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University of Technology

Water and nutrient retention under Swiss chard *(Beta vulgaris* Var. *cicla*) and cabbage (*Brassica oleracea* Var*. capitata* L) cultivated in soil amended with zeolite

By

Olwetu Antonia Sindesi

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Supervisor: Dr Bongani Ncube
Co-supervisor: Dr Muinat N. Lewu

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DECLARATION

I, **Olwetu Antonia Sindesi**, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

15/10/2020

Signed **Date**

ABSTRACT

Poor soil fertility and irrigation water shortages are major challenges to vegetable production. Farmers have used different methods to address these challenges. Some methods such as the application of organic materials on soils have fallen short in providing stable non-decomposable soil amendments. A greenhouse pot experiment was conducted at the Agricultural Research Council (ARC), Infruitec-Nietvoorbij, Stellenbosch, South Africa to evaluate the effects of zeolite on the growth and yield of cabbage cv. Copenhagen (*Brassica oleracea* Var. *capitata* L), and Swiss chard cv. Ford Hook (*Beta vulgaris* Var. *cicla*). The experiment investigated the water and nutrient retention ability of zeolite amended sandy soils as influenced by zeolite. Six-weeks old seedlings were planted one seedling per pot during transplanting.

The study was conducted over 2 growing seasons; the first being late autumn through to late spring 2018 for both vegetables; the second, early autumn to early spring 2019 for Swiss chard and winter/spring 2019 for cabbage. The experiment was laid out in a randomised complete block design (RCBD) and replicated six times. Prior to the commencement of the study, a baseline composite soil sample was collected for soil analyses to determine the macronutrients, electrical resistance, cation exchange capacity (CEC), exchangeable cations, pH and trace elements in the soil. At the end of each growing season, representative soil samples were also analysed for the same parameters.

Data collection on growth parameters commenced on the third week after transplanting (WAT) for cabbage and the fourth WAT for Swiss chard. Measurements were recorded once a week for leaf plant height, width, leaf length and leaf area in both vegetables. At eight WAT, harvesting of the leaves and stem of Swiss chard commenced, it was a continuous harvest which was carried out at three weeks intervals. Five harvests were done in total. Cabbage head was harvested at maturity (19^{th} WAT). Fresh mass of both cabbage and Swiss chard yield were recorded at harvest while the dry mass was determined after oven-drying at 70^{o}C until constant weight. The dry samples were separately milled, stored in marked air-tight containers and refrigerated for the determination of their nutritional composition. Soil water content was regularly monitored gravimetrically and through weighing of pots. Soil moisture in each pot was maintained between 50% and 70% field capacity throughout the period of the experiment.

All data were statistically analysed by the Biometric Department of the ARC Infruitec-Nietvoorbij, Stellenbosch. The data were subjected to analysis of variance (ANOVA) to detect treatment and where necessary, seasonal effects. For interactions that were not significant at $p<0.05$, Fisher's least significant difference was used to compare treatment means.

In the first season, the leaf area and plant height of cabbage decreased ($p<0.05$) with increased zeolite. Whereas, in the second season, these parameters increased as zeolite application increased. The same trend was also observed with Swiss chard.

The first harvest for Swiss chard yielded higher biomass on the non-amended treatment. Thereafter, the zeolite amended treatments continued to show improved Swiss chard yields. Cabbage did not show any significant yield response ($p>0.05$) to zeolite in the first season. However, in the second season, higher yields were recorded in the zeolite amended treatments. The nutritional composition of cabbage head showed no significant difference ($p>0.05$) in terms of the proximate analysis, although the results were comparable with previous cabbage studies. Mineral composition of cabbage showed that the non-amended treatment had higher ($p<0.05$) Ca, Zn and B contents, with a lower level of Na. For Swiss chard, Ca, Mn, Zn and Fe contents were all higher ($p<0.05$) on the non-amended treatment compared to the zeolite amended treatments.

The demand for water by cabbage significantly ($p<0.05$) reduced with increased zeolite rates, in the first season. However, in the second season, 30% zeolite required the least ($p<0.05$) irrigation followed by the non-amended treatment, while 10% and 20% zeolite treatments utilized the most water. Swiss chard irrigation in both seasons showed that the non-amended treatment had less irrigation water requirement compared to the zeolite amended treatments. On the other hand, soil chemical composition showed that zeolite application increased ($p<0.05$) cation exchangeability, pH and soluble S. Soil chemical composition further indicated that there could be a limit to zeolite application with N availability. Zeolite showed potential in ameliorating agricultural soil acidity and improving soil water retention. However, there is a need to carry out these experiments under field conditions to see if these benefits can be sustained, especially at smallholder farmers' level.

Keywords: Zeolite, Swiss chard, cabbage, sandy soil, soil moisture retention, green leafy vegetables, soil amendment, soil conditioner, vegetable growth.

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DEDICATION

To my lovely children Lolwethu Sindesi, Simile Sindesi, Asenathi Faltein and Khazimla Sindesi

OTHER RESEARCH OUTPUTS

Journal articles

1. **Sindesi, O.A., Ncube, B., Lewu, M.N., Mulidzi, A.R. and Lewu, F.B.** Cabbage and Swiss Chard irrigation requirement affecting yield and soil chemical responses in zeolite amended sandy soil. Submitted to the *African Journal of Food, Agriculture, Nutrition And Development (AJFAND).*
2. **Sindesi, O.A., Lewu, M.N., Ncube, B., Mulidzi, A.R. and Lewu, F.B.** Mineral composition of potted cabbage (Brassica oleracea var. capitata L) grown in zeolite amended sandy soil. To be submitted to the *Journal of Food Quality.*

Conference Papers

1. **Sindesi, O.A., Lewu, M.N., Ncube, B., Mulidzi, A.R., Lewu, F.B.** 2020. Effects of zeolite on the performance of cabbage (*Brassica olereacea* Var. *capitata* L). Combined Congress, 20-23 January 2020, University of the Free State, Bloemfontein, South Africa.
2. **Lewu, M.N., Sindesi, O.A., Meyers, A., Mulidzi, A.R., Ncube, B., Lewu, F.B.** 2020. Effects of zeolite soil amendment on soil microbial enzyme activities associated with potted Swiss chard and cabbage crops. Combined Congress, 20-23 January 2020, University of the Free State, Bloemfontein, South Africa.
3. **Lewu, M.N., Mulidzi, A.R., Sindesi, O.A., Ncube, B., Lewu, F.B.** 2019. Growth parameters of Swiss chard in response to zeolite and irrigation application. Combined Congress, 21-24 January 2019 University of the Free State, Bloemfontein, South Africa.

TABLE OF CONTENTS

LIST OF FIGURES AND PICTURES

LIST OF TABLES

GLOSSARY

Abbreviations	Description
ANOVA	Analysis of variance
ARC	Agricultural Research Council
BC	British Colombia
Ca	Calcium
CCI	Chlorophyll content index
CEC	Cation exchange capacity
DAFF	South African Department of Agriculture Forestry and Fisheries
DMRT	Duncan multiple range test
FAO	Food and Agriculture Organisation of the United Nations
FC	Field capacity
Fe	Iron
GDP	Gross domestic product
K	Potassium
Mg	Magnesium
mm	Millimetre
Mn	Manganese
N	Nitrogen
Na	Sodium
NH_4^+	Ammonium
NH_4-N	Ammonium Nitrogen
NO_3-N	Nitrate Nitrogen
pH	Potential of hydrogen
ppm	Parts per million
S	Sulphur
SiO_4+AlO_4	Aluminosilicates
WHO	Worlds Health Organisation

CLARIFICATION OF TERMS

Heavy metals: Any metal that has a relatively high density, greater than 7.0 g cm^{-1}, and is toxic at a low concentration such as lead (Pb), nickel (Ni), mercury (Hg) and arsenic (As). Some metals can be of less density but because of meeting the criteria of toxicity may be regarded as heavy metals.

Soil amendment: Any material that can be mixed with the soil to improve its physical and chemical properties such as aeration, permeability, water infiltration, drainage, structure water retention and nutrient retention. They can either be fertilisers or soil conditioners.

Soil conditioner: Any material that contains limited amounts of nutrients but is incorporated into the soil for their beneficial impact on the biological, physical and chemical properties within the soil.

Zeolite: Aluminosilicate minerals in which aluminium and silica tetrahedra are connected by shared oxygen atoms to form a three-dimensional framework.

CHAPTER ONE
INTRODUCTION

1.1 Background

Poor soil fertility and water scarcity are some of the limitations to vegetable productivity in Africa, including South Africa (Schlecht *et al*., 2006; Tadele, 2017; Thierfelder *et al*., 2018), especially for smallholder farmers, who have limited resources (Mpandeli *et al*., 2015; Mupangwa *et al*., 2017). Farmers use various methods to try and overcome these challenges and some of these methods include the use of conservation agriculture which has been used to address soil physicochemical property decline (Mupangwa *et al*., 2018). In traditional agricultural systems, fallowing has been used to recover soil nutrients in deteriorated soils. However, the shortage of suitable cropping land has prevented its widespread use (Schlecht *et al*., 2006; Bationo *et al*., 2007). This has resulted in increased and over-application of inorganic mineral fertilisers, which leads to damage of soils and the environment (Bationo *et al*., 2007). Moreover, with more mineral fertiliser application, end of season crop residue removal and leaching of excessive nitrates, the soil is left more acidic and requires a lime application which has an additional financial implication (Dumale *et al*., 2011; Usowicz and Lipiec, 2017).

Adding to the problems are climate-related droughts which have intensified irrigation water shortages in Africa, leading to low crop productivity. Improved fertiliser uses and more water retentive production practices are needed to overcome these challenges (Misra, 2014). Some soil conservation techniques have been used to reduce the impacts associated with soil nutrient and moisture decline (Blanco and Lal, 2010). There has been the incorporation of soil conditioning materials such as crop residues, manure, and other organic materials (Ogunwole *et al*., 2010). However, the disadvantage of the use of organic amendments like manure is that they decompose over time, reducing their beneficial effects. An ideal soil amendment should be relatively stable to provide water, nutrient retention and release that are comparable with organic amendments.

In recent years inorganic soil conditioning materials such as zeolite have been utilised to improve soil quality and crop productivity (Polat *et al*., 2004; Ramesh and Reddy, 2011; de Campos Bernardi *et al*., 2013). Zeolites are aluminosilicate minerals with porous structures which have a high cation exchange capacity and a great affinity for ammonium (NH_4^+) and potassium (K^+) cations (de Campos Bernardi *et al*., 2010; Ramesh and Reddy, 2011). It has been used in various application areas such as the manufacturing industry, agriculture, environmental protection, and even in medicine. Zeolite can either be mined or synthetically produced and there are currently about 150 types of synthetically produced zeolites with about 50 types that are natural (He *et al*., 2002).

Clinoptilolite zeolite is the most commonly known natural zeolite type and is the one mostly used in agriculture. This natural zeolite type is stable against weathering impact and abrasion tests (He *et al*., 2002). Upon its application to soils, it improves the physicochemical properties of the soil. Clinoptilolite zeolite is also prevalent in nature and inexpensive (Diale *et al*., 2011). Large deposits of zeolite have been found in numerous countries such as Cuba, the United States of America (USA), Russia, Japan, Italy, South Africa, Hungary and Bulgaria (Ramesh *et al*., 2015). Zeolite has been used in agriculture by Iran, Turkey, Poland, Serbia, Malaysia, Japan, Brazil and many other countries as a slow-releasing carrier of agrochemicals and soil conditioner (Reháková *et al*., 2004; Ramesh and Reddy, 2011). In South Africa, zeolite is mined in Kwa-Zulu Natal and Western Cape provinces (Diale *et al*., 2011).

Zeolite application to agrochemicals has been linked to increased chemical efficiency, as zeolite adsorbs nutrients and slow releases them (Szerement *et al*., 2014). Impact of zeolite on plant growth and yield has also been investigated (Gül *et al*., 2005; Ramesh and Rendy 2011; Jie *et al*., 2015; Ramesh *et al*., 2015). However, there has been limited research on the agricultural application of zeolite in South Africa. There is limited information on the impacts of zeolite on the growth of vegetables such as cabbage (*Brassica oleracea* Var*. capitata* L) and Swiss chard (*Beta vulgaris* Var*. cicla*), which contribute significantly to diet in South Africa (Afolayan and Jimoh 2009; Bvenura and Afolayan 2015). The need to investigate the impacts of zeolite as a soil conditioner for vegetables under the South African conditions is important given the challenges of soil fertility decline and climate-related droughts.

1.2 Objectives

Main Objective

The main objective of the research was to investigate the effects of zeolite application on soil moisture and nutrient retention, vegetable growth, yield and nutritional quality of cabbage and Swiss chard.

Specific Objectives

1) To investigate the effect of zeolite application on cabbage and Swiss chard growth; above-ground yield and root biomass
2) To assess the effect of zeolite application on cabbage and Swiss chard nutrient contents
3) To investigate the effect of zeolite application on soil moisture and nutrient retention under cabbage and Swiss chard cultivation.

1.3 Hypotheses

1) Zeolite application will increase cabbage and Swiss chard growth; above-ground yield and root biomass
2) Cabbage and Swiss chard nutrient content will increase with the application of zeolite
3) Zeolite application will increase soil moisture and nutrient retention under cabbage and Swiss chard cultivation.

1.4 Problem Statement

South Africa is a drought-prone country which has many challenges that range from economic to food insecurity challenges (Midgley and Methner, 2016). Subsistence farming systems have been identified as one of the ways to overcome these challenges. However, subsistence farmers are usually faced with limitations to accessing input resources like fertilizers and especially accessing financial resources (Schlecht *et al*., 2006; Tadele, 2017; Thierfelder *et al*., 2018). Zeolite has shown potential as an inexpensive soil conditioner that can decrease fertiliser and irrigation requirements while improving soil quality (Ramesh *et al*., 2015). However, zeolite has not received any demand as a soil amendment in South Africa, although its properties suggest that it could dramatically increase soil moisture retention and reduce irrigation water use while promoting increased yields. There is also a lack of information about zeolite application for efficient vegetable production in South Africa. As such, it is not used for vegetable production purposes but exported to other countries such as the US where it is used in the molecular sieve businesses and in chemical firms (Diale *et al*., 2011).

1.5 Significance

South Africa is a drought-prone country with varying climatic conditions. Recently, between 2014 and 2017, the Western Cape experienced a severe drought due to climate change (Midgley and Methner, 2016). The drought-affected agricultural crop production by reducing the yield and quality of crop harvests (Chijioke *et al*., 2011). With prolonged heightened temperatures, also being a result of drought, increasing the capacity of air to absorb water vapour, consequently generating a 10% higher water demand (Kuschke and Jordan, 2017).

Irrigation water shortage is one of the major factors affecting plant growth. Climate change is leading to severe water scarcities which are contributing to major crop vulnerability in Arica (Chijioke *et al*., 2011). The variation in rainfall and uneven distributions are the causes of water scarcities. These variations with the decrease in rainfall and the increase in temperatures are most likely going to add to the loss of arable land due to decreased soil moisture, increased aridity, increased salinity and groundwater depletion (Bals *et al*., 2008). In the Western Cape, the challenge of drought is coupled with the occurrence of mainly sandy soils which may intensify irrigation water requirements. This makes soil moisture conservation vital for agricultural productivity to be maintained at its optimal.

Soil moisture conservation in agricultural production has been through the use of no-till and minimum tillage systems (Blanco-Canqui and Lal, 2008). Minimum-tillage systems include mulching, strip and ridge tillage. Other means of conserving soil water as noted by SUSTAINET EA (2010) include establishing water retaining pits and retention ditches. However, the latter techniques have not been efficiently utilised by farmers owing to many farmers' lack of skills to design and establish such conservational structures. Some farmers have applied organic materials to amend and conserve soil moisture. However, because of their fast decomposition rate, the benefits become limited. There is, therefore, a need to find stable soil amendments that can last longer in the soil such as zeolite (de Campos Bernardi *et al*., 2013).

The knowledge of zeolite application for efficient crop production is lacking in South Africa. This research focused on zeolite as a sandy soil conditioner. Sandy soil has been identified by Musekiwa and Majola (2013) as soil with a high nutrient leaching potential and minimal water holding capacity. Sandy soil is considered as the most abundant soil type in the Western Cape and it is generally used in South Africa for the cultivation of vegetables. Cabbage and Swiss chard were selected as test vegetables for the experiment as they have become one of the leading consumed vegetables among South African citizens, they are cheap sources of minerals and vitamins.

CHAPTER TWO

LITERATURE REVIEW

2.1 Importance of fruits and vegetables in diets

Vegetables are known to contain high amounts of vitamins and minerals that are beneficial for the maintenance of human health and disease prevention (Ogbede *et al*., 2015). Short-term clinical research as noted by the Joint FAO/WHO (2004) shows that the consumption of fruits and vegetables can help achieve and maintain healthy body weight. However, long-term epidemiological studies and several other health-related studies have shown inconsistent results (Joint FAO/WHO, 2004). All plants are potential sources of antioxidants, and humans can use antioxidants either as dietary food supplements or as a drug (Pyo *et al*., 2004; Sacan and Yanardag, 2010), as such plants and plant products are rich sources of phytochemicals.

Diets rich in fruits and vegetables have been considered by studies to significantly reduce ischaemic heart diseases and stroke risks (Joint FAO/WHO, 2004; Gunathilake and Ranaweera, 2016). Gunathilake and Ranaweera (2016) singling out green leafy vegetables concur with Reif *et al*. (2013) that in diet, they contain large amounts of minerals and antioxidant vitamins. The nutritional composition of these green vegetables allows them to be suitable for treatment and maintenance of chronic diseases such as some types of cancer and cardiovascular diseases (Pyo *et al*., 2004; Reif *et al*., 2013; Gunathilake and Ranaweera, 2016).

Some other health-related diseases that vegetables have been found to protect against include diseases associated with ageing such as cataracts, brain and immune dysfunction (Pyo et al., 2004). They also possess anti-carcinogenic, antibacterial and anti-diabetic properties (Gunathilake and Ranaweera, 2016). These are largely due to the presence of carotenoids, vitamin C and E, phenolic and thiol (SH) compounds (Pyo *et al*., 2004). Gunathilake and Ranaweera (2016), also concluded that these effects are partly due to antioxidants, with the major antioxidants being polyphenols and carotenoids. Carotenoids are precursors of vitamin A, and as such, make them valuable antioxidants (Reif *et al*., 2013).

Stein *et al*. (2016) noted that the mineral element and subsequently, the nutrients that can be found on the leaves of plants are directly linked to the soil exchangeable concentration of those mineral elements. This means that an element found in the soil has a potential to be found in the leaves of the plants that grew on the soil, provided that the element is readily available to the plant as a concentrated element within the soil. Therefore, soil amendments that have the potential to induce soil nutrient retention may prove to directly affect vegetable nutrition as it relates to human health.

2.2 Selection of vegetables

In recent years, indigenous leafy vegetables have played an important role in the traditional food culture of African households with some leafy vegetables used because of their medicinal properties (Mariga *et al*., 2012). In the works of Vorster (2007) and Van-Ransburg *et al.* (2007), they noted that in the past years in South Africa, indigenous leafy vegetables were of particular use to the diet of South African rural women and their children. Mariga *et al*. (2012) substantiated that these vegetables helped and, in some households, continue to help ensure household food security while offering a variety in family diets. These indigenous leafy vegetables are cooked with a minimal amount of water and maize meal crumbled over it to form a paste. In South Africa, this paste is known as morogo (Setswana language) or Mifino (Xhosa language) (Njeme *et al*., 2014).

Indigenous leafy vegetable harvesting and consumption is noted by Van-Ransburg *et al.* (2007) to have been most important in the Limpopo, Eastern Cape, and Kwa-Zulu Natal provinces. These provinces comprise most of the rural homesteads of South Africa. The most used indigenous vegetable species were *Amaranthus hybridus*, *Biddens pilosa*, B*. biternata, Cleome gynandra, Corchorus tridens, Chenopodium album* and *Tribulus terrestris (*Van-Ransburg *et al.*, 2007; Vorster, 2007). Bvenura and Aflayan (2015) suggest that Indigenous leafy vegetables have superior nutritional quality than exotic vegetables and can tolerate more drought and higher heat than exotic vegetables. However, because of declining soil fertility, livestock over-grazing and the relocation of people from rural households to urban areas, the consumption of indigenous vegetables has also declined (Vorster, 2007). With the decline in indigenous leafy vegetables, exotic vegetable consumption has increased (Vorster, 2007). Currently, spinach (*Spinacia olereacea)*, Swiss chard (*Beta vulgaris* Var. *cicla)* and cabbage (*Brassica oleracea* Var*. capitata* L.*)* have replaced much of the indigenous leafy vegetables in the African continent. They are now highly preferred as their status is higher than the status of the traditional leafy vegetables, therefore, they are not seen as poor man's food (Van-Ransburg *et al.,* 2007).

Cabbage is a herbaceous green leafy vegetable that has a compact head which is composed of leaves that are snuggled against each other (Nma *et al*., 2013). It belongs to the *Brassica* genus and the *Brassicaceae* family. The colour of *B. oleracea* Var*. capitata* L. ranges from pale green to dark green (Ogbede *et al*., 2015). The now known cabbage was altered from the wild mustard in the Mediterranean, although recorded as a winter vegetable, it can be grown in all seasons (Aksoy *et al*., 2014). According to Kapusta-Duch *et al*. (2012), the *Brassicaceae* plant family has enormous economic importance as it comprises of about 340 genera and around 3700 species. Cabbage was used by the Greeks and Romans as medicine for curing some diseases (Ogbede *et al*., 2015; Aksoy *et al*., 2014).

Cabbage is rich in beneficial minerals especially Ca, P, K, and Mg; however, it is also rich in vitamin A, B1, B2, B3, B6, B12, C, K, U and pro-vitamin A (carotene). Interestingly, vitamin U is only procurable in cabbage and is involved in the curing of peptic ulcer (Aksoy *et al*., 2014). Kapusta-Duch *et al*. (2012) also noted that cabbage has beneficial metabolites such as sulphur containing glucosinolates, anthocyanins, flavonoids, and terpenes. These phytochemicals found in cabbage help to prevent oxidative stress, induce detoxification enzymes, stimulate the immune system, and decreases the risk of cancer and proliferation of cancer cells (Kapusta-Duch *et al*., 2012). Health benefits of cabbage can, therefore, be linked to these phytochemicals.

Cabbage can further be helpful in the management and treatment of sicknesses such as gout and rheumatism, beneficial in relieving gastric pain and hyperacidity, short-term rapid weight loss, as an immune stimulant and provides people's cardiovascular system with valuable support in the form of cholesterol reduction (Aksoy *et al*., 2014; Ogbede *et al*., 2015). Akosoy *et al*. (2014) established that cabbage comprises natural antioxidants and has the potential to cure some forms of cancer.

Swiss chard, on the other hand, has often been wrongly called spinach in South Africa (Maboko and Du-Plooy, 2013), it is a herbaceous biennial plant that is related to the beetroot. Their largest difference in South Africa is that beetroot is mostly grown for its roots while Swiss chard is grown for its edible leaves (Pyo *et al*., 2004). Swiss chard is characterised by large fleshy dark green leaves that are born on broadleaf stalks which may be white or red depending on the variety but may also be orange in ornamental Swiss chard (Sacan and Yanardag, 2010; Maboko and Du-Plooy, 2013). It is a year-round leafy vegetable that is low cost in terms of cultivation yet having wide uses in traditional dishes (Sacan and Yanardag, 2010).

Swiss chard is well adapted to long days and hot conditions (Maboko and Du-Plooy, 2013). It belongs to the *Chenopodiaceae* family and can serve as a leafy vegetable and as an ornamental plant. However, as a vegetable, its leaves are highly nutritional (Pyo *et al*., 2004; Sacan and Yanardag, 2010; Maboko and Du-Plooy, 2013; Maboko *et al*., 2017). Several authors reported that the leaves follow the trends of other green leafy vegetables, as such, they have relatively high levels of vitamins A, B, C and minerals K, Ca, Na, Fe and P (Pyo *et al*., 2004; Maboko and Du-Plooy, 2013; Maboko *et al*., 2017). Sacan and Yanardag, (2010) mention that Swiss chard has been used in some parts of the world as a traditional remedy for liver and kidney diseases. It is also recorded to stimulate the immune and hematopoietic systems while also being recommended as a special diet for cancer treatment among cancer patients.

With research, the influences of zeolite on vegetable growth and yield have been conducted on various vegetable crops, for instance, soya bean, pepper (Ramesh and Rendy, 2011), lettuce, tomato (de Campos Bernardi *et al.,* 2010), sweet potato (Ramesh *et al.,* 2015) crisp head lettuce (Gül *et al.,* 2005) white radish, okra and pakchoy (Jie *et al*., 2015). However, no zeolite research has been conducted on Swiss chard and cabbage. Moreover, these two vegetables are currently part of most people's diet in South Africa (Afolayan and Jimoh, 2009; Bvenura and Afolayan, 2015). Given that cabbage and Swiss chard have become a part of consumer's normal day-to-day diets, finding ways of amplifying their nutritional contents and increasing their availability is of great importance.

2.3 Leafy vegetables in South Africa

Leafy vegetables which include but not limited to Swiss chard, cabbage, turnip, lettuce, parsley and various traditional indigenous vegetables are consumed for their edible leaves (Shannon and Grieve, 1999). They can be both cool and warm-season vegetables depending on the kind and variety chosen. They can be grown both as annuals and perennials, which also depends on how they are harvested (Banks and Bradley, 2015). Leafy vegetables will thrive at temperatures between 15 and 18^{o}C and will tolerate short-term exposure to weak frosts (Maseko *et al.,* 2018). The general soil required for them is loose, fertile, moist and sandy loam soil with pH ranging from 6.0 to 7.0 (ARC, 2013). Relf and McDaniel (2015) advised that leafy vegetable seeds should be sown in trays in a conducive environment and then later transplanted to the field at approximately six weeks. At the end of their growing season, leafy vegetables can further be cut by hand during harvesting while damaged leaves are removed for better appearance and presentation (Kelley and Boyham, 2009).

In South Africa, cabbage and Swiss chard have gained popularity in household usage, and are used as salads, eaten with the main meal and even made as juice (ARC, 2013). The major production provinces of leafy vegetables in South Africa are KwaZulu-Natal, Mpumalanga, Western Cape, Gauteng, Eastern Cape and Limpopo (Statistics South Africa, 2016). Leafy vegetables can be grown in a wide range of environmental conditions (Kelley and Boham, 2009). Therefore, because of South Africa's climate, most vegetables especially those that originated from Europe and North America do well wherever they are planted within the country (Ingwe, 2009). Encompassing the fact that the general climate of South Africa is conducive to leafy vegetable production, Ingwe (2009) identifies variables required to note when planting most exotic vegetables in South Africa: i) what to plant, and the best time to plant the seeds and transplant seedlings, ii) the best places to plant the seed and transplant seedlings, and iii) giving the plants some regular attention at least daily. Although most leafy vegetables require generally similar growing conditions some specifications are depending on the various leafy vegetable plants.

Swiss chard has a relatively short growing period before the first harvest, this makes it a good fore and after-crop in crop rotation (Kolota *et al*., 2010). Swiss chard is considered a cool-season vegetable although it can withstand a bit of frost. Its optimal temperatures range from 7 to 24^{0}C and as such can be planted throughout the year (DAFF, 2010). Although it can be planted throughout the year, its planting times have an impact on its nutritional value and yield (Kolota *et al*., 2010).

Generally, leafy vegetables that are grown in spring have higher yields with lower contents of dry matter and vitamin C while having high amounts of sugar (Kolota *et al*., 2010). Pokluda and Kuben (2001) noted that the mineral contents, total quality and yields of Swiss chard are influenced by the amount, frequency and method of fertilization. This is because it thrives on well-drained, fertile and adequately moist soil (DAFF, 2010). Swiss chard cannot tolerate acidic soils, as such it requires near-neutral soil pH i.e. between 6 and 7 (DAFF, 2010; Mitic *et al*., 2013). Due to its hard, woody and deep root system, it requires sandy to loam soils for optimal growth (Maboko *et al*., 2017).

Kolat *et al*. (2010) evaluated the difference in the nutritional value of Swiss chard grown in various seasons and found that the quality of autumn harvested leaves of Swiss chard had been diminished by a high nitrate accumulation, even though the recommended nitrogen rate was applied. Their findings also showed that there was more vitamin C content found on autumn grown Swiss chard than that grown in summer. Their results showed higher yields on Swiss chard grown in the summer season which was linked to solar radiation. Swiss chard tolerates high soil salinity and accumulates more Na than other leafy vegetables, however, if salinity is too high it will start to show signs of decreased yields (Poluda and Kuben, 2002). In a similar note, Kolata *et al*. (2010) found that Swiss chard that was grown in spring accumulated high Mg which is one of the elements that contribute to soil salinity. However, the accumulation of Mg was associated with good soil temperature conditions.

In terms of fertilisation, Swiss chard mostly requires a nitrogen-based fertiliser as it encourages leaf growth (DAFF, 2010). According to FSSA (2007), Swiss chard will generally require 100-140 ppm soil nitrogen (N), 100 ppm soil phosphorus (P) and 120 ppm soil potassium (K) to get optimal yield. Therefore, the application of fertiliser should be based on soil analysis reports.

Cabbage, on the other hand, is generally a cool-season vegetable; however, there are various recently established varieties which allow its production to be extended to warmer seasons (ARC, 2013). Its optimum growth temperatures range between 17 and 24^{o}C, and it gives the best growth and highest yields when production is under cool and moist condition (Kemble *et al*., 1999; ARC, 2013). Young plants and matured cabbage heads are however sensitive to extremely cold temperatures along with sudden temperature drops. However, throughout its other growth stages, it can tolerate minimum temperatures of 4 to 5^{o}C. As such, best quality and yields are obtained in cabbages that mature between autumn and spring (Kemble *et al*., 1999). Although cabbage is resistant to little frost, its exposure to prolonged durations of low temperature during the growth period may result in bolting. Also, high temperature and low moisture levels during the growth may result in small heads (ARC, 2013). The taste as a constituent of quality also turns strong and bitter in cabbages grown in hot and dry conditions (Kelley and Boyham, 2009).

Cabbage can generally grow well in all types of soils, but its best production is obtained in light, fertile and well-drained soils (Kelley and Boyham, 2009). A soil pH of around 6 and 7 is recommended by many authors, as it is very sensitive to acidity (Kemble *et al*., 1999; Kelley and Boyham, 2009; ARC, 2013). Sand to sandy loam soil with adequate organic contents that will not dry out quickly are preferred in cabbage production (Kemble *et al*., 1999). Cabbage is a shallow-rooted vegetable (30.5 -38 cm); therefore, preference of sandy soil is justifiable, it is, however, a heavy nutrient feeder. So adequate soil tillage and fertilisation is required at transplanting (Kemble *et al*., 1999). Optimal cabbage yields will need 160-260 ppm soil N, 100 ppm P and 160 ppm K (FSSA, 2007). Most of the fertiliser can be applied before transplanting, and 50% of the nitrogen should be applied as a side-dress twice throughout the growth period (ARC, 2013).

Cabbage is extremely prone to pests; as such, an integrated pest management practice is advised, with regular scouting involved (Kemble *et al*., 1999). In warmer months, pest management must be stricter as there is a heightened threat due to more insect attacks on the vegetable (ARC, 2013). Due to its high susceptibility to pests, mono-cropping cabbage or rotating it with other vegetables from the cruciferous family must be avoided (Kelley and Boyham, 2009). Cabbage harvesting can be done when the heads are well-formed and are firm, this will be generally between 90 and 110 days depending on growing conditions and variety (Kelley and Boyham, 2009; ARC, 2013). Harvesting can be done by cutting the stem near the soil but not allowing for the stem to stick out too long from the head as it may damage other cabbages, during storage and transportation.

Andaloro *et al*. (1983) identified eight stages that cabbage goes through before reaching a marketable age, as seen in Figure 2.1. The stages are Stage 1: Called cotyledon, where there are only seed leaves and no true leaves present. Stage 2: Called seedling, has up to 5 true leaves; Stage 3: has 6-8 true leaves; Stage 4: has 9-12 true leaves, with stem and leaf base still visible from the above view; Stage 5: Called pre-cupping, has 13-19 leaves, bases of leaves and stem are being fully covered from the above view; Stage 6: Called cupping, having 20-26 leaves, innermost leaves that are still growing in an upright manner are concealed by large old leaves that surround them; Stage 7: Called early head formation which has inner heart leaves starting to develop into a ball-like structure of overlapping leaves; Stage 8: Called head fill, where the head is firm and visible, however, cannot be harvested as it has not hardened; Stage 9: Called maturity stage, no visible new leaf formation, head obtained its maximum hardness and size and may split if not harvested.

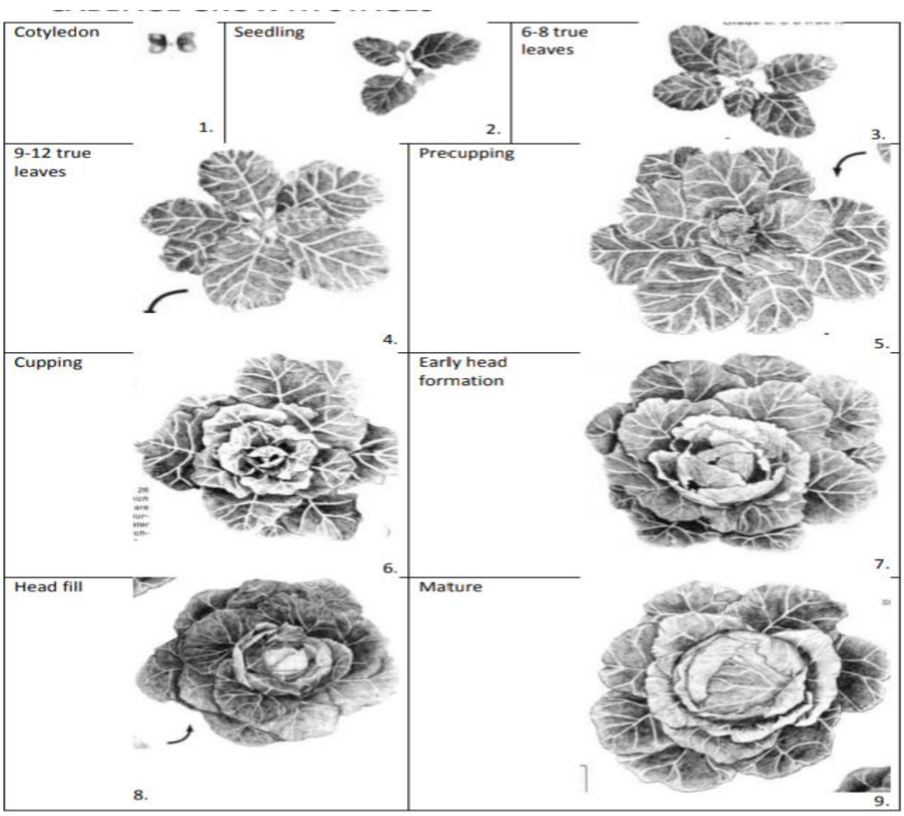


Figure 2. 1 Cabbage growth stages (adapted from Andaloro *et al*., 1983)

In South Africa, most exotic vegetables are generally produced on sandy soils, which often exhibit signs of low water retention, high permeability, and shortages in macro and micronutrients (Weber *et al*., 2007; Yao *et al.,* 2012; Usowicz and Lipiec 2017). Sandy soil may also induce water deficit in rain-fed areas even on irrigated land, its infiltration rates may increase the water requirements for the growing season (Datta *et al*., 2017). Water deficit also adversely affects agricultural productivity. Therefore, soil types are also considered to be determinants of agricultural productivity (Usowicz and Lipiec 2017). Disadvantages of sandy soils are that they have low cation exchange capacity (CEC) as a result of low clay and organic carbon content (Tahir and Marschner, 2016). Sandy soils low surface area encourages the leaching of exchangeable basic ions which may result in the soils being slightly acidic (Yao *et al.,* 2012). However, sandy soils require low energy inputs for tillage which can allow for resource-poor farmers to manually work the soil without machinery. Sandy soils also warm up quicker than heavier soils in spring and as a result production on it can start earlier (Usowicz and Lipiec 2017).

With climate change and water scarcity lowering agricultural productivity (Misra, 2014; Kuschke and Jordan, 2017), the sustainability of crop production in particular exotic leafy vegetables on sandy soil, relies on the adoption of more resilient production practices (Kuschke and Jordan, 2017). The production practices should induce proper nutrient and moisture retention in land used for the production of exotic vegetables, to optimise yield and nutritional quality. Part of these practices is the option of adding soil conditioners that have the potential to conserve water while improving soil health and maintaining good quality production.

2.4 Vegetable water requirements for Swiss chard and cabbage

Swiss chard has a shallow root system which is adapted to cool weather and where evapotranspiration is low; however, little is known about its water requirements. During Swiss chard growth, soil water should be kept above 50% field capacity (Mhlauli, 2000). Cabbage is slightly different from Swiss chard; it is considered to have relatively low evapotranspiration due to thick and waxy covering leaves which are common to the *Brassica* sp. It generally requires uniform water throughout the growth cycle. As such deficit irrigation on cabbage is not applicable. Cabbage is vulnerable to water stress on the last three to four weeks before harvest, water stress at this growth stage can drastically reduce yield and quality (Kemble *et al*., 2014). Excessive water application during the head fill and maturity stages of cabbage can also contribute to cabbage head bursting (Mhlauli, 2000).

Water requirements for cabbage may vary between 380 and 500 mm each season (Brouwer and Heibloem, 1986; Mhlauli, 2000). This, however, depends on the soil factors and environmental conditions. Cabbage irrigation should commence during the early stages of growth at 65% of available water. At the later stages of growth, it should be kept around 75% available water. Mhlauli (2000) found that for optimal yield, cabbage required 430 mm of water per season. While the work of Tiwari *et al*. (2003) found the highest cabbage yield of 111.72 t ha^{-1} under a drip and mulch treatment on sandy loam soil. Tiwari *et al*. (2003) suggested that cabbage water requirements per day range from 4.66 to 6.62 L.

2.5 Soil amendments

Soil amendments are any material that can be mixed with the soil to improve its physical properties such as aeration, permeability, water infiltration, drainage, structure water retention and nutrient retention (Davis and Whiting, 2000; Traunfeld, 2013). Soil amendments can either be fertilisers or soil conditioners. The main goal of applying soil amendments is to create a conducive plant root environment to promote healthy plant growth (Traunfeld, 2013). Soil amendments work better when they are mixed into the topsoil (Ippolito *et al*., 2011).

Not all soil amendments are soil conditioners, soil conditioners are defined as any materials that contain limited amounts of nutrients but are incorporated into the soil for their beneficial impact on the biological, physical and chemical properties within the soil (BC Agricultural Research and Development Corporation, 2010). Soil conditioners can be used to address two primary categories of problems at contaminated sites which are i) contaminant bioavailability or phyto-availability and ii) poor soil health and ecosystem function (United States Environmental Protection Agency, 2007). Soil conditioners can be of organic or inorganic nature, the former being derived from organisms that were once living and the latter being either mined or synthesised (Traunfeld, 2013).

Soil organic conditioners include animal and plant residues, farmyard and green manures etc. These conditioners increase the contents of organic matter in the soil which is used as an energy source by bacteria, fungi and earthworms in the soil (Davis, 2000). It also influences the soil structure, soil water holding capacity, CEC and the formation of stable soil aggregates (Davis, 2000). These go in line with the suggestion of Eldardiry and EI-Handy (2015) that in the process of rehabilitating physiochemical characteristics of degraded soils, the problem of decline needs to be addressed not only through nutrients but also through water holding capacity. Inorganic soil amendments are a collection of industrial mineral by-products being minerals themselves, mined minerals, and coal combustion products (the United States Environmental Protection Agency, 2007).

The United States Environmental Protection Agency (2007), further discusses a group of soil conditioners termed soil pH amendments, which are soil conditioners that are alkaline by nature. They have a pH neutralizing power which is expressed on a calcium-carbonate equivalent (CCE) basis. These conditioners can be of mined, synthesised and/or organic origins, for instance, lime, wood ash and synthesised zeolite (the United States Environmental Protection Agency, 2007). According to Davis and Whiting (2000), soil conditioners on clay soils should improve the soil aggregation, increase porosity and permeability, and improve the aeration, drainage and plant root depth. While on sandy soil, conditioners should increase water and nutrient holding capacity.

Davis and Whiting (2000), further note that not all available soil amendments are suitable for usage in just any soil. This is because some soil amendments may carry additional properties or contents that may contaminate or degrade the soils even further, for instance, wood ash has been found to contain high salts and high pH (BC Agricultural Research and Development Corporation, 2010). Therefore, there is a need to find and utilise soil amendments and conditioners that will produce good results as each soil may require.

Zeolite is part of soil conditioners that can produce good conditioning results on sandy soil. It has also been used for many other uses apart from soil conditioning. For instance, Mumpton (1985) noted that Bulgaria, Hungary, Yugoslavia, Korea and Mexico mined zeolite for commercial reasons (export). In the United States of America, it is used as mainstays of the molecular sieve business. In Germany, France, Great Britain, Belgium, Italy and Japan it is used in chemical firms (Diale *et al*., 2011). In an agricultural context, Mumpton (1985); Diale *et al*. (2011) and Ramesh and Reddy (2011) note that Japan has used zeolite to control moisture content, malodour of animal waste and to increase the pH of volcanic soils since the 1960s. Zeolites are aluminosilicates (SiO_4+AlO_4) minerals with porous structures which have high CEC and a great affinity for NH_4^+ (ammonium) (He *et al*., 2002). Zeolite can either be mined (natural zeolite) or be synthetically produced (Noori *et al*., 2007; Jha and Singh, 2016). The aluminosilicates (SiO_4+AlO_4) rings of zeolite are shown in Figure 2.2.

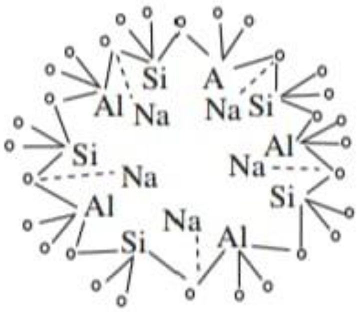


Figure 2. 2 [SiO4]4- and [AlO4]5- in a ring of sodium zeolite (Extracted from Jha and Singh, 2016)

South Africa is noted to have the potential for producing synthetic zeolite (Polat *et al*., 2004) and currently mines natural zeolite in Kwa-Zulu Natal and Western Cape (Diale *et al*., 2011). However, most of the produced zeolite in South Africa is exported to the United States of America rather than being used for agricultural purposes (Diale *et al*., 2011).

2.6 Effects of zeolite on soil chemical composition

Zeolite has been reported to have the ability to increase the pH of acidic soils to near neutral values, similarly to agricultural lime (Tsadilas, *et al*., 1997; Ramesh *et al*., 2015). Polat *et al*. (2004), found that using zeolite in conjunction with fertilisers can help buffer soil pH levels, thereby reducing the need for a lime application. This was further reinforced by Ramesh and Reddy (2011) who established that the application of zeolite to soil increased the availability of N, P, Ca, Mg and K, these are the soil nutrients which are immobilised in acidic soils as soil heavy metals become more mobile.

The problem of heavy metal contamination has been related to the acidification of arable land. As such, as the pH decreases, the more soluble and bioavailable heavy metals become (Garau *et al*., 2007). Soil acidification has been identified as an increasingly urgent pollutant problem all over the world (Lockwood *et al*., 2003). Acidic and heavy metal contaminated soils retard crop growth and yield. Therefore, their contamination reduction is critical in optimising agricultural crop production (Ramesh and Reddy, 2011).

Heavy metals are not easily biodegradable and persist in soils for long periods (Garau *et al*., 2007; Ramesh and Reddy, 2011). Their competitiveness in soils may account for some of the essential plant micronutrient unavailability (Bolan *et al*., 2003). They can be identified as elements with a density greater than 7.0 g cm^{-3} such as Zn, Fe, Si, Pb, and Mn (Kushwaha *et al*., 2018). However, some metals can be of less density but because of meeting the criteria of toxicity, they may be regarded as heavy metals. Soil contamination by these metals is essentially chemical soil degradation which in overall links to the decline of plant required nutrient (Doula *et al*., 2012).

Zeolite as a class of aluminosilicates is characterised by negative charges and can reduce heavy metal bioavailability (Garau *et al*., 2007). It was found by Moreno *et al*. (2017) to increase the chemical fertility in soils amended with it. In an earlier study by Tsadilas *et al*. (1997) zeolite was found to have increased the sorption of Cd in soils and as a result, its leaching was decreased, as it became insoluble. This process is recommended by Ramesh and Reddy (2011) to be the best for reducing the phyto-availability of these nondegradable heavy metals. Given the sorption and CEC of zeolite and its ability to slow-release nutrients, it can amend heavy metal toxicity (de Campos Bernardi *et al*., 2013; Gül *et al*., 2005). In a study by Reháková *et al*. (2004) zeolite showed the ability to suppress heavy metals from being toxic to plants. This was in line with the findings of Polat *et al*. (2004), who found that zeolite can buffer soil pH thereby decreasing the bioavailability of heavy metals.

In a different sense, zeolite's ability to sorb heavy metals into its cavities and channels and further block their reception to plants by making them insoluble (Reháková *et al.,* 2004), can be explained by the CEC of zeolite used to attract positively charged ions (Ramesh and Reddy, 2011). This happens when the cations in the zeolite are being released to form part of the plant-available nutrients, and the heavy metals take their places in the zeolite structure. Figure 2.3 shows the ion exchange process of NH_4Cl in sodium zeolite, it shows how the NH_4^+ replaces the Na^+ cations on zeolite. This explains the conclusion made by Reháková *et al.* (2004) that adding zeolite to soils leads to a significant decrease in the contents of heavy metals in plant tissues. Therefore, zeolite in physical terms is only involved in the fixation of heavy metals, which are thus still in the soil but in a non-available form. As such zeolite application could be useful for soils that are already contaminated with heavy metals (Ramesh and Reddy, 2011).

The main attribution for zeolites ability to ameliorate soil acidity and heavy metal contamination has been reported by many authors to be its high CEC or extremely effective ion exchange (Latifah *et al*. 2011; Ramesh and Reddy, 2011; de Campos Bernardi *et al*., 2013). This makes it possible for zeolite to bio-geochemically transform or retard positively charged nutrients in the soil, temporarily (Wassmann and Olli, 2004; Crouse, 2007). This retardation of positively charged nutrients allows zeolite the ability to prevent unnecessary loss of soil nutrients caused by leaching when applied to soils (de Campos Bernardi *et al*., 2013). This is because the cations which make up some of the soil nutrients can be exchanged through ion exchange with zeolite, hence they are retained within the zeolite structure, thereby increasing soil nutrient retention (Ramesh and Reddy, 2011). The high CEC that retains nutrients in the zeolite, coupled with the large porosity from zeolite structure which results in soil water retention is directly linked to the reduction of soil nutrient leaching.

In another study, zeolite was found to have a greater affinity for ammonium (NH_4^+) and potassium (K^+) cations more than the other cations (de Campos Bernardi *et al*., 2013). As such, it has been used and reported to reduce ammonia emission (NH_3) from animal manure by 16%, while nitrogen leaching was also reduced (Malekian *et al*., 2011). In a study carried out by Ramesh and Reddy (2011), zeolite lowered nitrate concentration in soil leachates, due to its NH_4^+ affinity. Zaman and Nguyen (2010) on the other hand, found that zeolite reduced soil NH_4^+ concentrations and based their findings on zeolites sorption properties. This finding was not covered in the work of other authors (de Campos Bernardi *et al*., 2013; Ramesh and Reddy, 2011). Given the sorption ability of zeolite, this explains why the NH_4^+ concentration was reduced in the soil while other studies claim that it was not leached. Since each study focused on different components of the same situation, these findings are not considered to be at variance with one another. Ramesh and Reddy (2011) further noted that zeolite has been widely used in Japan for promoting nitrogen retention in soils, Figure 2.3 also illustrates how N is retained through ion exchange.

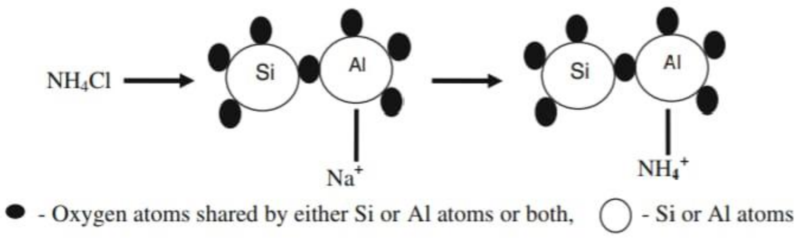


Figure 2. 3 Ion exchange process in a mixture of ammonium chloride and sodium zeolite (Extracted from Jha and Singh, 2016)

According to Latifah *et al.* (2011) zeolite regulated the release of NH_4^+ activities following urea application which limited the intensity of nitrification in the soil. However, Ramesh and Reddy (2011) based this on the theory that the channels in zeolite protect NH_4^+ from too much nitrification by microorganisms. The entrances of these channels are large enough for cations like NH_4^+ and K^+ to enter, but not large enough to permit nitrifying bacteria entry. These authors further explained that nitrogen molecules that get into these zeolite channels are retained by electrostatic attraction, followed by modifications of molecular angles, and single and double bonds that occur in it. Hence, NH_4^+ that is absorbed in the channels of zeolite will be slowly released, allowing a progressive absorption by plants.

Although zeolite has been observed to be negatively charged, and able to sob positively charged ions such as NH_4^+, for more nutrient retention. Another school of thought, noting the sorption ability of zeolite, believed that zeolite may initially immobilize NH_4-N in the soil when it is applied which means that there will be reduced N availability to the crop. Reduced N availability results in a negative effect on plant growth (Ramesh and Reddy, 2011). However, as the growth proceeds zeolite is reported to increase nutrient availability in soils due to increased soil surface area and CEC on sandy soil. The increased nutrient availability has also been attributed to root growth resulting in an increased ability by plants to assimilate the nutrients from the structure of zeolite (Lee *et al*., 2019). Amendments that can retain soil nutrients, minimise deep percolation of water and nutrient leaching in sandy soil are essential, especially the ones that promote the sustainability of vegetable production.

2.7 Effect of zeolite on soil moisture retention

Soil moisture retention is the ability of soil to hold onto water for a long periods of time. The structural description of zeolite, "composed of a system of canal, cavities and pores", suggests that it can influence soils moisture retention (de Campos Bernardi *et al*., 2013). Its high water-holding capacity can be attributed to the canal and pores in its structure. The structure makes it possible to have a more retentive water reservoir in plant root zones while improving the horizontal spread of moisture after irrigation, through the capillary suction properties of zeolite (Garau *et al*., 2007). Ramesh and Reddy (2011) underline that the pores are the main characteristics that allow for zeolite to retain moisture for long periods. Increased moisture retention through zeolite application further increases water efficiency. This increases plant available water in the soil, which is the water between field capacity and permanent wilting point (de Campos Bernardi *et al*., 2013). The major moisture benefit with the application of zeolite is that it can absorb up to 50% of its weight in moisture, yet its structure remains undamaged even if the water is removed through heating (Ramesh and Reddy, 2011). Due to the stable structure of zeolite, water is stored in the root zone of plants longer. This allows for water to be directly available to plant roots when required (Vieja *et al*., 2011).

Zeolite increases soil water holding capacity without reducing air-filled pore spaces (Ramesh and Reddy, 2011; Vieja *et al*., 2011; de Campos Bernardi *et al*., 2013). Ramesh and Reddy (2011) note that the maximum benefits from zeolite can be obtained from its application on coarse-textured low CEC soils, therefore, lower application rates can be applied to it (Ippolito *et al*., 2011). However, zeolite can be used on other soil types including usage on non-wetting sands, which are finer than normal particle sands (Martín *et al*., 2017). On these non-wetting sands, it mostly assists in the initiation of soil water infiltration and later on its retention.

In agriculture, part of the problem that leads to poor soil water holding capacity is the excessive application of chemical fertilisers (Vengadaramana and Jashothan, 2012). This is because excessive application indirectly decreases soil biological activity, which leads to the deterioration of soil physical and chemical quality (Ramesh *et al*., 2015). As such, zeolite can be mixed with other soil amendments, that will encourage soil biological activities, and it will still benefit the soil. For instance, Ramesh *et al*. (2015) mixed zeolite with fly ash and found that soil water holding capacity was increased by 20.9%. The combination of zeolite with fly ash altered soil texture, thereby increasing porosity. In the study, it was also noted that the application method of zeolite also affected soil moisture retention potential, where zeolite that is incorporated into the soil has better moisture retention potential than band placed zeolites. With drought and limited availability of irrigation water, easy sustainable soil moisture conservation techniques must be employed for the sustainability and optimisation of vegetable production.

2.8 Zeolite based fertilizers

Zeolite has been used as carriers for agrochemicals such as pesticides, insecticides, herbicides and fertilizers (Reháková *et al.,* 2004). Zeolite is reported to be suitable carriers due to its ability to absorb nutrients and slowly release them to plant roots. de Campos Bernardi *et al*. (2013) found that zeolite absorbed P and NH_4-N when mixed before soil application. During the growth of the plant, it is then slowly released. This was linked with the high CEC of zeolite, which further led to a reduction in leaching losses of exchangeable cations which included K^+. These authors further substantiated that when urea is used in conjunction with zeolite, its N has the potential to be slowly released to the plants' root zone, Gül *et al*. (2005) phrased the practice “optimizing the root environment”.

Optimizing the root environment with zeolite occurs because most of the applied nutrients are held in the structure of the zeolite, making it difficult to volatilize and to leach. This increases the efficiency of N and other nutrients. Mixing zeolite with chemical fertilisers before application, can be done for basal fertiliser application and also for topdressing (de Campos Bernardi *et al*., 2013; Reháková *et al.,* 2004), either way, the same result will be achieved. Reháková *et al*. (2004) termed fertilisers that are mixed with zeolite before their application as "Zeolite based fertilisers". These fertilisers, when applied on soils at the beginning of the growing period, can supply an even fertilising effect throughout the whole growing period (de Campos Bernardi *et al*., 2013; Reháková *et al.,* 2004). This benefit of zeolite is better realised at high rain periods when nutrients are not all washed out at once because of the high water holding capacity and high CEC of zeolite (Reháková *et al.,* 2004).

It is, however, more convenient to amend soils with zeolite at planting since this material has relatively long-lasting effects. Additionally, it would be more difficult to incorporate it in productions like orchards when trees have fully grown (He *et al*., 2002). Moreover, for the best timing of zeolite application, plant root destruction through late incorporation or band placing needs to be taken into consideration. On another train of thought, Ramesh and Reddy (2011) agree that zeolite can be used as both nutrient carrier and as a soil conditioner to free insoluble nutrients in the soil. Several authors attributed this to zeolite's effectiveness in ion exchange. In total, when mixed with inorganic chemicals like NPK fertilisers, zeolite enhances the action of the compounds to slow-release fertilisers which is important for optimizing vegetable production and for environmental sustainability.

2.9 Effect of zeolite on plant growth and yield

Crop yield is defined as the ratio of quantity harvested divided by area harvested, for instance, kg ha^{-1}, quantity/area (Reynolds *et al*., 2015). Crop yields differ in terms of plant parts that are harvested, as such different crops will have different yield while grown on the same or similar soil area and/or type. Zeolite's affinity towards nutrients may be used to improve plant growing media thereby improving crop yields (de Campos Bernardi *et al*., 2010). Zeolite improves the availability of plant required nutrients such as N, P, Ca and Mg while also increasing water holding capacity in soils. Through this process, plants uptake of these nutrients is increased therefore their growth and yields are improved. The increase of plant growth as influenced by zeolite application varies according to soil types (Garau *et al*., 2007; Ramesh and Reddy, 2011). Zeolite reduces N leaching, while increasing N use efficiency, as it has great affinity to NH_4^+. Nitrogen is a constituent of plant chlorophyll, it is vital to plant growth and influences crop yield and quality, especially in green leafy vegetables and the vegetative growth of other field crops (Malekian *et al*., 2011). On soya bean production, zeolite encourages the initiation of vegetative phenology on allophonic soil (Ramesh and Reddy, 2011).

In another facet, a limitation that can be associated with the application of zeolite on soils is the limitation of N in the initial phases of plant growth (Ramesh and Reddy, 2011). Again, because of zeolites high affinity for NH_4^+ and K^+, it may allow the chemical structure to be filled with mostly NH_4^+ and K^+ cations. This would make other nutrients to have difficulties in finding vacant sites inside the zeolite, through this phenomenon they may end up being leached (Reháková *et al.,* 2004; Malekian *et al*., 2011). As a result, some crops which require fewer rates of N during the formation of their economic yield parts may have limited amounts of nutrients that are required for that particular growth (Ippolito *et al*., 2011). Ramesh and Reddy (2011) confirmed this and reported that pepper fruit size decreased as zeolite application increased due to greatest affinity to NH_4^+-N. On another note, de Campos Bernardi *et al*. (2010) grew four successive crops in the same pots with the application of zeolite, the crops were lettuce, tomato, Andropogon grass and rice. The results showed that the rate of zeolite required for maximum production in the last crop (rice) was much larger than the one required by the first crop (lettuce), which may be a decline of zeolites efficiency with time.

de Campos Bernardi *et al*. (2010) also found that lettuce (*Lactuca sativa*) as a leafy vegetable, showed an increase in fresh and dry matter yield when cultivated with zeolite, this was related to the supply of KNO_3-. However, the authors also found that tomato (*Lycopersicon esculentum* cv. Finestra) showed an increase in fruit yield, fruit quality and dry matter yield. This contradicts the finding of Ramesh and Reddy (2011) as they noted a decrease in fruit sizes of pepper. The tomato fruit size and the quality increase were attributed to the increasing availability of K^+ with the increased application of zeolite. Possibly the fertiliser programme was not constant with the fertiliser programme for the pepper that is noted by Ramesh and Reddy (2011). Sweet corn is another crop that Ramesh and Reddy (2011) found to have decreased yields with the increasing application of zeolite. Nevertheless, a combination of fly ash and zeolite, increased the leaf numbers, branch numbers and vine length of sweet potato. It proved beneficial to tuber yield and plant biomass (Ramesh and Reddy, 2011; Ramesh *et al*., 2015). The sweet potato yield increase was linked to physical soil condition improvement, which leads to successful underground growth. Some studies that explored both fresh and dry yield weight of crops, observed that zeolite as a slow nutrient releaser contributed to the reduction of soil contamination and improved crop yields (Aainaa *et al*., 2018; Gül *et al*., 2005).

Zeolite as a nutrient absorber allows nutrients to enter its structural cavities, which are then gradually released allowing plants to progressively absorb the nutrients during their growth period, thereby resulting in higher dry matter production (de Campos Bernardi *et al*., 2010; Ramesh and Reddy, 2011). With the benefits and shortfalls of zeolite, it is important to find the best application rates which will not only allow for large retention of nitrogen while other nutrients are lost, as getting all required nutrients is imperative for healthy and proper plant growth.

2.10 Effect of zeolite on plant nutrient contents

Soil conditioners improve and condition soil physical, chemical and biological properties. Their influence on soil properties allows the root zone environment of plants to be optimised for improved and maximised growth, yield and quality (Davis and Whiting, 2000; Traunfeld, 2013). Leaf tissue nutritional contents in leafy vegetables have been used as a quality attribute in various research papers (Barrett *et al*., 2010; Dias, 2013; Colonna *et al*., 2016). According to Barrett *et al*. (2010), fruit and vegetable nutritional quality is important as it is used as a key attribute in improving and maintaining human health. For instance, fruits and vegetables carry macro and micronutrients which are linked to health benefits (Pyo *et al*., 2004; Barrett *et al*., 2010; Kapusta-Duch *et al*., 2012; Maboko and Du-Plooy, 2013; Aksoy *et al*., 2014; Maboko *et al*., 2017). Plant nutritional quality is influenced by several factors which include soil factors, climate, crop variety, crop management practices and post-harvest handling and storage (Hornick, 1992). The contents of elements in the plant nutrient environment (soil/growth medium) govern the plants mineral composition which characterises their nutritional conditions (Jarvan *et al*., 2004). This, therefore, means soil health is linked to the production of nutritious foods (Hornick, 1992).

Haynes and Swift (1986) noted that soil amendments that decreased soil pH and increased Al and Mn availability produced crops with higher contents of Al and Mn in their leaf tissues.

Zeolite as a soil conditioner was found to increase the content of N and K in crisp-head lettuce plant tissue (Gül *et al*., 2005). Abdi *et al*. (2006) also found that zeolite increased the protein in strawberries (*Fragaria x ananassa Duch*), protein is a product of N. The study by Gül *et al*. (2005) also found that the contents of Ca and Mg were relatively low in crisp-head lettuce that was cultivated under zeolite than that cultivated under perlite. This phenomenon was linked to zeolites affinity to NH_4^+ and K^+, and which leads to other nutrients not receiving vacant cites in zeolite channels thereby leaching. Other nutritional contents that zeolite has been seen to increase are crude fibre and dry matter on beet (Abdi *et al*., 2006). Zeolites influence to plant nutritional content still needs more probing, as there is not much information on the various plants.

CHAPTER THREE
RESEARCH DESIGN AND METHODOLOGY

3.1 Experimental site

The research was conducted at the Agricultural Research Council (ARC) Infruitec-Nietvoorbij in Stellenbosch, Western Cape (latitude 33.914476° S and longitude 18.861322° E), shown in Figure 3. 1.

Figure 3. 1 Map showing the Agricultural Research Council (ARC) Infruitec-Nietvoorbij in Stellenbosch (Google Earth, 2020)

The Stellenbosch region is characterised by a Mediterranean climate with cold and wet winter and dry, hot summers. The sandy soil used for the experiment was collected from the ARC research farm in Bien Donne, Paarl with the following coordinates latitude 33.84274° S and longitude 18.98425° E (Saayman, 2013).

The soils in the Paarl area are categorised into three types, one of the Table Mountain sandstone, on the mountain slopes surrounding Paarl and some sandy soil derived from decomposed granite and finally clay soil from the Malmesbury shale (Adelana *et al*., 2010).

3.2 Experimental design

The greenhouse pot experiment was laid out in a randomised complete block design (RCBD) as shown in Table 3.1. Environmental conditions in the greenhouse were not controlled.

Table 3. 1 Experiment layout

Randomised complete block design (RCBD)

Cabbage

Block	1	2	3	4	5	6	7	8	9	10	11	12
1	▪	1	▪	▪	Control	▪	▪	2	▪	▪	3	▪
2	▪	Control	▪	▪	3	▪	▪	1	▪	▪	2	▪
3	▪	2	▪	▪	1	▪	▪	3	▪	▪	Control	▪
4	▪	3	▪	▪	2	▪	▪	Control	▪	▪	1	▪
5	▪	1	▪	▪	3	▪	▪	2	▪	▪	Control	▪
6	▪	2	▪	▪	Control	▪	▪	1	▪	▪	3	▪

Swiss chard

Block	1	2	3	4	5	6	7	8	9	10	11	12
1	▪	3	▪	▪	2	▪	▪	Control	▪	▪	1	▪
2	▪	2	▪	▪	3	▪	▪	1	▪	▪	Control	▪
3	▪	1	▪	▪	Control	▪	▪	3	▪	▪	2	▪
4	▪	Control	▪	▪	1	▪	▪	2	▪	▪	3	▪
5	▪	3	▪	▪	Control	▪	▪	1	▪	▪	2	▪
6	▪	1	▪	▪	2	▪	▪	3	▪	▪	Control	▪

ANOVA	
Source	d.f.
Block	6-1=5
Zeolite	4-1=3
Error	(6-1) (4-1) =15
Total	6x4-1=23

*Note
An experimental unit consisted of 3 pots receiving the same treatment

Key	
Treatment	Zeolite %
Control	0
1	10
2	20
3	30

The experiment consisted of four zeolite to soil treatments at ratios 0:10, 1:9, 2:8 and 3:7 each with 18 replicate pot plants for two test vegetables, Swiss chard and cabbage. The treatment application rates are shown in Table 3.2 and the zeolite is shown in Figure 3.2.

Table 3. 2 Treatment delineation and the amount of soil placed in each pot

Treatment	Zeolite in each pot (kg)	Soil in each pot (kg)	Approximate zeolite t ha^{-1}
0% Zeolite	0	12	0
10% Zeolite	1.2	10.8	222
20% Zeolite	2.4	9.6	500
30% Zeolite	3.6	8.4	857

Figure 3. 2 Clinoptilolite zeolite used in the study

The experiment was conducted over two growing seasons. The first season started in late autumn to late spring 2018 for both vegetables. The second season was early autumn to early spring 2019 for Swiss chard while winter/spring 2019 for cabbage. Only the growth, yield and vegetable water application data were collected in the second season.

3.3 Soil preparation

In the first season, sandy soil from virgin land was collected from Bien Donne, the soil was sieved through a 3 mm sieve to remove organic material. The soil from Bien Donne was acidic and contained low levels of calcium and magnesium. Therefore, dolomitic lime (CaMg $(CO_3)_2$) was added to the soil to increase the pH before placing the soil in the pots. Dolomitic lime was applied at a rate of 8 t ha^{-1}. The lime was mixed with the dry soil after which water was applied, mixed in and then left to incubate in a pile for a week. The soil pH was amended from 3.8 to 5.4.

At soil pH 5.4 each pot was filled with 12 kg of sandy soil or mixed with zeolite at weight by weight ratios (Zheljazkov and Warman, 2004) as mentioned in Table 3.2. Zeolite was then thoroughly mixed with the sandy soil before being brought to field capacity in the pot. In the second season, the same soil from the first season was used for transplanting, with the soil from the non-amended treatment requiring 3 t ha^{-1} lime application to rectify the pH.

3.4 Vegetable fertilisation

The fertilisation programme for both vegetables, in both seasons, constituted of a pre-planting application of mineral fertilisers: 90 kg N ha^{-1} (Urea 46; 195.65 kg ha^{-1}) 100 kg P ha^{-1} (Single-super Phosphate 20; 500 kg ha^{-1}) and 160 kg K ha^{-1} (Potassium Chloride 50; 320 kg ha^{-1}) for cabbage while 90 kg N ha^{-1} (Urea 46; 195.65 kg ha^{-1}) 100 kg P ha^{-1} (Single-super Phosphate 20; 500 kg ha^{-1}) and 120 kg K ha^{-1} (Potassium Chloride 50; 240 kg ha^{-1}) was for Swiss chard. The application of fertiliser was based on the recommendation given on FSSA (2007) for both vegetables.

At 3 and 6 WAT, cabbage received 170 kg N ha^{-1} (Urea 46; 369, 57 kg ha^{-1}), this was applied as split applications of 85 kg N ha^{-1}per application. Swiss chard received 50 kg N ha^{-1} (Urea 46; 108,73 kg ha^{-1}) at 4 and 8 WAT. This was also applied on split applications of 25 kg N ha^{-1} (FSSA, 2007).

3.5 Planting

Swiss chard, cv. Ford Hook Giant and cabbage, cv. Copenhagen six-weeks-old, rail system grown seedlings were used for planting. The Seedlings were produced at Western Cape Seedlings, a wholesale plant nursery in Cape Town. The seedlings were transplanted on pots of 30 cm diameter and 30 cm depth, each pot contained one plant.

3.6 Irrigation

The field capacity (FC) of the potted sandy soil and zeolite amended sandy soil were determined using the gravimetric method. The amounts of water required to get the soil to FC was added to the soil before transplanting. The gravimetric method was also used to assess the soil moisture so that when moisture was under 50% FC, irrigation water was applied to bring the soil moisture to 70% FC using manual irrigation method.

3.7 Weed and pest control

Throughout the experiment weeding was done manually as weeds appeared on the pots, the weed control measures consisted of hand forks and hand pulling. The weeds were then incorporated back into the soil. All the yellow dead leaves from the plants were allowed to fall back into the soil and worked back in.

Insect pests were controlled using Makhro Cyper® (active ingredient: cypermethrin, 200 g L^{-1}), using 1 mL in 10 L of water in the first growing season. In the second growing season, Avi Gard Mercaptothion® (active ingredient Organophosphate 500 g L^{-1}) was used at a rate of 15 mL of chemical to 10 L of water. The application time of the pesticides was determined through scouting and identification of pests.

3.8 Data collection methods

3.8.1 Growth parameter data collection

The data collection methods for cabbage and Swiss chard growth parameters are presented in Table 3.3 The parameters were the number of leaves per plant, leaf width, leaf length, plant height, leaf chlorophyll content index (CCI), leaf area, fresh and dry yields.

Table 3. 3 Methods used to collect data for growth parameters of both test vegetables

Growth Parameter Observed	Method
Number of leaves	For Swiss chard, all the true leaves that were adequately grown and observed to have moved away from the main growing point were counted and recorded. For cabbage, the non-wrapper leaves were counted. From the stage of pre-cupping till head maturity all the leaves that started to fold inside were no longer counted only non-wrapper leaves that were dissociated with the head were counted.
Leaf width	Leaf width was measured with a “mm” ruler, the leaf width being the maximum value perpendicular to the midrib (Wang and Zhang, 2012). The biggest leaf on the plant was selected for this observation in both vegetables.
Leaf length	Leaf length was also measured with a “mm” ruler. The leaf length is the maximum value along the midrib (Wang and Zhang, 2012). The biggest leaf on the plant was selected for this observation in both vegetables.
Plant height	Was measured with a tape measure, observing the length between the soil surface and the highest leaf tip in both vegetables.
Chlorophyll (CCI)	Data for leaf CCI was taken using a chlorophyll content meter CCM-200 plus, seen in Figure 3.3. It was measured from the top edge of the biggest leaf for both vegetables. In the first week of observation, there was no CCI data collection in both seasons, due to late acquisition of the apparatus in the first season.
Leaf area	Leaf area for Swiss chard was calculated by developing ratio and regression estimators, using the leaf length and the leaf width (Pandey and Singh, 2011; Wang and Zhang, 2012). For cabbage the area of an oval shape was used to estimate leaf area per leaf using the leaf length and leaf width as $r^1$and r^2 in the formula, leaf area= pi x r^1/2 x r^2/2.
Swiss chard yield	Swiss chard harvesting commenced four WAT. After that, it was harvested every 21 days for four more harvests. During harvesting, Swiss chard leaves that were 15 cm or more in length were harvested. The fresh weight of the harvested samples was determined using a weighing scale, samples were then placed in a paper bag and oven-dried at 60°C to constant weight. Since harvesting was continuous, total yield (fresh and dry) was determined at the last harvest, by adding all the weights recorded for the five harvests as total yield.
Cabbage head diameter	The head diameter of cabbage was measured at the widest part of the head using a tape measuring.
Cabbage head circumference	The head circumference was measured by a flexible tape measure.
Cabbage yield	Cabbage was harvested after 130 days from transplanting. The heads were cut at the base near the stalk, with their non-wrapper leaves. The fresh yield of the cabbage was separated into two categories, one with untrimmed head and the other with trimmed head. The trimmed head yield was further oven-dried at 60°C to constant weight.
Leaf samples Swiss chard and cabbage	At each harvest of Swiss chard and that of cabbage, after oven-drying at 60℃ and weighed for dry mass, dry samples were stored in marked, airtight zip plastic bag and stored in a refrigerator at 5℃ for further mineral and proximate analysis.
Root biomass	Data on root biomass for both vegetables were collected at the end of each growing season by sieving the soil to get only the roots. Root samples were then placed in a sieve and further rinsed in flowing tap water to eliminate soil residues. Samples were allowed to air-dry and weigh for fresh weight. Dry weight was obtained after oven-drying at 60°C to constant weight.

Figure 3. 3 Chlorophyll content meter CCM-200 plus

3.8.2 Soil chemical analysis

A composite soil sample for baseline chemical analysis was collected from thoroughly mixed sandy soil that was collected from Bienne Donne, before the addition of zeolite. For both vegetables, post-harvest soil chemical analysis was only done once, which was at the end of the first growing season, when the experiment was terminated. This soil samples were analysed at a commercial laboratory (Bemlab) for treatment effects using the standard procedures of the Non-affiliated Soil Analysis Work Committee (1990). Soil carbon (C), exchangeable cations (Na, K, Ca, and Mg), available nitrogen (NO_3-N and NH_4-N), trace elements (Fe, Cu, Mn, Zn, and B), pH (KCl), electrical resistance, total potassium (K) and phosphorus (P) (Bray II) were determined.

3.8.3 Vegetable water application

Gravimetric soil moisture method was used to assess the amount of water in the soil before irrigation. All irrigation water applied was monitored and kept between 50% and 70% FC throughout the vegetable growth, all water applications were recorded.

3.8.4 Leaf nutrient concentration for Swiss chard and cabbage

Analysis of the nutrient composition of the vegetable leaves was only done once, which was at the end of the first growing season. The leaf mineral contents were analysed at Bemlab to determine the Nitrogen (N) (Leco-combustion method) P, K, calcium (Ca), magnesium (Mg), sodium (Na), manganese (Mn), iron (Fe), zinc (Zn), copper (Cu) and boron (B) using Hydrochloric total acid digestion.

The proximate analysis for both Swiss chard and cabbage was conducted to analyse ash, crude lipid and crude fibre contents using the method described by the Association of Official Analytical Chemists (AOAC, 1984). The micro-Kjeldahl method was used to determine crude protein (N x 6.25) while caloric value was calculated using Atwater factor [(crude protein x) + (crude lipid x 9) + (carbohydrate x 4)] (Okalebo *et al*., 2002).

3.9 Statistical data analysis

All data from the experiment were subjected to analysis of variance (ANOVA) using SAS (version 9.4, SAS Institute Inc., Cary, NC, USA, 2000). Analysis of variance was performed for each season separately, using the SAS statistical software. Results of the two seasons were also combined and investigated in one overall ANOVA (John and Quenouille, 1977) after testing for season homogeneity of variance using Levene's test (Levene, 1960). The Shapiro-Wilk test was performed to test for deviation from normality (Shapiro, 1965). Fisher's least significant difference was calculated at the 5% level to compare treatment means (Ott, 1998). A probability level of 5% was considered significant for all tests.

CHAPTER FOUR
RESULTS

4.1 Initial soil and zeolite characteristics

The characteristics of the clinoptilolite zeolite used for this study are shown in Table 4.1. The zeolite had a granular appearance with a white to a grey colour. The pH ranged between 8 and 9 with a cation exchange capacity of 16 mg kg^{-1}. The mineralogy of the zeolite was more than 90% clinoptilolite and less than 5% quartz.

Table 4.1 Properties of zeolite

Physical properties	Description
Colour (Crude)	White to Grey
Appearance	Granules
Moisture (%)	< 15
Loose bulk density (g cm^{-3})	1.20
Particle size distribution	80% 1- 5 mm nominal (10% > 5 mm and 10% < 1 mm)
pH (30 g in 60 ml water)	8-9
CEC (mg/kg)	16
Water adsorption (on sinter plate)	400%
Viscosity marsh funnel (seconds)	21
Surface Area (Bet method m^2 g^{-1})	43
Average pore volume (cm^3 g^{-1})	>0.10
Average pore size (nm)	7
Specific gravity (g cm^{-3})	2.51
Chemical analysis	(%) Typical
SiO_2	64.30
Al_2O_3	12.70
TiO_2	0.10
MgO	1.30
Na_2O	2.30
Fe_2O_3	1.30
CaO	1.20
K_2O	1.70
Loss on ignition	8.40
Mineralogy	Approximate
% Clinoptilolite	> 90
% Quartz	< 5

Chemical properties of the soil before the application of zeolite (Table 4.2) was adequate for proper plant growth.

Table 4. 2 Baseline chemical characteristics of the initial soil before zeolite application

Chemical analysis		Value
pH (KCl)		5.40
CEC (cmol(+) kg^{-1}) (pH 7)		5.46
C (%)		0.89
Electric resistance (Ohm)		900
Ex. Cations (cmol(+) kg^{-1})	Na	0.11
	Ca	5.83
	K	0.12
	Mg	0.39
	mg kg^{-1}	
Total K		47
P (Bray II)		47
NO_3-N		32.76
NH_4-N		7.11
Cu		0.40
Zn		6.20
Mn		24.2
B		0.16
Fe		362
Soluble S		14.66

At the end of the first season, in both vegetables, the soil pH, CEC, total K and all the exchangeable cations of the non-amended treatments were lower than those of the initial soil. Whereas, these parameters increased on the zeolite amended treatments. However, NO_3-N, NH_4-N, Mn, Fe, Zn and S contents all became reduced compared with the initial levels in all treatments. Moreover, the soil electrical resistance increased on the 0% zeolite treatment while it decreased on the zeolite amended treatments.

4.2 Effect of zeolite on cabbage growth and yield

4.2.1 Cabbage growth as affected by zeolite

In the first season, there were no significant differences ($p>0.05$) in the maximum chlorophyll content index (CCI) values while on the contrary, the 10% zeolite treatment had a significantly highest CCI ($p<0.05$) value in the second season (compared to the 0 zeolite treatment), though not significantly higher than those of other zeolite treatments (Table 4.3). The chlorophyll contents of cabbage leaves were higher in the first season than that of the second season across treatments. In the first season, there was no difference in the maximum CCI values that were attained ($p>0.05$) while in the second season, the weeks tended to increase with increased zeolite application. The largest value for the maximum leaf area was observed in the non-amended treatment in the first season ($p<0.05$) while the reverse was the case in the second growing season, where 0% zeolite had the least ($p<0.05$) maximum leaf area. There were no significant differences among treatments in the time it took to reach the maximum leaf area, except for the non-amended treatment in the first season where 0% zeolite treatment took longer ($p<0.05$) to reach its maximum leaf area.

The maximum plant height values in the first season tended to decrease with increasing zeolite application. While in the second season, they increased ($p<0.05$) with increased zeolite application. In both seasons the number of WAT, that the maximum plant height was reached were shorter ($p<0.05$) on the non-amended cabbage treatment, with no significant differences ($p>0.05$) between the amended treatments. In terms of the maximum number of leaves per plant, there were observed differences ($p<0.05$) among treatments in the first season. However, in the second season, there were more leaves ($p<0.05$) on the non-amended treatment. The number of leaves on cabbage plants in the second season tended to decrease with increasing zeolite application, in the second.

Table 4. 3 Effect of zeolite on cabbage growth parameters

	CCI		**Leaf Area (cm^2)**		**Plant Height (cm)**		**Number of Leaves**	
Season	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Treatment	**Maximum**							
0% Zeolite	70.04[a]	52.37[c]	287.16[a]	86.65[e]	23.43[c]	21.80[d]	11.70[d]	20.80[a]
10% Zeolite	73.04[a]	61.59[b]	116.14[d]	306.53[a]	23.31[bc]	25.12[a]	11.90[d]	20.25[ab]
20% Zeolite	78.04[a]	55.58[bc]	247.92[b]	122.70[d]	22.81[d]	25.27[a]	11.81[d]	19.98[bc]
30% Zeolite	70.03[a]	58.73[bc]	198.04[c]	121.69[d]	21.83[d]	24.64[ab]	12.26[d]	19.43[c]
LSD	8,32		35,08		1.47		0.80	
	Number of weeks after transplanting that the maximum was reached							
0% Zeolite	5.72[ab]	3.18[d]	9.80[a]	6.04[b]	3.88[b]	2.14[c]		
10% Zeolite	6.25[a]	4.30[c]	5.50[b]	5.99[b]	4.30[a]	3.16[b]		
20% Zeolite	6.71[a]	4.12[cd]	6.53[b]	6.17[b]	4.30[a]	3.25[b]		
30% Zeolite	5.97[a]	4.68[bc]	5.33[b]	6.90[b]	4.39[a]	3.79[b]		
LSD	1.10		1.77		0.77			

Data are given in mean
Values with different letters within the same column show a significant difference at $p<0.05$
LSD= Least significant difference

4.2.2 Cabbage head diameter, circumference and yield responses to zeolite

The fresh weight of cabbage was separated into two categories, the mass of the untrimmed head and the mass of the trimmed head which represented the marketable cabbage head. For fresh weight, the results (Figure 4.1 and Figure 4.2) show that in both categories, there generally were no yield differences ($p>0.05$) except for the 0% zeolite amended treatment in the second season. It had the least fresh yields ($p<0.05$).

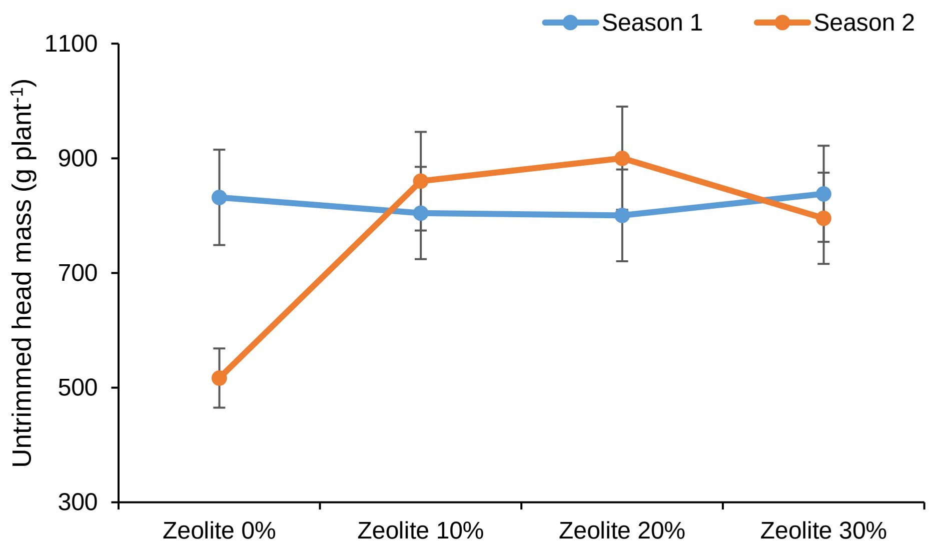


Figure 4. 1 Effect of zeolite on untrimmed cabbage fresh mass

Overlapping error bars indicate no significance at p<0.05

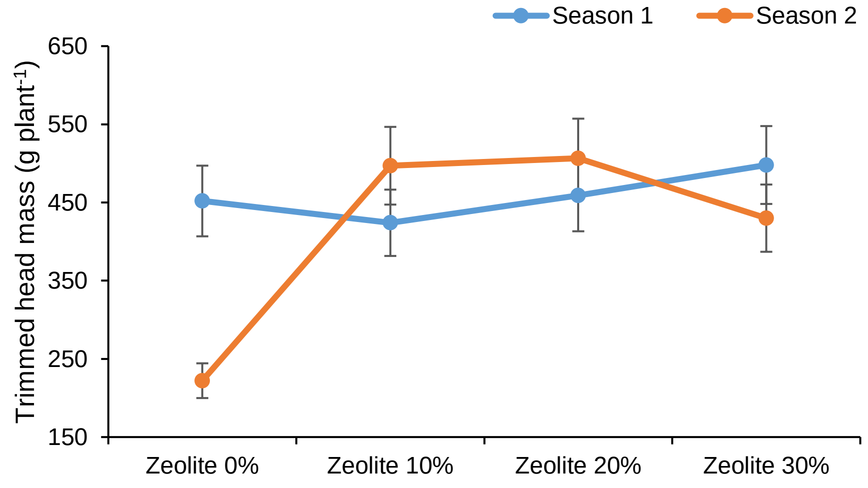


Figure 4. 2 Effect of zeolite on trimmed cabbage fresh mass

Overlapping error bars indicate no significance at p<0.05

The trimmed cabbage dry masses (Figure 4.3) show that in the first season, there was generally a difference between treatment dry yields ($p<0.05$). In the first season, the 30% zeolite treatment had the largest dry matter content while the 0% zeolite treatment had the least. In the second season, the 0% zeolite treatment still had the least dry matter among the treatment. Additionally, the dry matter in the second season was generally higher in all treatments than the first season.

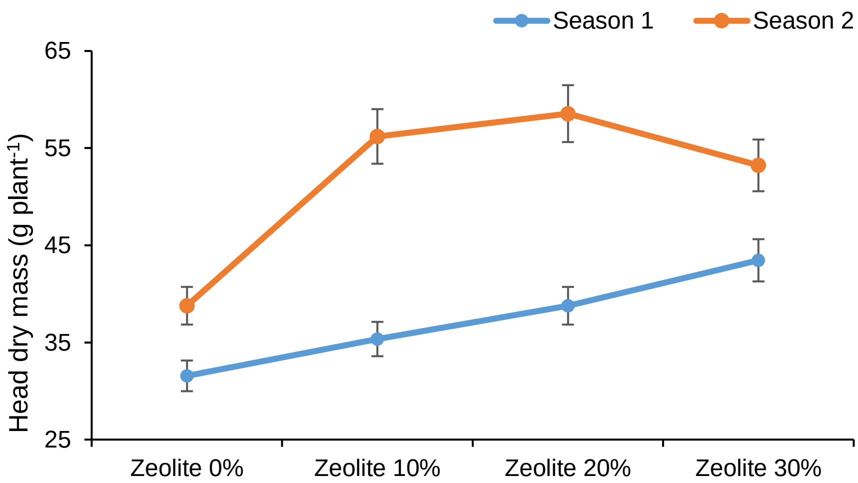


Figure 4. 3 Effect of zeolite on trimmed cabbage dry mass
Overlapping error bars indicate no significance at p<0.05

Cabbage head diameter and circumference (Figure 4.4 and Figure 4.5) of the first season were generally lower than the values obtained in the second season, except for the non-amended treatments. In the first season, there were no differences ($p>0.05$) in head diameters and circumferences among treatments. However, in the second season, the non-amended treatment had less ($p<0.05$) diameter and circumference values than the zeolite amended treatments.

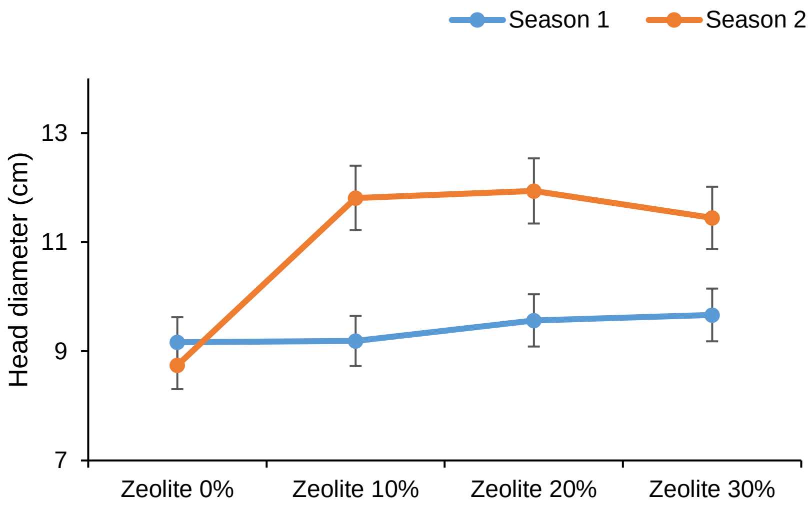


Figure 4. 4 Effect of zeolite on cabbage head diameter

Overlapping error bars indicate no significance at p<0.05

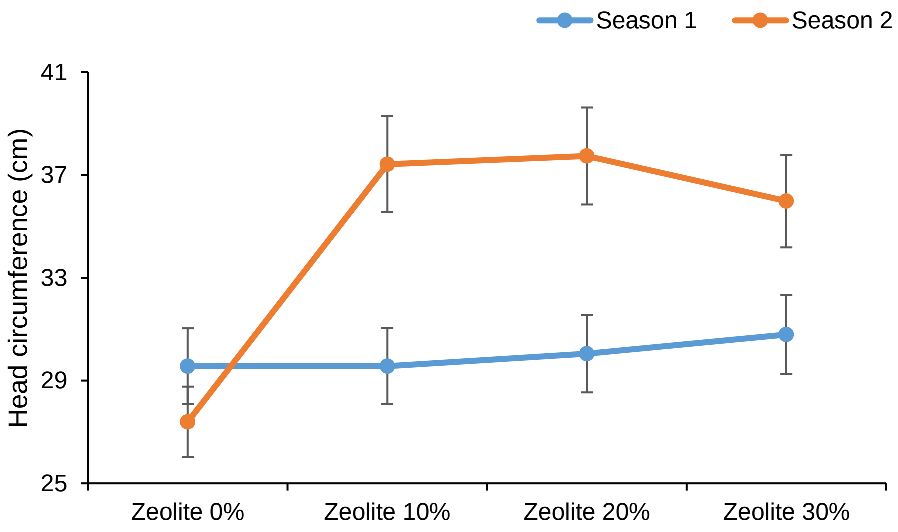


Figure 4. 5 Effect of zeolite on cabbage head circumference

Overlapping error bars indicate no significance at p<0.05

4.2.3 Effect of zeolite on cabbage root biomass

Table 4.4 shows the fresh and dry root weight of cabbage for the first growing season. The results of fresh root biomass showed no significant difference among treatments ($p>0.05$) while the dry root mass was only significantly lower in the 20% zeolite treatment when compared to the non-amended treatment. The 20% zeolite had a mean value for fresh root biomass of 16.66 g pot^{-1} and 6.89 g pot^{-1} for dry mass.

Table 4. 4 Effect of zeolite on the root biomass of cabbage

Treatment	Mass (g pot^{-1})	
	Fresh	Dry
0% zeolite	18.43 ± 9.40[a]	8.84 ± 2.57[a]
10% zeolite	22.45 ± 7.86[a]	8.62 ± 2.81[ab]
20% zeolite	16.66 ± 2.74[a]	6.89 ± 0.50[b]
30% zeolite	17.88 ± 5.06[a]	7.27 ± 1.55[ab]
LSD:	6.44	1.87

Data are given in mean ± standard deviation
Values with different letters within the same column show a significant difference at $p<0.05$
LSD= Least significant difference

4.3 Cabbage nutritional composition as affected by zeolite

4.3.1 Effect of zeolite on cabbage mineral composition

The mineral composition of cabbage grown in the first season is shown in Table 4.5. The macro-minerals are given in g $100g^{-1}$ while the micro-minerals are given in mg kg^{-1} on dry matter basis. The results show that K was the most abundant mineral in the cabbage, with mean values ranging from 4.60 to 5.93 g $100g^{-1}$. Cu was also observed to be the least abundant at mean values ranging from 2.83 to 3.5 mg kg^{-1}.

There were no significant differences ($p>0.05$) among treatments for P, Mg, Cu, and Fe minerals. However, Ca, Zn and B showed similar trends at $p<0.05$. They all had significantly higher ($p<0.05$) contents on the non-amended treatment. The results further indicate that there were no differences ($p>0.05$) between these three minerals on the zeolite amended soils. The non-amended soil had superior mean values 0.58 g $100g^{-1}$, 34.67 and 38.50 mg kg^{-1} for Ca, Zn and B respectively.

Cabbage K contents as the most abundant mineral, had a significantly higher (5.93 g $100g^{-1}$) mean value on cabbages grown on the 10% zeolite treatment compared to 0% zeolite treatment. There was less ($p<0.05$) Na contents on cabbage grown on the non-amended treatment in comparison with the zeolite amended ones which had no differences ($p>0.05$) among them. Micromineral Mn tended to increase with increased zeolite application with the exception of the 10% zeolite application which showed a significantly smaller mean value ($p<0.05$) than cabbages produced in all other treatments, except for the 0% zeolite treatment.

Table 4. 5 Effect of zeolite on the mineral composition of cabbage

Treatment	Composition (g 100 g^{-1} DM)					Composition (mg kg^{-1} DM)				
	P	K	Ca	Mg	Na	Cu	Fe	Mn	Zn	B
0% Zeolite	0.44 ± 0.70[a]	4.60 ± 0.64[b]	0.58 ± 0.11[a]	0.21 ± 0.04[a]	0.46 ± 0.55[b]	3.50 ± 0.55[a]	60.00 ± 16.59[a]	29.17 ± 6.27[a]	34.67 ± 6.22[a]	38.50 ± 9.42[a]
10% Zeolite	0.48 ± 0.48[a]	5.93 ± 0.49[a]	0.43 ± 0.05[b]	0.20 ± 0.02[a]	0.61 ± 0.14[a]	2.83 ± 0.98[a]	58.60 ± 9.61[a]	24.00 ± 4.05[ab]	29.00 ± 4.94[b]	27.50 ± 3.15[b]
20% Zeolite	0.42 ± 0.47[a]	5.43 ± 0.72[a]	0.40 ± 0.64[b]	0.19 ± 0.02[a]	0.70 ± 0.15[a]	3.33 ± 1.03[a]	50.33 ± 6.15[a]	29.60 ± 3.65[a]	26.67 ± 1.75[b]	24.83 ± 3.19[b]
30% Zeolite	0.45 ± 0.72[a]	5.42 ± 1.12[a]	0.44 ± 0.09[b]	0.19 ± 0.03[a]	0.61 ± 0.06[a]	2.83 ± 0.41[a]	50.33 ± 9.99[a]	30.83 ± 5.71[a]	26.17 ± 4.17[b]	27.33 ± 4.97[b]
LSD:	0.06	0.90	0.09	0.04	0.13	1.01	10.46	5.47	4.79	6.46

Data are given in mean ± standard deviation
Values with different letters within the same column show a significant difference at $p<0.05$
LSD= Least significant difference

4.3.2 Effect of zeolite on cabbage proximate composition

Table 4.6 shows the proximate composition of the cabbage heads. The results for all the proximate variables were not different among treatments ($p>0.05$).

Table 4. 6 Effects of zeolite on the proximate composition of cabbage

	Composition (% DM)						
	Moisture	Crude Lipid	Ash	Crude Fibre	Crude Protein	Carbohydrates	Caloric Value (kcal)
0% Zeolite	92.80 ± 1.13[a]	1.50 ± 0.55[a]	9.25 ± 1.41[a]	22.17 ± 4.75[a]	19.82 ± 2.13[a]	47.26 ± 6.34[a]	281.83 ± 23.93[a]
10% Zeolite	91.31 ± 1.59[a]	2.17 ± 1.33[a]	10.67 ± 1.86[a]	22.83 ± 4.17[a]	19.12 ± 2.53[a]	45.22 ± 7.29[a]	276.83 ± 19.33[a]
20% Zeolite	91.12 ± 1.89[a]	2.17 ± 0.75[a]	10.50 ± 1.73[a]	20.83 ± 6.79[a]	19.45 ± 1.07[a]	47.05 ± 8.04[a]	281.83 ± 31.20[a]
30% Zeolite	90.92 ± 1.75[a]	1.67 ± 0.52[a]	10.00 ± 1.70[a]	24.33 ± 8.36[a]	18.34 ± 2.24[a]	45.66 ± 5.87[a]	271.00 ± 30.16[a]
LSD	2.12	1.86	2.53	1.04	8.31	9.12	35.33

Data are given in mean ± standard deviation
Values with different letters within the same column show a significant difference at $p<0.05$
LSD= Least significant difference

4.4 Cabbage water application as influenced by zeolite

The mean values of the total water applied to each cabbage plant are shown in Figure 4.6. There was a significant difference between 0%, 10% zeolite and 20%, 30% zeolite applications in the first season. However, in the second season, the non-amended treatment and the 30% zeolite treatment required the least ($p<0.05$) amount of irrigation water. In the second season, 10% and 20% zeolite treatments showed no significant differences ($p<0.05$) and they required the most irrigation. The first season also showed that an increase in zeolite application decreased the irrigation water requirements of the plants. However, in the second season, the decreasing trend can be observed from the 10% zeolite application onwards with 20% zeolite application having a slight non-significant decrease.

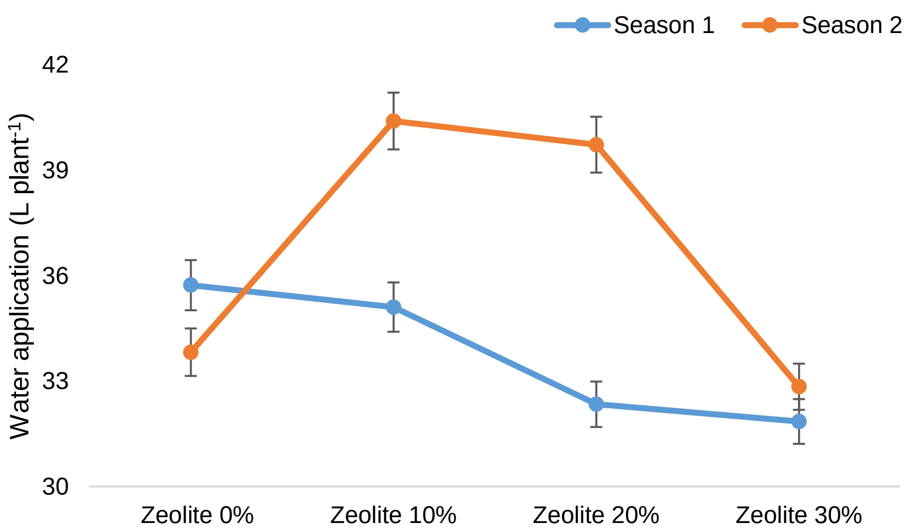


Figure 4. 6 Effect of zeolite on total season water requirement of cabbage
Overlapping error bars indicate no significance at $p<0.05$

4.5 Effect of zeolite on soil nutrient retention in cabbage potting soil

4.5.1 Soil exchangeable cations

The soil exchangeable cations, CEC, pH and resistance of cabbage potting soil are shown in Table 4.7. Soil exchangeable cations, pH and CEC increased with increase in zeolite application. However, soil electric resistance decreased ($p<0.05$) with increased zeolite application.

Table 4. 7 Effect of zeolite on the exchangeable cations and related soil properties under the cabbage at the end of the first season

Treatment	(cmol(+) kg^{-1})				pH	Electric resistance (Ohm)	CEC (cmol(+) kg^{-1})
	Na	K	Ca	Mg			
0% Zeolite	0.10 ± 0.04^{d}	0.05 ± 0.01^{d}	5.12 ± 0.15^{d}	0.27 ± 0.03^{d}	4.90 ± 0.00^{d}	1368.00 ± 34.21^{a}	4.89 ± 0.42^{d}
10% Zeolite	3.99 ± 0.27^{c}	0.78 ± 0.07^{c}	8.33 ± 0.26^{c}	1.49 ± 0.06^{c}	6.07 ± 0.05^{c}	526.67 ± 37.24^{b}	9.08 ± 1.32^{c}
20% Zeolite	8.20 ± 1.01^{b}	1.76 ± 0.23^{b}	10.29 ± 0.42^{b}	2.50 ± 0.11^{b}	6.68 ± 0.41^{b}	340.00 ± 36.33^{c}	12.23 ± 1.35^{b}
30% Zeolite	12.15 ± 0.95^{a}	2.64 ± 0.25^{a}	12.39 ± 0.62^{a}	3.59 ± 0.13^{a}	6.98 ± 0.84^{a}	258.00 ± 13.04^{d}	15.89 ± 1.29^{a}
LSD	0.87	0.21	0.49	0.10	0.05	23.53	1.10

Data are given in mean ± standard deviation
Values with different letters within the same column show a significant difference at $p<0.05$
LSD= Least significant difference

4.5.2 Soil macronutrients

Most of the plant macronutrients presented in Table 4.8 increased with all the treatments compared with the initial planting soil, with the exception of total K and NO_3-N. Compared to the baseline soil chemistry, the NO_3-N decreased in all the treatments while total K only decreased in 0% zeolite treatment. Most of the plant macronutrients for cabbage potting soil exhibited differences ($p<0.05$) at the end of the first growing season, except for NO_3-N which had no treatment differences ($p>0.05$). Zeolite application increased the availability of soluble S with increased zeolite application. The 10 and 20% zeolite treatments did not show significant differences among each other for soluble S. NH_4-N in the cabbage potting soil showed no differences ($p>0.05$) between 0% zeolite and 30% zeolite application. Whereas, the 10% and 20% zeolite treatments had significantly higher mean values than the former treatments.

Table 4. 8 Effects of zeolite on the macronutrients of soil under the cabbage at the end of the first season

Treatment	(mg kg^{-1})					C (%)
	Soluble S	P Bray II	NO_3-N	NH_4-N	Total K	
0% Zeolite	14.94 ± 1.26[c]	72.94 ± 6.44[a]	17.65 ± 3.44[a]	19.43 ± 3.63[b]	21.53 ± 0.52[d]	2.46 ± 0.10[a]
10% Zeolite	17.77 ± 1.32[b]	71.85 ± 2.49[ab]	19.22 ± 8.52[a]	23.85 ± 4.65[a]	304.83 ± 27.88[c]	2.25 ± 0.23[b]
20% Zeolite	19.47 ± 1.41[b]	68.43 ± 1.70[b]	19.35 ± 9.27[a]	23.75 ± 5.66[a]	686.50 ± 90.60[b]	2.04 ± 0.14[c]
30% Zeolite	23.61 ± 3.27[a]	64.20 ± 2.64[c]	17.47 ± 9.13[a]	19.57 ± 3.27[b]	1034.00 ± 96.36[a]	1.86 ± 0.75[c]
LSD	2.40	3.49	7.15	3.42	81.33	0.20

Data are given in mean ± standard deviation
Values with different letters within the same column show a significant difference at $p<0.05$
LSD= Least significant difference

4.5.3 Soil trace elements

The trace elements of cabbage potting soil are presented in Table 4.9. The results show that the most abundant plant micronutrient or trace element was Fe which had mean values ranging from 171.58 to 274.62 mg kg^{-1}. Furthermore, Fe availability decreased ($p<0.05$) with the increase in zeolite application. This was the opposite of what was observed with Mn and B, as they increased with the increase in zeolite application. The 10% and 20% zeolite treatments had higher ($p<0.05$) Zn contents than the 0% and 30% zeolite treatments. There was also a significant increase in the contents of Cu with increased zeolite application.

Table 4. 9 Effects of zeolite on the trace elements of cabbage potting soil at the end of the first season

Treatment	(mg kg^{-1})				
	Cu	Zn	Mn	B	Fe
0% Zeolite	0.62 ± 0.07^{b}	2.97 ± 0.11^{b}	9.73 ± 2.02^{c}	0.22 ± 0.07^{c}	274.62 ± 9.12^{a}
10% Zeolite	0.84 ± 0.03^{a}	3.21 ± 0.15^{a}	14.16 ± 2.59^{b}	0.43 ± 0.07^{b}	262.81 ± 15.06^{b}
20% Zeolite	0.85 ± 0.06^{a}	3.36 ± 0.20^{a}	16.44 ± 2.45^{ab}	0.52 ± 0.06^{b}	240.14 ± 3.67^{c}
30% Zeolite	0.82 ± 0.04^{a}	2.99 ± 0.14^{b}	17.27 ± 2.16^{a}	0.71 ± 0.17^{a}	171.58 ± 4.90^{d}
LSD	0.06	0.17	2.40	0.11	8.57

Data are given in mean ± standard deviation
Values with different letters within the same column show a significant difference at $p<0.05$
LSD= Least significant difference

4.6 Effect of zeolite on Swiss chard growth

4.6.1 Effect of zeolite on Swiss chard growth parameters

Table 4.10 shows the plant growth parameters: leaf chlorophyll content index (CCI), leaf area (cm^2), plant height (cm) and the number of leaves for Swiss chard. The leaf CCI results show that throughout the observation weeks, the non-amended treatment (0% zeolite) generally had more chlorophyll contents. Additionally, the CCI tended to decrease with increased zeolite application. However, there were not many differences between the first and second seasons CCI. The leaf area showed the opposite trend from the CCI, it tended to increase with increased zeolite application especially after the first week of observation in season one, where the non-amended treatment had a larger leaf area than the amended treatments and generally in the second season.

The first three plant height observations (week one to week four) in the first season showed a superior tendency on the non-amended treatment. However, in the second season plant height significantly increased with increased application of zeolite in all the observations. The number of leaves per plant, also showed superiority ($p<0.05$) in the first observation of the first growing season and thereafter, the number of leaves tended to increase with increased zeolite application. However, in the second season, all the observations showed an increase in the number of leaves per plant with increased zeolite application. There was more leaf count in the first season than the second season throughout the observation weeks.

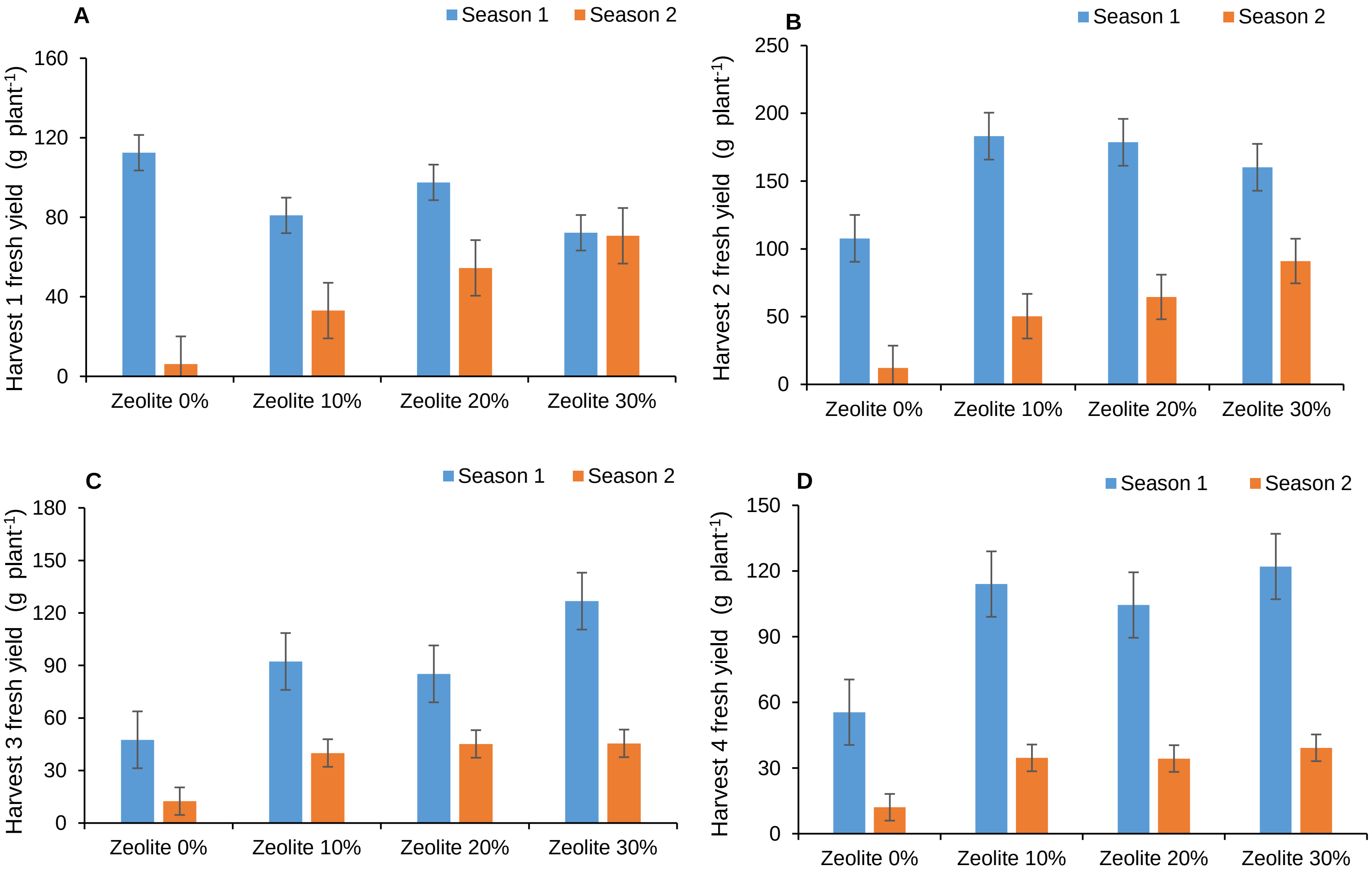
Table 4. 10 The effects of zeolite on Swiss chard growth

		Chlorophyll		Leaf Area (cm^2)		Plant Height (cm)		Number of Leaves	
Season		1	2	1	2	1	2	1	2
Treatment	Week								
0% Zeolite	1	.	.	59.39^{a}	22.50^{c}	11.52^{b}	11.19^{cb}	5.67^{a}	3.44^{c}
10% Zeolite	1	.	.	22.58^{c}	25.04^{c}	10.89^{bc}	11.23^{b}	4.72^{b}	3.22^{c}
20% Zeolite	1	.	.	53.56^{ab}	35.73^{bc}	8.98^{cd}	13.75^{a}	5.22^{ab}	3.72^{c}
30% Zeolite	1	.	.	18.65^{c}	59.84^{a}	7.82^{d}	14.79^{a}	4.67^{b}	3.89^{c}
LSD		.		20.89		2.21		0.75	
0% Zeolite	4	18.04^{ab}	21.53^{a}	193.80^{bc}	33.42^{f}	23.34^{abc}	19.94^{bcd}	6.89^{abc}	4.39^{d}
10% Zeolite	4	13.23^{d}	15.77^{bcd}	230.61^{ab}	86.24^{ef}	14.07^{e}	19.62^{cd}	6.83^{abc}	5.67^{cd}
20% Zeolite	4	16.59^{bcd}	17.49^{bc}	265.8^{a}	110.77^{de}	21.68^{abcd}	24.22^{ab}	7.72^{a}	6.17^{bc}
30% Zeolite	4	13.84^{cd}	17.72^{ab}	237.05^{ab}	142.48^{cd}	17.33^{e}	26.23^{a}	7.22^{ab}	6.56^{abc}
LSD		4.01		26.69		4.57		1.37	
0% Zeolite	7	35.37^{a}	23.53^{cd}	86.53^{d}	7.94^{e}	30.54^{a}	17.72^{b}	14.39^{a}	3.94^{b}
10% Zeolite	7	27.66^{c}	16.99^{e}	108.26^{d}	175.94^{b}	29.56^{a}	25.07^{a}	15.06^{a}	4.61^{b}
20% Zeolite	7	30.04^{b}	19.32^{de}	128.95^{bcd}	150.21^{bc}	29.60^{a}	26.57^{a}	15.33^{a}	5.06^{b}
30% Zeolite	7	26.53^{bc}	20.38^{de}	228.44^{a}	94.11^{d}	28.47^{a}	29.19^{a}	16.39^{a}	6.06^{b}
LSD		5.17		49.67		5.7.97		3.57	
0% Zeolite	10	28.25^{ab}	26.49^{ab}	106.34^{bc}	65.53^{cd}	25.31^{a}	18.11^{b}	10.56^{b}	4.00^{d}
10% Zeolite	10	23.71^{abc}	18.78^{c}	89.98^{c}	137.73^{b}	26.38^{a}	22.48^{a}	13.28^{a}	5.06^{cd}
20% Zeolite	10	28.49^{a}	20.55^{c}	90.21^{c}	142.67^{b}	25.03^{a}	24.91^{a}	12.94^{a}	6.33^{c}
30% Zeolite	10	23.27^{bc}	26.24^{ab}	221.87^{a}	34.05^{d}	26.64^{a}	24.36^{a}	15.17^{a}	6.72^{c}
LSD		5.10		29.72		4.3.67		2.32	
0% Zeolite	13	29.21^{a}	31.19^{a}	79.08^{bc}	66.84^{c}	26.79^{abc}	17.51^{e}	10.44^{bc}	4.722^{e}
10% Zeolite	13	26.34^{ab}	18.36^{c}	41.94^{d}	91.21^{b}	28.78^{a}	21.00^{de}	13.50^{ab}	6.67^{de}
20% Zeolite	13	26.16^{ab}	17.52^{c}	133.67^{a}	99.16^{b}	27.09^{ab}	22.58^{cd}	14.83^{a}	8.17^{cd}
30% Zeolite	13	22.96^{bc}	21.74^{c}	91.14^{b}	3.81^{e}	29.16^{a}	24.40^{bcd}	14.72^{a}	8.94^{cd}
LSD		6.02		23.27		4.2.59		3.10	
0% Zeolite	16	27.03^{b}	33.04^{a}	96.92^{ab}	76.78^{bc}	26.98^{ab}	18.49^{d}	11.06^{bc}	5.39^{e}
10% Zeolite	16	24.44^{bc}	23.77^{bc}	11.03^{c}	117.16^{a}	27.49^{ab}	22.31^{c}	13.44^{ab}	7.78^{de}
20% Zeolite	16	24.71^{bc}	21.80^{c}	64.59^{c}	97.00^{ab}	27.78^{a}	23.93^{bc}	14.78^{a}	8.67^{cd}
30% Zeolite	16	21.56^{c}	25.16^{bc}	107.20^{a}	69.54^{c}	29.08^{a}	25.86^{abc}	13.72^{a}	9.39^{cd}
LSD		5.02		26.55		3.72		2.67	

Data are given in mean.
Values with different letters within the same column show a significant difference at $p<0.05$
LSD= Least significant difference

4.6.2 Effect of zeolite on continuous Swiss Chard harvested yield

The results for continuous Swiss chard fresh yield over five harvests are presented in Figure 4.7. Subfigures A, B, C, D and E each represent one of the five harvests. The results from the first season show that at harvest 1, which was four WAT, the non-amended treatment had a significantly higher yield than the 30% zeolite treatment. However, all the zeolite amended treatment showed no significant difference among themselves in terms of yield. The results further show that the control (0% zeolite treatment) had a significantly lower yield throughout the rest of the harvests compared to all the zeolite amended treatments.


A
Season 1
Season 2
Harvest 1 fresh yield (g plant-1)
160
120
80
40
0
Zeolite 0%
Zeolite 10%
Zeolite 20%
Zeolite 30%
B
Season 1
Season 2
Harvest 2 fresh yield (g plant-1)
250
200
150
100
50
0
Zeolite 0%
Zeolite 10%
Zeolite 20%
Zeolite 30%
C
Season 1
Season 2
Harvest 3 fresh yield (g plant-1)
180
150
120
90
60
30
0
Zeolite 0%
Zeolite 10%
Zeolite 20%
Zeolite 30%
D
Season 1
Season 2
Harvest 4 fresh yield (g plant-1)
150
120
90
60
30
0
Zeolite 0%
Zeolite 10%
Zeolite 20%
Zeolite 30%

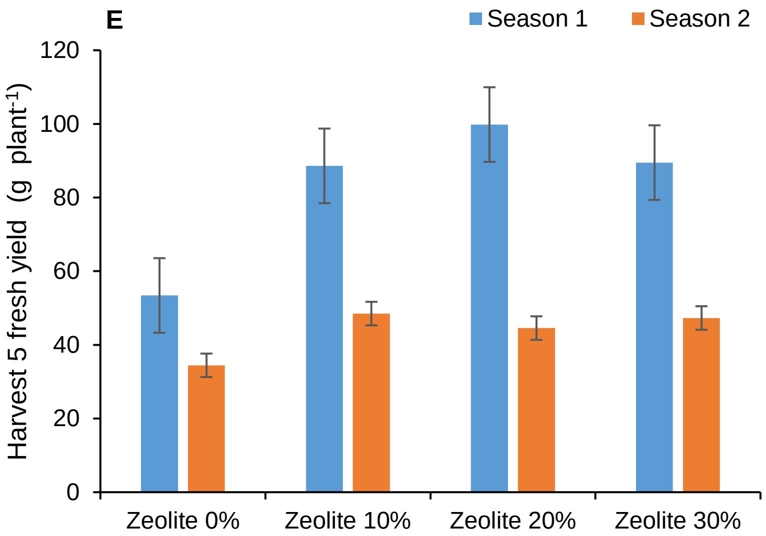
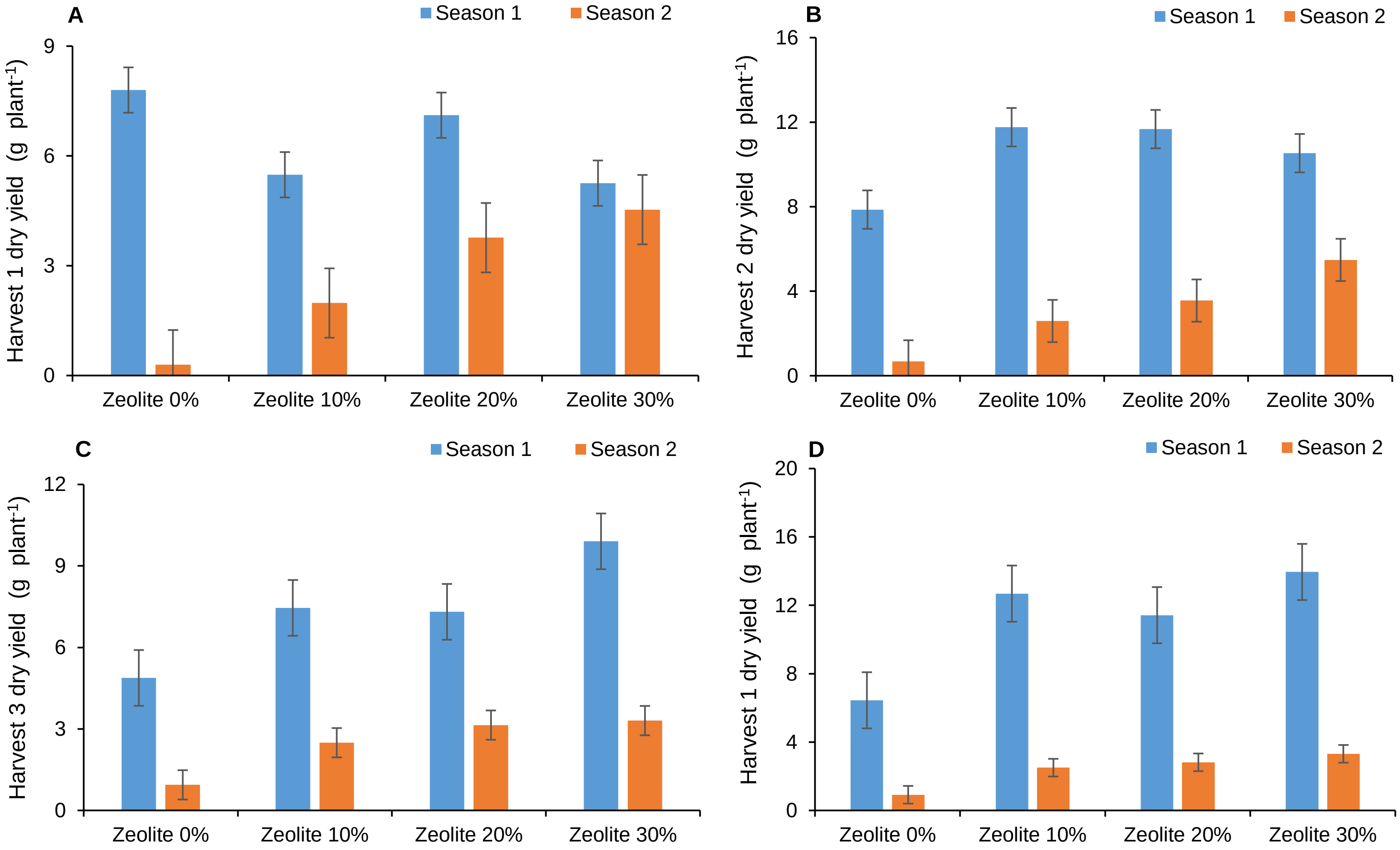


Figure 4. 7 Effect of zeolite on the continuous harvested fresh yield of Swiss chard

Letters A-E represent subfigures which show the five different harvests

Overlapping error bars indicate no significance at $p<0.05$

Figure 4.8 with subfigures A, B, C, D and E represent the results for continuous Swiss chard dry yield over the five harvests. Subfigures A, B, C, D and E each represent one of the five harvests. The results indicated that at harvest one of season one, Swiss chard cultivated on the non-amended treatment had a higher ($p<0.05$) dry matter content. The results further show that the 0% zeolite treatment had lower yields throughout the rest of the harvests in both seasons. Higher ($p<0.05$) dry matter yields were observed in all the harvests in the first season compared to the second season.


A
Season 1
Season 2
Harvest 1 dry yield (g plant-1)
9
6
3
0
Zeolite 0%
Zeolite 10%
Zeolite 20%
Zeolite 30%
B
Season 1
Season 2
Harvest 2 dry yield (g plant-1)
16
12
8
4
0
Zeolite 0%
Zeolite 10%
Zeolite 20%
Zeolite 30%
C
Season 1
Season 2
Harvest 3 dry yield (g plant-1)
12
9
6
3
0
Zeolite 0%
Zeolite 10%
Zeolite 20%
Zeolite 30%
D
Season 1
Season 2
Harvest 1 dry yield (g plant-1)
20
16
12
8
4
0
Zeolite 0%
Zeolite 10%
Zeolite 20%
Zeolite 30%

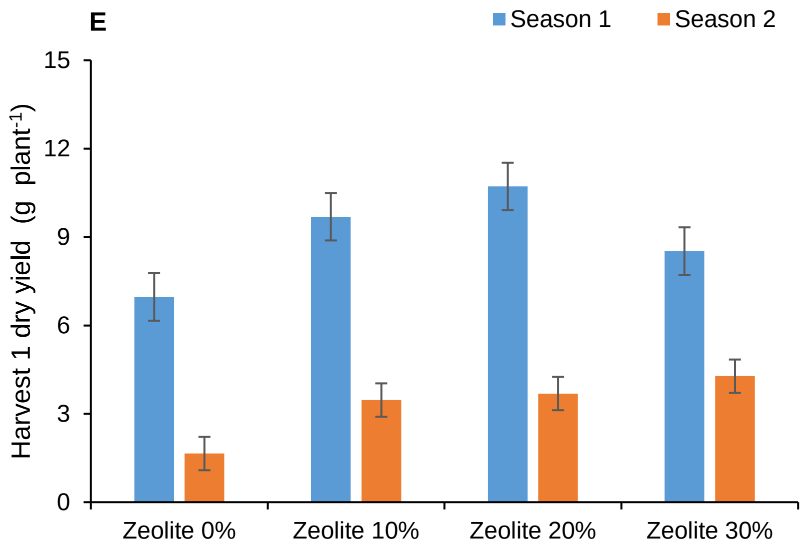


Figure 4. 8 Effect of zeolite on the continuous harvested dry yield of Swiss chard

Letters A-E represent subfigures which show the five different harvests

Overlapping error bars indicate no significance at $p<0.05$

4.6.3 Effect of zeolite on total Swiss chard harvest yield

Figure 4.9 (A and B) shows the results of the sum of all the five harvests fresh and dry masses, for both seasons. Subfigure A represents the total fresh masses and subfigure B represents the total dry yields. There was more ($p<0.05$) harvested mass (fresh and dry) in the first season. Both dry and fresh masses, responded in the same trend, with the first season's masses (fresh and dry) being higher ($p<0.05$) on the zeolite amended treatments, while on the second season, there was a noticeable increase with increased zeolite application.

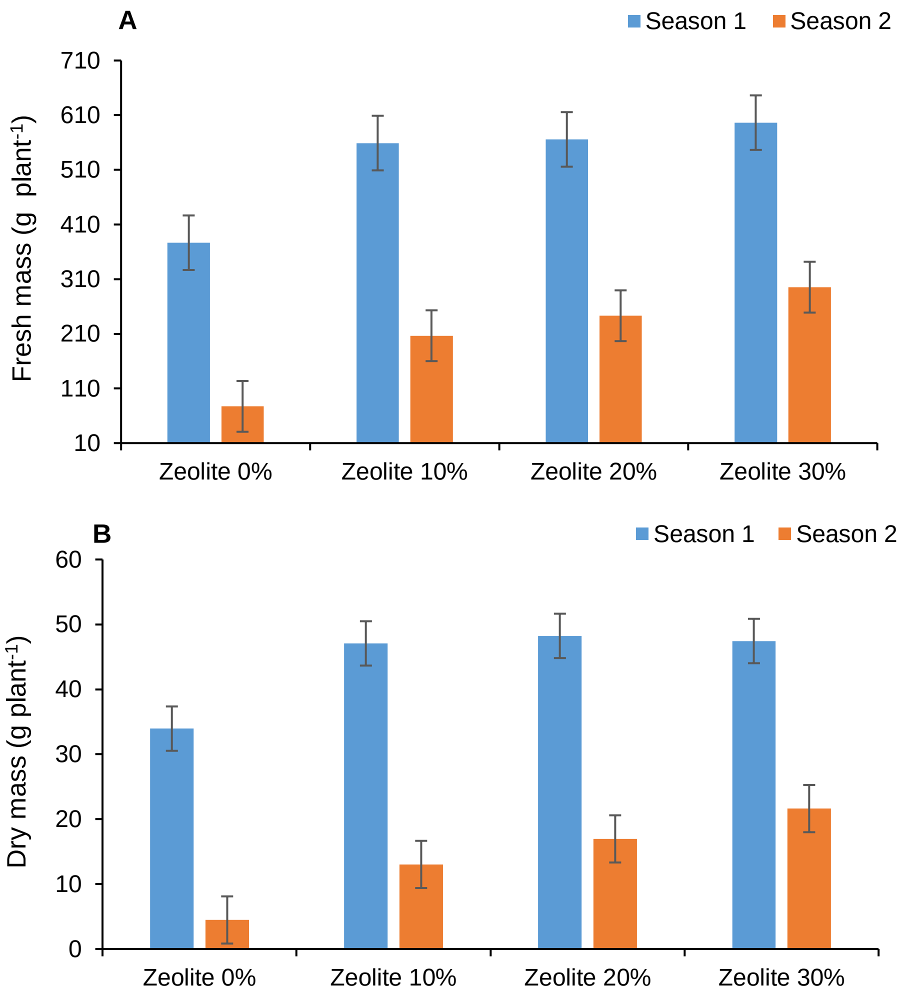


Figure 4. 9 Effect of zeolite on the total seasonal fresh and dry yield of Swiss chard

Letters A and B represent subfigures

Overlapping error bars indicate no significance at $p<0.05$

4.3.4 Effect of zeolite on root biomass

Fresh and dry masses of Swiss chard roots in both seasons are shown in Figure 4.10 (A and B). Subfigure A represents the fresh root masses and subfigure B represents the root dry masses. There was significantly more root mass in the first season on each treatment than the second season. For the first season, the fresh root masses of zeolite amended treatments were higher ($p<0.05$) than in the non-amended treatment. However, the dry root mass generally did not show significant differences between treatments in the first season except between the 10% and 30% zeolite treatments. The 30% zeolite treatment showed the least root dry mass in the first season. However, the root masses of the second season consistently showed a constant increase ($p<0.05$) in root mass with the increase in zeolite application.

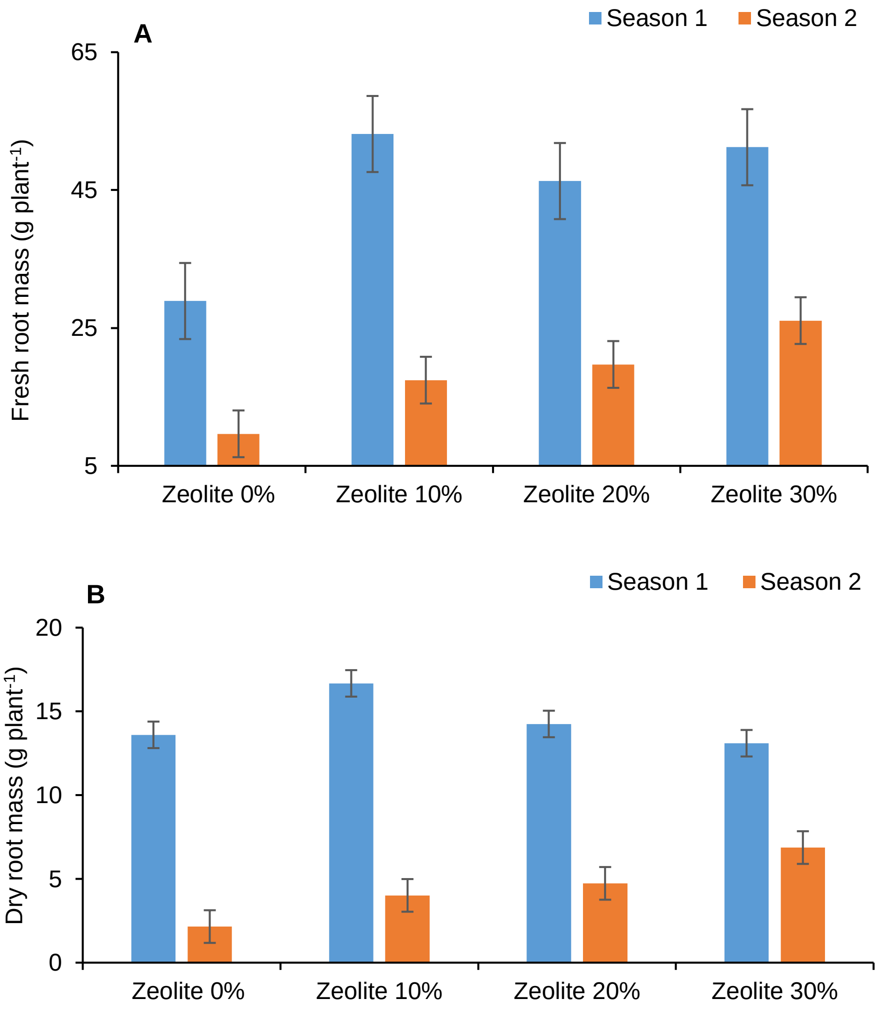


Figure 4. 10 Effect of zeolite on Swiss chard fresh and dry root mass

Letters A and B represent subfigures

Overlapping error bars indicate no significance at p<0.05

4.7 Effect of zeolite on Swiss chard nutritional composition

4.7.1 Effect of zeolite on Swiss chard macro-mineral composition

The Ca contents of Swiss chard are shown in Figure 4.11. There was higher Ca ($p<0.05$) in the 0% zeolite treatment throughout the five harvests. The results also show with significance, that Ca decreased with increased zeolite application.

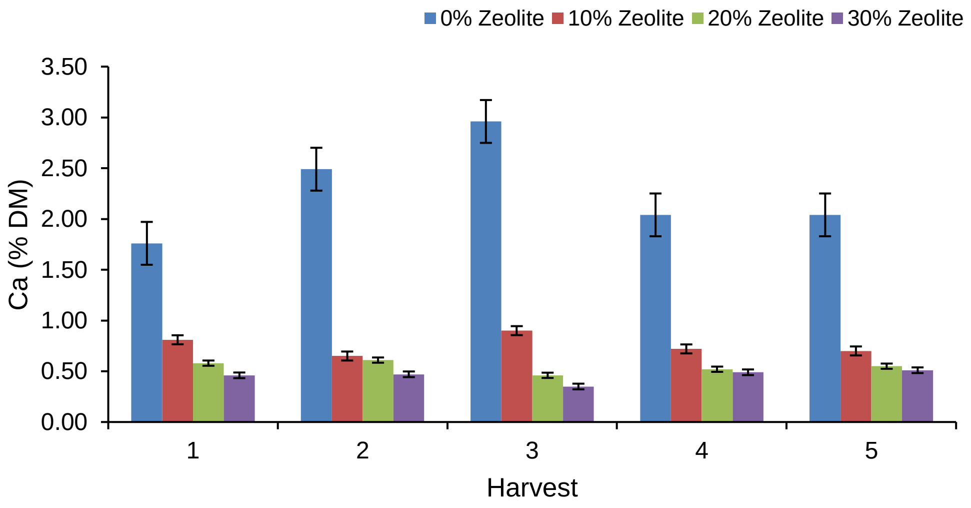


Figure 4. 11 Effect of zeolite on Swiss chard leaf Ca
Overlapping error bars indicate no significance at p<0.05

Figure 4.12 shows the leaf Mg contents of Swiss chard for the five harvests of the first growing season. There was significantly less Mg in the Swiss chard leaves of the 0% zeolite treatment during the first harvest ($p<0.05$). The second harvest showed no significant differences ($p<0.05$) among treatments. From the third harvest onwards, the non-amended treatment generally contained more Mg contents in Swiss chard leaves when compared with the zeolite amended treatments. Additionally, there was a gradual decrease in Mg contents with every harvest, from the first to the fourth harvest in the zeolite amended treatments.

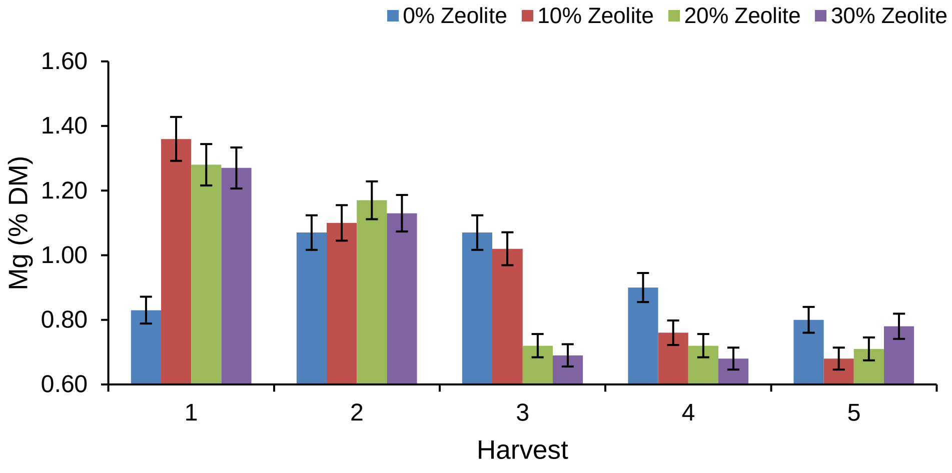


Figure 4. 12 Effect of zeolite on Swiss chard leaf Mg

Overlapping error bars indicate no significance at p<0.05

Figure 4.13 shows the K contents in Swiss chard leaves for all the treatments throughout the five harvests of the first growing season. The results show that the zeolite amended treatments had significantly ($p<0.05$) higher K on the last three harvests. Although the results do not fully capture a constant trend of the influence of zeolite on Swiss chard leaf K, the 0% zeolite treatment significantly decreased in K contents with continuous harvesting.

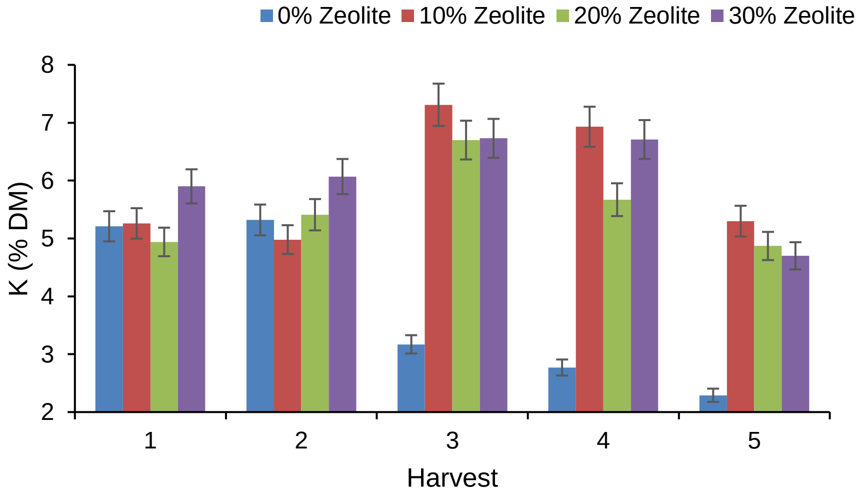


Figure 4. 13 Effect of zeolite on Swiss chard leaf K

Overlapping error bars indicate no significance at p<0.05

Swiss chard P contents are shown in Figure 4.14. The P contents ranged from 0.36% to 0.88%. The P contents did not show any consistency in treatment influence. However, the last two harvests portray the zeolite amended treatments as tending to have more P contents than the 0% zeolite treatment.

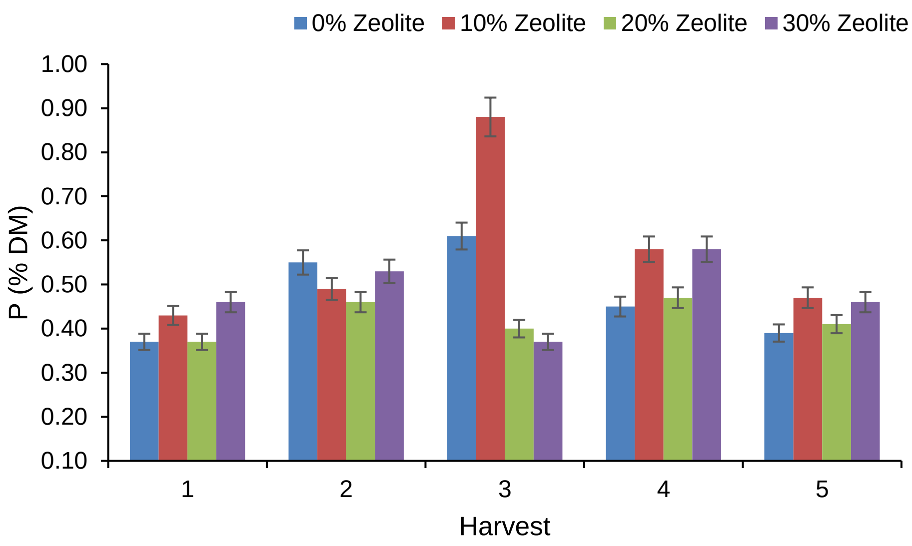


Figure 4. 14 Effect of zeolite on Swiss chard leaf P
Overlapping error bars indicate no significance at p<0.05

Swiss chard grown on zeolite amended treatments had significantly higher ($p<0.05$) Na content than the 0% zeolite treatment (Figure 4.15). There was, however, no clear trend observed with Swiss chard Na contents among the zeolite amended treatments. Moreover, the Swiss chard leaves from the 20% zeolite treatment showed slightly more Na contents in three of the harvest.

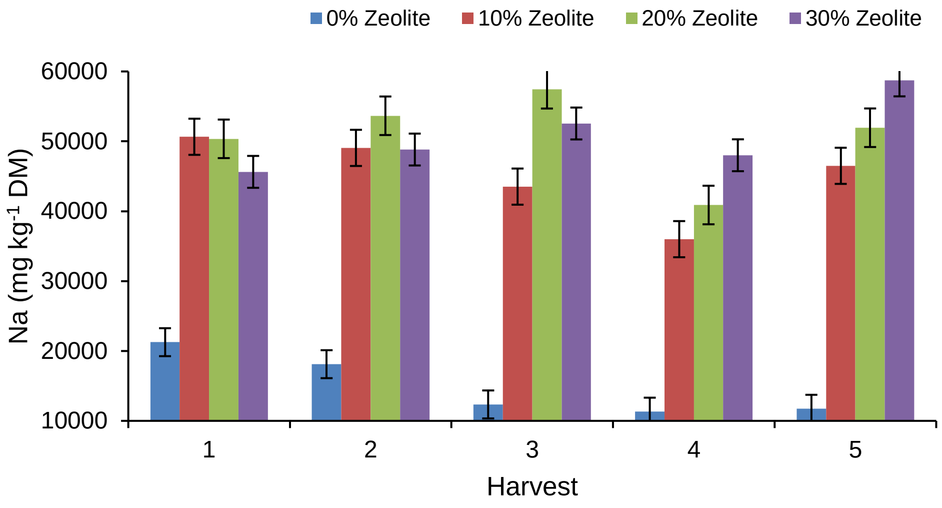


Figure 4. 15 Effect of zeolite on Swiss chard leaf Na

Overlapping error bars indicate no significance at p<0.05

4.7.2 Effect of zeolite on Swiss chard micromineral composition

There was a gradual increase of Mn in Swiss chard leaves with continuous harvesting (Figure 4.16). There was a significantly higher ($p<0.05$) Mn contents on Swiss chard grown from the non-amended treatment. Generally, there were no significant differences ($p<0.05$) among the zeolite amended treatments.

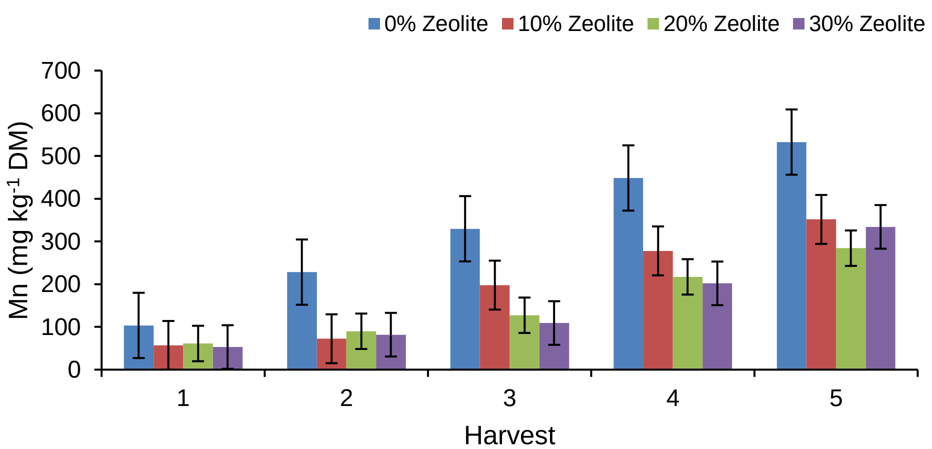


Figure 4. 16 Effect of zeolite on Swiss chard leaf Mn

Overlapping error bars indicate no significance at p<0.05

Figure 4.17 shows the Fe contents of Swiss chard leaves. There were generally more Fe contents in Swiss chard grown on the 0% zeolite treatment. In general, no treatment differences ($p>0.05$) were observed among the zeolite amended treatments, except for harvest 3, which had more Fe contents on the 10% zeolite amended treatment.

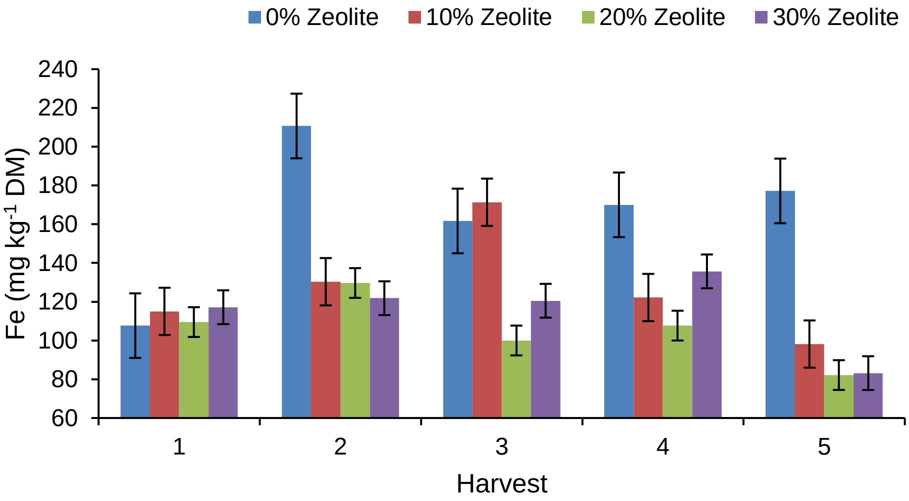


Figure 4. 17 Effect of zeolite on Swiss chard leaf Fe

Overlapping error bars indicate no significance at $p<0.05$

The Cu contents on Swiss chard leaves for all the harvests are presented in Figure 4.18. The lowest Cu content was 5 mg kg^{-1} with the highest being 25 mg kg^{-1}. The first harvest had the lowest levels of Cu in all the treatments, while the highest results on the zeolite amended treatments were obtained in the third harvest.

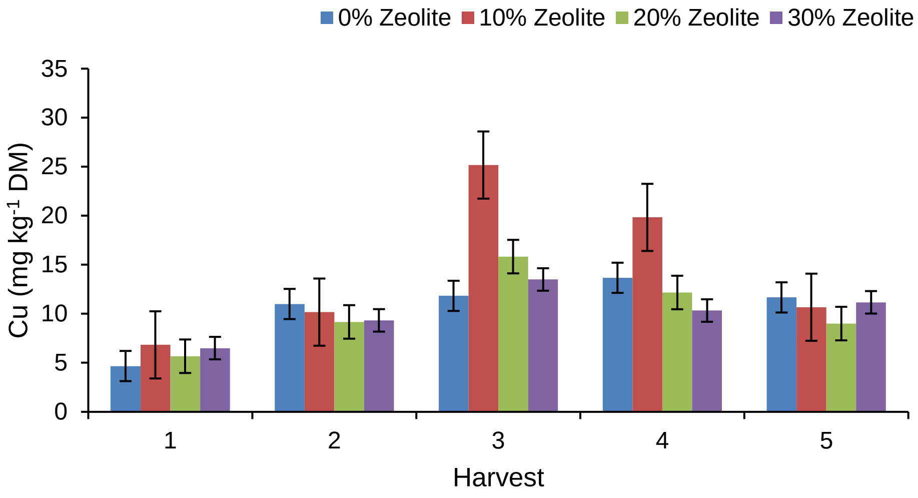


Figure 4. 18 Effect of zeolite on Swiss chard leaf Cu

Overlapping error bars indicate no significance at p<0.05

Figure 4.19 shows the Zn contents in Swiss chard leaves. The results show that there was a significantly higher Zn on the 0% zeolite treatment in all the five harvests. There were no significant differences among the zeolite amended treatments in four of the harvest, except harvest three. Harvest three showed that the 10% zeolite treatment had significantly more ($p<0.05$) Zn contents than the other zeolite amended treatments.

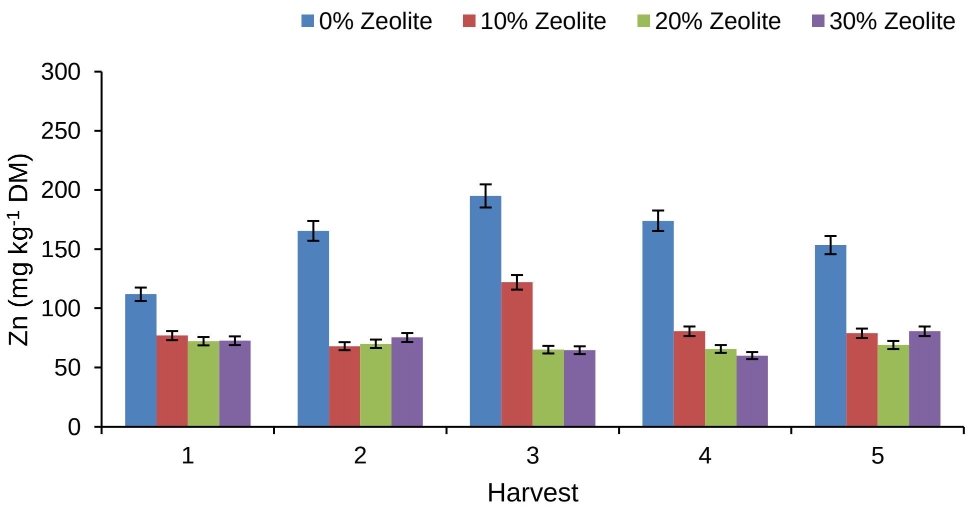


Figure 4. 19 Effect of zeolite on Swiss chard leaf Zn

Overlapping error bars indicate no significance at p<0.05

4.7.2 Effect of zeolite on proximate composition

Swiss chard leaf moisture contents tended to gradually decrease with continuous harvesting (Figure 4.20). The zeolite amended treatment generally had higher leaf moisture contents throughout the five harvests, except for the first and fourth harvests which were not significantly ($p>0.05$) different from one or all the zeolite treatments. Furthermore, the first harvest had only the 30% zeolite treatment being significantly different ($p<0.05$) from 0% zeolite treatment while on the fourth harvest, there were no differences ($p>0.05$) among all the treatments.

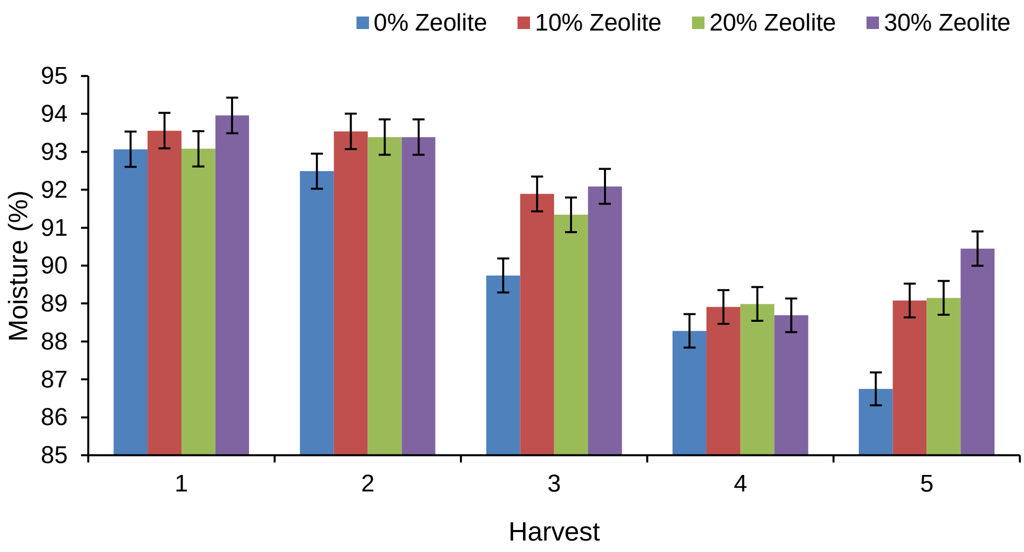


Figure 4. 20 Effect of zeolite on Swiss chard leaf moisture

Overlapping error bars indicate no significance at $p<0.05$

Figure 4.21 shows the crude ash contents of Swiss chard leaves in all the five continuous harvests. There was significantly ($p<0.05$) more crude ash in the zeolite amended treatments than the 0% zeolite treatment throughout the harvests. it further showed an increasing tendency with the increased application of zeolite. The second harvest showed the best crude ash contents in all the treatments when compared to other harvests, except for the non-amended treatment.

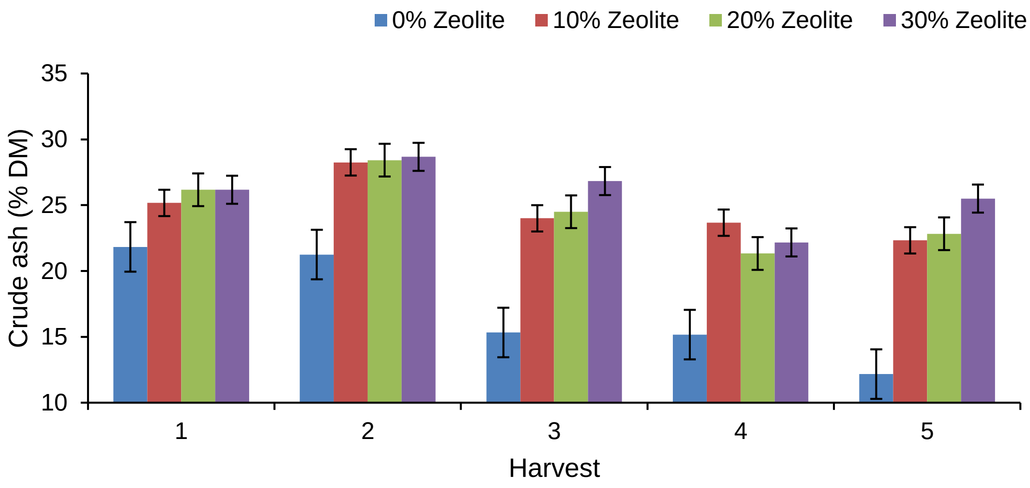


Figure 4. 21 Effect of zeolite on Swiss chard leaf crude ash

Overlapping error bars indicate no significance at p<0.05

Figure 4.22 shows the crude protein contents of Swiss chard leaves. The results show that there was more crude protein in the first harvest than the rest of the harvests. The crude protein contents further decreased with continuous harvesting, from the first to the fourth harvest. On the second and fourth harvest crude protein significantly decreased ($p>0.05$) with increasing zeolite amendment. The crude protein contents over the growing season of this Swiss chard ranged between 14% and 31%, with most of the high values obtained in the first two harvests.

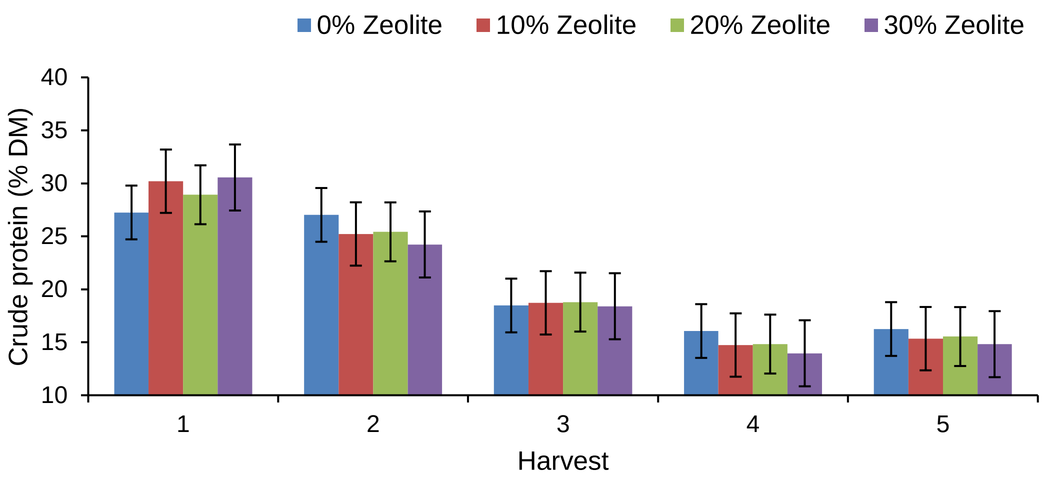


Figure 4. 22 Effect of zeolite on Swiss chard leaf crude protein

Overlapping error bars indicate no significance at p<0.05

Figure 4.23 shows the crude lipid contents of Swiss chard leaves throughout the five harvests. There were significantly more ($p<0.05$) crude lipids in the second harvest of the Swiss chard accross treatments. There was also more ($p<0.05$) crude lipid contents for the non-amended treatment in the first and second harvests while the third and fourth harvest had superior crude lipid contents on the zeolite amended treatments. No significant differences ($p>0.05$) were observed among treatments in the fifth harvest.

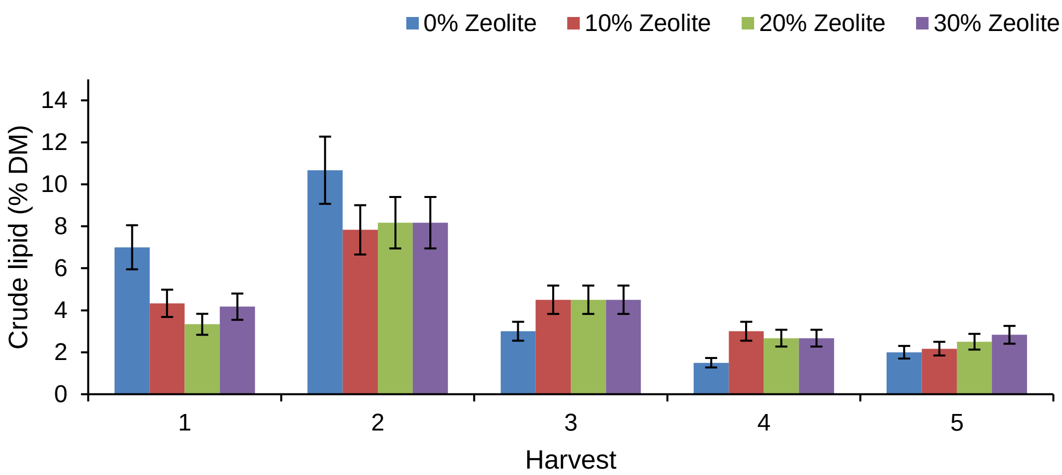


Figure 4. 23 Effect of zeolite on Swiss chard leaf crude lipid
Overlapping error bars indicate no significance at p<0.05

Swiss chard crude fibre contents for the five continuous harvests are shown in Figure 4.24. The results show that the 0% zeolite treatment had more crude fibre content in four of the harvests with the exception being the second harvest. There was also a clear gradual increase in crude fibre contents for 0% zeolite treatment. While all the zeolite amended treatments did increase from the first harvest. Though the increase was not constant and fluctuated throughout the harvests.

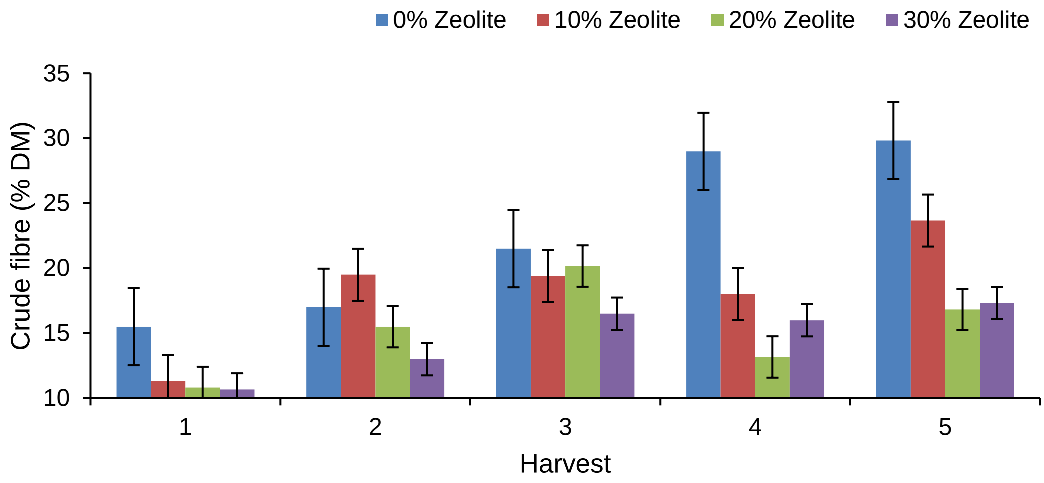


Figure 4. 24 Effect of zeolite on Swiss chard leaf crude fibre

Overlapping error bars indicate no significance at p<0.05

Figure 4.25 shows the carbohydrate contents of Swiss chard leaves. There was generally no constant trend for the carbohydrate content results. There were no significant differences in carbohydrate contents among treatments for the first and fifth harvest. The results further revealed that the highest carbohydrate contents could be obtained during harvest four, in the zeolite amended treatments while the lowest contents were observed during the second harvest.

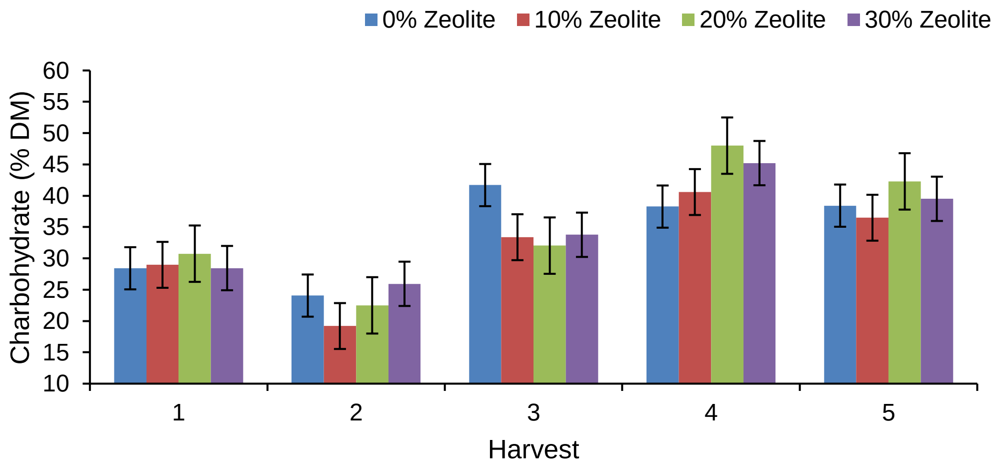


Figure 4. 25 Effect of zeolite on Swiss chard approximate leaf carbohydrate

Overlapping error bars indicate no significance at p<0.05

Figure 4.26 shows the caloric value of Swiss chard throughout the harvests of the growing season. The results show that 0% zeolite treatment had a significantly ($p<0.05$) higher caloric value than the zeolite amended treatment in the second harvest. No significant differences ($p>0.05$) were observed in the first and third harvests.

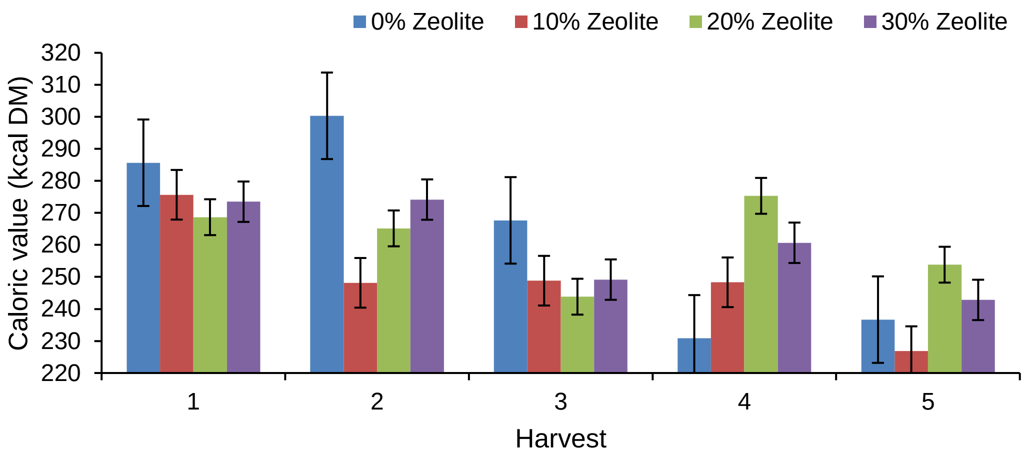


Figure 4. 26 Effect of zeolite on Swiss chard leaf caloric value

Overlapping error bars indicate no significance at p<0.05

4.8 Swiss chard water application as influenced by zeolite

The total irrigation received by each Swiss chard potted plants throughout the study (Figure 27) shows that there was more water application in the first season. In both seasons, there was less ($p<0.05$) water application on the non-amended treatment. However, the 10% zeolite treatment consistently had significantly more water application than the other zeolite amended treatments during the first growing season. In the second season, all the zeolite amended treatments showed no significant differences ($p>0.05$) in their water requirement.

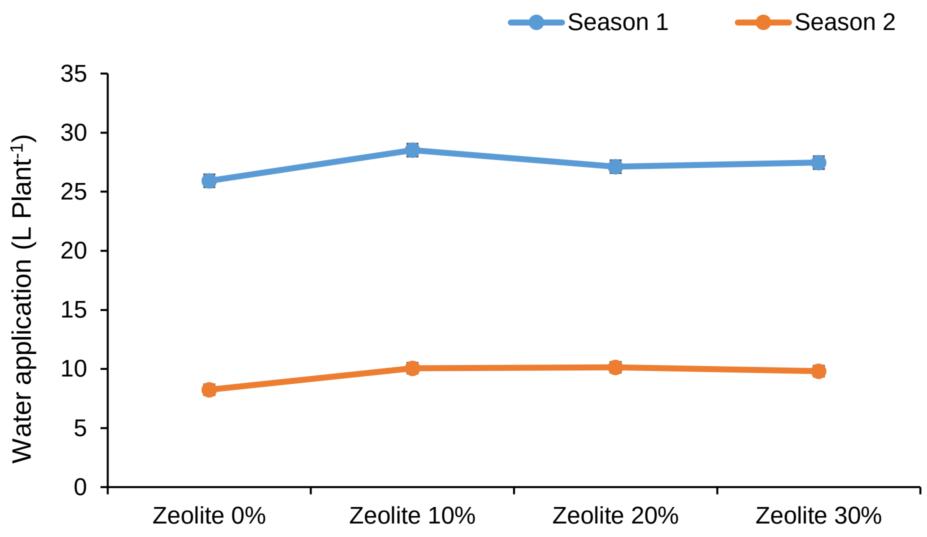


Figure 4. 27 Effect of zeolite on total seasonal water application for Swiss chard Overlapping error bars indicate no significance at $p<0.05$

4.9 Effect of zeolite on soil nutrient retention in Swiss chard potting soil

4.9.1 Soil exchangeable cations

The soil exchangeable cations, CEC, pH and electric resistance of Swiss chard potting soils are shown in Table 4.11. When compared with the baseline chemical status of the soil, there was an increase ($p<0.05$) of cation exchangeability with all the exchangeable cations (Ca, Na, K, and Mg) in the zeolite amended treatments. An increase ($p<0.05$) in CEC and soil pH with increased zeolite was also observed. The 0% zeolite treatment showed more acidity at the end of the growing season than the initial planting soil. Soil enteric resistance, however, significantly decreased ($p<0.05$) with the increase in zeolite application.

Table 4. 11 Effect of zeolite on the soil exchangeable cations, CEC and pH for the Swiss chard potting soil

Treatment	(cmol(+) kg^{-1})				CEC (cmol(+) kg^{-1})	pH	Electric Resistance
	Ca	Na	K	Mg			
0% Zeolite	5.57 ± 0.24[d]	0.05 ± 0.02[d]	0.03 ± 0.20[d]	0.21 ± 0.02[d]	4.93 ± 0.48[d]	5.00 ± 0.00[d]	1248.33 ± 66.76[a]
10% Zeolite	8.47 ± 0.35[c]	3.48 ± 0.60[c]	0.75 ± 0.15[c]	1.40 ± 0.08[c]	9.62 ± 0.40[c]	6.05 ± 0.08[c]	585.00 ± 32.09[b]
20% Zeolite	10.13 ± 0.19[b]	7.45 ± 0.77[b]	1.69 ± 0.16[b]	2.43 ± 0.07[b]	12.64 ± 1.55[b]	6.63 ± 0.05[b]	408.33 ± 18.35[c]
30% Zeolite	12.61 ± 0.32[a]	11.80 ± 0.89[a]	2.68 ± 0.23[a]	3.56 ± 0.06[a]	17.33 ± 1.28[a]	7.03 ± 0.08[a]	313.33 ± 19.66[d]
LSD	0.36	0.83	0.19	0.07	1.29	0.07	41.57

Data are given in mean ± standard deviation
Values with different letters within the same column show a significant difference at $p<0.05$
LSD= Least significant difference
*Ohm= Electric resistance

4.9.2 Soil macronutrients

Table 4.12 shows the macronutrients in Swiss chard potting soil after the first growing season. There were no differences ($p>0.05$) observed on NO_3-N contents, while there were differences ($p<0.05$) with NH_4-N. The 20% zeolite treatment had a significantly higher NH_4-N. Soil P decreased ($p<0.05$) with the increase in zeolite application. As a result, the 30% zeolite treatment had 20% less P than the 0% zeolite treatment. Both total K and soluble S showed opposite results from the soil P, their availability increased ($p<0.05$) with the increased application of zeolite. However, the C (%) contents tended to decrease with the increase in zeolite application. The 30% zeolite treatment showed a significant decrease in soil C (%).

Table 4. 12 Effect of zeolite on soil macronutrients for the Swiss chard potting soil at the end of the first season

Treatment	(mg kg^{-1})					C (%)
	NO_3-N	NH_4-N	P (Bray II)	Total K	Soluble S	
0% Zeolite	6.05 ± 2.20[a]	17.83 ± 1.38[b]	77.98 ± 3.85[a]	10.17 ± 7.88[d]	22.15 ± 2.20[d]	2.35 ± 0.12[a]
10% Zeolite	8.57 ± 5.95[a]	18.73 ± 2.13[ab]	70.04 ± 5.16[b]	292.83 ± 60.32[c]	26.66 ± 1.46[c]	2.22 ± 0.18[a]
20% Zeolite	7.88 ± 2.48[a]	20.53 ± 3.08[a]	67.97 ± 5.05[b]	661.67 ± 63.99[b]	34.74 ± 1.88[b]	2.19 ± 0.14[a]
30% Zeolite	7.85 ± 3.14[a]	17.53 ± 1.65[b]	62.58 ± 3.83[c]	1045.50± 89.87[a]	40.02 ± 2.93[a]	1.88 ± 0.28[b]
LSD	4.07	2.00	5.34	74.23	2.57	0.25

Data are given in mean ± standard deviation
Values with different letters within the same column show a significant difference at $p<0.05$
LSD= Least significant difference

4.9.3 Soil trace elements

Table 4.13 shows the soil trace elements of Swiss chard potting soil at the end of the growing season. The results show that there was a significant increase in the Mn and B contents, with increased zeolite application. The 20% and 30% of zeolite treatments were not significantly different from each other for Mn ($p>0.05$). The soil B contents showed no difference ($p>0.05$) between 0% and 10% zeolite treatments. However, soil Fe contents decreased with increased zeolite application. Availability of Cu also showed a significantly lower value on the non-amended treatment while the zeolite amended treatments showed no significant differences among treatments ($p>0.05$). However, there were no significant differences in Zn contents in both zeolite amended and the non-amended treatments.

Table 4. 13 Effect of zeolite on soil trace elements for the Swiss chard potting soil at the end of the first season

Treatment	(mg kg^{-1})				
	Mn	B	Fe	Zn	Cu
0% Zeolite	7.78 ± 1.91^{c}	0.29 ± 0.04^{c}	272.25 ± 12.82^{a}	2.71 ± 0.14^{a}	0.60 ± 0.10^{b}
10% Zeolite	10.05 ± 1.43^{b}	0.31 ± 0.08^{c}	248.63 ± 9.67^{b}	2.83 ± 0.32^{a}	0.75 ± 0.10^{a}
20% Zeolite	12.35 ± 0.50^{a}	0.48 ± 0.10^{b}	232.12 ± 26.17^{b}	2.89 ± 0.13^{a}	0.83 ± 0.06^{a}
30% Zeolite	12.79 ± 2.43^{a}	0.61 ± 0.07^{a}	169.40 ± 21.79^{c}	2.76 ± 0.16^{a}	0.75 ± 0.05^{a}
LSD	2.25	0.10	18.84	0.25	0.11

Data are given in mean ± standard deviation
Values with different letters within the same column show a significant difference at $p<0.05$
LSD= Least significant difference

CHAPTER FIVE
DISCUSSION

5.1 Swiss chard and cabbage growth and yield as influenced by zeolite

5.1.1 Effects of zeolite on cabbage growth

Leaf growth of leafy vegetables is directly linked to the availability of inorganic N including soil moisture and other plant growth requirements (Spargo *et al*., 2013). Leaf chlorophyll is closely related to the physiological functions of leaves because it absorbs light and transfers it into photosynthates (Sims and Ganon, 2002). However, chlorophyll distribution is not uniform in leaves, it is affected by environmental stress and leaf senescence (Sims and Ganon, 2002; Xiong *et al*., 2015). Sims and Ganon (2002) noted that young leaves generally have low photosynthetic rate, while old leaf abscission rapidly reduces chlorophyll contents. The results of leaf area and chlorophyll content index (CCI) for cabbage in this study had an irregular trend in both seasons and did not follow the trend suggested in the study by Sims and Ganon (2002). This can be associated partly with the method used to collect the data as the biggest leaves were selected on each plant. Leaf senescence may have already been initiated on the leaves thereby decreasing leaf photosynthetic ability (Krieger-Liszkay *et al*., 2019).

The deviation of the results (leaf area and CCI) from having a linear or similar trend during plant growth as suggested by Sims and Ganon (2002) can also, be attributed to the use of SPAD readings from chlorophyll meters. The SPAD readings measure transmitted radiation through the leaf at two wavelengths; 650 and 940 nm. This may cause variation in results due to the variability of measuring conditions and the structural differences among leaves that may further cause differences in light reflection or scattering effect (Daughtry *et al*., 2000; Sims and Ganon, 2002; Xiong *et al*., 2015). With the observed variabilities and the non-uniform distribution of chlorophyll in plant leaves, the measured chlorophyll contents may provide information about the physiological state of the leaves, with that information also being related to leaf senescence. The leaf CCI findings in this study were different to those found in the study by Abdi *et al*. (2006) where zeolite increased net photosynthetic rate and petiole length of the strawberry plant (*Fragariaxananassa Duch*.). The difference may be attributed to plant differences and differences in plant growth requirements.

Nevertheless, the maximum leaf area (198 to 287 cm^2) and plant height (21 to 23 cm) values of the cabbage in the first season were consistent with the findings of Ramesh and Reddy (2011). The authors found that the application of zeolite may initially immobilize NH_4-N in the soil right after it is applied. This reduced N availability to the crop which negatively impacts plant growth. The maximum leaf area and plant height values observed in this study indicate that the non-amended treatment had the largest values in the first year, with a decrease with increasing zeolite application. In the second season, the non-amended treatment obtained the lowest values, with better growth observed on the 10% zeolite amended treatment. This also proves that a high zeolite dose on soils may also limit plant growth. These findings are consistent with the findings of Ozbahce *et al*. (2015) who found the greatest plant growth on zeolite 90 t ha^{-1} dose rather than from their highest zeolite dose (120 t ha^{-1}).

The rate of increase in the number of non-wrapper leaves on cabbages gradually reduces as heads fully grow (Haque *et al*., 2015). The amount of non-wrapper leaves in studies focusing on the Copenhagen cultivar were also closely related to the number of leaves obtained in these results. Ogedegbe and Law-Ogbomo (2013) recording a range from 6 to 19 leaves per plant and Terefe *et al*. (2018) recorded the number of non-wrapper leaves ranging from 14 to 18 leaves per plant. The maximum number of leaves in this study increased in the first season with increasing zeolite application (11 leaves per plant to 13 leaves per plant). In the second season, this was reversed as the leaves decreased from 21 leaves per plant to 19 leaves per plant. The observation highlights the rate of cabbage growth in the first season, the non-amended treatment had quicker growth while in the second season the growth rate was slow. The first season results agreed with the study of Ramesh and Reddy (2011) who found that a combination of fly ash and zeolite, increased the numbers of leaves, number of branch and vine length of sweet potato. However, the nature of cabbage is to decrease the number of non-wrapper leaves with time.

Similarly, the plant height as a measure of the agronomic characteristics of plant growth is also affected by the availability of N. Plant height trends observed in the first season (decreased) of this study are directly consistent with the observations made in several studies that probed the influence of zeolite on crop growth. This trend can also be attributed to zeolites affinity towards nitrogen (Ramesh and Reddy, 2011; Zaman and Nguyen, 2010; de Campos Bernardi *et al*., 2013), which makes it limited for plant assimilation. Cabbage growth in the second season for cabbage grown on the non-amended treatments was generally poorer than the amended treatments. Nitrogen (NH_4-N) immobilisation by zeolite occurs when zeolite adsorbs N into its cavities which is beneficial in protecting it against too much nitrification by microorganisms (Ramesh and Reddy, 2011). This initially immobilizes NH_4-N in the soil (Ramesh and Reddy, 2011). The highest dose of zeolite reduced cabbage plant height compared to the other zeolite amended treatments. This showed that the larger the zeolite dose, the more the initial adsorption of NH_4-N, due to a greater surface area, resulting in less N assimilation by plants (Lee *et al*., 2019).

5.1.2 Effect of zeolite on cabbage head diameter and circumference

Cabbage head diameters obtained in this study ranged between 8.74 and 11.94 cm. These were in line with the observations of Andaloro *et al*. (1983) who observed that mature cabbage head diameters should be between 6 and 12 cm. The diameters were also less than the highest diameter recorded by Olaniyi and Ojetayo (2011) at 16 cm on the same Copenhagen cabbage cultivar, grown using neem organic fertiliser. The diameter differences show possible differences in plant growth conditions, potentially the season of planting, however, the season is not mentioned in the work. The head circumferences obtained from this work ranged from 27 cm (0% zeolite season 2) to 38 cm (20% zeolite season 2). Choudhuri and Jana (2012) observed a circumference range of 11 to 17 cm on their cabbage which was intercropped with other vegetables, resource (water and nutrients) competition may have led to smaller cabbage heads.

Zeolite did not improve cabbage head diameter and circumference in the first season. In the second season, both these variables were improved by zeolite, however, the 30% zeolite treatment had a slightly decreased diameter and circumference compared to the other zeolite amended treatments. The first season's observations are linked to zeolites initial effect on soil N, while the latter season (second season, 30% zeolite treatment) proved that a large zeolite dose may have adverse effects on plant assimilation of N from the soil (Ramesh and Reddy, 2011; Zaman and Nguyen, 2010; de Campos Bernardi *et al*., 2013; Lee *et al*., 2019).

5.1.3 Effect of zeolite on cabbage head yield

The marketable head masses in this study (222 to 504 g head^{-1}) were closer to the lower head weight of the range obtained by Hope *et al*. (2016) on different cabbage varieties treated with different levels of NPK. Their obtained range was 402 to 1877 g head^{-1}. The marketable head masses were only improved by zeolite application in the second season. Additionally, cabbage head dry masses recorded in this study were greater than the dry mass obtained in the study of Olaniyi and Ojetayo (2011) even though the same Copenhagen cultivar was used in both studies. Olaniyi and Ojetayo (2011) obtained head dry massed that ranged from 4.4 to 28 g head^{-1} while in this study the range was from 31.56 to 58.55 g head^{-1}. The authors did not report on the season that the cabbage was planted; however, the differences may be associated with a conducive plant growth environment. Head dry mass, on the other hand, increased at 20% and 30% zeolite application in the first season. In the second season, zeolite proved to increase head dry mass for all the zeolite amended treatments. These findings are in line with those of de Campos Bernardi *et al*. (2010) who found that lettuce (*Lactuca sativa*) as a leafy vegetable, showed an increase in fresh and dry matter yield when cultivated with zeolite amended soils.

The fresh yields (marketable and untrimmed) were less on the non-amended treatment in the second season. This may be attributed to depreciated soil nutrition in the soil particularly with the soil macronutrients (N, P, K, S and soil exchangeable cations) (Uchida, 2000). Essential plant nutrient deficiencies retard plant growth (Stevens *et al*., 2018). Additionally, dry matter yield increase with zeolite can be associated with, high retention of N in the soil which may reduce the ability for plant roots to assimilate the nutrients or immobilised nutrients not being timelessly released into the soil solution for plant uptake (Lee *et al*., 2019). The major contributor, however, is the slow-release of N to plant roots throughout the season while initially reducing its availability to crops (de Campos Bernardi et al., 2010; Ramesh and Reddy, 2011).

Lee *et al*. (2019) found reduced rice tiller production due to high retention of N by zeolite which led to less grain production. This showed that the reduced availability or stronger interaction between the zeolite and adsorbed N than the plant roots ability to assimilate the nutrient leads to less than optimal growing conditions for plants. In the case of rice, more tillers can be linked to more inflorescence and greater grain production. However, in the yields of leafy vegetables, the limitation of N or any other production factor, related to the below-ground environment, may lead to greater production of dry mass as observed by Rouphael *et al*. (2012).

5.1.4 Effect of zeolite on Swiss chard growth

Young leaves generally have a low photosynthetic ability (Sims and Ganon, 2002), as such plants with less leaf area are linked to lower CCI. In this study that was not the case, leaf CCI and leaf area did not show a direct linear relationship. Leaf CCI decreased while leaf area increased with increased zeolite application. However, because the leaf parameters were observed before the harvests, the trends may also be attributed to leaf senescence induced by leaf age which results in the breakdown of the chlorophyll. Chlorophyll breakdown is the earliest but unseen symptom of leaf senescence (Gan *et al*., 1997; Lim *et al*., 2005; Yamaguchi *et al*., 2010). The more observable symptom of leaf senescence is the yellowing of leaves, however, by the time leaf yellowing starts to be observed, chlorophyll breakdown as a leaf senescence processes has occurred (Asari and Chen, 2011).
Swiss chard leaf CCI generally decreased with increased zeolite application, while leaf area increased. Since increased leaf area is associated with plant growth and decrease in leaf CCI is associated with leaf senescence. The response of these two parameters to zeolite may be associated with improvements in the plant growth environment. The plant growth environment (soil or growth medium) govern plants growth and yields (Jarvan *et al*., 2004). Zeolite improves the nutrient and moisture status of soil (Gül *et al*., 2005; Garau *et al*., 2007; Ramesh and Reddy, 2011; de Campos Bernardi *et al*., 2013; Ramesh *et al*., 2015). Zeolite's function on Swiss chard plant height can be observed from the seventh week, in the first season, while in the second season its function is observed throughout. The general increase in Swiss chard plant height in response to zeolite application is similar to that observed by Al-Busaidi *et al*. (2008) and Azarpour *et al*. (2011) who observed increased plant heights on barley (*Hordeum vulgare*) and cowpea (*Vigna unguiculata* L.) respectively. Plant height increase with zeolite amendment is a result of zeolite producing a conducive environment for plant growth (Al-Busaidi *et al*., 2008).

The plant height trends in week 1, 4 and 7 in the first season may suggest an initial unfavourable growing condition on the zeolite amended treatment. This is similar to that of the leaf count, as noted by Ramesh and Reddy (2011), the zeolite initially makes NH_4-N unavailable to plants. In the second season, the Swiss chard observed less growth. The limited Swiss chard growth, on the second season, compared to the first season was a result of different planting dates. The number of leaves on the Swiss chard further indicates zeolites plant growth-inducing potential. In the study by Ramesh and Reddy (2011) zeolite increased the number of leaves, number of branches and vine length of sweet potato. However, the first season growth parameters of this study, suggests that plant growth requirements were more conducive for the Swiss chard on the non-amended treatment. In particular, soil N on the 0% zeolite treatment was not adsorbed by zeolite (de Campos Bernardi et al., 2010; Zaman and Nguyen, 2010; Lee *et al*., 2019). This may have allowed for better Swiss chard growth before the first harvest of the first season. In the first season, zeolite adsorbed soil NH_4-N in the initial stage and only slowly released it at a later stage (Ramesh and Reddy, 2011). The mentioned later stage, where zeolite starts slowly releasing the N to plant roots, can be observed from week seven of the first growing season till the end of the experiment. In the second season, however, Swiss chard showed poor growth on the 0% zeolite treatment throughout, this was associated with diminished soil status.

5.1.5 Effect of zeolite on Swiss chard yield

The Swiss chard total cumulative dry masses obtained in the first growing season were within the range (33.95 to 47.44 g plant^{-1}) of individual plant, equivalents of the results obtained in the work of Maboko and Du Plooy (2013). The total cumulative fresh yield was also in line with those obtained in the recent works of Maboko *et al*. (2017) which ranged from 373 to 532 g plant^{-1} and 32 to 50 g plant^{-1} for fresh and dry mass respectively. The yields for the second growing season did not compare to the yields obtained by Maboko *et al*. (2017) nor those of Maboko and Du Plooy (2013) and were extremely lower than those obtained in the first year. In this study, the yield differences are a result of different transplanting dates.

Swiss chard total fresh and dry yield masses provided evidence of zeolite increasing plant yields as suggested by the findings of de Campos Bernardi *et al*. (2010). de Campos Bernardi *et al*. (2010) found that lettuce (*Lactuca sativa*) fresh and dry yields increased when cultivated in zeolite amended soil. The improved dry yields can be linked to zeolites property to sorb and slowly release nutrient N (Zaman and Nguyen, 2010; Ramesh and Reddy, 2011; de Campos Bernardi *et al*., 2013; Lee *et al*., 2019). The improved fresh mass can be associated with improved plant growth environment (soil) on zeolite amended treatments (Garau *et al*., 2007; Gül *et al*., 2005; de Campos Bernardi *et al*., 2013; Ramesh *et al*., 2015). The increase in dry yield including the larger continuous yields obtained on zeolite treatments can also be attributed to the general soil quality improvement (soil pH and increased aggregate adhesion leading to improved water retaining properties) caused by the application of zeolite (Ramesh and Reddy, 2011; Torkashvand and Shadparvar, 2013; Lee *et al*., 2019). Huang *et al*. (2019)

also noted a direct relationship between leaf dry weight and fresh weight, on broad-leaved plants, this means that dry foliar mass increases with increased leaf fresh mass.

5.1.6 Swiss chard and cabbage root biomass as influenced by zeolite

Crop root biomass is influenced by the number of photosynthates that are allocated between the roots and the shoots (Claus and George, 2005; Hu *et al*., 2018). When mineral elements are scarce, plants often allocate a greater proportion of photosynthates to the root system, while when the mineral elements are at excess plants will allocate more photosynthates to the above-ground biomass (Hermans *et al.,* 2006). The fresh root biomass of Swiss chard in both seasons showed that there was less biomass on the non-amended treatment, which when compared to the cumulative yield can be associated with less plant growth rather than soil nutrient availability. Cabbage root mass (fresh and dry) generally did not respond to zeolite, partially because cabbage yields were also not affected in the first growing season.
Cabbage and Swiss chard are leafy vegetables, their yields are directly related to their leaf growth (Shannon and Grieve, 1999). In connection with zeolite application, the results were contradicting the finding of Turk *et al*. (2006) which showed that root growth of Alfalfa decreased with the increased application of zeolite, where (in their work) with 20% zeolite + 80% soil treatment obtained 9.12 g pot^{-1} dry root mass while a 100% zeolite treatment obtained 3.69 g pot^{-1} dry mass. Zeolites ability to condition the root environment allowed for better growth with Swiss chard but not with cabbage, better root environment-induced both above and below ground masses. This is constant with the suggestion made by Gül *et al*. (2005) that zeolite optimises the root environment. This occurred because most of the applied nutrient was held in the structure of the zeolite, making it difficult to volatilize and to leach, thereby increasing the efficiency of nutrients nitrogen. In totality, this can be attributed to the general soil quality improvement (soil pH and increased aggregate adhesion leading to improved water retaining properties) caused by the application of zeolite (de Campos Bernardi et al., 2010; Lee et al., 2019; Ramesh and Reddy, 2011; Torkashvand and Shadparvar, 2013).

5.2 Vegetable nutrient composition as influenced by zeolite

5.2.1 Effect of zeolite on leaf mineral composition

5.2.1.1 The response of cabbage mineral content to zeolite application

Cabbage is considered a rich source of beneficial minerals especially Ca, P, K, and Mg. In this study, K proved to be the most abundant mineral in cabbage. The highly abundant leaf K in the composition of this cabbage was in line with the findings of Wills *et al*. (1984); Warman and Havard (1997) and Anunciação *et al*. (2011) whom all reached the same conclusion about K in cabbage. Plant nutritional contents can be influenced by genotype characteristics, climate conditions and management practices. The application of different nutrient sources and soil amendments also influences plant mineral contents (Jarvan *et al*., 2004; Natesh *et al*., 2017).

In this study, cabbage P did not show any difference among treatments and this was consistent with the findings of Paskovic *et al*. (2013). In a study by Zheng *et al*. (2019), P contents on rice cultivated under zeolite amended soils increased with zeolite. In relation to soil P in this study, the cabbage P contents did not relate to the trend observed in soil P. Soil P decreased with increasing zeolite application and the general decrease was attributed to P not being adsorbed into zeolite cavities thereby making it easily available for plant assimilation (Aainaa *et al*., 2018; Zheng *et al*., 2019). Soil P in this study decreased while the cabbage did not increase its uptake, P may have been lost from the system via leaching (Erickson *et al*., 2005).

Both cabbage K and Na were increased by the application of zeolite, the K increase was consistent with the findings of Gül *et al*. (2005), who found that zeolite as a soil conditioner was able to increase the content of both N and K in the plant tissue of crisp-head lettuce. The effect of zeolite on cabbage K was however contradictory to the findings of Paskovic *et al*. (2013) as they found no significant difference on radicchio cultivated under various levels of zeolite. Soil K and Na increased with zeolite, the increase may be attributed to the 2.3% Na_2O and 1.7% K_2O in the zeolite's composition, which in return may have permitted better K and Na assimilation by cabbage (de Campos Bernardi *et al*., 2013; Ozbahce, 2018).

On the other hand, cabbage Ca and Mg showed different trends to each other, cabbage mineral Ca was reduced by the application of zeolite, while the Mg composition was not affected. This did not link with the trend observed on the soil exchangeable Ca and Mg as both cations increased with increased zeolite application. The increase in the exchangeability of Ca and Mg were largely due to zeolites CEC and improved soil pH (Ramesh and Reddy, 2011). The increase, however, did not relate to cabbage leaf tissue nutrient composition. Nevertheless, the cabbage mineral Ca, Mg and K in this study generally conformed with the findings of Paskovic *et al*. (2013) although their results showed a nonsignificant increase (Mg and K) in radicchio leaves with a decrease in Ca as a result of zeolite application. The study by Gül *et al*. (2005) also found that the contents of Ca and Mg were relatively low in crisp-head lettuce that was cultivated under zeolite than that cultivated under perlite, which is relatively true for this study. The results also confirmed the findings of Ozbahce *et al*. (2015), they found that there were no differences in Ca and Mg contents in beans among zeolite doses which was attributed to high soil pH and excessive P. Ca^{2+} cations move to zeolite exchangeable sites which allows for more P availability, however, it (Ca) becomes limited to plants (Ozbahce *et al*., 2015; Aainaa *et al*., 2018; Zheng *et al*., 2019). In this study, only soil pH may attribute to the trend observed in Ca and Mg, as soil P decreased while it did not show any increase on cabbage leaves from the zeolite amended treatments.

Zeolite has been shown to sorb heavy metals into its cavities and channels and further block their reception to plants by making them insoluble (Reháková *et al*., 2004; Latifah *et al*., 2011; Ramesh and Reddy, 2011; de Campos Bernardi *et al*., 2013). Much of this has been attributed to the CEC of zeolite which exchanges plant nutrients and sorbs soil heavy metals while slowly releasing the nutrient such as K and NH_4-N (Ramesh and Reddy, 2011). This has also been related to the alkalinity of zeolite which increases soil pH. The adsorption of metals in soil is generally directly proportional to soil pH, which also governs metal uptake by plants (Rieuwerts *et al*., 1998; Kukier *et al*., 2004; Fornes *et al*., 2009).

The soil heavy metals in this study responded differently to zeolite application. Soil Fe generally decreased with zeolite application, the other soil trace elements (Zn, Cu and Mn) tended to increase even though the soil pH was increased. This was against the suggestions of Reháková *et al*. (2004); Latifah *et al*. (2011); Ramesh and Reddy (2011) and de Campos Bernardi *et al*. (2013). It also contradicted the findings in an earlier study by Tsadilas *et al*. (1997) which found that zeolite increased the sorption of heavy metal Cd on soils and as a result, it became insoluble and unavailable. Zeolite application in this study decreased cabbage Zn and B contents while it did not influence cabbage Cu and Fe contents. The results did not conform to Haynes and Swift (1986) who noted that soil with increased Al and Mn produced crops with high contents of Al and Mn in their leaf tissues as most of the soil heavy metal in this study increased, due to zeolite, but did not equally increase in cabbage mineral contents. According to Ozbahce *et al*. (2015) some of the differences between some of the soil available nutrients and cabbage nutrients not relating may result from high lime content (liming effect from zeolite), high pH of the soil, and climatic conditions such as high temperature and water availability.

5.2.1.2 The response of Swiss chard mineral content to zeolite application

Swiss chard contains a considerable amount of K, Ca and Mg (Bakry *et al*., 2014). Apart from the above mentioned, Swiss chard from this study showed Na as one of the abundant minerals in their leaves. Swiss chard K, P and Na all tended to increase with increasing zeolite application. Increase in Swiss chard K observed in this study was in line with the K increase observed by Gül *et al*. (2005) on crisp-head lettuce. Similarly, to the observations on cabbage K and Na contents, soil K and Na increased with zeolite, the increase may be attributed to the 2.3% Na_2O and 1.7% K_2O in the zeolite's composition, which in turn may have allowed for better K and Na assimilation by both cabbage and Swiss chard in this study (de Campos Bernardi *et al*., 2013; Ozbahce, 2018). Additionally, the increase in Swiss chard P contents followed the same trend as the P observations found by Zheng *et al*. (2019) on rice cultivated under zeolite amended soils. In the case of Swiss chard, soil P decreased with increased zeolite application. This was partially due to zeolite not protecting it in its channels, which made it easily available for plant assimilation and leaching (Erickson *et al*., 2005; Aainaa *et al*., 2018; Zheng *et al*., 2019).

Swiss chard grown on the non-amended treatment had higher levels of Ca contents and generally decreased with increasing zeolite, throughout the harvests. This observation was similar to that of Gül *et al*. (2005) who found relatively low Ca and Mg on crisp-head lettuce that were cultivated under zeolite than that cultivated under perlite. In this study, Mg only showed a clear decrease with the increase in zeolite application on the first, third and fourth harvest. The differences between the leaf minerals and the trends in between the different harvests can be associated with climatic conditions such as high temperature and water availability (Ozbahce *et al*., 2015). Swiss chard was grown from late autumn to late spring 2018, which made its growth to go from a cool to cold and again a warm period. The results of this were slow growth during the cold period which utilised less water, then again vigorous growth during the warmer periods which had more metabolic processes requiring more irrigation (Veres *et al*., 2019). Ozbahce *et al*. (2015), found that there were no differences in Ca and Mg contents in beans among zeolite doses which were attributed to high soil pH and excessive P. Increased P assimilation by plants decreases Ca in particular as Ca^{2+} is a reactive product to soil P, therefore, if conditions allow for both to be readily available and assimilable by plants they may react (Aainaa *et al*., 2018).

The Fe contents on the Swiss chard leaves of this study were relatively lower than the contents of the local Swiss chard found in Limpopo (288.4 mg kg^{-1}) and used in the work of Mariga *et al*. (2014). Microminerals Zn and Fe are generally the two most deficient minerals in human bodies (Castillo-Duran and Cassorla, 1999; Prasad, 2012; Gupta and Gupta, 2014). In this study, these micro minerals including Mn all tended to decrease with increased zeolite application. Many authors have attributed this to zeolites ability to sorb heavy metals into its cavities and channels and further block their reception to plants by making them insoluble (Reháková *et al*., 2004; Latifah *et al*., 2011; Ramesh and Reddy, 2011; de Campos Bernardi *et al*., 2013). However, in this study, the soil heavy metals on Swiss chard soil all increased with increased zeolite application except for soil Fe. The increase in soil metals at the end of the growing season suggests that Swiss chard was not able to assimilate the metals possibly due to the near-neutral soil pH (Ozbahce *et al*., 2015). Pasković *et al*. (2013) also observed a contradictory increase in radicchio leaf Mn, Fe and Zn with an increase on zeolite treated medium at 0.31 and 11 g kg^{-1}, they also found that Ca significantly decreased from 25.70 to 19.10 g kg^{-1} in the above respective zeolite application, which is similar to the Ca contents on Swiss chard observed in this study.

5.2.2 Proximate composition of Swiss chard and cabbage in response to zeolite application

There has not been much research on zeolites influence on the proximate composition of plants. However, some authors have observed that the N contents of plant tissue increases with increased zeolite application (Gül *et al*., 2005; Ozbahce *et al*., 2015). Most of the N increase in plants has been attributed to the steady supply of N on zeolite amended soils. In this study, crude protein was calculated for both Swiss chard and cabbage based on the N contents. There were no differences among treatment for both vegetables, however, the crude

protein on Swiss chard tended to decrease with the number of harvests. Abdi *et al*. (2006) found that zeolite increased the protein in strawberries (*Fragaria x ananassa Duch*), which was not true for this study. Zeolite as a soil conditioner appears to have an initial negative effect on plant growth, this may also be linked to the proximate composition of the vegetables observed in this study. There may have been a limitation to zeolites ability to condition the soil for proper proximate nutritional composition, similarly to the observation on the growth and yield parameters. Other proximate nutritional contents that zeolite has been seen to increase are crude fibre and dry matter (moisture content) on beet (Abdi *et al*., 2006)
Swiss chard moisture % showed that there was less moisture on the non-amended treatments. In line with the irrigation received, the 0% zeolite treatment had the least. Similarly, with cabbage irrigation, there was generally no difference in the first season, as a result, cabbage moisture % also showed no differences. Cabbage proximate composition was comparable to that obtained by many authors, Ndlovu and Afolayan (2008); Tanongkankit *et al*. (2012) and Mohammed and Luka (2013). Swiss chard proximate composition also showed similar results to Abuye *et al*. (2003); Mariga *et al*. (2012); Bakry *et al*. (2014) and Mzougi *et al*. (2018).

These results (both vegetables) were generally much higher in values than that of the South African dark green leafy vegetables collected by Schonfeldt and Pretorious (2011) namely; *Amaranthus tricolor, Cucurbita maxima* (pumpkin leaves), *Vigna unguiculata* (cowpea leaves), *Cleome gynandra* (cat's whiskers) and *Corchorus tridens* (wild jute), except for the moisture % which ranged from 81 to 89.9% and was similar to the moisture % obtained in these results. These dark green leafy vegetables showed inferior proximate composition which deviates from the suggestion made by Van-Ransburg *et al*. (2007), that exotic leafy vegetables have less nutrition than the traditional or indigenous leafy vegetables.

5.3 Vegetable water application as influenced by zeolite

Vegetable irrigation should make water reservations for evapotranspiration losses (Mirás-Avalos *et al*., 2019). Plants with vigorous vegetative growth normally have higher water demand due to metabolic processes which lead to more transpiration (Veres *et al*., 2019). The water application of cabbage (31.85 to 40.40 L plant^{-1}) in both growing seasons were higher than the average consumption of 24 L plant^{-1} that Tiwari *et al*. (2003) obtained on cabbage planted on sandy loam soil, under drip irrigation and mulch treatment. Tiwari *et al*. (2003) also obtained cabbage yields that were larger than that obtained in this study. The length of the growing season, season difference, cabbage variety and the production management practices are some of the factors that may have been responsible for these variations (Roux et al., 2016; Beshir, 2017). The effect of zeolite on total cabbage irrigation was in line with the observations made by other authors (Xiubin and Zhanbin, 2001; Ippolito et al., 2011; Ramesh et al., 2015) whom all found decreased irrigation requirements with zeolite application. The increase in zeolite probably led to more soil moisture retention, through increased aggregate adhesion leading to water-retaining properties, thereby, reducing irrigation needs (Xiubin and Zhanbin. 2001; Ippolito *et al*., 2011; Torkashvand and Shadparvar, 2013). In the second season, cabbage cultivated on the non-amended treatment showed little water requirements, partially due to limited growth resulting in fewer metabolic activities which can be observed through reduced yield (Robbins and Dinneeny, 2018).

On the other hand, the total Swiss chard irrigation for the first growing season was slightly higher than the water suggested by Mhlauli (2000) which is equivalent to 23.4 L plant^{-1}. However, in the second season of this study, water application was over 50% less than the suggested seasonal water usage, this was also linked to limited growth due to cold weather. The applied water results indicate that Swiss chard did not mature enough (vegetative) to be able to increase its metabolism activities that would allow for more water usage (Daiss *et al*., 2008). As such, for the Swiss chard, the highest water applied per plant was with the 10% zeolite amended treatment, for the first growing season.

The applied irrigation water for Swiss chard in the second season showed less water application on the non-amended treatment. There was also less water applied in the second season on all the treatments. This was linked with the obtained yield trends of the second season. The trend proved that the larger the amount of zeolite, the more the Swiss chard growth, thus, the more the metabolic activities (Daiss *et al*., 2008; Veres *et al*., 2019). Vigorous vegetable growth leads to higher evapotranspiration rates, hence, higher water demand (Brouwer and Heibloem, 1986; Daiss *et al*., 2008). Vigorous growth can be attributed to zeolite's ability to improve the release of water, improve soil pH and nutrient retention for plants. Xiubin and Zhanbin (2001) observed the water release in zeolite treated soils at 40 °C. Their results confirmed more water contents in zeolite treated soils and showed that there was a more rapid water release than untreated soils, partly due to less force holding the water in the soil and also increased soil pore and holding channels, created by increased aggregate adhesion, due to increased zeolite application (Torkashvand and Shadparvar, 2013).

5.4 Soil chemical composition as influenced by zeolite

5.4.1 Effect of zeolite on soil cation exchange and pH

The exchangeable cations on the growing soils of both vegetables followed the same trend as the CEC. They all increased with the increase in zeolite application. The link between these soil characteristics was in line with the suggestion made by Brown and Lemon (2019) that soils with high CEC are less susceptible to the deficiency of exchangeable cations. The increase in CEC with increased zeolite application was also in line with the findings by Ramesh and Reddy (2011). The authors associated the increase in soil CEC with increased soil surface, which is due to zeolites increased application. The high CEC of the applied zeolite (16 mg kg^{-1}) is responsible for the CEC increase in the soil at the end of the season. The increased zeolite application increased the soils CEC even more. These results were further consistent with the results obtained by Kavoosi (2007), Ippolito *et al*. (2011) and Latifah *et al.* (2017), who also observed increase in the CEC with the application of zeolite.

The most abundant exchangeable cation in the soils was Ca with mean values ranging from 5.12 to 12.39 cmol (+) kg^{-1} for cabbage and 5.57 to 12.61 cmol (+) kg^{-1} for Swiss chard. This abundance is consistent with the normal exchange cation composition of normal healthy soils (Enji *et al*., 2003). Soil exchangeable cations from this study were similar to the observations reported in tomato cultivated with zeolite (Stylianou et al., 2004). Additionally, the increase in soil exchangeable K was different from the observations made by Aainaa *et al*. (2014) who found that exchangeable K was not significantly increased by zeolite. The authors noted that K concentrations are mostly influenced by soil properties and plant requirements. In this case, the strong affinity of zeolite exchange sites for cations is to be attributed to the increase in soil exchangeable cations. Also, given that the applied zeolite composed of CaO, Na_2O, K_2O and MgO at 1.20, 1.70, 2.30 and 1.30% respectively, this may explain part of the increased exchangeability of the cations.

Soil pH was also increased by increased zeolite application, however, soil electric resistance decreased in the soils of both vegetables. The increase in soil pH was consistent with the findings of de Campos Bernardi *et al*. (2010); Ramesh and Reddy (2011); Torkashvand and Shadparvar (2013) and Lee *et al*. (2019) whom all found increases in soil pH due to zeolite. The increase in soil pH with the application of zeolite was due to the alkaline nature (pH 8-9) of zeolite and its negative charges that allowed cation sorption (Aainaa *et al*., 2018). In this study pH results for the 0% zeolite amended soils were below the optimal soil pH (4.9 and 5.0) required by vegetables, as suggested by Grubinger (2015) to be between 6 and 6.8. The soil pH of the non-amended treatment decreased below the baseline soil pH. This demonstrated the liming effect of zeolite on the amended soils, which was also observed by other authors (Polat *et al*., 2004; Ramesh and Reddy, 2011). At the end of the season, soil pH decreased on the 0% zeolite treatment. This may be due to the application of urea (46% N) fertiliser, and carbon removal in the form of yield, which contributed to the N and C cycles respectively (Zhou *et al*., 2014; Zhang *et al*., 2019). These (N and C cycles) contribute to proton releases in soil (Hydrogen) which acidifies the soil. Without any amendment, soils are unable to ameliorate acidity (Qafoku, 2014). These results showed that zeolite can neutralise pH of acidic soils to near neutral values, similarly to agricultural lime, while increasing the availability of salts such as Ca and Mg which leads to decreased electric resistance (Tsadilas. *et al*., 1997; Ramesh *et al*., 2015).

5.4.2 Effect of zeolite on soil macronutrients

Soil macronutrients such as C, N, P, K and S are soil minerals that are required by plants at relatively large amounts. For the global continental crust, a mean value of 260 mg kg^{-1} S has been identified as the generally acceptable total S content (Manfred, 2012). However, the analysed S on this study is soluble S which according to Spargo *et al.* (2013) has no clearly defined optimal soil composition range. In this study, soil total K and S increased with increasing zeolite application. The soil total K increase in response to zeolite application in this study may be associated with the K_2O content in the applied zeolite and zeolites affinity to K^+ cations (de Campos Bernardi *et al*., 2013). The cavities or porous matrix and cation exchange capacity (CEC) of zeolite protect K^+ cations due to large pores, which permit adsorption of cations, however, the pores are not large enough to permit bacteria entry (Ramesh and Reddy, 2011).

These results demonstrate an increase in soil soluble S with increased zeolite application. Thirunavukkarasu and Subramanian (2014) also found that sulphate-loaded zeolite encouraged a slow release of sulphate. This slow release of sulphate by zeolite is achieved by making it slowly soluble and therefore it is steadily released. Zeolites pores, cages and channels present in its structures holds SO_4^{2-} against losses (He *et al*., 2002; Polat *et al*., 2004; Noori *et al*., 2007; Jha and Singh, 2016) in this way, it is protected against leaching.

The P and soil C contents results were the only macronutrients that indicated a decrease with increased zeolite. However, the retained plant-available P contents on the soil after the growing season of cabbage and Swiss chard for all the treatments were in the high range of soil P that is required for lucrative crop production, 40 to 100 mg kg^{-1} (Horneck. 2011). The results contrast with the findings by Abdi *et al*. (2006) who found that mineral N, P and K all increased in the soil with zeolite application, although K in this study did increase. The decreasing P with increased zeolite in this study may be due to higher plant uptake. Soil P does not adsorb into zeolite channels to allow for a slow-release nutrient in a protected environment (Abdi *et al*., 2006). Aainaa *et al*. (2018) explained that, hypothetically, P uptake can be increased by the move of reactive products such as Ca^{2+} and $H_2PO_4^-$ into zeolites exchangeable sites which then provide a sink for the removal of the reactive products. Without this process, P becomes readily available for plant uptake and may be exposed to other losses such as leaching.

The C contents decrease with the increase in zeolite application was not in line with the findings of Hachhum and Mahanta (2014) who found that zeolite was able to absorb industrially produced atmospheric CO_2. The liming effect of zeolite can account for part of the decrease in C contents. Liming increases the biological activity of the soil thereby favouring the mineralisation of organic matter which is linked to the utilisation of C and losses of CO_2 (Paradelo *et al*., 2015). Additionally, the increased applications of zeolite reduced the organic components of the soil, therefore the application of zeolite as a mineral decreased C% before the mineralisation of organic matter occurred.

For N availability, NH_4-N increased with the increase in zeolite application, except for the 30% zeolite treatment. Soil N needs to be in its mineral form (NO_3 or NH_4) to be available to plants. The behaviour of the two types of soil mineral N in this study revealed that there may be a threshold application rate for zeolite application to get benefits from N. At the end of the season both NH_4-N and NO_3-N were almost similar at the higher zeolite rates and the 0% zeolite treatment. Given that after a crop growing season there is normally little available nitrogen remaining in the soil, due to plant usage and leaching. In this study, the NO_3-N (32.76 mg kg^{-1}) reduced from the initial baseline soil while NH_4-N (7.11 mg kg^{-1}) increased. This proved that zeolite has an affinity to NH_4-N more than to NO_3-N and has a greater affinity to K as de Campos Bernardi *et al*. (2013) suggested. Zaman and Nguyen (2010) also explained that adsorption of NH_4-N into zeolites cavities decreases soil N losses thereby ensuring its gradual release directly to plant roots and decreases problems of leaching. This benefit to N however, limits plant-available N which also reduces plant growth (de Campos Bernardi *et al*., 2010; Ramesh and Reddy, 2011; Zaman and Nguyen, 2010; Lee *et al*., 2019).

In this regard, from zeolite adsorbing more NH_4-N than NO_3-N, the vegetables assimilated more NO_3-N due to limitations with adsorption of NH_4-N. The NH_4-N increase from the baseline soil, may partly be linked to the application of the urea [CO $(NH_2)_2$] which is convertible into NH_3 or NH_4 by the enzyme urease (Sigurdarson *et al*., 2018); more than being due to zeolite affinity towards it (Abdi et al., 2006; de Campos Bernardi *et* al., 2013; Aainaa *et al*., 2018). The pore structure and CEC of zeolite protect soil nutrients and slowly releases them to plant roots (Ramesh and Reddy, 2011). It is through this process that zeolite adsorbs nutrients from chemical fertilisers, reducing leaching and allowing slow release to plants (Abdi *et al*., 2006). Aainaa *et al*. (2018) also suggested that the cation selectivity of zeolite favours K^+ more than NH_4^+. This would allow it to fill more of its channels with K^+ cations than NH_4^+ cations.

5.4.3 Effect of zeolite on soil trace elements

The availability of soil heavy metal has been associated with low soil pH. Oseni *et al*. (2013) observed that the mobility of trace elements or heavy metals was reduced with the increase in soil pH. This was attributed to the precipitation of trace elements as insoluble hydroxides, carbonates and organic complexes. Zeolite's ability to ameliorate heavy metal contamination has been reported by many authors to be linked to zeolites high CEC or extremely effective ion exchange (Tsadilas *et al*., 1997; Reháková *et al*., 2004; Latifah *et al*., 2011; Ramesh and Reddy, 2011; de Campos Bernardi *et al*., 2013). However, in this study, the application of zeolite significantly increased the soil pH but also increased the availability of some trace elements (Mn, B, and Cu). The increase in soil Mn due to zeolite application was in line with findings from the study by Ozbahce (2018), although, Zn in this study did not conform to the observed increase. Soil Fe decreased with the increase in zeolite application which is generally what other authors have found for heavy metals. The increase in Zn and Mn in the study by Ozbahce (2018) was linked with the zeolite which contained Zn and Mn. In this study, this was not true for Fe, although the applied zeolite contained Fe_2O_3 (1.30%) soil Fe at the end of the season decreased.

Zeolite can assist in soil heavy metal stabilisation techniques as it accelerates the soil natural reactions (sorption, precipitation and complexation reactions) which reduce mobility and bioavailability of heavy metals to plants (Madejón *et al*., 2006). Similar to biochar findings of Chibuike and Obiora (2014), zeolite increase soil pH and may have heavy metal sorption ability, which should reduce their bioavailability for plant uptake. However, because zeolite is only involved in the fixation of heavy metals as most of them do not undergo microbial or chemical degradation (Garau et al., 2007; Ramesh and Reddy, 2011; Wuana and Okieimen, 2011), this may account for the differences in soil heavy metal response to zeolite. Zeolite may have filled its internal sites with other cations, the ones it has more affinity for, therefore, making other heavy metals unable to find vacant sites inside the zeolite (Ippolito *et al*., 2011). On the other hand, the deviation from zeolite's normal influence on heavy metals may be associated with a decrease in C% with the increased application of zeolite. Soil C is normally responsible for the binding of these trace minerals (Ingram and Fernandes, 2001).

CHAPTER SIX
CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Soil nutrient depletion and water scarcity are limitations to optimal vegetable production. The objective of this study was to investigate the application of zeolite as a soil conditioner on Swiss chard and cabbage vegetable growth, yields, and its effect on soil water and nutrient retention. The greenhouse pot experiment showed that the application of zeolite responded differently to some of the growth parameters of the two vegetables. However, the conditioner initially limited vegetable growth, in the first growing season. Nearing to the end of the first growing season and on the second season, a positive effect of zeolite was observed on Swiss chard growth. Cabbage growth only showed positive effects in the second season. This showed that zeolite influenced plants differently, depending on how the plant was harvested.

The continuous harvesting of Swiss chard showed increased yields within the first season, in the amended treatments, proving zeolites ability to increase vegetable yields. The below-ground biomasses were inconclusive in the first season for both vegetables and did not show a clear trend with the increase in zeolite application. Although the root biomass of cabbage was not observed for the second season, that of Swiss chard successfully increased with zeolite. The plant mineral composition for both vegetables proved that zeolite application decreases Ca, while K increased. The proximate composition of cabbage was unaffected by zeolite, while that of Swiss chard did not show any relationship with the increased application of zeolite. It was however clear that Swiss chard moisture contents were increased by zeolite application.

With irrigation being based on plant water requirements, the water application trends differed between the two vegetables. Yet, the water application followed the growth and yield of the vegetables, where treatments with less vegetative growth utilised less water. Nevertheless, the cabbage water application of the first season showed the water-retaining properties of zeolite when all yields were the same. The soil chemical analysis which was done after the first growing season showed zeolites ability to increase the soil exchangeable cations, CEC and pH in the soils of both vegetable, this showed zeolites' ability to ameliorate degraded soil. On another note, both NO_3-N and NH_4-N showed that there might be a limit to zeolite application. Moreover, zeolite increased soil trace elements, except for Fe, even though soil pH was increased. This study showed zeolites potential to ameliorate soil acidity, increase soil nutrient and water retention while conditioning the plant growth environment for optimised yields.

6.2 Recommendations

- Based on the observed trends from the early stages after zeolite application, in the first growing season, the use of zeolite as a soil conditioner in vegetable production should be planned so that the soil is given enough fallowing time after application. This should be at least eight weeks, for it to settle and activate the benefits while the vegetables are still young.
- In terms of production outputs, soil nutrient availability and the different water usage results of this study, the 20% zeolite treatment is recommended as a working standard zeolite application rate for leafy vegetables. However, more probing into root vegetables, other types of vegetables and field vegetables for zeolite application rates are still required on South African food crops and the environment.
- Field experiments are still needed to fully establish the most appropriate zeolite application rates that will be economical and yet productively efficient for resource-poor farmers.
- Also, further studies are required on the effect of zeolite on vegetable nutritional content especially on the proximate composition of vegetables.
- There is also a need to close the zeolite utilisation gap in South Africa for vegetable production purposes through agricultural extension.

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APPENDIX

Appendix A: Pots used in the experiment