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Effect of zeolite-amended sandy soils on growth & yield of Copenhagen cabbage

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Abstract. A greenhouse pot experiment was conducted at the Agricultural Research Council, Infruitec-Nietvoorbij, Stellenbosch, South Africa, to assess the effect of zeolite on the fresh head yield & growth characteristics of cabbage cv. Copenhagen. Zeolite was applied at 0:10, 1:9, 2:8, & 3:7 zeolite to sandy soil (w/w). Cabbage growth parameters, plant height, & number of loose leaves showed significant improvements ($p < 0.05$) under zeolite-amended treatments in the second growing season. Maximum chlorophyll content index (CCI) values ranged from 70.03 to 78.04 in the first season & 52.37 to 61.59 in the second growing season. While leaf area showed no significant differences ($p > 0.05$) in the first growing season. Additionally, marketable cabbage head traits (head diameter, head circumference, & fresh weight) exhibited no significant differences ($p > 0.05$) among treatments in the first season. Still, significant improvements were observed in the second season. Zeolite applications at 30% reduced cabbage yields by 15.12% (without loose outer leaves) & by 11.64% (with outer leaves) compared to a 20% zeolite application. Furthermore, the findings highlight a practical implication: a 20% zeolite amendment appears to be the optimal level for improving cabbage yield without the negative effects observed at higher application rates. Overall, this study revealed that zeolite could enhance certain cabbage growth parameters & yield, particularly in the second season. This indicates that zeolite might require a fallowing period within the soil to fully benefit plant growth. Additionally, the results also indicate that zeolite soil amendment may have a limit to its beneficial effects. To support broader adoption, the study recommends applying zeolite at 20% prior to planting, integrated with conventional fertilisers, and guided by soil testing in follow-up seasons.

Key words: agronomic characteristics, growth rate, soil amendment, fresh market vegetables, *Brassica oleracea* var. *capitata* L.

INTRODUCTION

Vegetables are a cost-effective source of essential micronutrients & vitamins that support healthy diets (Sindesi et al., 2023). Among them, cabbage (*Brassica oleracea* var. *capitata* L.) is valued for its nutritional & medicinal properties, contributing to both food security & health promotion (Šamec et al., 2017). During the COVID-19 pandemic, cabbage was notably consumed in fermented forms as a potential mitigation strategy in regions such as Eastern Asia, Central Europe, & the Balkans Naicker et al., 2021; Bousquet et al., 2021; Sooriyaarachchi et al., 2022). It is also recognised as one of the top twenty important food crops globally (FAO, 1988; Gelaye, 2024). In Africa, cabbage & other leafy vegetables are predominantly grown by smallholder farmers who face constraints due to socio-economic, institutional, resource & environmental factors (Mdoda et al., 2022). These farmers often lack access to arable land & irrigation water, which limits their ability to produce food for the growing population (Chikozho et al., 2020). These limitations are further amplified by soil deterioration mainly caused by monocropping & the over-application of inorganic fertilisers (Lin et al., 2019; Tao et al., 2024).

To ensure increased crop production & productivity to meet future food demands, it is important to identify & research innovations that may reduce the constraints faced by small-scale & smallholder food producers (Gordillo & Jeronimo, 2017). The importance of cabbage as a food source & its contribution to food security & sovereignty (Mganga, & Sanga, 2024) support this claim. Cabbage is, however, a heavy nutrient feeder & poor soil conditions, such as soil fertility decline & climate-related soil moisture losses, limit its productivity among resource-poor farmers (Manyevere et al., 2014; Gelaye, 2024). Organic soil conditioners such as crop residues & manures have been used to reduce this limitation & increase crop productivity. However, they have a short life in soils as they are easily decomposed (Sindesi et al., 2023). Fallowing was also used to reclaim degraded & nutrient-depleted soils, however, the reduction of arable lands, particularly in African countries, prohibits its wide use (Tryphone & Thomas, 2023). Zeolites have shown potential as stable soil conditioners, with a longer soil life, in improving soil physicochemical properties, such as nutrient retention, nutrient availability & soil moisture holding capacity (Gondek et al., 2023; Hassan et al., 2024; Zheng et al., 2024).

Zeolites are microporous aluminosilicate minerals with high cation exchange capacity (CEC), water absorption & retention properties, & a strong affinity towards ammonium (NH_4^+) & potassium (K^+) ions (Liu et al., 2022). Zeolite has been used to improve crop growth & yield by improving soil conditions that affect crop growth & yield (Noori et al., 2006; Cairo et al., 2017; Jakkula & Wani, 2018; Sindesi et al., 2021; Hassan et al., 2024). The study by Sindesi et al. (2023) demonstrates that crops may have plant-specific growth & yield responses to zeolite application. Understanding the growth changes promoted by applying soil conditioners such as zeolite is vital for researchers before advocating for its use by farmers to maximise vegetable yields (Go et al., 2022). However, limited research exists on the response of specific vegetable crops, such as cabbage, to varying levels of zeolite under controlled conditions, especially across different growing seasons. However, limited research exists on the response of specific vegetable crops, such as cabbage, to varying levels of zeolite under controlled conditions, especially across different growing seasons. This study addresses that gap by evaluating the effect of different zeolite application levels on growth parameters & fresh head yield of cabbage cv. Copenhagen across two growing seasons. In this study, zeolite was applied specifically to enhance the nutrient and water-holding capacity of sandy soil and to assess its effect on cabbage growth and marketable yield over two growing seasons. Cabbage growth has been measured using agronomic & morphophysiological characteristics such as leaf area, plant height, vegetation index, chlorophyll content, cabbage head size & others (Adzić et al., 2012; Jun et al., 2015). These characteristics are affected by environmental factors & soil conditions such as temperature, soil fertility & moisture (Borges et al., 2018). As such, it was expected that zeolite soil conditioning would positively influence cabbage fresh yield & growth parameters.

MATERIALS AND METHODS

Research Design & Site

The greenhouse pot experiment was conducted at the Agricultural Research Council, Infruitec-Nietvoorbij, Stellenbosch, South Africa (33.914476° S & 18.861322° E). Six-week-old cabbage (*Brassica oleracea var. capitata* L cv Copenhagen) seedlings were transplanted & grown in zeolite-amended sandy soil over 2 seasons, 2017–18 & 2018–19. The 2018 season commenced in late autumn & ended in late spring, while the 2019 season spanned from early autumn to early spring. The treatments were ratios of zeolite to sandy soil on weight-to-weight ratios of 0:10, 1:9, 2:8 & 3:7 zeolite to sandy soil (w/w). The baseline sandy soil had a $pH_{(KCl)}$ of 5.4, which is below the recommended range for optimal cabbage growth. It contained 0.89% organic carbon, 47.00 mg kg^{-1} of available phosphorus (P), 32.76 mg kg^{-1} of nitrate-nitrogen (NO_3-N), & 7.1 mg kg^{-1} of ammonium-nitrogen (NH_4-N) (Sindesi et al., 2024). Micromineral concentrations were 362.6 mg kg^{-1} for iron (Fe), 6.2 mg kg^{-1} for zinc (Zn), 24.2 mg kg^{-1} for manganese (Mn), & 0.4 mg kg^{-1} for copper (Cu) (Sindesi et al., 2022). The used zeolite was of clinoptilolite mineralogy, composed of 64.30% silicate (SiO_2) & 12.70% aluminium oxide (Al_2O_2); other minor minerals of the zeolite are shown in Table 1. The $pH_{(H2O)}$ of the zeolite was 9, & the cation exchange capacity was 16 mg kg^{-1}. Treatments were arranged in a randomised complete block design with six replications. Cabbage was harvested 133 days after transplanting; the management practices carried out during the growth of the cabbage were reported by Sindesi et al. (2021) & Sindesi et al. (2023).

Table 1. Mineral composition of the used zeolite

Chemical analysis	(%)
TiO_3	0.1
MgO	1.3
Na_2O	2.3
Fe_2O_4	1.3
CaO	1.2
K_2O	1.7

Before transplanting, basal fertilisation was carried out using urea (46% N) & single superphosphate (20% P) at rates of 1.17 g pot^{-1} & 3.00 g pot^{-1}, respectively. Potassium chloride (50% K) was applied at 1.92 g/pot. A supplemental side-dressing of urea (1.11 g pot^{-1}) was applied in two equal split applications at 3 & 6 weeks after transplanting. Cabbage seedlings were transplanted at a rate of one seedling per 30 cm diameter & depth plastic pot. Weeds were controlled manually. Pest management included the application of Makhro Cyper® (cypermethrin, 200 g L^{-1}) at 1 mL per 10 L of water during the first growing season. In the second season, Avi Gard

Mercaptothion® (organophosphate, 500 g L^{-1}) was applied at 15 mL per 10 L of water, due to apparent pest resistance to cypermethrin. All treatments were irrigated to pot capacity (PC) before planting. Soil moisture was monitored throughout the experiment using the gravimetric method & periodic pot weighing. During the study, soil water content was maintained between 50% & 70% of PC. The volume of irrigation applied varied based on fluctuations observed in the gravimetric measurements to ensure consistent moisture levels across treatments. Seasonal irrigation results are published in Sindesi et al. (2023). Furthermore, Growth conditions within the greenhouse, including temperature, humidity, & light, were not actively controlled & were dependent on the external environmental conditions. The greenhouse was covered only with polythene plastic, without any additional climate control systems.

Data Collection

Data on plant height, the number of loose leaves per plant, leaf width & leaf length of cabbage were collected on a continuous basis from three weeks after transplanting until the 19^{th} week after transplanting. Data on the head diameter & circumference were only measured on the day of harvest.

Number of loose leaves

Loose leaves were counted from the stage of pre-cupping till head maturity. All the leaves that started to fold in & were attached to the cabbage head were no longer counted, while only those that were dissociated from the head were counted.

Plant height

Plant height was measured with tape, observing the length between the soil surface & the highest leaf tip.

Leaf area

For leaf area, the leaf width (maximum value perpendicular to the midrib) & the leaf length (maximum value along the midrib) were measured. The leaf area was estimated using the formula of an oval shape, using the leaf length & leaf width as r_1 & r_2 in the formula, leaf area = pi x $r_1/2$ x $r_2/2$.

Leaf Chlorophyll content index

Data for leaf chlorophyll content index (CCI) was taken at the top edge of the biggest leaf on each plant, using a chlorophyll content meter CCM-200 plus manufactured by Opti-Sciences, United States of America.

Fresh yield

This study considered two types of cabbage fresh yield i) cabbage heads with loose outer leaves & ii) cabbage heads without loose outer leaves. Both the yield weights were taken on the day of harvest (133 days after transplanting).

Statistical analysis

The maximum values obtained for cabbage growth parameters, throughout the study (CCI, loose number of leaves, plant height & leaf area) were established. Data were then analysed using Statistical Analysis System (SAS) software (version 9.4, SAS

Institute Inc., Cary, NC, USA, 2000) for Analysis of Variance (ANOVA). Seasonal homogeneity of variance was tested with Levene's test, after which the results of both seasons were merged & studied in a single overall ANOVA. The Shapiro-Wilk test was carried out to test for deviation from normality & insignificant interactions. Fisher's least significant difference was calculated at the 5% level to compare treatment means. For all tests, a probability level of 5% was considered significant.

RESULTS AND DISCUSSION

Cabbage growth characteristics

The growth of vegetables, such as cabbage, typically follows a dynamic pattern of initial slow growth, followed by rapid growth, & then slow growth as plants reach maturity. It can be divided into four stages: the seedling stage, the growth acceleration stage (transplant & cupping), head formation, & the maturity stage (Go et al., 2022). According to Ogedegbe & Law-Ogbomo (2013), plant growth is regulated by physical input, while growth patterns & development are governed by input utilisation. In the growth acceleration stage of cabbage, there is little development until the cabbage starts to form the head. This stage mainly increases the number of cabbage leaves, plant height & leaf area (Stranderg & White, 1979). These are important agronomic attributes in cabbage production (Hossain et al., 2015). The faster the maximum values are reached for these growth parameters, the quicker the head is formed, often resulting in better yields during the season.

In this study, the maximum leaf chlorophyll content index (CCI) & leaf area (Fig. 1) were both higher ($p < 0.05$) in the first growing season compared to the second season in all the treatments. With values ranging from 70.03 to 78.04 for CCI in the first growing season & 52.37 to 61.59 in the second growing season. This may be due to favourable growing conditions in the first growing season (mostly spring) for these two cabbage growth parameters (Karungi et al., 2010). The maximum values obtained for leaf CCI were not significantly different ($p > 0.05$) across treatments in the first growing season. However, the values showed a tendency to increase with increasing zeolite application, with the zeolite 20% treatment (CCI =78.04) being the limit to the tendency.

The leaf CCI values obtained for cabbage grown on zeolite-amended soils were generally higher than those grown on the non-amended control treatment in both seasons. The CCI results were consistent with the findings of Saeed et al. (2019), who found that zeolite treatment improved the photosynthetic rate, transpiration rate, stomatal conductance & chlorophyll content-SPAD compared to the control. This observation can be attributed to zeolite's ability to adsorb heavy metals & potentially toxic elements, reducing their availability in the growth medium, thereby reducing uptake & promoting proper plant health (Naveed et al., 2020).

The results further showed a decrease ($p < 0.05$) in the maximum leaf area in the first growing season as zeolite application increased. Contrary to the first season, the leaf area tended to increase with the increase in zeolite application in the second growing season. The observed trends for leaf area may be attributed to zeolites' affinity towards $NH_4^{+,}$ which has been reported to be responsible for lowering plant growth (Jakkula & Wani, 2018). Zeolite's high affinity for NH_4^+-N allows it to selectively adsorb & retain NH_4^+ ions within its porous structure (Zheng et al., 2024). This can temporarily reduce the availability of NH_4^+-N for plant uptake & nitrification, potentially leading to a short-term delay in some plant growth parameters. Potentially accounting for the first season's decreased maximum leaf areas. Jarosz et al. (2022) & Liu et al. (2023) suggest that the duration of this effect can vary depending on factors such as the type of zeolite, soil conditions, & environmental factors. Additionally, the gradual increase in maximum leaf area within the second season can be due to nutrients released (from zeolite pores) by zeolite over time, thereby providing a more sustained supply to the plants in the second year (Szatanik-Kloc et al., 2021).

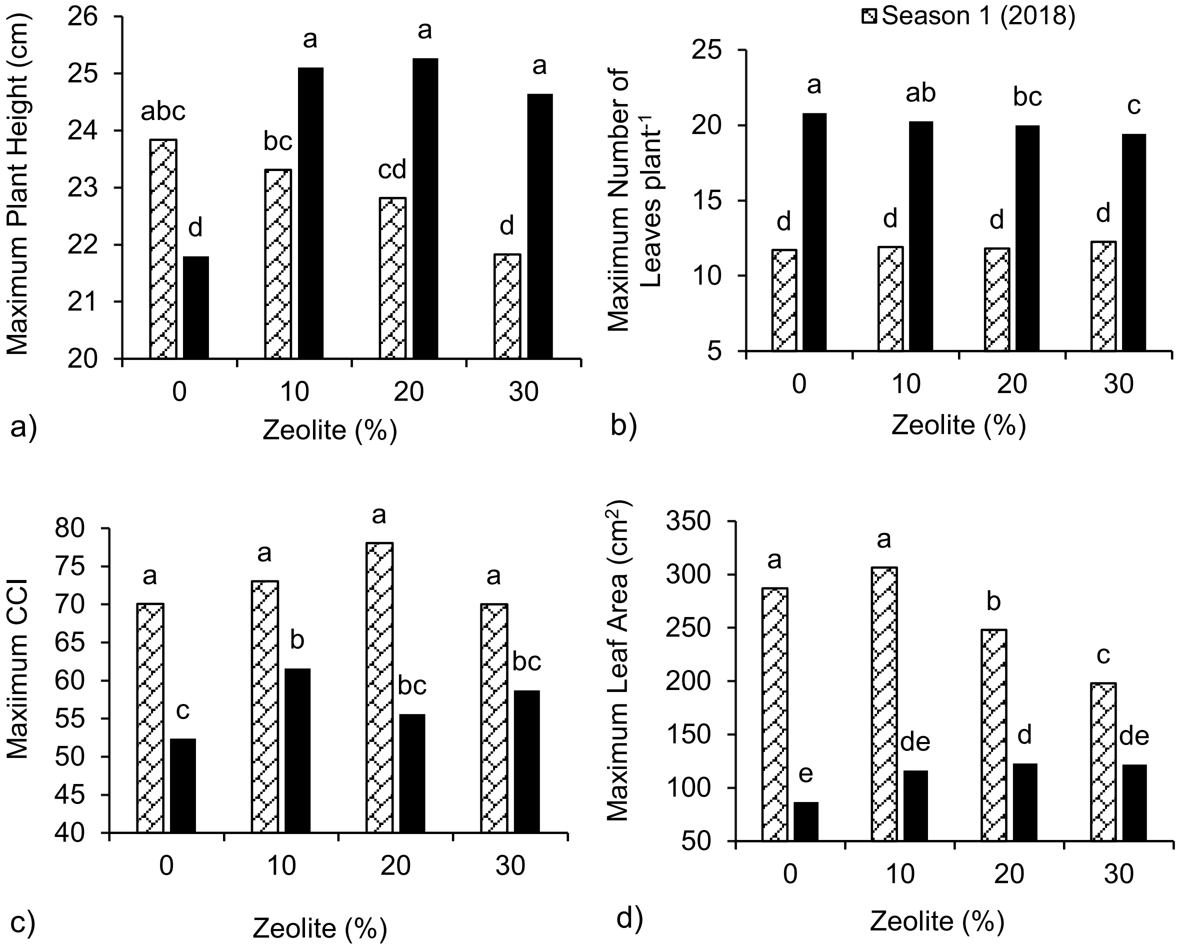

Figure 1. Response of cabbage maximum agronomic characteristics to zeolite application. Panels (a), (b), (c), and (d) represent different growth parameters. Bars sharing the same letter are not significantly different at $p > 0.05$ according to Fisher's Least Significant Difference (*LSD*) test.

For maximum plant height, when the two seasons were compared, the second growing season of cabbage showed improved plant growth in zeolite-amended soils. The plant height of the non-amended treatment reduced from the first growing season to the second season, from 23.84 to 21.79 cm, respectively. This reduction can be attributed to soil degradation & nutrient reduction in the non-amended soil in the second growing season. Belete & Yadete (2023) highlighted that monocropping, together with the removal of crop residues, depletes certain nutrients from the field & encourages soil degradation & reduced crop growth. This can be seen in the plant height result obtained from the non-amended treatment. The study by Sindesi et al. (2023) further reiterated this, where the soil nitrate (NO_3-N), NH_4-N, phosphorus (P), soil $pH_{(KCL)}$ & Total K levels became reduced ($p < 0.05$) at the end of the second growing season of cabbage. More importantly, the two nitrogen (N) forms (NO_3-N, NH_4-N) are known to play a vital role in the biochemical & physiological functions of a plant in relation to the physical growth of plants such as plant height (Leghari et al., 2016).

On the other hand, the results obtained for plant height on the zeolite amended treatments show the potential of zeolite to slow-release nutrients to plant root zones (Al-Busaidi et al., 2008; Szatanik-Kloc et al., 2021; Sindesi et al., 2023). The results further highlighted the possibility of zeolite requiring time to fully activate within the soil before the full benefit is realised. Additionally, the seasonal order observed in results obtained for the maximum number of loose outer leaves & plant height was in contrast with the observed trends in leaf CCI & leaf area. The second season results tended to have larger values for plant height & number of leaves compared to the first growing season. This may suggest that different seasons influence various plant agronomic characteristics differently. Hatfield & Prueger (2015) found that warm temperatures increased the rate of phenological development, but they found no effect on leaf area or vegetative biomass when compared to normal temperatures.

Moreover, in this study, the relationship between leaf CCI, number of leaves & plant height showed that CCI does not present a holistic approach to monitoring plant growth & health, as suggested by Hidayah & Putri (2019). The results from the second growing season further revealed that cabbage tended to favour the production of several smaller but longer leaves than broader leaves, thereby limiting the biochemical processes (photosynthesis) of each leaf. The higher number of loose outer leaves & taller plants in the second season was consistent with the findings of Červenski et al. (2018), who reported that late planting of cabbage results in large above-ground biomass. This assertion was also confirmed by the cabbage dry matter yields reported by Sindesi et al. (2023). These results on the agronomic characteristics of cabbage also show that zeolite may have a different influence on various plant growth parameters.

Responses of marketable cabbage head traits to zeolite application

The size of the cabbage head is an important attribute considered by the fresh vegetable market. The head size may be rated by head weight or by head dimensions (Kołota & Chohura, 2015). The results obtained for cabbage head diameter & circumference in this study are shown in Fig. 2. In the first growing season, there were no significant differences in the cabbage head diameter & circumference ($p > 0.05$) across treatments. However, in the second growing season, all cabbages grown on the zeolite-amended treatments had significantly larger ($p < 0.05$) head sizes compared to those grown in the non-amended treatments. This may be due to a temporal restriction in nutrient availability caused by zeolites' adsorption of nutrients such as NH_4^+-N, phosphorus (P) & potassium (K). This restriction phenomenon was also observed by Doni et al. (2024), who found an increase in total K & a decrease in available K in vineyard soils amended with zeolite. The authors linked this with zeolites' strong affinity for K^+, which encouraged the cation to be held tightly in the structure of zeolite, thereby increasing its retention while reducing its availability in the soil solution. This reduced availability can also be true with NH_4^+-N. Another possibility for the observed non-significant influence on cabbage head size may be that the cabbages had reverted to gene-regulated sizes (Sun et al., 2021) due to the ineffectiveness of zeolite during this period & potentially a non-optimal growing season, as most of the growth in the first growing season was in autumn.

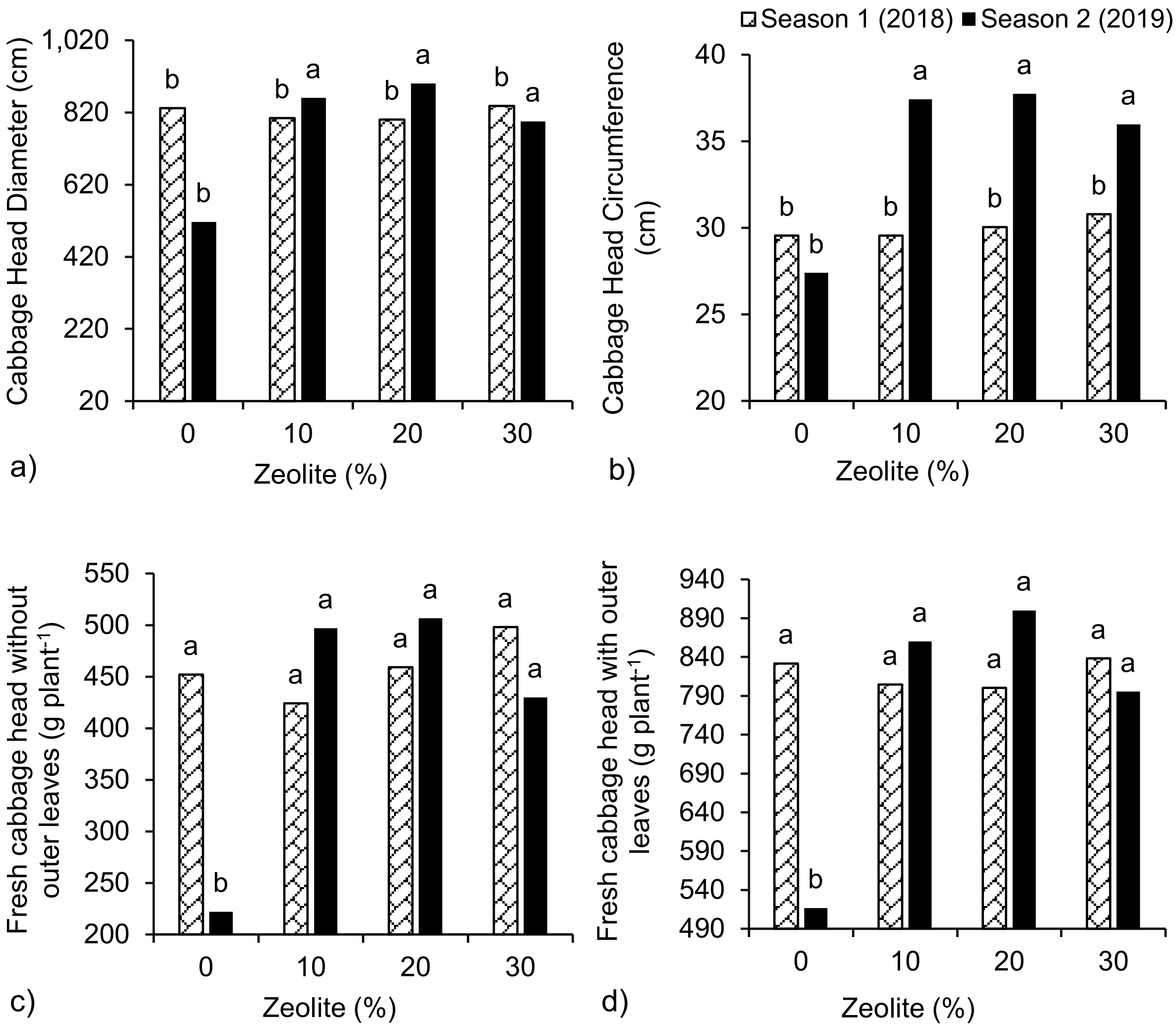

Figure 2. Effect of zeolite on cabbage marketable traits. Panels (a), (b), (c), and (d) represent different marketable traits of cabbage. Bars sharing the same letter are not significantly different at $p > 0.05$ according to Fisher's Least Significant Difference (*LSD*) test.

The head diameters obtained in this study were less than the diameters (12.79 to 14.52 cm) obtained by Tabor et al. (2022). Consequently, the head circumferences were also less than the circumferences ranging between 32.80 to 50.00 cm obtained by Ogedegbe & Ogbomo (2013). The difference in the diameter may be attributed to the differences in environment, plant available water & temperatures. The experiment by Tabor et al. (2022) was conducted in open-field conditions, while the current study was conducted in a greenhouse with no internal environmental manipulation. Hence, there might have been tendencies of heat extremes within the greenhouse. Environmental factors such as soil moisture, temperature and light intensity have been noted to affect crop production (Hazrati et al., 2017). Likewise, the variation between the head circumferences may be due to the fertilisation programme implemented. This study utilised less N fertiliser compared to the study by Ogedegbe & Ogbomo (2013). Gelaye et al. (2024) note that cabbage is a highly demanding vegetable crop for major plant nutrients, including N. Nitrogen increases plant meristematic cells, which support continuous growth & development by containing active stem cells that divide to produce all the tissues & organs of the plant (Mira et al., 2018). In essence, if a plant is supplied with an optimum amount of nitrogen, there is a tendency to increase leaf cell number & cell size, with an overall increase in leaf production, hence, cabbage is a leafy vegetable.

However, the influence of zeolite on cabbage head circumference & diameter was more obvious in the second growing season. This further reiterated the ability of zeolite to initially adsorb nutrients into its structure, using its high cation exchange capacity properties, thereby reducing their solubility for a period before slowly releasing them into the plant root zone (Li et al., 2013). The results can also be an indication of a long-lasting improvement of soil physicochemical properties by zeolites (Szatanik-Kloc et al., 2021), as cabbage head sizes (diameter & circumference) significantly improved compared to the non-amended treatment in the second growing season, while those of the non-amended treatments reduced from their initial values. On the other hand, for cabbage head yields (with & without the loose outer leaves), there were generally no significant differences ($p > 0.05$) among the treatments and seasons, except for significantly lower weights of cabbage heads grown on the non-amended treatments in the second season. The comparable yields for the non-amended treatment with the zeolite treatments in the first growing season show that the used soil was in good condition to facilitate cabbage production. Additionally, the significantly reduced ($p < 0.05$) yields in the second growing season may be due to the potential decline of soil quality (Karungi et al., 2010), especially in the control treatment. Details of the soil fertility decline were reported by Sindesi et al. (2023).

The observed higher yields (Season 2) from cabbage grown on the zeolite-amended (10 & 20% zeolite) soils agree with the findings of Mahmoodabadi et al. (2009) & Li et al. (2013), who reported on the effects of zeolite on the yields of soybean & kale, respectively. The increase in yields in Season 2 due to zeolite application may be attributed to the high CEC of zeolites. High CEC reduces N losses & heavy metal toxicity, while the porous structure of zeolite increases water & nutrient holding capacity within the root zone, leading to improved crop yields (Ikhajiagbe et al., 2019). Chatzistathis et al. (2021) also found increased root biomass for chestnuts grown on zeolite-treated soils. The increase in root biomass from the study by Chatzistathis et al. (2021) may explain the increases in total biomass, as it is responsible for water & nutrient uptake. The slight decrease observed in cabbage yields from the 20% & 30% zeolite application may be an indication of a negative impact from an over-application of zeolite. The fresh yield of cabbage without loose outer leaves was reduced ($p > 0.05$) by an average of 76.59 g plant^{-1} from 20% zeolite application treatment to 30% zeolite application. This reduction accounted for a 15.12% reduction, while the reduction of the average weight of cabbage heads with outer leaves was only reduced by 11.64% between these treatments. Zeolites have selectivity for major essential nutrients, including NH_4^+, phosphate (PO_4^{2-}), NO_3^-, K^+ & sulphate (SO_4^{2-}), in their unique porous structure. This is beneficial as it reduces nutrient leaching (Mondal et al., 2021). However, when the zeolite is applied in large quantities, this adsorption of nutrients by zeolite may encourage much stronger bonds with the nutrients, which are much larger than the forces used by plants during nutrient assimilation, leading to less nutrient use by plants.

CONCLUSION

Cabbage *cv* Copenhagen responded positively to zeolite application in terms of growth & fresh yield, especially in the second growing season. The study demonstrated that zeolite requires time before it can be fully activated after soil incorporation. These results also demonstrate that zeolite can be used to improve some of the cabbage growth indicators, but not all of them. The results from this study also show that there is a possibility of zeolite over-application within cropping systems. From this study, there is a need to conduct further research on zeolite as a soil conditioner, especially under field conditions. More importantly, long-term field experiments that will determine whether zeolite will provide lasting improvements in the soil's physicochemical properties & plant growth should be explored. Additionally, studies should aim to develop practical application guidelines, including optimal rates, timing, & integration with existing fertilisation regimes, to facilitate the adoption of zeolite use by smallholder & commercial vegetable producers. As demonstrated by this study, smallholder and commercial vegetable producers are encouraged to apply zeolite prior to planting, at an optimum rate of 20% zeolite to sandy soil. Furthermore, zeolite should be applied alongside or just before conventional fertilisers to help synchronise nutrient release with crop demand. In follow-up seasons, nutrient applications should be guided by soil laboratory analyses to avoid over-fertilisation and ensure sustained soil health.

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