvests were carried out before termination of the trial. Only leaves longer than 15 cm were harvested. The fresh weight of the yield was measured using a weighing scale. After which, the sample dry weight was obtained by oven-drying samples using a forced-air oven at 70 ºC until constant weight (+/- 72 hrs.). The fresh and dry weight of Swiss chard was used to calculate the moisture content of Swiss chard leaves. Oven-dried samples were analysed for crude ash using the method described by the Association of Official Analytical Chemists [16] ashing at a temperature of 550 °C for 8 hours. Nitrogen (N) was analysed using the micro-Kjeldahl method by digesting it in concentrated sulfuric acid (H_2SO_4) [17]. Crude protein (N x 6.25) was determined from the Leaf N.

2.3. Statistical analysis

Data were subjected to a one-way analysis of variance (ANOVA) using SAS (version 9.4, SAS Institute Inc., Cary, NC, USA, 2000). Analysis of variance was performed using the SAS statistical software. Post-hoc comparisons among treatment means were conducted using Fisher's least significant difference (LSD) test at a 5% significance level. A probability level of 5% was considered significant for all tests.

3. Results and Discussion

3.1. Impact of zeolite soil application on dry matter yield of Swiss chard

The results of Swiss chard dry matter yield are presented in Table 1. The dry matter yield of the first Swiss chard harvest (DYH-1) shows that the non-amended treatment had a significantly higher dry yield than the zeolite-amended treatments, although this was not significant compared to the 10% and 20% zeolite applications. This can be attributed to an initial reduction in ammonium (NH_4-N) and potassium (K) cation availability due to zeolite's affinity towards these cations [18]; [19]. This affinity allows zeolite to adsorb these cations into its channels reducing their availability to the plant while also reducing leaching [20]; [21]. The reduction of N and K nutrients reduces plant growth, this can be observed by a decrease in leaf size and ultimately reduced yields. The gradual release of these cations, NH_4^+ in particular, can be observed by the improved dry matter yields on the zeolite-amended treatments from DYH-2 to DYH-5. These may also be linked to reduced N availability on the non-amended treatment. N availability can be associated with improved plant growth and yields. N is responsible for various plant metabolic processes including the production of plant meristematic cells which support the plant's continuous growth and development, leading to higher yields [22]. The overall higher ($P \leq 0.05$) dry matter yields of Swiss chard on the zeolite-amended treatments may also be linked to the high cation exchange capacity (CEC) and porous nature of zeolite. The high CEC permits the availability of other plant nutrients such as Ca^{2+} and Mg^{2+} [23], which encourages optimal plant growth and improved yields. Additionally, the porous nature of zeolite increases the soil water holding capacity and therefore facilitates water mobility in leaves via the xylem, which improves plant metabolic activities leading to improved plant growth [24].

Table 1. Effect of zeolite application on dry matter yield (g/3 plants) of Swiss chard across five harvests

Zeolite (%)	DYH-1	DYH-2	DYH-3	DYH-4	DYH-5
0	**23.4a**	23.582b	14.633c	19.333b	20.9c
10	16.457ab	**35.283a**	22.367b	**38.05a**	29.067ab
20	**21.337a**	**35.008a**	21.933b	**34.267a**	**32.15a**
30	13.598b	**31.593a**	**29.717a**	**41.85a**	25.567b
LSD ($p \leq 0.05$)	7.7335	6.135	2.9343	9.1729	4.3318

Note: Means in the same column with the same superscript are not significantly different ($P \geq 0.05$). LSD = Least significant difference, DYH = Dry matter yield at harvest

3.2. Swiss chard moisture content in response to zeolite application

During growth, the moisture in crops assists in maintaining the protoplasmic contents of the cells [25]. This assists the plant in carrying out various essential cellular functions such as energy production, protein synthesis, cell division and more. Therefore, high moisture content during growth is beneficial to plants as it encourages cellular functions and plant growth. However, the high moisture content in post-harvest handling of vegetables makes them susceptible to microbial spoilage, as microorganisms such as bacteria and fungi easily reproduce in moist conditions [25]; [26]. In this study, zeolite application significantly improved the moisture content (%) of Swiss chard leaves (Table 2) for most of the harvests, except for the fourth harvest. The fourth harvest did not show any significant differences among treatments.

Table 2. Swiss chard moisture content (%) in response to zeolite application on a dry weight basis

Zeolite (%)	MH-1 (%)	MH-2 (%)	MH-3 (%)	MH-4 (%)	MH-5 (%)
0	93.07^{b}	93.49^{b}	89.74^{c}	$\mathbf{88.28^{a}}$	86.75^{b}
10	$\mathbf{93.56^{ab}}$	$\mathbf{93.54^{a}}$	$\mathbf{91.88^{ab}}$	$\mathbf{88.91^{a}}$	$\mathbf{89.08^{a}}$
20	$\mathbf{93.08^{b}}$	$\mathbf{93.39^{a}}$	$\mathbf{91.34^{b}}$	$\mathbf{88.99^{a}}$	$\mathbf{89.15^{a}}$
30	$\mathbf{93.96^{a}}$	$\mathbf{93.39^{a}}$	$\mathbf{92.09^{a}}$	$\mathbf{88.69^{a}}$	$\mathbf{90.45^{a}}$
LSD ($p \leq 0.05$)	0.67	0.69	0.73	1.59	1.44

Note: Means in the same column with the same superscript are not significantly different ($P \geq 0.05$). LSD = Least significant difference, MH = Moisture Content (%) at harvest

These results may be attributed to increased water availability in zeolite-amended soils. This is due to zeolites' large free spaces and channels within the silicate (SiO_4) and aluminate (AlO_4) structure [10]; [27]. These channels allow up to 30% water adsorption by zeolite, the adsorbed water can be removed without disturbing the crystal structure of the zeolite [28]. An increase in soil water holding capacity with increased zeolite application was observed in the study by Ravali [29]. High soil moisture during growth has been linked with high crop moisture content. However, other environmental factors such as air temperature, relative humidity, dew point temperature, and solar radiation also play a crucial role in crop moisture content [30]. These factors may be responsible for the observed general decline in Swiss chard moisture content, observed from MH-3 to MH-5. The Swiss chard growing season started in late autumn to late spring 2018. The first two harvests were generally in winter when air temperatures and solar radiation were relatively low, with high relative humidity. This environment was conducive to water uptake and retention by plants [31]. On the other hand, the last three harvests coincided with the spring season when air temperatures and solar radiation had increased, thereby encouraging more water losses through transpiration.

3.3. Effect of zeolite soil amendment on the crude ash content of Swiss chard

Crude ash in vegetable plants is the inorganic residue that remains after the plant material has been completely burned [32]. It is primarily composed of minerals such as K, Ca, Mg, P, and S, as well as trace elements like iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn). It has been used as a measure to indicate the mineral composition of foods [33]; [34]. However, [25] highlighted that high ash content is not necessarily a conclusive factor regarding the health benefits of vegetables. This is due to the possibility of leafy vegetables assimilating toxic metals which can contribute to the ash percentage of the vegetable. Table 3 represents the crude ash content of Swiss chard grown in zeolite-amended soils. The results show that there was more ash content on zeolite-amended soils than on the control throughout the different harvests.

Crude ash reflects the total mineral composition of plants; therefore, it is highly influenced by factors such as mineral availability in the soil, soil pH, water availability and other essential plant growth resources [25]; [26]. Zeolite has been shown to improve soil pH, mineral availability and water availability in soils, through its alkaline nature, providing adsorbed essential nutrients to plants and its porous characteristics [36]; [37]. Soil pH and cation exchange capacity (CEC) improvements from this study are shown in the study by Sindesi [38]. Improvements in soil pH and CEC may help plants to absorb more minerals thereby increasing crude ash accumulation. There was a gradual decrease in crude ash contents as the harvests progressed, with the exception of the first harvest (AH-1), going to the second harvest (AH-2) in the zeolite-amended soils. This observation may be because the benefit of zeolite took a while before it could be effectively realised in the soil. From AH-2 to AH-5, the observed crude ash reduction may be attributed to a slight reduction in soil pH and CEC, due to urea application. The slight decrease in these soil parameters is published in the work [38]. In soil, urea is converted to ammonium (NH_4^+) and eventually to nitrate (NO_3^-), the nitrification process releases hydrogen ions (H^+) into the soil, which leads to a decrease in soil pH [39].

Table 3. Influence of zeolite on the crude content (%) of Swiss chard on dry weight basis

Zeolite (%)	AH-1 (%)	AH-2 (%)	AH-3	AH-4 (%)	AH-5 (%)
0	21.83^b	21.25^b	15.33^c	15.17^b	12.17^c
10	**25.17^a**	**28.25^a**	24.00^b	**23.67^a**	23.33^b
20	**26.17^a**	**28.42^a**	24.50^b	**21.33^a**	22.83^b
30	**26.17^a**	**28.67^a**	**26.83^a**	**22.17^a**	**25.50^a**
LSD ($p \leq 0.05$)	2.14	1.56	1.95	2.96	1.79

Note: Means in the same column with the same superscript are not significantly different ($P \geq 0.05$). LSD = Least significant difference, AH = Ash Content (%) at harvest

3.4. Influence of zeolite soil application on crude protein content of Swiss chard

Nitrogen (N) is the primary component of proteins; crude protein is the measure of the total protein in a plant. Crude protein and N are closely linked in plants as crude protein can be calculated using the value of N contents in plants [40]. N assimilation by plants can be influenced by the type of N fertiliser applied and environmental conditions which include soil pH, temperature, irrigation etc. [41]. Due to the high alkalinity and free channels of zeolite, this soil amendment can improve soil pH and increase the water-holding capacity of the soil, thereby, increasing nutrient availability to plants [23]; [24]. Table 4 presents the crude protein contents of Swiss chard grown under various levels of zeolite soil amendment. In general, from PH-3 to PH-5, there were no significant differences in the crude protein contents in all the treatments. The results also show that the non-amended treatment generally accumulated higher crude protein than the zeolite-amended treatments as seen in harvests two (PH-2) to harvest five (PH-5). This may be due to the strong affinity of zeolite to NH_4^+ which allows zeolite to adsorb NH_4^+ into its structure, thereby reducing its availability to plants [20].

The adsorbed NH_4^+ is initially made unavailable to plants and then gradually released for plant use over time. The gradual release of the adsorbed NH_4^+ prolongs N in the soil and allows it to be available in some critical plant growth stages [42]. Although the adsorption disadvantages plant growth and plant N accumulation, it however, reduces N_2O emissions, NH_4^+-N and NO_3^--N leaching [37]; [43]. In addition to the strong affinity of zeolite to NH_4^+, N availability may have been reduced by plant assimilation during the growing season. Soil N reductions can also be attributed to the repeated harvests done for this study, this can also be seen in the NH_4^+-N and NO_3^-–N results presented in the work by [12]. This is demonstrated by the dry matter yield results presented in Table 1. Swiss chard is a green leafy vegetable and requires moderate amounts of N for optimal leaf formation and yields [44]. Soil N is reduced by plant assimilation, leaching and N_2O emissions [41]. N is responsible for various plant metabolic processes and protein synthesis which is essential for cell growth, cell division and leaf growth [45]. Leaf growth is essential for Swiss chard yields. The growth process requires more N, so plants may have diverted assimilated N to the growth rather than to crude protein synthesis. However, specific allocations of nitrogen between growth and protein synthesis are influenced by various factors, such as plant genetics, environmental conditions, and the stage of plant development.

Table 4. Influence of zeolite soil amendment on the crude protein (%) contents of Swiss chard on dry weight basis

Zeolite (%)	PH-1 (%)	PH-2 (%)	PH-3 (%)	PH-4 (%)	PH-5 (%)
0	27.25^{c}	$\mathbf{27.02^{a}}$	$\mathbf{18.47^{a}}$	$\mathbf{16.03^{a}}$	$\mathbf{16.25^{a}}$
10	$\mathbf{30.20^{a}}$	25.22^{b}	$\mathbf{18.72^{a}}$	14.74^{ab}	$\mathbf{15.34^{a}}$
20	28.92^{b}	25.42^{b}	$\mathbf{18.79^{a}}$	14.83^{ab}	$\mathbf{15.54^{a}}$
30	$\mathbf{30.55^{a}}$	24.23^{c}	$\mathbf{18.40^{a}}$	13.96^{b}	$\mathbf{14.82^{a}}$
LSD ($p \leq 0.05$)	1.22	0.79	1.86	1.59	1.86

Note: Means in the same column with the same superscript are not significantly different ($P \geq 0.05$). LSD = Least significant difference, PH = Protein Content (%) at harvest

4. Conclusion

This study shows that zeolite at 20–30% zeolite application levels can be used to improve dry matter yields, enhance crop moisture content, and promote crude ash and/or mineral accumulation in leafy vegetables such as Swiss chard. These attributes are essential for improving food production, plant metabolic processes, and mineral nutrition accumulation. Additionally, these benefits highlight the potential of zeolite as a sustainable soil amendment for improving crop resilience in drought-prone regions, where water conservation is crucial for food security. However, a key novel finding of this study is that zeolite did not enhance crude protein content, likely due to its strong affinity for NH_4^+, which initially reduces N availability for plant uptake. These findings provide valuable insights into the selective benefits and limitations of zeolite in nutrient management strategies for sustainable vegetable production.

5. Acknowledgements

The authors would like to thank the National Research Foundation (NRF) of South Africa for financial support for this research, under NRF grant number: 114405. Any opinion, findings, conclusions, or recommendations expressed in this article are those of the author(s), and the NRF accepts no liability whatsoever in this regard.

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