

**Using silicon-based liquid fertiliser to improve growth, yield and quality of
beetroot (*Beta vulgaris* L.) grown under combined phosphorus and water
stress in Mpumalanga**

by

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DECLARATION OF OWN WORK

I, **Lethabo Cyril Sadiki** declare that this dissertation, **“Using silicon-based liquid fertiliser to improve growth, yield and quality of beetroot (*Beta vulgaris* L.) grown under combined phosphorus and water stress in Mpumalanga”**, submitted to the Central University of Technology, Free State, in fulfilment of the requirements of the degree Master of Agriculture is my independent work and has not been submitted to any other institution or organisation for any reason whatsoever. Where other people’s work has been used (either from a printed source, internet, or any other source), this has been properly acknowledged and referenced accordingly.

Signature:

Date:

DEDICATION

This collection of art and scientific works is dedicated to my late grandmother, Linah Mmatlou Mpholo, and late grandfathers, Motjeletjele Abraham Mpho and Mudibi Sadiki.

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ABSTRACT

Beetroot (*Beta vulgaris* L.) is a vital vegetable crop with significant health benefits due to its rich nutritional profile and bioactive compounds. However, its production, like any other crop, is threatened by the abiotic multi-stress conditions involving soil nutrient deficiencies, water deficit and acidity. In recent years, the silicon-based liquid fertilizer (SB) has emerged as a promising tool to enhance crop resilience to single abiotic stress; however, there is a dearth of information on the effects of SB application on crop performance under combined abiotic stresses. Hence, this study aimed to assess the (i) beetroot growth, yield and quality, and (ii) soil quality parameters in response to SB application and combined phosphorus (P) and water (W) deficit levels at crop harvest. To achieve the above-mentioned objectives, a 90-day experiment was conducted in the net house at the Nooitgedacht Research Station in Mpumalanga, South Africa, during the 2023/2024 and 2024/2025 cropping seasons. The 4×6 factorial design experiment was arranged in a completely randomised block design with three replications. The treatments consisted of four SBs with different concentrations [0 - distilled water as a control (SB₀), 0.2 (SB_{0.2}), 0.4 (SB_{0.4}), and 0.6 (SB_{0.6}) L/ha], a factorial combination of two P deficit levels [20 kg/ha (P₂₀) and 40 kg/ha (P₄₀)], and three W deficit levels [25% (W₂₅), 50% (W₅₀), and 100% (W₁₀₀) of evapotranspiration]: P₂₀W₂₅, P₄₀W₂₅, P₂₀W₅₀, P₄₀W₅₀, P₂₀W₁₀₀, and P₄₀W₁₀₀. The (W) stress and foliar SB application began at 14 and 28 days after transplanting (DAT), respectively. Plant height, number of leaves per plant, the leaf area, and leaf chlorophyll content were determined at 63 DAT, while stomatal conductance was measured at 70 DAT. The beetroot was harvested at 90 DAT to determine fresh leaf mass, dry leaf mass, fresh root mass, dry root mass, total fresh biomass, total dry biomass, root diameter, and beetroot quality parameters. The Shapiro-Wilks test and homogeneity of variance were performed on standardised residuals to test for any deviations from normality and homoscedasticity, respectively, to measure the equality of variances between seasons. Heteroscedasticity between the two growing periods was indicated by the results, which showed a lack of variance homogeneity ($P < 0.05$). The P₂₀W₂₅ significantly decreased the chlorophyll content by up to 38%, compared to P₄₀W₁₀₀. The SB_{0.2} application significantly increased the stomatal conductance by 21%, 30%, and 26% compared to SB₀, SB_{0.4}, and SB_{0.6}, respectively, at 70 DAT. Compared to SB₀×P₂₀W₂₅, SB_{0.2}×P₄₀W₁₀₀ increased stomatal conductance by 153% in season 1 and 60% in season 2. Plant height, number of leaves per plant, leaf area, and root quality parameters were not affected by the SB application and SB×PW. Leaf P content was significantly reduced by 120% for the P₂₀W₂₅ compared to

P₂₀W₁₀₀. The application of SB_{0.2}, SB_{0.4} and SB_{0.6} significantly reduced leaf Cu content by 32%, 39%, and 78%, respectively, relative to SB₀. Fresh root mass, dry root mass, total fresh biomass, and total dry biomass varied significantly with combined P and W deficit levels, season and the interaction of SB, combined P and W deficit levels and season. The SB_{0.4}×P₂₀W₁₀₀ led to a substantial increase in fresh root mass (97%) and dry root mass (86%) compared to SB₀×P₂₀W₂₅ in season 2. Fresh root mass, total fresh biomass, and total dry biomass recorded from P₂₀W₂₅ were significantly reduced by 46%, 28%, and 26%, respectively, compared to P₄₀W₁₀₀ in season 2. All yield parameters in season 2 were quantitatively higher than in season 1, with SB_{0.4}×P₂₀W₁₀₀ recording the highest values across all yield parameters. Compared to P₂₀W₁₀₀, P₂₀W₂₅ significantly reduced root P content by 50%, indicating that the extreme stress limits P uptake. The application of SB_{0.2}, SB_{0.4}, and SB_{0.6} significantly reduced root Ca content relative to the control. The SB_{0.4}×P₂₀W₂₅ significantly reduced the root Na content compared to SB₀×P₄₀W₂₅. This may be associated with osmotic adjustment and ionic balance regulation. Compared to control, SB_{0.4} and SB_{0.6} reduced Co content by up to 41% in season 1. The P₄₀W₁₀₀ treatment significantly reduced B content by 82% compared to the P₄₀W₂₅ treatment in season 1, while no significant effect was observed in season 2. The principal component analysis results showed that, in conclusion, the beetroot Ca, Mg, K, Na, P, Fe, Zn, and Mn content were strongly and positively associated with SB_{0.4}×P₂₀W₅₀ in season 1. Season 2 produced higher crop yield, whereas season 1 exhibited higher root P, K, Ca, Mg, Na, B, Co, Cu, Fe, Mn, and Zn content, suggesting a biomass dilution effect, in which increased yield in season 2 led to lower nutrient content due to the distribution of nutrients across greater biomass. The effect of the SB on soil Ca, Na, K, Mg, and pH (KCl) was not significant.

Keywords: Abiotic stress, nutrient deficit, plant stress, soil fertility, water scarcity.

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CHAPTER ONE

INTRODUCTION

1. INTRODUCTION

1.1 Background to the study

Globally, plants are constantly subjected to abiotic stresses such as water deficit, soil acidity and nutrient deficiencies caused by climate change, posing a challenge to food security (Nephali *et al.*, 2020). However, these environmental stress factors are more detrimental when occurring in combination (Pandey *et al.*, 2017). Abiotic stress is an external condition that adversely affects a plant's growth, development and yield (Verma *et al.*, 2022). Therefore, to guarantee sustainable food production and security, modern agriculture urgently needs innovative approaches.

Beetroot (*Beta vulgaris* L.) is the second most important sugar-producing crop after sugarcane, contributing to about 40% of the world sugar production (Hosseini *et al.*, 2019). It is produced primarily for human consumption, but it has been recently and extensively reported that it may be used in the production of energy, such as ethanol, bioethanol, molasses, cattle feed, pulp, and pectin (Tayyab *et al.*, 2023). Water (W) deficit, low soil pH (acidic), and low nutrient content are considered critical limiting factors reducing beetroot yield by up to 30% (Islam *et al.*, 2022; Kunene & Mahlambi, 2023; Kwizera *et al.*, 2023).

Water deficit stress is a significant abiotic stress that occurs due to the lack of available soil water to maintain plant growth and respiration demand, which leads to reduced plant water potential (Dong *et al.*, 2022). It can cause various morphological, physiological, and biochemical changes in plants, including stomatal conductance variation, leaf expansion, decreased plant development, and elongation of the plant stem (Kumar *et al.*, 2020). Phosphorus (P) is one of the vital elements which have significant roles in plant growth, and it is largely added to the soil through fertilisers, thereby increasing the physiological productivity of crops (Dhaliwal *et al.*, 2023; Shaaban *et al.*, 2023). However, its deficiency causes cellular and physiological changes, and substantially reduces plant growth (von Tucher *et al.*, 2018; Dokwal *et al.*, 2021; Meng *et al.*, 2021; Silva *et al.*, 2023). Additionally, humic soils in the Mpumalanga Province of South Africa's Highveld are believed to have substantial P fixation, raising concerns about the limited amount of P available for agricultural yield (Mkhonza *et al.*, 2020). According to Zharare & Vilane (2021), the Mpumalanga Lowveld's soils had relatively low P contents, which may have limited groundnut production. The severe soil P deficit stress in combination with W stress and acidic soil pH below 5.5 that binds P with Al and Fe, forming

high P-fixation is a major challenge that threatens crop productivity (Feng *et al.*, 2021). Significantly, Mokgethle (2025) reported challenge that smallholder farmers in Mbombela municipality, Mpumalanga province, confront, such as soil degradation, water shortage, moisture stress, and soil nutrient deficiency that requires regular fertilizer application. Therefore, effective strategies for managing combined P and W deficit stress are essential. The use of silicon-based fertilizers (SBs) is one such strategy. Recent research has shown the importance of SBs in plant physiology, and it is considered a beneficial plant nutrient in some of the most important crops cultivated in the greatest area. Silicon (Si) is a metalloid element and is the most commonly found element in the earth's crust after oxygen (Tayade *et al.*, 2022). Orthosilicic acid is the plant available form of Si present in a small amount in the soil, which is absorbed by plant roots at $\text{pH} < 9$, and its concentration ranges between 0.1 to 0.6 nM (Thakral *et al.*, 2021). Si-based fertilizers improve phosphorus (P) deficiency in soil primarily by increasing the availability of orthophosphate (P_i) through competitive sorption, where silicic acid ($\text{Si}(\text{OH})_2$) replaces adsorbed phosphate on the surfaces of iron (Fe) and aluminum (Al) oxides (Barão & Teixeira, 2024). Furthermore, Si application can shift the speciation of Fe-phases, releasing bound P into the soil solution or forming weaker Fe(II)-P compounds, thereby increasing the P pool available for plant uptake (Uhuegbue *et al.*, 2024). Additionally, Si-induced, pH-dependent mechanisms reduce the binding of P to aluminum in acidic soils and increase the exudation of organic acid anions from plant roots, further mobilizing soil P (Pavlovic *et al.*, 2021).

Foliar application of silicon (Si) increases chlorophyll and carotenoid content in onion and sweet pepper plants (Rangwala *et al.*, 2019; Abdelaal *et al.*, 2020). This may be associated with Si's role in regulating plants' physiological and biochemical processes and mitigating biotic and abiotic stresses (Mir *et al.*, 2022). The current study hypothesised that foliar application of a Si-based liquid fertiliser could enhance beetroot growth, yield, and quality and soil quality parameters under combined P and W deficit stress.

1.2 Problem statement

Beetroot is an important vegetable crop with significant health benefits due to its rich nutritional profile and bioactive compounds. However, its production, like any other crop, is threatened by the combined abiotic multi-stress conditions involving soil nutrient deficiencies, water deficit and acidity. It is a fact that in recent history, retail shops in South Africa sell liquid-based fertilizers, including the SBs. Silicon-based liquid fertilisers have emerged as a

promising tool to enhance crop resilience to single abiotic stress; however, there is a dearth of information on the effects of SB application on crop performance under combined abiotic stresses in beetroot grown in Mpumalanga province. Therefore, there is a need to fill this gap by evaluating the SB application with the hypotheses that it will improve the soil quality and beetroot growth, yield and quality under combined P and W deficit stress.

1.3 Justification for the study

Biostimulants, labelled as fertilizers in South Africa, are recommended for application to food crops and use various modes of action and mechanisms to enhance the growth, yield and quality of plants. So far, efficacy of most locally sold liquid-based fertilizers is not well-known among smallholder farmers in the Mpumalanga Highveld region. This lack of exposure, coupled with environmental abiotic stress such as soil acidity, P deficiency, and W crisis for irrigation faced by agronomic and horticultural crops in the region, provides a strong justification for conducting a study assessing whether adding SBs enhance the growth, yield, quality of beetroot, as well as postharvest soil quality under combined P and W deficit stress. Results from studies conducted outside South Africa involving the addition of SBs reveal positive effects on crop performance. For instance, de Melo Filho *et al.* (2020) reported an increase in the efficiency of carboxylation and net photosynthesis of beetroot following Si application. Similarly, Elsheery *et al.* (2020) reported improved leaf photosynthesis responses and fluorescence yield in sugarcane (*Saccharum officinarum* L.) when 30 ppm of Si nanoparticles were applied. In line with these findings, Li *et al.* (2020) reported that Si nanoparticles increase plant performance, reduce mercury uptake in the epidermis and pericycle of roots and stems, and enhance the photosynthetic content and antioxidant enzyme activities in soybean plants (*Glycine max* L.) during mercury exposure. Therefore, given that SBs are sold and readily-available in South Africa, and bear claims on the labels that they increase the growth, yield and quality of food crops, this study aimed to assess the effects of SBs application on plant growth, yield, root quality and postharvest soil quality grown under combined P and W deficit stress in the province of Mpumalanga was conducted.

1.4 Aim and specific objectives

1.4.1 Aim

To assess beetroot growth, yield and quality, and postharvest soil quality parameters in response to SB application and combined P and W levels.

1.4.2 Specific objectives

- (i) To determine beetroot growth, yield and quality in response to SB application and combined P and W levels.
- (ii) To determine postharvest soil quality parameters in response to SB application and combined P and W.

1.5 Hypotheses

- (i) The SB application will improve growth, yield and quality of beetroot grown under P and W deficit levels.
- (ii) The SB application will improve postharvest soil quality parameters under combined P and W deficit levels.

1.6 Dissertation overview

The dissertation comprises five chapters: Chapter one provides an introduction which includes the background information, problem statement, justification for the study aim and objectives, hypotheses, and dissertation overview. Chapter two provides the literature review focusing on beetroot production, multi-stress impact on crops, and Si-based liquid fertiliser. Chapter three provides materials and methods of the study, including study site description, seedling material, crop management, soil collection, preparation and characterisation, plant, and experimental design, experimental layout, data collection and statistical analysis. Chapter four provides results and discussion with interpretation and discussion of growth parameters, leaf chlorophyll content and stomatal conductance, yield parameters, quality content, and soil quality parameters. Chapter five provides the summary, conclusion and recommendations. Outside the contents of the chapter, the dissertation provides the appendices. The outcomes of this study include peer-reviewed journal articles and several conference presentations, as outlined below:

1.6.1 Published journal articles

Chapter 1: Khetsha, Z., Van Der Watt, E., Masowa, M., Legodi, L., Satshi, S., Sadiki, L. & Moyo, K., 2024. Phytohormone-based biostimulants as an alternative mitigating strategy for horticultural plants grown under adverse multistress conditions: Common South African stress factors. *Caraka Tani: Journal of Sustainable Agriculture*, 39(1), 167-193.

Chapter 2: Sadiki, L.C., Van Der Watt, E., Masowa, M.M. & Khetsha, Z.P. 2025. Using silicon-based biostimulant and phosphorus application as an alternative solution for beetroot (*Beta vulgaris* L.) grown under multi-stress in South Africa: A short review. *Acta Horticulturae*, 1416: 185-192.

1.6.2 International conference presentation

Chapter 2: Sadiki, L.C., Van Der Watt, E., Masowa, M.M. & Khetsha, Z.P. 2024. Using silicon-based biostimulant and phosphorus application as an alternative solution for beetroot (*Beta vulgaris* L.) grown under multi-stress in South Africa: A short review. EHC2024: European Horticulture Congress, International Symposium on Sustainable Vegetable Production from Seed to Health Booster Sources 1416, 12-16 May 2024, Bucharest, Romania. “*Oral virtual presentation*”.

1.6.3. National conference presentations

Chapter 2: Sadiki, L.C., Van Der Watt, E., Masowa, M.M. & Khetsha, Z.P. 2025. Using silicon-based biostimulant and phosphorus application as an alternative solution for beetroot (*Beta vulgaris* L.) grown under multi-stress in South Africa: A short review. SASAE2024: 57TH South African Society for Agricultural Extension Annual conference, 26-29 August 2024, Bloemfontein, Free state, South Africa. “*Oral presentation*”.

Chapters 3-5: Sadiki, L.C., Van Der Watt, E., Masowa, M.M. & Khetsha, Z.P. 2025. Yield and nutrient content of beetroot in response to multi-stress and silicon-based biostimulant application. Combined Congress, 19-22 January 2026, Tlokwe/Potchefstroom, North West University. “*Poster Presentation*”.

CHAPTER TWO

LITERATURE REVIEW

2. LITERATURE REVIEW

2.1 Review of beetroot (*Beta vulgaris* L.) production system

2.1.1 Morphological description of beetroot production

Beetroot (*Beta vulgaris* L.) belongs to the Chenopodiaceae family (Tekeli *et al.*, 2023). It is commonly known as beetroot, chard, spinach beet, sea beet, garden beet and white beet, among others. It is important throughout the world as a source of food and income for consumers, processors, and producers (Tamiru *et al.*, 2017; Tekeli *et al.*, 2023). Beetroot is a biennial crop, grown as an annual for its root. It produces green tops and a flesh-swollen taproot during its first growing season. Beetroot also has medicinal properties which provide some positive effects on the human body (Tamiru *et al.*, 2017).

2.1.2 Beetroot scale of production and economic importance

Global production of about 229.19 million tonnes of beetroot was achieved on 4.5 million hectares of beetroot cultivation in 2021 (Stoica *et al.*, 2025). The Russian Federation (45 million tonnes), France (33 million tonnes), the United States (31 million tonnes), and Germany (30 million tonnes) were among the top producers. The regional production comprises 67.3% of the world's production which came from Europe, with Asia coming in at 14%, the Americas at 12.6%, and Africa at 6.1%. In South Africa, the precise production numbers are not given, although the Department of Agriculture, Land Reform and Rural Development (DALRRD) reports that South Africans produced beetroot from 2011 to 2020 (DAFF, 2021). Rantao (2013) reported that, on average, about 37 000 tonnes of beetroot is produced in South Africa annually. However, with a history of rising production in some years and modest declines in others, beetroot production in South Africa remains steady at about 51 000 tonnes (DAFF, 2021). The Western Cape, Kwazulu-Natal, Mpumalanga, Gauteng, and North West are the primary beetroot-producing regions in South Africa.

The economic significance of beetroot can be better described in the context of the food industry, nutritional value, by-product utilisation and the perspective of potential applications. In support, beetroot is an important ingredient in the food industry since it contains fibre, antioxidants, and natural food colouring, and is an additive in various products like yoghurt, ice cream and other food items (Chhikara *et al.*, 2019). In terms of nutritional value, it contains a variety of health-promoting bioactive compounds, such as flavonoids, phenolic acids, and

betalains. As part of the utilisation of by-products, beetroot peels and pomace, among others, can be utilised as biofuel, animal feed, or natural food additions, which will cut waste and increase income (Igual *et al.*, 2023). Because of their antioxidant, anti-inflammatory, and colouring properties, beetroot extracts have potential applications or uses in pharmaceuticals, cosmetics and textiles.

2.1.3 Marketing of beetroot in South Africa

Beetroot marketing is a vibrant and varied industry in South Africa that includes both local and international markets. In South Africa, the commercialisation of beetroot is unrestricted and unregulated. Beetroot prices are dictated by supply and demand in the market. The market, processors, and direct sales to retailers and wholesalers are all used by the industry (DAFF, 2021). Through marketing firms and export agents, beetroot is shipped to foreign nations, as well as being imported into South Africa from other nations. The distribution of the annual beetroot crop is given in Table 2.1.

Table 2.1: Beetroot sold through national market channels.

Years	Fresh Produce Market (Tonnes)	Exports (Tonnes)	Processing (Tonnes)
2011	36 775	5 174	10 496
2012	41 882	4 246	11 505
2013	37 229	3 839	10 232
2014	37 622	4 116	8 830
2015	48 141	5 977	13 679
2016	44 263	5 698	14 125
2017	45 028	5 183	8 777
2018	56 248	6 417	8 728
2019	48 663	5 359	8 591
2020	46 562	4 956	13 548

Source: Statistics and economic analysis (DAFF, 2021).

2.1.4 Beetroot cultivation requirements

2.1.4.1 Soil and root media

Sandy to deep, well-drained sandy loam or silt loam that is high in organic matter is recommended for optimum yield. A guideline by the Agricultural Research Council of South Africa outlined that cloddy, stony, poor, or very shallow soils are unsuitable. Uniform soil moisture is essential for good quality. When grown in soil that is compacted or with high clay content is high, roots of beetroot become deformed and develop a tough texture that reduces quality. Beetroot thrive in deep, rich sandy loam, with a pH between (but not below) 6 and 6.5

(ARC, 2014). This is contrary to Starke Ayres (2019), whose beetroot production guideline states that the ideal pH for beetroot production is between 6.0 and 8.0. Beetroot prefers deep, friable, well-drained, sandy loams to silt loams, and beds are preferable to lower the water table and ensure good drainage.

Beetroot grows best under cool conditions, almost all year round. If drainage is satisfactory, almost any soil is suitable, except acidic soil, and it somewhat tolerates alkaline soil. Acid soils are likely to create nutrient deficiency problems and should therefore be avoided (Addo, 2021). Most light soil is well-suited for beet production. Topsoil characterised by a high clay content should be ploughed and mixed thoroughly with well-composted organic matter to enhance root development. Soil pH should be 6–8 for beetroot (Tamiru *et al.*, 2017).

2.1.4.2 Plant population

Beetroot can be planted in the open field, in the shade, or in a greenhouse as a pot experiment. Rantao (2013) conducted a study in Bloemfontein, where beetroot was planted in pots arranged in the glasshouse. The basis of the surface area of the pot was 0.096 m². Polyethene pots (35 cm diameter by 28 cm high) were filled with soil, and seeds from the cultivar Detroit Dark Red were planted at a depth of 2.5 cm. Seeds were spaced 7.5 cm apart in a single row arranged in the centre of the pot, and the soil was wet to field capacity. Plants were thinned to five per pot once the first true leaves appeared, approximately two weeks after planting, representing a population of 433 plants per ha⁻¹.

Furthermore, Sinta & Garo (2021) conducted a field study that consisted of treatments with four plant densities, namely, 133 333, 100 000, 80 000, and 66 666 plants ha⁻¹ and four rates of N fertiliser, namely 0, 46, 92, and 138 kg N ha⁻¹. Each plot was 3 m x 3 m in size, consisting of six rows. Distances between plots and replications were 0.5 and 1.0 m, respectively. Contrary to Tamiru *et al.* (2017), who conducted a study on different plot sizes, the area for a single plot was (1 m x 1.5 m) or (1.5 m²), with a spacing of (30 x 20 cm).

In a study by Mampa *et al.* (2017), five-week-old seedlings were transplanted onto 20 cm-high and 1 m-wide raised beds with four rows per bed. Beds were 90 cm apart. Seedlings were planted in a plot size of 1.6 m² at a plant spacing of 20 cm between rows and 10 cm within rows. Under open field conditions, beetroot can also be planted in a 50 kg sack comprising 10, 15 and 20 plants per sack as an alternative solution for assessing the different plant densities (Mtsweni, 2019).

2.1.4.3 Moisture requirements

In general, water requirements depend on soil type and climatic conditions. As a guideline, 300–350 mm of water is required throughout the growing cycle – an average of 4 mm per day. This depends on the season, the variety's water requirements, and the soil type (Starke Ayres, 2019). Alternatively, mulching around the plants helps to conserve soil moisture. Moisture fluctuations cause root cracking, slow leaf development, and contribute to low yields. In fact, water stress during the first six weeks of growth often leads to premature flowering and low yields (Tamiru *et al.*, 2017). Beetroot has shallow roots, with an effective depth of 300 mm, and it is important to water the plants regularly and frequently.

Mampa *et al.* (2017) conducted a study on beetroot and applied moisture requirement as follows: plants were irrigated with drip irrigation (between 09:00 and 11:00) at a delivery rate of 2 L per hour, a constant pressure of 200 kPa, and an emitter spacing of 20 cm. Plants were irrigated three times per week (three irrigation cycles), with an application rate of 0.6 to 1.2 L (12 to 24 L/plot of 1.6 m²) of water per irrigation cycle. The amount of irrigation was gradually increased as the plants developed.

2.1.4.4 Fertiliser requirements

Generally, it is well known that fertilisation is one of the most important agricultural practices for ensuring good agricultural production. Proper fertiliser management keeps the production of each crop sustainable. Fertilisation is also important in beetroot crop production technology to achieve optimum yield and root quality. Beetroot has high demands for nutrient elements, needed to support vegetative biomass (Markoski *et al.*, 2015). In particular, it requires higher rates of N, P, K, Mg and Ca, as well as micronutrients such as B (Petek *et al.*, 2019). Foliar nutrition is an application of water-soluble fertilisers directly to the leaf. Foliar fertilisers are quickly absorbed by plants and are commonly used as nutritional supplements for the plants (Hong *et al.*, 2021) and as an alternative nutrition in conditions when plants show a high necessity for nutrients or in cases of deficiency in soil fertility.

To achieve proper fertiliser management, it is of great importance that a soil analysis or test is considered, as it is the most accurate guide to fertiliser requirements. The Fertiliser Association of Southern Africa's (FSSA) book for fertiliser recommendation can be used as a guideline for fertiliser requirements (FSSA, 2016). The table that follows indicates a guideline on how to

select the Nitrogen: Phosphorus: Potassium (NPK) requirements of beetroot production in line with the soil analysis results from the laboratory (Table 2.2).

Table 2.2: Indication of the NPK requirements of beetroot vegetable.

Yield (t ha ⁻¹)	N (mg kg ⁻¹)	P (Bray 1) (mg kg ⁻¹)			K (mg kg ⁻¹)		
Soil analysis results	16–20% clay	1–20	21–50	>50	10–80	81–150	>150
	Application requirements (kg ha ⁻¹)						
Target yield 30-tonne ha ⁻¹	100	100	70	40	100	80	60

Source: *Fertilizer Handbook (FSSA, 2016)*.

Mampa *et al.* (2017) conducted a study to assess the effects of N application and leaf harvest percentage on the yield and quality of roots and leaves of beetroot. Limestone ammonium nitrate (28% N) was used as a source of N. Total N fertiliser at a 50% rate was applied at transplanting, and the other 50% was applied as top dressing 5 weeks after transplanting. Phosphorus and K were not required, based on the soil analysis results. The results showed increases in leaf and root yield with an increase in N application. Nitrogen application at 90 and 120 kg ha⁻¹ increased fresh leaf weight, leaf number, and fresh and dry root weight, including root diameter and length, except for leaf area, which was significantly higher at 120 kg ha⁻¹ N (Mampa *et al.*, 2017). Other studies on fodder beetroot reported an increase in root diameter and length with an increase in N application (Reid *et al.*, 2020). Moreover, Chepkoech (2015) highlighted that most leafy vegetables prefer obtaining N from nitrate sources rather than from ammonium or urea, and that the application of nitrate fertiliser usually promotes the growth of these species.

Given these studies, it can be noted that the investigation of N fertiliser's effects on beetroot is common, whilst there is little literature on the effects of P-levels on beetroot production. Instead, most studies conducted normally consider phosphorus and potash as basal application rather than a factor under investigation. However, aside from studying the effects of inorganic N, other studies have assessed the effects of organic nutrients and biostimulants on yield characters of beetroot (Devi *et al.*, 2016; Chaudhari *et al.*, 2024). Artyszak *et al.* (2021), assessed the effect of foliar fertilisation containing SB and potassium on the yield and technological quality of beetroot under drought stress. The results revealed that the increased

yield were obtained when beetroot plants were treated with the SB during drought stress. Furthermore, Barão (2023), reviewed the use of Various SBs, including both solid and liquid forms, across different crops and experiments, with over 682 cases analysed. The results showed that for vegetables, which includes beetroot, the highest frequency of measurements reported yield improvements between 50 and 100% after SB application. Also, registered symptom alleviation in 74% of cases where stresses or limitations were studied confirming the role of Si in helping crops endure abiotic stress. Therefore, in this context, this study investigated the effects of SB in response to combined P and W deficit levels on beetroot to close the gap of limited P-level investigations on beetroot, rather than the continuous N-level investigations, and single stress only.

2.1.4.5 Climate requirements

The best planting times for beetroot are spring and autumn, but the vegetables also do well during summer on South Africa's Highveld and winter in the Lowveld. The optimum temperature for growth is between 15°C and 20°C. Beetroot is not particularly sensitive to heat if there is sufficient moisture in the soil to meet the plant's water requirements. Although tolerant to cold, they grow extremely slowly in winter. In addition, leaves may be damaged, and growth retarded if there is frost before harvesting. Cold weather might also delay maturity, and the tops tend to be smaller. Direct sowing can result in good germination between 6°C and 24°C. On hot, sunny days, high temperatures that develop at, or just below, the soil surface might badly injure young plants or kill them. High temperatures for long periods may not only retard growth and depress yield, but could also cause an undesirable strong flavour, concentric rings, and a coarse texture (ARC, 2014). For optimum growth, this crop requires temperatures of 12–19°C or 15–20°C (ARC, 2013; Starke Ayres, 2014). A reduction in yield quantity and quality (flavour and texture) was observed to occur in addition to growth retardation, especially during prolonged high temperatures (ARC, 2013).

2.1.4.6 Harvesting techniques

Beetroot is normally ready for harvest between 75 and 90 days after sowing in summer, and 100 and 120 days after sowing in winter. Due to the variable nature of beetroot and uneven spacing from multi-germ seed, harvesting generally occurs in stages. The first harvest is a thinning-out process where beetroot is sized between 3 and 4 cm in diameter. Most of the beetroot can be harvested when it attains a width of 7.5 cm. This can be done manually or

mechanically using modified potato harvesters. The harvested yield will vary significantly because of climate, fertilisation, disease infestation and variety planted, but average yields range between 15 and 25 tonnes per hectare. Some growers can achieve yields of 40–45 tonnes (ARC, 2014).

However, most beets grown commercially are harvested when fully mature to obtain the highest yields. Beets should be handled carefully after harvesting to avoid damaging the roots. Damage reduces shelf life and increases the chances of decay and disease. Fresh market beets can be stored successfully for 10–14 days at 0°C and 98–100% relative humidity (ARC, 2013). Beetroot quality indices are based on root shape, size, uniformity, intensive colour (with minimum zoning), firmness, smoothness, cleanness, trimming of rootlets and freedom from defects.

Before storage, beets should be topped and sorted to remove all diseased or mechanically damaged roots. Large roots store better than smaller ones, as they shrivel more slowly (Starke Ayres, 2019). It must be ensured that soil debris is minimised in the bulk bins so that the beets have sufficient fresh air in storage (Chandel & Chauhan, 2025). Viskelis *et al.* (2019) conducted a study to evaluate and optimise the process of storing various beetroot varieties and evaluate their suitability for processing. Beetroot varieties ‘Detroit 2’, ‘Boro H’, ‘Boltardy’, ‘Kestrel H’, ‘Pablo H’, ‘Bona’, ‘Wodan H’, ‘Rhonda H’, ‘Subeto H’, ‘Action H’, and ‘Joniai’ were investigated. The findings showed that increasing the carbon dioxide content from 0.03% up to 3%, 5% or 8% and reducing oxygen content from 21% to 10% or 5% positively impacts the chemical composition of the stored beetroots. After the evaluation of various varieties of beetroots after storage, the following varieties were found to be the most suitable for storage and subsequent processing: ‘Kestrel H’, ‘Joniai’, ‘Pablo H’, and ‘Rhonda H’. The optimal composition of controlled atmosphere for beetroot storage is 5% CO₂, 5% O₂, and 90% N. Furthermore, the average production of beetroot was 67% after storage, meaning that storage losses averaged 33%, similar to that of onions. The beetroot of the ‘Kestrel H’ variety remained up to 78%. Other good varieties for storage were ‘Pablo H’, ‘Bona’, ‘Subeto H’, and ‘Joniai’. However, other studies have shown that beetroot storage depends on storage conditions, variety, genotype, agroclimatic cultivation conditions, and fertilisation (Karklelienė *et al.*, 2018; Karklelienė *et al.*, 2023).

2.2 Multi-abiotic stress factors affecting beetroot and horticultural plants: Scoping review

2.2.1 Global losses associated with multi-abiotic stress factors

Over the last few decades and presently, the rising temperatures due to global warming have significantly impacted the growth and development of plants. The unpredictable climatic conditions caused by global warming will continue to increase abiotic and biotic stresses on plants and harm the quality and productivity of crops as stress can inhibit plant growth and development (Zhang *et al.*, 2020). Plants respond to stress in various forms, such as changes in cell metabolism, decreased growth rates and yields, changes in gene expression, and so on, as a way for plants to adapt to stress (Zhang *et al.*, 2022).

Stress is divided into biotic and abiotic stresses depending on the nature of the trigger factor. Biotic stress comes from biological factors affecting plant development and productivity, including insects, bacteria, fungi, and weeds. Concurrently, abiotic stress comes from physical and chemical environmental factors, such as changes in radiation, drought (which is highly associated with water deficits suffered by plants), salinity and soil acidity (which are highly associated with low pH in soils), nutrient deficiencies due to low fertility and extreme temperatures (Dewi *et al.*, 2023; Maryani *et al.*, 2019).

According to Hanus-Fajerska *et al.* (2023) and McKay *et al.* (2022), forecast scenarios indicate a steady increase in average annual air temperature of about 1.5–2°C is still expected to rise in the coming decades. The number of days with temperatures below the annual average is expected to drop by half for a given area, while the number of days with maximum temperatures will double. In vast areas on a global scale, the frequency of prolonged droughts will be increasing, and, at the same time, the frequency of hurricanes and floods will increase, mainly in coastal areas. In the described instances, these conditions are unsuitable for plant growth and development. Therefore, the food base of the human population across the globe is being seriously threatened (Kwak, 2019). For this reason, research on the response of plants to multi-stress conditions is constantly being undertaken, and attempts are being made to obtain lines with an increased degree of tolerance to various types of abiotic stresses (Numan *et al.*, 2021).

Dey & Raichaudhuri (2022) reported that temperature stress diminishes photosynthetic efficiency, crop yield, and seed germination. Furthermore, other studies have shown that *Striga*

hermonthica parasitism and recurrent drought are important biotic and abiotic constraints to maize production in Sub-Saharan Africa (Amegbor *et al.*, 2017; Badu-Apraku *et al.*, 2020). This is partly due to the frequency and unpredictability of drought in the region, which often coincides with *Striga* parasitism on farmers' fields, resulting in high yield losses (Badu-Apraku *et al.*, 2018). Damage to the maize crop due to moisture stress is unpredictable, as different factors determine it. It is not limited to rainfall patterns, soil moisture and water holding capacity, and water losses through evapotranspiration (Badu-Apraku *et al.*, 2023). Moreover, Pietrak *et al.* (2023) reported that plants of *A. nipponicum* cv. Red Beauty exposed to salinity stress in shade conditions had a lower fresh weight of the aboveground part by 19% and had a reduced fresh weight of the aboveground part by 16.3% compared to control plants; however, the salted plants had shorter fronds by 18.9%.

2.2.2 Extent of multi-abiotic stress factors affecting horticultural plants

There are numerous existing studies on plant responses to single stress factors. However, the effects of combined stresses on plant physiological and metabolic processes have been studied much less (Sack & Buckley, 2020). The resistance mechanisms to environmental stresses are known mainly in seed plants, and not much is known about how non-flowering plants, including beetroot, respond to abiotic stresses (Pietrak *et al.*, 2023).

Plants wither due to low pH conditions in acidic soils and dissolution of harmful elements, such as Al, Fe, and Mn, which are dissolved under acidic conditions. Although soil pH is a useful indicator for evaluating soil acid conditions for successful revegetation and/or farming, the dissolution of harmful elements under acidic conditions should be considered (Di Carlo *et al.*, 2019). For instance, Al, which constitutes approximately 7% of the Earth's mass, is easily released in water with the change of pH, inhibiting plant growth, including root growth and its function (Dutta & Bora, 2019). Al generally exists as $\text{Al}(\text{OH})_3$, which is insoluble in soils, dissolves in water as Al^{3+} under acidic conditions ($\text{pH} < 4.5$), and is released as $\text{Al}(\text{OH})_4$ under alkaline conditions. The Al^{3+} easily reacts with phosphoric acid and then causes P deficiency in plants by forming insoluble aluminium phosphate in soils (Singh *et al.*, 2022).

Soil pH influence nutrient availability to plants. For examples, plants grown in pH (H_2O) less than 5.5 tend to show deficiencies of P, N, K^+ , Ca^{2+} , Mg^{2+} , and toxicities of H^+ , Al^{3+} and Mn^{2+} (Peterson, 2020). At low pH levels, Mn^{4+} is reduced to Mn^{2+} and toxicity results when plants absorb an excess of Mn^{2+} . The absorbed Mn^{2+} can act as a toxic agent to plants that decreases

photosynthesis, ultimately reducing yield (Li *et al.*, 2019). When acidic soils have high iron levels, molybdenum deficiency occurs, especially in soils with a pH less than 5.6 (Peterson, 2020). Acidic soils can also limit root growth and reduce the activity of some helpful soil microorganisms (Naz *et al.*, 2022).

Phosphorus deficiency is a major abiotic stress that limits plant growth and crop productivity worldwide (Khan *et al.*, 2023). It is associated with highly weathered soils, a high capacity to fix P in forms generally unavailable to plants, and low fertiliser use, particularly in areas commonly inhabited by resource-poor farmers. Neelam *et al.* (2017) showed that some rice cultivars exhibited variation in ability to absorb P-fixing soils

Phosphorus shortage can also trigger a similar phytochemical response in plants (Galieni *et al.*, 2015). Studies have shown that nutrient deficiency can yield negative results on growth and yield. For example, Galieni *et al.* (2015) reported that the growth and yield of lettuce plants were significantly affected by the imposed limiting growth conditions, except for the no P application treatment; the stress treatments induced a significant reduction in leaf number (29 leaves). For instance, leaf length decreased by 21% in 0 kg ha⁻¹ N and increased by 56.7% in low light compared to the control; no differences were induced by 0 kg ha⁻¹ P and W stress. The control (0 kg ha⁻¹) N treatment significantly reduced the fresh biomass of lettuce leaves.

Stagnari *et al.* (2014) reported that W stress reduced storage root weight by 62% at the W deficit (W) 30% and 50% treatments, and similar trends were also reported on leaf W content in beetroot. Furthermore, Stagnari *et al.* (2014) reported that moisture stress induced a significantly higher concentration of total phenolic content (86% increase) and betalains (52% and 70% increases in betacyanin and betaxanthin) and, consequently, a higher antioxidant activity was obtained. Minerals such as Mg, P and especially Zn (2.9 and 1.1 mg 100 g⁻¹ dry weight in W 50% and W 100% treatments, respectively) and Fe (5.6 and 2.4 mg 100 g⁻¹ DW in W 30% and W100% treatments, respectively) were highly concentrated in W stressed roots alike for NDF (neutral detergent fibre) and ADF (acid-detergent fibre). Since W plays an important role in mineral mobilisation, W deficit may reduce uptake of Fe, Zn and Cu and also result in higher mineral concentrations (Ahanger *et al.*, 2016). In addition, studies dealing with horticultural crops reported increases in antioxidant concentrations under W stress (Francini & Sebastiani, 2019). In the case of aromatic plants, this insufficiency may cause significant changes in the yield and composition of essential oils. Water stress decreased the oil yield of rosemary (Sarmoum *et al.*, 2019) and the essential oil yield of dragonhead (Karimzadeh &

Hatami, 2019). By contrast, W stress caused a significant increase in the oil yield of citronella grass expressed based on plant fresh mass (Abduh *et al.*, 2020). The severity of W stress response can further vary with cultivar and plant density in other crops like parsley (Karkanis *et al.*, 2018).

2.2.3 Effect of multi-abiotic stress factors on horticultural plants

2.2.3.1 Soil acidity

Soils in arid and semi-arid regions are commonly alkaline with a high pH because of W scarcity, in addition to low precipitation and potential evapotranspiration, as indicated by the negative correlations between soil pH and temperature and between soil pH and precipitation (Beheiry *et al.*, 2023). Soil pH is an influential factor in the adsorption/absorption and availability of nutrients in the soil owing to the close relationship between them. In addition, most of the chemical, fertility, and biological properties of soil are strongly associated with soil pH; thus, in turn, it also affects plant growth and development (Usharani *et al.*, 2019).

The available information regarding the strong association between soil pH and nutrient availability suggests the ability of plants to take up nutrients through their root hairs, root tips (Beheiry *et al.*, 2023), as well as the fixation/adsorption capacity, which limits the assimilation by plants and is affected by soil pH values, either being extremely acidic or alkaline. Recently, some studies have reported that the soil pH in Egypt varies from neutral to strongly alkaline as an inherent characteristic of the soil, resulting from the nature of the parent material along with the prevailing climatic conditions (Al-Soghir, 2022). Awad *et al.* (2021) conducted two field experiments for two summer seasons (2019 and 2020) to study the response of sweet potato (Beauregard cv.) plants grown in calcareous soil ($\text{CaCO}_3 = 10.8\text{--}11.3\%$) to foliar nourishment with zinc oxide nanoparticles (ZnONPs) and ascorbic acid (ASA) applied individually or in a mixture. Both ZnONPs and ASA were applied in three doses: 0, 1 000, or 1 500 mg L⁻¹ for ZnONPs, and 0, 250, and 500 mg L⁻¹ for ASA. The highest values of Fe and Mn content were recorded in both seasons, while those of P and Cu were recorded in the 2020 season with ZnONPs applied at 1 500 mg L⁻¹ and the results indicate low availability of some nutrients, especially P and other micro-nutrients for Mo, is strongly related to an increase in soil pH. The decrease in micro-nutrient availability in alkaline soil could be explained by the fact that these cations become strongly bonded with soil organic matter and soil colloids as the pH approaches 8.

Wotchoko (2019) conducted a study aimed at comparing the effects of basalt dust, poultry manure and NPK 20-10-10 fertilisers, single and combined, on the growth and yield of beetroot in Nkwen (Northwest Cameroon). The main results revealed that the land has a severe limitation due to high acidity and thus has potential unsuitability for beetroot cultivation. Although all treatments improved the soil characteristics, basalt dust shows the highest capacity to supply nutrients to the soils. Poultry manure showed the best efficiency in uplifting soil acidity, although all the treatments improved the original soil pH. The best yields of beetroot were obtained in treatment (T) 1 (5 tonnes ha⁻¹ poultry manure), followed by T4 (2.5 tonnes ha⁻¹ basalt dust). The yields were recorded in decreasing order as T1> T4> T3> T8> T6> T5> T0> T7> T2 (for total biomass weight) and T4> T1> T3> T8> T6> T5> T0> T7> T2 (bulb weight). However, the lesson learned from the study was that beetroot under acidic conditions could be improved by using different amendments, and the use of Si-fertilisers as an alternative farming tool can be considered as well. Johan *et al.* (2021) reported that soil pH values in the mid-hill Himalayan region range from 4 to 6 (acidic) because of high rainfall and highly weathered soils. In acidic soils, P becomes unavailable to plants as it gets fixed in the soil by sesquioxides, eventually leading to P deficiency. Thus, P becomes the most limiting nutrient in the crop production system (Rathore & Kumar, 2022). The reduced level of available P can adversely affect plant height, lateral plant spread, flower number, flower size, biomass, and pollen production (Jiang *et al.*, 2016).

Soil acidity is a serious concern in the agricultural farming of South Africa. Peterson (2020) conducted a study of breeding maize (*Zea mays* L.) for tolerance to acidic soils to improve maize yields. The study aimed to identify maize genotypes with tolerance to acidic soils, as well as identifying secondary traits associated with the tolerance to soil acidity, and findings showed highly significant and positive correlations observed between ear diameter (0.9 mm), ear length (0.9 cm), and leaf area (0.7 cm²), with 1 000 kernel weight indicated that such traits could be useful in identifying genotypes that are tolerant to soil acidity under field conditions. However, multistress challenges associated with abiotic stresses such as soil acidity, moisture stress and nutrition are a serious concern in Mpumalanga. Zharare & Vilane (2021) reported a deficiency of P in Manguzi soils, as compared to the index levels (8 to 10 mg kg⁻¹) for healthy growth of groundnut plants, which is associated with soil acidity in the lowveld of the Mpumalanga province.

Many researchers report the beneficial influence of Si on the growth of crop plants through mitigating environmental stresses. Silicon alleviates plant environmental stresses by regulating the physiological and biochemical processes. It can contribute to maintaining the plant water balance, improving photosynthesis and nutrient uptake, regulating the activities of antioxidant enzymes and stress-tolerant gene expression, and reducing oxidative stress (Wadas, 2023).

Wadas (2023) conducted a study on the effect of Si (sodium silicate) on the nutritional value and sensory quality of new potatoes under acidic to slightly acidic reaction (pH-KCl 5.2–5.7). The outcomes of the study revealed that Si had no effect on the dry matter, total sugars and monosaccharides, protein, L-ascorbic acid, or nitrate content in new potato tubers, but it increased the starch content under water deficit conditions. Other studies show that soil or foliar application of Si improved potato growth (Wadas, 2021) and tuber yields (Trawczyński, 2021). Contrarily, Artyszak *et al.* (2015) observed no effect on the sucrose and alpha-amino-nitrogen content in beetroot following the foliar application of Si fertiliser.

2.2.3.2 Water deficit

Generally, plants exposed to W stress have lower evapotranspiration which further leads to the development of certain W stress symptoms such as leaf wilting, reduced leaf area, decrease in stem diameter growth and stunted plant growth, and changes in physiological and biochemical processes such as stomatal conductance, leaf W status, photosynthesis, sap flow, leaf temperature, hormonal balance, osmotic adjustments (Parkash & Singh, 2020).

Water deficit stress exposure frequently constrains plant and agri-food production globally (Rezaei-Chiyaneh *et al.*, 2023). Exposure to W deficit can be defined as a lack of plant-available W for a sustained period. This exposure leads to inhibiting plant growth and development by changing plant physiological and biochemical activities, resulting in productivity and quality losses (Thomason & Battaglia, 2020; Raza *et al.*, 2021). Physiologically, W deficit can reduce photosynthetic rates, enhance phenology, truncate root growth, and enhance senescence (Ibrahim *et al.*, 2018).

Moisture deficit is one of the most limiting factors that cause losses in yield and quality of the sugar beet (Nause *et al.*, 2020). A field experiment was conducted at Shandaweel Agricultural Research Station, Sohag Governorate, Egypt, in the 2019/2020 and 2020/2021 growing seasons to study the effects of W deficit irrigation and bio-fertilisers on the growth, yield and quality of beetroot. The results of the study indicated that W stress led to a significant reduction in all

studied traits except for recoverable sugar% (Ahmed *et al.*, 2023). Contrarily, Osman *et al.* (2019) showed that the highest values of sugar beet root yield (34.95 and 30.20 t/fed) and sugar yield (5.00 and 3.18 t/fed) were obtained under a drought period of six weeks before harvesting in the first and second seasons, respectively, in clay soil. Moreover, delayed irrigation causes significant decreases in sugar beet plant growth parameters (root diameter, root weight, and root yield), while increasing root length compared to the optimal irrigated treatment (Abu-Ellail & El-Mansoub, 2020). Abu-Ellail *et al.* (2021) revealed that elongated irrigation intervals (four weeks) led to a marked decrease in root diameter, root weight and root yield, while increasing root length, sucrose%, extractable sugar%, and sugar yield in both growing seasons. Seleiman *et al.* (2023) reported that W deficit significantly reduced yield traits (average tuber weight, number of plant tubers, and tuber yield) and quality traits (tuber diameter, crude protein, and mineral content). However, it enhanced tuber dry weight, specific gravity, ascorbic acid, starch, and total soluble solids in the production of potatoes.

Rezaei-Chiyaneh *et al.* (2023) reported that plant height, lateral branches, canopy diameter, and dry matter yield all decreased due to moderate water stress (Field capacity%; FC 75 and severe FC 50). Pirasteh-Anosheh *et al.* (2016) noted that W stress conditions reduce the entry of carbon dioxide into the closed stomata due to dehydration, reducing the supply of photosynthetic materials and plant productivity. Similarly, Amani Machiani *et al.* (2021) noted that thyme (*Thymus Vulgaris* L.) dry matter yield decreased by 27% and 40%, respectively, due to moderate and severe drought stress.

Biostimulants can be considered a new tool in mitigating W deficit stress. For instance, Rezaei-Chiyaneh *et al.* (2023) conducted a study aimed at understanding how biostimulants influence W deficit stress perceived by savoury plants (*Satureja hortensis* L.), an important herb used for nutritional and herbal purposes in the Middle East. The findings of the study indicated positive results under three irrigation regimens (low, moderate, and severe W deficit stress [Field Capacity]; FC 100%, FC 75%, and FC 50%, respectively). Foliar application of a Si-fertiliser increased dry matter yield, essential oil content and essential oil yield by 22%, 31%, and 57%, respectively. The greatest essential oil yields resulted from the moderate (FC 75) and severe W deficit stress (FC 50) treatments.

Seleiman *et al.* (2023) conducted a study to examine the influences of 0, 50, and 100 mg L⁻¹ ZnO nanoparticles and 0, 25, and 50 mg L⁻¹ SiO₂ nanoparticles on the yield and quality traits of potato plants grown under W deficit conditions (100%, 75%, and 50% ETc). Foliar

application of ZnO and SiO₂ nanoparticles under W deficit treatments significantly enhanced yield and improved quality traits of potato plants. Moreover, significant and positive correlations were found among yield traits. It is based on the above evidence that the use of Si-based biostimulants could be used as an alternative solution to combat W deficit stress.

2.2.3.3 Phosphorus deficiency

Phosphorus is one of the macro-nutrients essential for plant growth, being a highly required resource after N to improve the productive performance of several crops, especially in highly weathered soils. However, a large part of the nutrients applied in the form of fertilisers becomes ‘inert’ in the medium term and cannot be assimilated by plants. Adjusting the use of P is thus a matter of extreme importance for environmental sustainability and socioeconomic development (Silva *et al.*, 2023). Therefore, alternatives to the management of this nutrient are needed, and the use of Si-based biostimulants is an option to optimise its use by crops, allowing the exploration of available fractions of P nutrient that are not easily accessible in soils and reducing the demand for P fertilisers.

In the plant, P is a constituent of certain sugars, nucleic acids, lipids, and other compounds. In metabolism, it is a mediator of carbohydrate synthesis and acts in the activation and inactivation of enzymes. It also stimulates germination, root growth, flowering, and seed formation (Malhotra *et al.*, 2018). It is even involved in energy transfer processes such as photosynthesis and is also a component of molecules such as adenosine triphosphate (ATP) and guanosine triphosphate (GTP) (Bisson *et al.*, 2017).

In contrast to N and K, in moist, upland soils, P is generally highly insoluble in the soil, which leads to limited plant-available P in the soil solution (Weil & Brady, 2016). Upon application, the P contained in granular P-fertiliser get fixed and immobilised by reaction with cations, such as iron (Fe²⁺) and aluminium (Al³⁺) under acidic conditions and calcium (Ca²⁺) under alkaline soil pH conditions (Weil & Brady, 2016). Generally, a pH between 5 and 7 is optimal for P availability (Weil & Brady, 2016). Consequently, because P is not readily available to plants and is quickly immobilised upon application, P is often over-applied to ensure sufficient P is available for crops (Weil & Brady, 2016).

Phosphorus is described as a limiting factor in plant growth in several studies, where its deprivation triggers cellular and physiological changes (Dokwal *et al.*, 2021; Tiziani *et al.*, 2020). Meng *et al.* (2021) showed that P availability positively affected the growth of sour

pummelo (*Citrus grandis*). Its deficiency limits the accumulation of dry matter in leaves and branches. In addition, the results reported by Silva *et al.* (2023) show that low P also inhibits plant growth, affecting the absorption of other nutrients, decreasing photosynthetic performance, and increasing the production of reactive oxygen species. Therefore, the availability of P nutrient in the soil directly influences crop productivity (Silva *et al.*, 2021).

Approximately 30–40% of the world's cultivated land is deficient in P. Phosphorus deficiency has become one of the main limiting factors for crop growth due to the loss of the nutrient caused by high temperatures and heavy rain, or acidic rain due to mining/other industries releasing sulphurous gases as human activities, and the fixation of P by iron and aluminium oxides in the soil (Meng *et al.*, 2021). Furthermore, inorganic P readily forms complexes with oxides and hydroxides of iron and aluminium in acidic soils and with calcium in alkaline soils, with up to 80% of P applied as fertiliser becoming unavailable for most crops. Such a situation is aggravated by inadequate and imbalanced use of fertilisers, leading to reduced nutrient availability for crop growth. P is often a limiting factor because most of the P in soil exists in a form unavailable to plants (Meng *et al.*, 2021).

Meng *et al.* (2021) reported decreased dry weight of roots and shoots of lettuce and tomato, and the leaf number of Chinese milk vetch (*Astragalus sinicus* L.), alfalfa (*Medicago sativa* L.), lettuce (*Lactuca sativa* L.), tomato (*Solanum lycopersicum* L.), and marigold (*Calendula officinalis* L.) due to P deficiency. Silva *et al.* (2019) reported a significant low yield under low P levels when comparing two beetroot cultivars, Cabernet and Fortuna. Wang *et al.* (2021) investigated the effects of P fertilizer and irrigation on dry matter accumulation and P use efficiency in beetroot over two growing seasons and compared treatments with 105 kg P ha⁻¹ and 0 kg P ha⁻¹ (representing P deficiency) under both rainfed and irrigated conditions. The findings recorded that the highest beetroot yield was achieved with 105 kg P ha⁻¹ under irrigation, demonstrating the positive effect of P application. Demirbaş (2021), reported the yield increase with rising P doses, showing detrimental impact of low P levels on beetroot production. Ramazanova *et al.* (2024), reported that low soil fertility and suboptimal nutrient management, which includes P, constrains beetroot production, and further reported a control treatment where no fertiliser P was applied, exhibited expectedly low biomass growth (0.16 kg from 10 plants) in beetroot. In South Africa, Sadiki *et al.* (2025), in a short-review that focuses on the combined effects of adverse environmental stressors, including P deficiency which causes severe consequences for the growth and quality of horticultural crops like beetroot,

explained that P deficiency, either alone or combined with other stressors, is a critical limiting factor that globally reduces beetroot yield by 5-30%. Generally, the literature focusing on P deficiency effects on beetroot production in Mpumalanga province (MP) of South Africa is not sufficiently reported. However, other cases in the cropping fields of MP involving P deficiency are reported. For instance, Malele (2023), reported the reinforcing of the potential for P due to deficiencies in fields that smallholder farmers in Limpopo and MP provinces often grow pigeon peas in an intercrop system with maize and mangoes without any fertiliser applications. Malele (2023), further reported that most of the smallholder and subsistence farmers interviewed (103 out of 114) were crops with very low grain yields, with fewer farmers producing more than 200 kg per hectare, which is consistent with the challenges of poor soil fertility and other limiting factors like drought and poor practices. Chauke *et al.* (2022), noted that most soils in smallholder farming areas in South Africa are low in available P, averaging less than 10 mg/kg Bray 1, and further identified low native soil P availability and poor utilization efficiency of added P as a limiting factor for smallholder farmer soybean production under dryland conditions at Sheepmoor, MP.

In order to reduce household food insecurity, the MP provincial administration launched the Phezukomkhono Mlimi (PKM) initiative in 2005 (Sambo *et al.*, 2025). Increasing food production with the goal of improving food accessibility and generating revenue by selling the excess produce is one of the PKM program's main goals (Machube, 2021). Smallholder and subsistence farmers who grow grain and vegetables are supported by the PKM program. It gives the recipients tractors, chemicals, NPK fertilizers, and seeds so they can grow their own food (Shabangu, 2015). One important function of NPK fertilizer distribution is to replenish deficient soil P that was taken during harvesting and consequently addressing P deficiency gap. Although, majority of Mpumalanga smallholder farmers rely on this programme for fertiliser supply as an alternative solution for combating the soil infertility issues including P deficiency. As such, in a long run, the use of inorganic fertilisers only, might pose a threat to the ecosystem. Therefore, this study seeks alternatives approach such as the use of group 2 organic fertiliser such SB under combined abiotic stress environments.

2.2.4 Combined effects of soil acidity, moisture deficit, and phosphorus deficiency on horticultural crops including beetroot

Ever since unpredictable climate change has been on the rise, plants have had to deal with numerous abiotic stresses, including deficit or excessive W, nutrient shortages or imbalances,

soil acidity or alkalinity and other related stresses, such as low or high temperature, high light intensity and ultraviolet radiation (Ambrosini *et al.*, 2021). These stresses are accountable for great crop yield loss (Wani *et al.*, 2016) and are exacerbated by recent climate changes (Ambrosini *et al.*, 2021). The negative impact on plant growth is worsened when these stresses are combined; for instance, drought and heat stress were responsible for as much as the 40% of reduction in crop yield for maize (Daryanto *et al.*, 2016), and up to 68% for cowpea (Farooq *et al.*, 2017). Moreover, W shortage and soil salinity trigger oxidative, osmotic and temperature stress, representing another major challenge for productivity (Landi *et al.*, 2017).

Nutritional imbalance, such as nutrient deficiency under W deficit conditions, depresses plant growth and productivity by affecting nutrient uptake, transport, and distribution (Bhattacharya, 2021). Despite contradictory reports on the effects of nutrient supply on plant growth under W deficit conditions, it is generally accepted that an increased nutrient supply will not improve plant growth when the nutrient is already present in sufficient amounts in the soil and there is a severe W deficit. Furthermore, it is generally known that nutrient availability requires water for solubility, transport, and distribution, and its availability is pH dependent.

Other studies indicated that, in a field experiment conducted to study the effects of individual or combined deficiencies in nutrients and water on photosynthesis, there were decreases in grain yield and leaf photosynthetic performance that were observed in wheat cultivation (Kang *et al.*, 2023). When plants undergo W stress regimens, growth, chlorophyll, and yield attributes decreased significantly compared to the control. While antioxidant enzymes peroxidase, catalase and superoxide dismutase, osmolytes such as proline and glycine betaine increased in response to W stress (Sultan *et al.*, 2023). Other studies with effects of combined multi-stress on horticultural crops have been reported (Table 2.3).

Table 2.3: Combined stress of soil acidity, moisture deficit, and phosphorus deficiency on horticultural crops including beetroot.

Crops	Combined stresses	Negative impact	Citation
Soya, cowpea, wheat and maize	P-deficiency + drought (water deficit)	Decrease in the biomass of the roots and shoots	Bechtaoui <i>et al.</i> (2021)
Cucumber plants (<i>Cucumis sativus</i> L.), either non-grafted or grafted (<i>Cucurbita maxima</i> Duchesne)	Low pH (soil acidity) + Al toxicity	In both grafted and non-grafted plants, shoot dry mass at pH 3.5 was reduced by 25% and 26%, respectively, compared to the pH 6.0 treatment. In both non-grafted and rootstock-grafted plants, shoot dry mass dropped by 67 and 58% at pH 3.5 + 1.5 mM Al over the pH 6.0 treatment, and by 84 and 76% at pH 3.5 + 3.0 mM Al.	Rouphael <i>et al.</i> (2016)
Pepper seedlings (cv. Demre)	P-deficiency + soil alkalinity	The decrease in Na content of the shoot and root of the pepper seedling.	Çimrin <i>et al.</i> (2010)
Barley and beetroot	Low pH (soil acidity) + P-deficiency	Beetroot yield was drastically decreased by 27%. Winter barley yields tended to decrease by 6.8%.	von Tucher <i>et al.</i> (2018)
Cotton genotypes (Jimian169; strong tolerant to low P and DES926; weak tolerant to low P)	Low P (P-deficit) + induced drought (moisture deficit)	According to the findings, PEG-induced drought significantly reduced growth, dry matter production, photosynthesis, and P use efficiency when P was low. It also increased the accumulation of reactive oxygen species (ROS) and caused oxidative stress from excessive malondialdehyde (MDA) in DES926 compared to Jimian169.	Iqbal <i>et al.</i> (2023)
Beetroot (<i>Beta vulgaris</i> L.) genotypes, 24367 (putative drought tolerant) and N6 (putative drought-intolerant)	Drought (moisture deficit) + Nutrient deficiency	In response to drought stress, both genotypes' relative water content (RWC) dropped, and their leaf temperature rose. When beetroot seedlings cultivated in nutrient culture were exposed to nitrogen deficiency stress, their hydraulic conductance and sap flow dropped.	Shaw <i>et al.</i> (2002)
Mungbean (<i>Vigna radiata</i> L.; R. Wilczek)	Low P (P-deficiency) + Drought (moisture deficit)	When compared to individual stresses, a notable decrease in P uptake in seeds and shoots, as well as gas exchange characteristics (photosynthesis, stomatal conductance, transpiration, and instantaneous water use efficiency) was noted under combined stress.	Meena <i>et al.</i> (2021)

2.3 Effect of silicon-based liquid fertiliser on horticultural plants

2.3.1 Background of fertilizers and the regulation framework in South Africa

In South Africa, agricultural inputs are regulated under the fertilizers, farm feeds, agricultural remedies and stock remedies Act of 36 of 1947. The directorate of agricultural inputs control oversees the registration of these products, including fertilizers and biostimulants. Fertilizers are classified by groups based on their nutritional and composition, usually in accordance with Act 36 of 1947. The group 1 fertilizers are high-concentration fertilizers containing a total of 100 g/kg or more NPK, or any combination thereof. For instance, inorganic/chemical fertilizers such as 2:3:2 (22) popular known for general-purpose garden fertilizer used for vegetables, and the multi-feed used for foliar feeding as water-soluble fertilizer. These group 1 fertilizers should be registered with the registrar of Act 36 of 1947 and renewed every three years. The group 2 fertilizers contain a total of less than 100 g/kg of NPK. These are including specialized blends, liquid fertilizers, or products with a lower concentration of macro-elements but high micro-elements. For examples micronutrient mixtures such as Zinc chelate or Iron chelate, and speciality liquids such Magnesium Nitrate or silicon. The group 3 fertilizers are natural or synthetic substances/organisms that improves plant growth or soil condition (physical, chemical or biological) and do not fit into Group 1 or 2 (FSSA, 2016). This review will focus mainly on group 2 fertilizers as an alternative management strategy to alleviate abiotic combined stress on beetroot production and other related agronomic crops. Among new technologies, group 2 fertilisers have consistently increased their relevance in recent years, and their economic relevance is expected to grow further. The availability on the market of many fertiliser products with different origins and putative functions might demonstrate their practical effectiveness and reliability as agronomic tools. However, there are still insufficient precise and scientifically sound indications for the most effective mode of application of fertilisers, even though their introduction in many integrated and organic production protocols for horticultural products has already become a practice.

This review aimed to provide practical information about applying an organic or non-microbial fertiliser products. The literature research was restricted to selected group 2 fertilizer. In this review, the analysis was focused on Si alone since it is by far the most studied and relevant one, at least concerning vegetable crops.

In terms of origin and composition, Si in soil generally occurs in complexed forms like aluminium and crystalline silicates, reaching high concentrations in mineral soil (up to around 28%) (Schaller *et al.*, 2021). These forms of Si are not available for plants that can absorb Si mainly as silicic acid, $\text{Si}(\text{OH})_4$. According to concentration in the plant tissues, Si can be considered as a macro-nutrient ($>0.1\%$ dry weight) or a micro-nutrient ($<0.05\%$ dry weight), depending on the crop species. However, Si deficiency rarely limits horticultural crops since these crops are not strong Si accumulators and because Si can be replenished with irrigation, as W is also a source of silicon (Savvas & Ntatsi, 2015).

In terms of commercial Si-products, silicon-based products can be solid or liquid. Solid Si-products are obtained from different sources (rocks, sediments, by-products from plants, recycled material). They are therefore characterised by different Si content and properties (availability for the plant) depending on the characteristics of the raw material (Laane, 2018). Silicon products can also be formulated as amorphous silica powder consisting of nanoparticles with sizes between 10 and 100 nm. Liquid products contain Si in different formulations, such as mono- or polysilicic acid. The Si concentration of liquid products corresponds to the Si content available for the plants. At high Si content, the product pH is high (± 9) and therefore dilution is required before product application (Zellner & Datnoff, 2020).

In terms of application mode, Si-based products can be applied to the soil or by foliar sprays. Soil application is the most effective way to increase Si concentration in plant tissues. Si is absorbed as silicic acid at the root level and once entered into the xylem vessels, is transported to shoots and leaves through the transpiration stream. At transpiration sites, Si accumulates as amorphous silica typically close to stomata openings, trichomes, lumens and intercellular voids. Foliar application is less efficient in increasing Si concentration in plant tissues. Generally, it requires a high concentration of the sprayed solution (up to 1500 ppm) to be effective (Zellner & Datnoff, 2020). However, the foliar application allows one to bypass problems related to possible Si immobilisation in the soil. It is therefore often chosen when repeated sprays of a target organ are needed. In this case, Si can be absorbed directly through the cuticle layer or openings in the leaf surface (cracks close to trichomes, stomata, pores and hydathodes) (Andreotti *et al.*, 2022).

2.3.2 Effects of silicon-based fertiliser on plant growth and development under biotic and abiotic stress factors

Silicon is a metalloid with an atomic mass of around 28.08 g mol^{-1} , the second most abundant element in the Earth's crust. There are three naturally occurring isotopic forms of Si (Souri *et al.*, 2021). In soils, Si is present in silica, silica gel and silicate (Souri *et al.*, 2021). Most Si compounds are insoluble in soil solution and unavailable for plant uptake (Luís Oliveira Cunha *et al.*, 2023). Silicic acid ($\text{Si}[\text{OH}]_4$), which is the available form of Si and is absorbed by plants, is the soluble form in the soil at pH levels lower than 9 (Mandlik *et al.*, 2020; Luís Oliveira Cunha *et al.*, 2023). The sources of Si available for soil application are naturally occurring calcium silicate based on rock or agro-industry residues (Luís Oliveira Cunha *et al.*, 2023). Other sources of Si can be supplied directly into the soil or in solution in fluid form, which are potassium silicate, sodium silicate, nanosilica, monosilicic acid and other derived sources (Dos Santos *et al.*, 2020; de Souza Júnior *et al.*, 2022). In plants, Si can attenuate the effects of several abiotic stresses, including salinity, drought, excess solar radiation, and heavy metals (Rocha *et al.*, 2021; Luís Oliveira Cunha *et al.*, 2023). Some research indicates that Si can increase photosynthesis, lignin, transpiration, antioxidant enzyme activity, yield and mitigate plant stress (Abdelaal *et al.*, 2020; Sales *et al.*, 2021; Luís Oliveira Cunha *et al.*, 2023).

The beneficial effect of Si on plants under stress conditions caused by nutrient deficiency has been attributed to the protection of the plant photosynthetic system, increased production of chlorophylls, stimulation of antioxidant systems, and improved physical integrity of membranes, in addition to maximised nutrient uptake (Sales *et al.*, 2021). Furthermore, Sales *et al.* (2021) reported that the Si supply in the solution mitigated the deleterious effects of nutrient deficiency by reducing electrolyte leakage, and further elaborated that previous reports have indicated that Si forms complexes with cell structural polymers, such as pectins and callose and cross-links with lignins and carbohydrates by associations with phenolic acids or aromatic rings, thus contributing to cell membrane structuring.

Abdelaal *et al.* (2020) reported that application of Si significantly increased concentrations of chlorophyll at a gram of fresh weight (Fw) (1.9 and $1.5 \text{ mg g}^{-1} \text{ Fw}$) as compared to untreated, salt-stressed plants (1.2 and $0.8 \text{ mg g}^{-1} \text{ Fw}$) at $1\,500$ and $3\,000 \text{ ppm}$, respectively. Additionally, chlorophyll b significantly increased (0.82 and $0.63 \text{ mg g}^{-1} \text{ Fw}$) compared to untreated plants (0.48 and $0.35 \text{ mg g}^{-1} \text{ Fw}$) at $1\,500$ and $3\,000 \text{ ppm}$ salt stress. Silicon application significantly increased relative water content (71% and 59%) compared to untreated sweet pepper plants

(60% and 49%) at 1 500 and 3 000 ppm, respectively. Proline accumulation under silicon treatment was 11.5 and 14.4 $\mu\text{g g}^{-1}$ Fw in salt-stressed plants at 1 500 and 3 000 ppm. This result suggests, that Si foliar application is an alternative solution for improving plant growth and nutritional composition under stress conditions such as alkalinity stress.

Olivera-Viciedo *et al.* (2024), explored the effects of SB application on the C:N:P stoichiometry and yield of beetroot grown in hydroponic conditions under ammonium-induced abiotic stress, and investigated whether SB application can mitigate the detrimental effects caused by toxic ammonium levels, which is a form of nitrogen fertilizer, and the results concluded that the presence of SB significantly increased N and P in shoots and roots and improved dry matter production under high ammonium levels, compared to plants without SB. Furthermore, Abdel-Moneam *et al.* (2024), reported a significantly improved beetroot yield and juice quality, due to combined application of boron and SB application, particularly under deficit irrigation. This can be concluded that the use of SB holds a strong potential in improving horticultural plant's growth, yield and other related nutritional composition. Further studies need to be conducted to investigate findings in relation to beetroot as one of the commodity crops in Mpumalanga.

2.3.3 Silicon-based fertilizer as an alternative strategy for combined stress

Several research studies have been conducted, focusing on the genetic modification of crop plants to achieve more crop resilience against abiotic stress factors such as W deficit, soil acidity, phosphorus deficiency and other related stresses. However, a quick shift in modern agriculture has focused on more organic, eco-friendly, and long-lasting systems to improve crop yield. As such, extensive research into microbial and non-microbial biostimulants or liquid plant fertilisers has been at the core of agricultural studies to improve crop growth and development and to attain tolerance against several biotic and abiotic stresses. Si-based liquid fertiliser is one of the alternative solutions to crop production, such as beetroot production, under the combined or multi-stress conditions.

Silicon can be applied as a fertiliser through foliar spraying, incorporation into the soil, or fertigation. Foliar application of Si is more effective than soil application (Wadas, 2021). The beneficial effects of foliar silicon application on plant growth under stress conditions have been reported for several agricultural and horticultural plants, including rice, wheat, canola, sugar beet, tomato, cucumber, and onion (Wadas, 2021). To date, few studies have focused on the

effect of Si on potato growth. Nearly all experiments were conducted in a hydroponic culture or pots in a greenhouse (Pilon *et al.*, 2014; Gowayed *et al.*, 2017). There is however insufficient knowledge of the effect of Si on beetroot growth under the selected combined in environmental conditions in the field.

Other authors reported that Si's foliar application increases chlorophyll and carotenoid content in onion and sweet pepper plants (Rangwala *et al.*, 2019; Abdelaal *et al.*, 2020). Wadas & Dębski (2022) conducted a study focused on the effect of Si foliar application on assimilation area and photosynthetic pigment content in potato plants. A one-year field experiment carried out showed that foliar application of Si (silica SiO_2 or sodium silicate nanoparticles Nano-NaSiO_3) enhanced the quantum yield of photosystem II and chlorophyll content in potato leaves under salinity stress but had no effect on chlorophyll content. Silicon stimulated potato growth only at low doses. However, Dorneles *et al.* (2018) reported that a higher Si concentration in a nutrient solution reduced potato growth parameter, mainly in leaf area. In addition, the excess of silicon may also lead to the immobilisation of essential elements for plant growth (Mg, Zn, Fe, Mo) in the apoplast (Farooq & Dietz, 2015). Foliar application of Si is effective only at very low doses and when started early in the vegetative stage (Laane, 2017).

2.3.4 Silicon-based fertiliser key activities, methods of application and mode of action in plants

Comprehending the mechanism of action of stabilized monosilicic acid necessitates a dual-lens approach (Charles, 2022). It serves as a metabolic stimulant that improves nutritional homeostasis and stress tolerance, as well as a structural architect that strengthens the integrity of cell walls (Singhal *et al.*, 2023). Compared to traditional soil-bound silicon sources, it can more effectively alleviate both biotic and abiotic pressure thanks to this complex influence (Begum & Zareen, 2026). Although silicon has historically been associated with mechanical fortification, the mechanism of action of stabilized monosilicic acid (H_4SiO_4) is becoming more well acknowledged for its intricate impact on the physiological and molecular landscape of plants (Nikolic & Kirkby, 2025). Applying the element, which is the only form of bioavailability, causes a multifaceted reaction that includes transcriptional reprogramming of stress-responsive genes and the control of antioxidant enzyme systems. More details on mode of action are presented in Table 2.4. Figure 2.1 summarises the essential roles that silicon plays in biotic and abiotic stress tolerance, noted by Hassan *et al.* (2024).

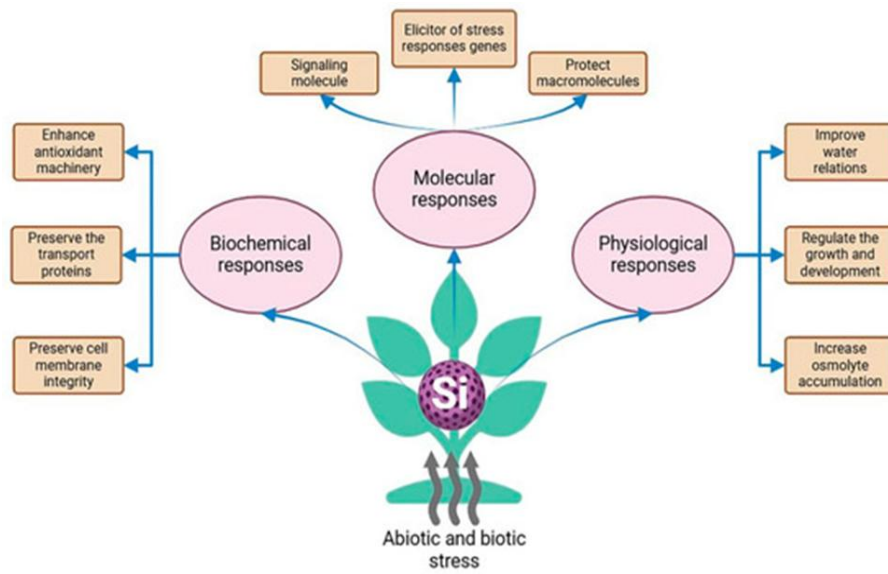


Figure 2.1: The essential roles that silicon plays in biotic and abiotic stress tolerance summarised by Hassan *et al.* (2024).

Table 2.4: Si-based liquid fertiliser mode of action in plants.

Mode of action	Activity	Citation
Rapid absorption and uptake	The only type of silicon that plants may directly absorb is monosilicic acid (MSA). When administered as a foliar spray, it is either directly absorbed via leaf cuticles or absorbed by roots and transmitted through the xylem.	Maurya <i>et al.</i> (2025)
Physical reinforcement	Following absorption, it travels to transpiring tissues through the xylem (stem and leaves). Just below the plant cuticle, silicic acid polymerizes to form phytoliths, a hard layer of amorphous silica. As a result, the plant structure is strengthened by a hard, tiny "shield."	Ali & Bijay-Singh (2025)
Biochemical Signaling	Rather than functioning solely as a conventional macronutrient, it functions as a signaling molecule that activates the plant's defense mechanisms.	Pustika <i>et al.</i> (2026)
Osmotic and stress modulation	Silicon has a high hydrophilicity (water-attracting). In times of drought or extreme heat, it aids the plant in controlling the movement of its stomata, which regulates transpiration and greatly lowers water loss.	Sahebi (2015)
Abiotic stress mitigation	Under drought or heat stress, MSA reduces excessive water loss by regulating stomatal conductance. It also increases the production of antioxidants, neutralizing harmful reactive oxygen species (ROS) caused by stress.	Hasanuzzaman <i>et al.</i> (2021)
Heavy metal sequestration	MSA binds to toxic heavy metals (e.g., aluminum, cadmium, arsenic) in the soil and root system, restricting their movement into the edible parts (or consumable flowers) of the plant.	Riyazuddin <i>et al.</i> (2021)

2.3.5 Recovery response mechanism of horticultural plants grown under combined stress conditions and treated with a silicon-based fertiliser

A possible method for increasing horticultural plants' resistance to multiple stresses and advancing sustainable agricultural methods is the use of Si-based fertilisers. By acting as a recovery factor, these group 2 fertilisers lessen the detrimental effects of biotic and abiotic stresses on plant development, production, and quality, such as disease, nutrient deficiency, salinity, wounding, soil acidity, and water deficits. Therefore, by enhancing plant tolerance and maximising resource utilisation, Si-based liquid fertilisers contribute to the development of more efficient and sustainable agricultural systems (Moyo *et al.*, 2024). Beyond its traditional function in nutrient intake, silicon exhibits a variety of effects that lead to notable enhancements in plant growth, photosynthetic efficiency, and stress tolerance (Garcia-Carros *et al.*, 2025). Si-treated plants may undergo mechanical and metabolic changes that cause these effects.

There is little information and research on combined or multi-stress as a recovery response mechanism for both agronomic and horticultural plants grown under stress and treated with a Si-based fertiliser. However, information about a single stress factor has been widely reported. For example, Wei *et al.* (2018) found that Si-rich amendments in rice reduced heavy metal accumulation while increasing growth in acidic soil contaminated with multiple metals (Cd, Zn, Cu, and Pb). Furthermore, Fischhof *et al.* (2018) found that Si-fertiliser and biostimulants improve cell wall integrity, and that the combination of Si-fertiliser and biostimulant increases foliar N, Fe, and Si levels. Moreover, Carvalho *et al.* (2022), demonstrates that SB application via fertigation mitigated the damage caused by combined N and P deficiencies, which are two limiting nutrient stress for the beetroot crop. Furthermore, in terms of the optimized recovery processes, the SB reversed physical damage sustained by beetroot plants under N and P deficiencies by optimizing physiological processes, nutritional efficiency, and plant growth. In terms of the mechanism of action, it suggested that the mechanism involves SB application promoting a significant increase in SB absorption, which in turn benefits the antioxidant defense system and increases antioxidant compounds, thereby alleviating deficiencies. Additionally, AlKahtani *et al.* (2021), explains the application of SB and proline individually or in combination effectively mitigates the negative effects of droughts on beetroot, which is closely related to beetroot. And identifies the recovery mechanism involves the regulation of profile, antioxidant enzymes (CAT and SOD), and phenolic compounds, leading to improved relative water content, chlorophyll content, and NPK contents in stressed beetroot plants. Due to limited information on multi-stress, this study will form a path for further information regarding the review of Si-based fertiliser effects on multi-stress conditions.

2.4 Conclusion

It is conclusive that the SB are continuously gaining more relevance in the agricultural farming practice. As depicted by the current review, there are recent papers investigating the use of group 2 fertilisers against abiotic stress, such as water deficit. Insights into the expansion of SBs to African countries, including South Africa, should be explored in the near future. Findings from this review deduced that there are still gaps in terms of beetroot study under multi-abiotic stress in South Africa. Most combinations of stresses in connection with moisture deficit are drought and salinity. There is therefore limited information on combined moisture deficit under soil acidity conditions, and less information on P-deficiency combined with water

deficit in South Africa. There is thus still more work to be done on beetroot production under combined or multi-stress in South Africa.

CHAPTER THREE

MATERIAL AND METHODS

3. MATERIAL AND METHODS

3.1 Study site description

A 90-day experiment was conducted at the Nooitgedacht Research Station, a farm located near Ermelo in Mpumalanga, South Africa (26°31'11.5" S, 29°56'42.3" E; 1694 m), in the net house during the 2023/2024 cropping season and repeated during the 2024/2025 cropping season (Figure 3.1). The net house measured 30 × 5 m. The research farm spans an area of about 1 219 ha. The altitude of this area is 1 694 m above sea level. The climate at the farm is classified as temperate, with distinct summer and winter seasons. The area experiences warm, rainy summers and cold temperatures ranging from -2 to 18°C. The average annual rainfall is approximately 700 to 800 mm, most falling between November and March (Table 3.1).

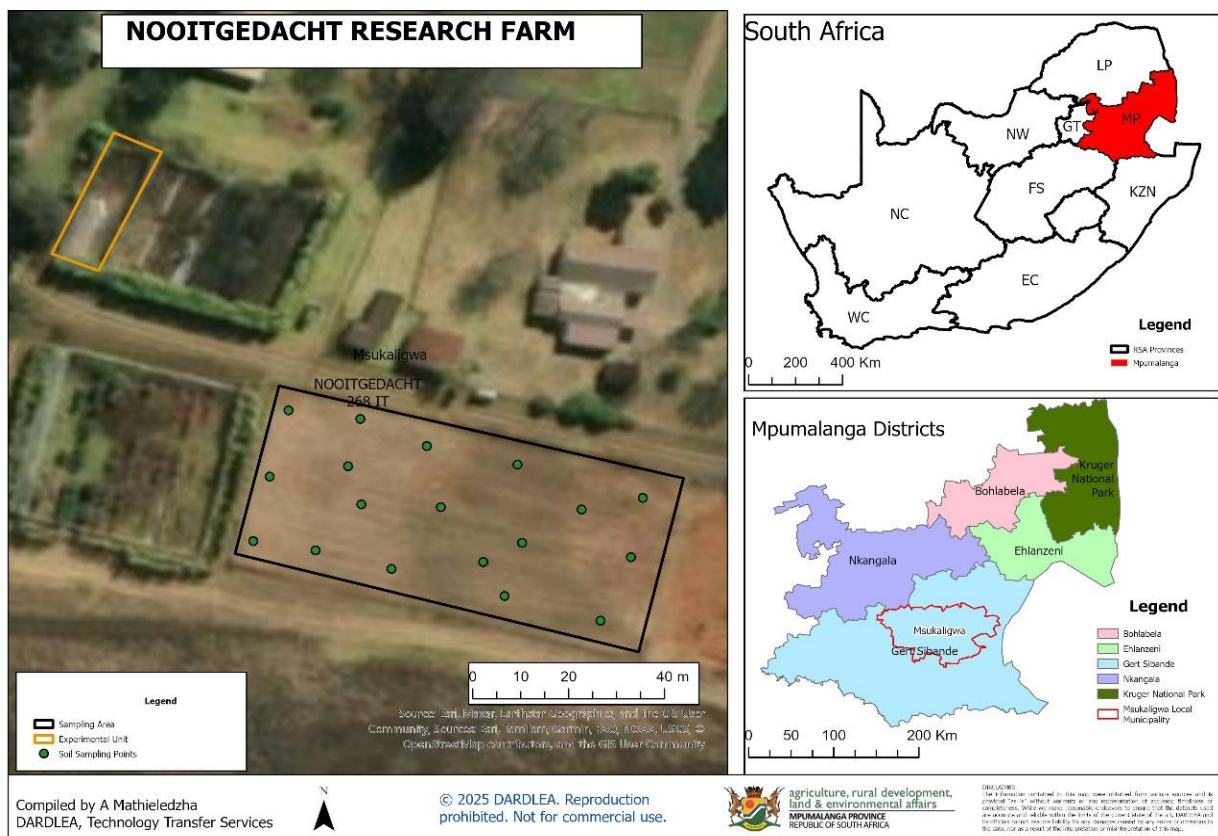


Figure 3.1: Location map of Nooitgedacht Research Farm in Mpumalanga Province, South Africa, showing the study area, illustrating soil sampling points and experimental units.

During the 2023/2024 and 2024/2025 cropping seasons, the mean temperatures, relative humidity, rainfall and reference evapotranspiration (ET_0) values were obtained from the Agricultural Research Council's automated weather station (Comp: 31219; station name: Ermelo-EDE farm), which is about 1 km to the experimental site (Table 3.1). However, rainfall

was not included in the experiments, because the rain shelter was made to cover the net-house during rainfall events. The soil around the experimental site was classified as Hutton soil form (Soil Classification Working Group, 1991) (Figure 3.1).

Table 3.1: Climate data for the 2023/24 (Season 1) and 2024/2025 (Season 2) cropping seasons (Moeletsi *et al.*, 2022).

Month	Temperature (°C)		Relative humidity (%)		Rainfall (mm)	ET ₀
	Min.	Max.	Min.	Max.		
Season 1						
Aug 2023	0.59	22.95	19.07	88.82	0	106.02
Sep 2023	6.16	26.85	21.44	85.52	46.74	125.09
Oct 2023	9.59	26.36	31.26	88.19	97.03	138.55
Nov 2023	12.08	28.28	33.61	89.49	58.42	149.39
Dec 2023	13.91	28.28	40.01	90.3	165.61	146.13
Jan 2024	13.50	28.00	39.88	92.1	104.14	149.35
Feb 2024	14.12	29.59	35.91	91.09	76.20	142.16
Mar 2024	13.51	29.03	34.38	91.25	71.37	135.48
Apr 2024	8.22	25.13	34.51	93.91	103.89	96.07
Season 2						
Aug 2024	0.89	25.04	0.89	80.93	0	107.64
Sep 2024	6.52	27.04	6.5	79.00	2.29	129.53
Oct 2024	8.45	28.03	8.45	81.04	28.96	153.34
Nov 2024	12.75	28.89	12.75	86.53	77.72	150.40
Dec 2024	15.22	29.86	15.22	85.57	194.82	159.18
Jan 2025	14.84	27.74	40.11	91.44	164.59	141.31
Feb 2025	16.06	27.48	44.36	90.1	233.17	112.91
Mar 2025	14.16	25.96	44.42	93.51	258.57	102.9
Apr 2025	10.85	22.42	48.02	94.16	130.56	77.11

ET₀, Reference evapotranspiration.



Figure 3.2: Classified soil; Orthic A topsoil/Red apedal B Horizon, Hutton (Hu) soil form (Soil Classification Working Group, 1991).

3.2 Experimental design and treatments

The 4×6 factorial design experiment was arranged in a Completely Randomised Block Design with three replications. The treatments comprised four Si-based fertilisers (SBs) of varying concentrations [0 - distilled water as a control (SB_0), 0.2 ($SB_{0.2}$), 0.4 ($SB_{0.4}$), and 0.6 L/ha ($SB_{0.6}$)], a factorial combination of two P deficit stress levels [20 kg/ha (P_{20}) and 40 kg/ha (P_{40})], and three water (W) deficit levels [25% (W_{25}), 50% (W_{50}), and 100% (W_{100}) of crop water requirement]: $P_{20}W_{25}$, $P_{40}W_{25}$, $P_{20}W_{50}$, $P_{40}W_{50}$, $P_{20}W_{100}$, and $P_{40}W_{100}$. The W_{25} , W_{50} , and W_{100} . The P_{20} (20 kg P/ha) and P_{40} (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W_{25} , W_{50} , and W_{100} represent the extreme water deficit level, moderate deficit level, and no deficit level or full irrigation of crop water requirement (ET_c), respectively. The experiment consisted of 24 treatment combinations as experimental units, where each treatment unit was represented by four potting bags, resulting in 96 potting bags per block (Figure 3.3a). The experimental units were 0.5 m apart, while blocks were 1 m apart, as described by Sinta & Garo (2021). The combined P and W stress began at 14 days after transplanting (DAT), while application of SB (CibuSil Max) commenced at 28 DAT. The SB was applied at 14-day intervals as a recovery mechanism to alleviate combined P and W deficit conditions.



Figure 3.3: Experimental layout showing potting bag arrangements (A), and general crop management practices involving weeding and pest and disease scouting (B).

3.3 Soil sampling, preparation and characterisation

The topsoil was collected at a depth of 0 to 20 cm from the field that had been fallow for over five years at the Nooitgedacht Experimental Farm (Figure 3.4a). The bulk soil was allowed to air-dry for three weeks. Thereafter, each potting bag (20 cm diameter and 30 cm height) was filled with 5 kg of soil. A sub-soil sample was also collected and analysed for physico-chemical properties following standard laboratory procedures (Non-Affiliated Soil Analyses Work Committee, 1990). The chemical properties comprised soil pH both for KCl and H₂O, electrical conductivity, cations (Ca, Mg, K and Na), and available soil P (Table 3.2). The physical properties included soil texture, bulk density and field capacity, permanent wilting point and available water holding capacity (Table 3.2).



Figure 3.4: Topsoil collection (0–20 cm) for experiment (A), net-house for experiment and prevention for birds (B).

Table 3.2: Selected physico-chemical properties of the soil before the establishment of experiments.

Soil property	Season 1	Season 2
Chemical properties		
pH (H ₂ O)	5.50	5.30
pH (KCl)	4.40	4.20
EC (mS/cm)	0.07	0.06
P (mg/kg)	10	8
K (mg/kg)	96	85
Ca (mg/kg)	201	199
Mg (mg/kg)	81	72
Na (mg/kg)	31	17
Physical properties		
Clay %	18.20	nd
Silt %	11.30	nd
Sand %	70.50	nd
Textural class	Sandy loam	nd
Bulk density (g/cm ³)	1.50	nd
Field capacity (mm/m)	289	nd
Permanent wilting point (mm/m)	118	nd
Available water holding capacity (mm/m)	172	nd

nd = not determined.

3.4 Seedling preparation and planting

Beetroot seeds (Detroit Dark Red cultivar) were purchased from a commercial seed supplier (Starke Ayres Pty Ltd, RSA) in Bloemfontein. The seeds were sown in 84-cell cavity polystyrene germination trays filled with a seedling growing medium supplied by Bark Unlimited Organics, Pretty Gardens (Bloemfontein, RSA), in the tunnel-house located at the Central University of Technology, Free State (CUT). The seedlings were fertigated with a nutrient solution described by Combrink and Kempen (2019) using a 2 L nozzle-calibrated precision sprayer at 0.3 MPa pressure (RedRhino, RSA) (Table 3.3). The seedlings were transported to the experimental site at six weeks after sowing, thinned and hardened for two days before transplanting into the potting bags filled with 5 kg of soil. The uniform six-week-old seedlings were transplanted in potting bags (1 seedling per potting bag) on the 19th of January 2024 for the first season and transplanted on the 7th of October 2024 for the second season.

Table 3.3: Fertiliser programme used in seasons 1 and 2, and nutrient solution composition for seedlings development up to six weeks.

Fertiliser	Quantity (per 250 L water)	
Hydroponic (Nutriplex)	2.5 kg	
NutriGro	2 kg	
Vita K	0.625 kg	
Fertiliser	Nutrient composition	Per 25 kg
Hydroponic (Nutriplex)	Nitrogen (N) g/kg	52
	Phosphorus (P) g/kg	50
	Potassium (K) g/kg	275.9
	Sulphur (S) g/kg	84
	Magnesium (Mg) g/kg	26.4
	Iron (Fe) mg/kg	2484
	Manganese (Mn) mg/kg	514
	Zinc (Zn) mg/kg	306
	Copper (Cu) mg/kg	34
	Boron (B) mg/kg	628
	Molybdenum (Mo) mg/kg	56
NutriGro	Nitrogen (N) g/kg	144
	Calcium (Ca) g/kg	150
	Magnesium (Mg) g/kg	19.7
Vita K	Potassium (K) g/kg	420
	Sulphur (S) g/kg	180
	Chlorine (Cl) g/kg	30
pH and EC levels	pH	EC (mS/cm)
	6.5 ± 1.0	2 ± 0.5

3.5 Crop management practices

3.5.1 Weeds and pest management

Weeds were manually removed throughout the growth period. Scouting for pests and insects (Figure 3.4, middle) was done routinely three times a day (8:00, 13:00, and 16:00), on a daily basis (Figure 3.3b). In Season 1, aphids (*Myzus persicae*) (Figure 3.5, left), tuber moths (*Phthorimaea operculella*) (Figure 3.5, right) and whiteflies (*Bemisia tabaci*; *Seasoneurodes vaporariorum*) were identified, whereas in Season 2, only aphids were found (Figure 3.4). A registered insecticide with acetamiprid (16 g/L) and bifenthrin (30 g/L) (Makhro Agro SA (Pty) Ltd, Act No. 36 of 1947) was applied to control the pests. The pesticide was repeated at an interval of 10–14 days.



Figure 3.5: Aphids (left), insect (middle), and tuber moth (right).

3.5.2 Irrigation scheduling

Prior to transplanting beetroot seedlings, an estimation of crop water requirements was conducted to guide the imposition of irrigation regimens. This approach integrated soil physical property analysis (Table 3.2). Hillel's (2003) formula was used to calculate the soil's available water-holding capacity (AWHC) using field capacity (FC), permanent wilting point (PWP), and bulk density (BD) using equation 1 below:

$$AWHC \text{ (mm/m)} = (FC - PWP) \dots\dots\dots \text{(Equation 1)}$$

Where: FC = Volumetric water content at field capacity, PWP = Volumetric water content at permanent wilting point.

This data was used to estimate the amount of plant-available water within a rooting depth of 30 cm (height of the potting bag). The obtained values provided a basis for understanding the soil's water-retention capacity, ensuring that imposed water regimens could be meaningfully related to the actual moisture availability.

The daily water requirement of the beetroot was calculated using reference evapotranspiration (ET_0) from a nearby automated weather station (Comp: 31219; station name: Ermelo- EDE farm), which is about 1 km from the experimental site. The standard model for calculating ET_0 (mm/day) was the FAO Penman-Monteith equation, which included meteorological variables like solar radiation, temperature, humidity, and wind speed (Allen *et al.*, 1998; Mabhaudhi *et al.*, 2013; Maseko *et al.*, 2019). To account for crop-specific water use at different growth stages, crop coefficient (K_c) values [Initial stage (0–20 DAT: $K_c = 0.70$); mid-season stage (30–60 DAT; $K_c = 1.050$); Late season stage (60–80+ DAT: $K_c = 0.9$)] were used to adjust ET_0 and calculate actual crop evapotranspiration (ET_c) using the equation below:

$$ETc = ET0 \times Kc \dots\dots\dots \text{(Equation 2)}$$

Where: ETc = crop water requirement, ET0 reference evapotranspiration, and Kc = crop factor.

The ETc values were then converted into daily irrigation volumes per potting pot (20 cm diameter) based on the surface area of the potting pot (0.0314 m²) using the equation below (Yusuf *et al.*, 2020):

$$\text{Water Volume (litres/day)} = ETc \text{ (mm)} \times PA \text{ (m}^2\text{)}\dots\dots\dots \text{(Equation 3)}$$

Where: ETc = crop water requirement, and PA = potting bag surface area.

The calculated water volumes were then converted to millilitres for practical application.

During the first two weeks, all the treatments received the same amount of water to establish the plants, and thereafter the irrigation treatments were imposed. Three irrigation regimens were implemented based on the daily ETc: 25% ETc (W₂₅ - extreme water stress deficit), 50% ETc (W₅₀ - moderate water stress deficit), and 100% ETc (W₁₀₀ - full irrigation)]. These treatments were applied manually three times per week, using a 1 000 mL graduated measuring cylinder to accurately measure and apply irrigation water to each potting bag.

3.5.3 Preparation and application of silicon-based liquid fertiliser

The SB was purchased from AgraForum South Africa (Pty) Ltd in Bloemfontein, Free State, South Africa. According to the manufacturer's guidelines, the recommended dosage for foliar application on vegetables is between 0.2 and 0.5 L/ha of fertiliser diluted in 500 L/ha of water. The information regarding the product name, registration and nutritional content is presented in Appendix 4.8.

To prepare the working SB solution for foliar application in this study, SB_{0.2}, SB_{0.4}, and SB_{0.6} were prepared by diluting 0.40, 0.80 and 1.20 mL of SB with 2 mL of wetting agent and deionised water in 1 000 mL volumetric flasks, respectively. A wetting agent (1%, v/v) was prepared by diluting 1 mL of the concentrated wetting agent in 100 mL of deionised water. To administer the SB treatments, the working SB solution was loaded into a calibrated hand-held sprayer (1 L capacity, 0.3 MPa pressure) and sprayed on plants until the entire upper surface of the leaves was thoroughly coated but not dripping excessively. The application of SB was repeated at an interval of 14 days, in accordance with crop physiological requirements and as

suggested by similar Si foliar spray studies (Laane, 2017; Ma & Yamaji, 2006). To prevent spray drift onto adjacent experimental plants, a paper box (450 mm × 300 mm × 650 mm) was used to shield the other treatment unit during SB application (Figure 3.6, left). The SB was applied in the morning (7:00) when the stomata were open (Santoso *et al.*, 2018), as shown in Figure 3.6 (right).



Figure 3.6: Measuring the shield box (left) and application of biostimulant (right).

3.5.4 Phosphorus application

The recommended P rate (100 kg/ha) for beetroot with the target yield of 30 tonnes/ha was obtained from the fertiliser handbook of the Fertilizer Society of South Africa (2016). As per the recommendation from the fertiliser guidelines, 100 kg/ha of P-fertilisation was suggested as sufficient, as indicated by the soil test results (Table 3.2). Hence, 20 kg/ha and 40 kg/ha rates were considered extreme and moderate P deficit levels. A full amount of P was applied before planting using the single superphosphate (10.5%) based on the calculated mass of soil used per pot and an assumption of 2 million kg/ha of soil per furrow slice (Masowa *et al.*, 2022). The fertiliser was mixed thoroughly with the soil.

3.6 Data collection

3.6.1 Growth parameters, chlorophyll content and stomatal conductance measurements

The plant height, number of leaves per plant, the leaf area, and leaf chlorophyll content were determined at 63 DAT, while stomatal conductance was measured 70 DAT. Plant height was measured from the soil surface to the leaf apex (tip) using a 30 cm ruler (Rantao, 2013). The number of leaves per plant was determined by manually counting the leaves per plant. The leaf length was measured with a ruler from the end of the petiole to the leaf apex, whereas the leaf width was measured with a ruler from the right margin to the left margin of the average leaf to estimate the leaf area (Kwizera *et al.*, 2023). The leaf area was estimated using the equation below (Varga *et al.*, 2021):

$$LA = L \text{ (cm)} \times W \text{ (cm)} \times 0.75 \dots\dots\dots \text{ (Equation 4)}$$

Where: LA is the leaf area; L is the length of the leaf; W is the width of the leaf; and 0.75 is the correction factor.

The leaf chlorophyll content

Pre-measurement calibration: the CCM-200 chlorophyll content meter was prepared for data collection through a standardised pre-measurement calibration protocol. The device was powered on after verifying battery sufficiency, followed by a zeroing procedure. This calibration was performed by depressing the measuring arm with an empty chamber, allowing the meter's optical components to normalize against an internal standard.

Chlorophyll content measurement: commenced once the interface displayed a “ready” status or a zero reading. Then after, the reading was measured on healthy and fully expanded leaves, selected from each experimental unit at 63 DAT in both seasons, using a portable non-destructive chlorophyll meter (Opti Sciences CCM 200, USA) on four represented plants (Chen & Black, 1992). To maintain technical accuracy through the study, this zero-calibration was repeated before each new batch of plants and whenever significant fluctuations in ambient temperature occurred.

The stomatal conductance

Calibration: A piece of Whatman no. 3 filter paper (or equivalent) was wetted with a single drop of distilled water. The paper was lightly shaken to remove excess water, ensuring a

glistening appearance without a visible meniscus. For plate installation, the wetted filter paper was placed flat over the hole in the calibration plate (side marked “Filter Paper”). For calibration execution, the calibration routine was initiated from the Configuration menu. The sensor head was clamped onto the calibration plate, ensuring the aluminum block seated firmly against the hard stop. For data Acquisition, the (SC-1, Decagon Devices, Pullman, WA, USA), automatically conducted 30-second calibration measurements, with the process repeating until three consecutive readings were within 7.5% of each other. For verification, following successful calibration and saving, a verification reading was taken. The resulting conductance value was confirmed to be within the expected range (216 to $264 \text{ mmol.m}^{-2} \cdot \text{s}^{-1}$) before taking the actual readings

Measurement: for accurate results, measurements were taken when the stomata were open between 10:00 and 14:00, as per Brewer *et al.* (2022), at 70 DAT before the termination. The measurement of the stomatal conductance was taken using a steady-state porometer (SC-1, Decagon Devices, Pullman, WA, USA) on a fully expanded mature leaf (Vitali *et al.*, 2015).

3.6.2 Yield parameters

The beetroot was manually harvested at 90 DAT to determine fresh leaf mass, dry leaf mass, fresh root mass, dry root mass, total fresh biomass, total dry biomass, root diameter and beetroot quality parameters on the 18th of April 2024 (season 1) and the 5th of January 2025 (season 2). The freshly harvested beetroot was washed with tap-water in clean 20 L buckets to remove dirt and debris. The cleaned beetroot was placed in a clear plastic bag and delivered to the laboratory (Figure 3.7, left). The excess moisture from the beetroot was removed with paper towels. The leaves were then separated from the roots (Figure 3.7, right). The mass of fresh leaves and roots was determined using a digital weighing scale with a maximum capacity of 1 200 g (RADWAG Wagi Elektroniczne, Poland, EU). Following this, the leaves were placed in brown paper bags and oven-dried using a Labcon forced circulation oven (FSOE-HD; Labcon Laboratory Equipment (PTY) LTD; Maraisburg, 1700, RSA) at 60°C for two days. After drying, the leaves were weighed to determine the dry mass. The root was cut into small portions using a knife and allowed to air-dry for a night to reduce excess moisture. Subsequently, the root was dried in an air-oven at 40°C for four days, following the same procedure used for leaf dry mass.

Total fresh biomass was obtained by summing fresh leaf mass and fresh root mass, while the total dry biomass was obtained by summing dry leaf mass and dry root mass. The F:D ratio was estimated by dividing the total fresh biomass by total dry biomass. Beetroot diameter was measured at right angles to the longitudinal axis using a Vernier calliper, as described by Yasaminshirazi *et al.* (2020).



Figure 3.7: Manual harvesting (left) and separating the leaves and roots (right).

3.6.3 Quality parameters

3.6.3.1 Total mineral concentration for beetroot leaves and roots

Total mineral concentration for the beetroot leaves and roots were determined using dry ashing method following the protocol of plant analyses as described by AGRILSA (2002) as follows:

Sample preparation: Beetroot clean leaves and air-dried sliced roots were placed in brown paper bags and oven-dried in a Labcon forced circulation oven (FSOE-HD; Labcon Laboratory Equipment (PTY) LTD; Maraisburg, 1700, RSA) at 60°C for 72 hours. Oven-dried, milled and ashed beetroot and leaf samples were used for the analysis of total P, K, Ca, Na, Mg, Mn, Cu, Fe, Mo, Co, B and Zn concentration.

Sample extraction: ashed mineral samples were extracted using 6 M HCl and 6 M HNO₃ and the solution was filtered into a 100 ml volumetric flask using a Whatman filter paper no. 40.

Preparation for the calibration standards for the ICP-OES: calibration standards were prepared by diluting commercially available 1,000 mg/L stock of selected elements (P, K, Ca, Mg, Na, Zn, Mn, Cu, Co, B, Mo and Fe) into a 100 ml volumetric flask filled with 0.5 N nitric acid. From the diluted stock solution, a calibration standard of (K, Ca, Mg: 5-500 mg/L), (P and Na: 1.0-100 mg/L) and (Zn, Mn, Mo, Fe, Co, B and Cu: 0.10-10.0 mg/L) were prepared with an appropriate matrix matching to the samples using 1 molar Nitric acid (HNO₃). as described by Kalra (1997) in handbook of reference methods for plant analysis.

Quality control measures: To ensure the quality results, initial calibration blank of 1 molar HNO₃ acid, 1 mg/l of initial calibration verification standard and continuing calibration blank run every 10 samples to ensure no memory effects. Continuing calibration verification standard run every 10 samples to ensure that calibration was still within specification (1mg/l). Quality control standard, high calibration verification standard to ensure that the upper range of calibration was still within specification as described by (Netshifhefhe, 2018).

Samples Analyses: The extracted sample solution from the 100 ml volumetric flask were then transferred into 15ml the test tubes and fitted into the sample rack, and their concentrations were measured using the Inductively Coupled Plasma-Optical Emission Spectroscopy instrument (ICP-OES -Optima 8300, Perkin Elmer, SA).

3.6.3.2 Phenolic content of beetroot

Sample preparation: Fresh beetroot was washed with distilled water to remove any soil particles or debris (Figure 3.7, left). To ensure uniform drying, the samples were sliced into thin sections (Figure 3.7, right). The sliced beetroot sample was then oven-dried at 40°C for four days using a Labcon forced circulation oven (Labcon Laboratory Equipment (PTY) LTD; Maraisburg, 1700, RSA). After drying, the samples were ground into fine powder with a Grindomix GM 200 laboratory mill (Retsch GmbH, Haan, Germany). Ground samples were analysed at Stellenbosch University's Department of Biochemistry (Western Cape, RSA) for phenolic analysis. This was performed according to the method described by Stander *et al.* (2017) and Mofokeng *et al.* (2020).

Extraction and Sample Preparation for Metabolomic Analysis: To extract metabolites, approximately 2 g of oven-dried and milled beetroot was accurately weighed into 50 mL polypropylene centrifuge tubes. Extraction was carried out with 15 mL of a solvent mixture consisting of 5 mL dimethyl sulfoxide (DMSO), 5 mL acetonitrile, and 5 mL of 50% methanol (MeOH) containing 0.1% formic acid (v/v). The mixture was ultrasonically treated for 30 minutes to improve extraction efficiency, followed by overnight shaking at room temperature to allow complete extraction of phenolic and secondary metabolites, as described by Dias *et al.* (2015). After extraction, 2 mL aliquots were withdrawn from each tube and centrifuged at 14 000 rpm for 10 minutes using a high-speed centrifuge to remove particulate matter. The resulting supernatant was carefully transferred into clean glass vials for subsequent liquid chromatography-mass spectrometry (LC-MS) analysis.

Liquid Chromatography-Mass Spectrometry (LC-MS) Analysis: High-resolution LC-MS analysis was performed using a Waters Synapt G2 quadrupole time-of-flight (QTOF) mass spectrometer (Waters Corp., Milford, MA, USA) coupled to a Waters Acquity ultra-performance liquid chromatograph (UPLC). Electrospray ionisation (ESI) was performed in negative ionisation mode using the following optimised source parameters: cone voltage at 15 V, desolvation temperature at 275°C, and desolvation gas flow rate of 650 L/h. Mass spectra were collected in the 150–1500 m/z range using both full scan (resolution mode) and data-independent acquisition (MSE mode), with low-energy (4 V) and high-energy (collision energy ramp 40–100 V) scans for structural elucidation. For mass accuracy, leucine enkephalin was used as a lock mass (reference mass), and sodium formate was used to calibrate the instrument before analysis. A Waters HSS T3 column (2.1 × 100 mm, 1.7 μ m particle size) was used at 55°C for chromatographic separation. The injection volume was set to 2 μ L. The mobile phases were composed of solvent A (0.1% formic acid in water) and solvent B (acetonitrile containing 0.1% formic acid). The gradient elution program was as follows: initial 100% A for 1 minute, followed by a linear increase to 28% B over 22 minutes, ramped up to 40% B over 50 seconds, held at 100% B for 1.5 minutes, and then re-equilibrated to initial conditions for 4 minutes. The flow rate was maintained. All samples were analysed three times to ensure analytical reproducibility. Data acquisition and processing were performed using MassLynx software (Waters Corp., USA).



Figure 3.8: Beetroot after harvesting (left) and sliced beetroot samples (right).

3.6.4 Collection and processing of postharvest soil quality parameters

A sub-sample of soil samples was collected from each potting bag at the depth of surface down to 15 cm and analysed following standard laboratory procedures (Non-Affiliated Soil Analyses Work Committee, 1990). The soil pH, which controls nutrient availability and solubility, was measured in a solution with a ratio of 1:2.5 in both deionised water (H_2O) and 1 M potassium chloride (KCl) using the electrode method (Thomas, 1996). The electrical conductivity (EC) as a concentration of soluble salt was determined using soil water suspension in the ratio of 1:2.5 and it was prepared by taking 10 g soil and 25 ml distilled water in a 50 ml beaker, as described by Jackson (2005), and the reading was measured using a HI9813-5 and HI9813-6 pH and EC Meters HANNA instrument, respectively.

Available P was extracted using Bray-1 method (Bray & Kurtz, 1945), where sample extraction was done by adding 50 ml of Bray-1 solution to 6.67 g of sample. The reagent A was achieved by first dissolving 12 g of ammonium molybdate in 250 ml of distilled water. Similarly, 0.29 g of antimony potassium tartrate was dissolved in a separate 100 ml of distilled water. Both reagents were mixed with 148 ml sulphuric acid to 1 L; the reagents were then transferred to a 2 L volumetric flask and filled to the mark with distilled water. Preparation of reagent B was done by dissolving 1.06 g of ascorbic acid into 200 ml of reagent A. A P-stock solution of 0.55 g potassium dihydrogen phosphate (KH_2PO_4) was used to prepare standard solutions, and its concentration and absorbance was read using ultraviolet-visible spectroscopy (LAMBDA 265 UV-VIS Spectroscopy, Perkin Elmer, RSA).

Other related soil parameters affecting the availability and uptake of P, such as the exchangeable cations (Ca, Mg, K, Na), were determined using the 1 M (NH₄OAc) extractable ammonium acetate adjusted at a pH of 7, where a 10 ± 0.05 g sample of air-dried soil was put through a ≤ 2 mm sieve and thereafter placed in a 100 ml extraction bottle. Next, 100 mL of NH₄OAc solution, cooled to $20 \pm 2^\circ\text{C}$, was added to the soil in the extraction bottle. The mixture was shaken horizontally on a reciprocating shaker at 180 oscillations per minute for 30 minutes. The extract was rapidly filtered using Whatman no. 40 filter papers and their concentrations measured using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES-Optima 8300, Perkin Elmer, RSA), as described by Peech (1965).

3.7 Statistical Analysis

Data on beetroot growth parameters, yield and quality as well as selected soil quality parameters were subjected to analysis of variance using PROC GLIMMIX, SAS version 9.4 (PROC GLIMMIX, SAS Institute 2013). Treatments' means were separated using the Tukey's post hoc test at 5% level of significance (Steel & Tourie, 1980). The Shapiro-Wilks test and homogeneity of variance were performed on standardised residuals to test for any deviations from normality and homoscedasticity, respectively (Shapiro & Wilk, 1965). The leaf and root mineral content, and soil parameters were subjected to multivariate data analysis, using principal component analysis (PCA-XLSTAT, 2015) to identify and evaluate the groupings between the variables. The Pearson's correlation was used to determine the relationships between the total leaf and root mineral content. For the phenolic profiling, waters acquity ultra-performance liquid chromatography combined with a PCA was used to profile the phenolics, and heatmaps were constructed to visualise or display the relative abundance and distribution of multiple phenolic compounds, and to provide an overview of complex data to allow for ease of identifying patterns and clusters.

CHAPTER FOUR

RESULTS AND DISCUSSION

4. RESULTS AND DISCUSSION

4.1 Analysis of the homoscedasticity across production seasons

Prior to evaluating the treatment effects between the two experimental seasons, the Shapiro-Wilks test and homogeneity of variance were performed on standardised residuals to test for any deviations from normality and homoscedasticity, respectively, which measures the equality of variances between seasons. Heteroscedasticity between the two cropping seasons was shown by the results, which showed a lack of variance homogeneity ($P < 0.05$). Since merging the datasets would have obscured significant seasonal impacts resulting from variations in soil moisture and climate, this statistical result supported the choice to examine and explain the results independently for each season.

The climatic data presented in Table 3.1 clearly demonstrate seasonal variability, with season 2 receiving substantially higher rainfall (1 061 mm) compared to season 1 (723 mm), along with slightly elevated minimum and maximum temperatures and lower evapotranspiration (ET_0) rates during the late growth phases. These better growing conditions in season 2 likely enhanced soil moisture retention, nutrient availability, and photosynthetic activity, which collectively improved plant vigour and biomass accumulation. Because temperature, rainfall, relative humidity, and ET_0 directly affect nutrient absorption, stomatal conductance, and assimilate partitioning in root crops like beetroot (*Beta vulgaris* L.), it was crucial to include these climatic data in order to explain the physiological and yield responses observed (Colla *et al.*, 2020; Jayara *et al.*, 2023).

4.2 Growth of beetroot in response to Si-based liquid fertiliser application, and combined phosphorus and water deficit levels

4.2.1 Plant growth parameters, leaf chlorophyll content and stomatal conductance

The results on the effect of Si-based liquid fertiliser (SB), combined phosphorus (P) and water (W) deficit levels, and cropping season on plant growth parameters, leaf chlorophyll content at 63 DAT, and leaf stomatal conductance at 70 DAT are reported in Table 4.1. Leaf stomatal conductance was significantly ($P < 0.0001$) affected by the application of SB, whereas plant height, number of leaves per plant, leaf area, and leaf chlorophyll content were not affected by the application of SB. The SB_{0.2} application significantly increased the leaf stomatal conductance by 21% compared to the control. This finding agrees with the findings of Zhou *et*

al. (2024), who reported a significant increase in stomatal conductance of beetroot due to foliar application of a SB. The non-significant effect of SB application on leaf chlorophyll content contradicts with the findings reported by AlKahtani *et al.* (2021) where the SB application, either individually or in combination with proline, significantly increases Chlorophyll a and Chlorophyll b concentrations in drought-stressed beetroot plants compared to untreated stressed plants.

The number of leaves per plant and leaf stomatal conductance were not affected by the combined P and W deficit levels, while plant height, leaf area, and the leaf chlorophyll content varied significantly with P and W deficit levels (Table 4.1). Phosphorus plays a fundamental role in regulating physiological responses and enhancing abiotic stress tolerance in plants (Hawkesford *et al.*, 2023). It has been reported that P deficit in the soil adversely affects fruit production, quality traits during vegetative growth and root development, ultimately resulting in reduced crop yields (Jezek *et al.*, 2023). Sebonela (2022), also reported stunted growth on Swiss chard due to P deficit and soil acidity. The P₄₀W₂₅ led to a substantial decrease in plant height and leaf area by 11%, compared to P₄₀W₁₀₀. Similar findings were observed by Elansary *et al.* (2019), who reported a significant decrease in plant height by 17% and 41% under 70% and 50% water deficit levels, respectively.

The leaf area and leaf chlorophyll content recorded from P₂₀W₂₅ were significantly reduced by 22% and 21%, respectively, compared to P₄₀W₁₀₀ (Table 4.1). Similar findings were observed by Elansary *et al.* (2019), who reported a significant decrease in leaf area by 24% and 52.40% under 70% and 50% W deficit levels, respectively. The leaf area results from this study may be corroborated with findings by Suminarti *et al.* (2020), who reported a 297% decrease in leaf area by from 350 mm/season relative to 1 150 mm/season.

A similar study conducted by Villa e Vila *et al.* (2024) addressed the reduced chlorophyll content by 48% and 60% under 80% and 60% irrigation based on the evapotranspiration (ET_c), respectively. The cropping season had a significant effect on plant height, number of leaves per plant, leaf chlorophyll content, and stomatal conductance ($P < 0.0001$). Plant height and number of leaves per plant were higher by 16% and 15%, respectively, while the leaf chlorophyll content and leaf stomatal conductance were higher by 93% and 16%, respectively, in season 2 than in season 1. The leaf area was not affected by the cropping season.

Table 4.1: The effect of Si-fertiliser, combined phosphorus and water deficit levels, and cropping season on plant growth parameters, leaf chlorophyll content at 63 DAT, and leaf stomatal conductance at 70 DAT.

Treatments	Plant height (cm)	Number of leaves per plant	Leaf area (cm ²)	Leaf chlorophyll content (CCI)	Leaf stomatal conductance (mmol/m ² s)
Fertiliser					
SB ₀	22.22 ± 2.84	8 ± 2.02	53.27 ± 10.85	26.52 ± 12.34	210.90 ± 50.40b
SB _{0.2}	21.45 ± 3.39	7 ± 1.65	54.71 ± 14.44	28.95 ± 10.89	254.29 ± 110.60a
SB _{0.4}	22.17 ± 2.90	8 ± 1.37	54.07 ± 14.39	27.36 ± 11.99	195.53 ± 51.91b
SB _{0.6}	21.51 ± 2.95	8 ± 1.62	53.66 ± 15.83	26.20 ± 8.85	201.59 ± 69.01b
LSD _(0.05)	ns	ns	ns	ns	25.52
F-value	1.10	0.76	0.08	1.25	8.65
P-value	0.3522	0.5208	0.9724	0.2966	<0.0001
Phosphorus and water deficit levels					
P ₂₀ W ₂₅	21.51 ± 2.39abc	8 ± 1.32	50.79 ± 10.22c	26.38 ± 11.55b	213.26 ± 46.10
P ₄₀ W ₂₅	20.82 ± 3.50c	7 ± 1.25	47.11 ± 9.29bc	26.94 ± 11.16ab	192.06 ± 54.34
P ₂₀ W ₅₀	21.23 ± 2.61bc	8 ± 1.58	50.81 ± 10.85abc	24.73 ± 10.39b	225.98 ± 72.50
P ₄₀ W ₅₀	21.33 ± 2.50abc	7 ± 1.84	52.76 ± 11.96abc	26.84 ± 11.51ab	210.78 ± 72.50
P ₂₀ W ₁₀₀	22.92 ± 2.56ab	8 ± 1.90	60.69 ± 15.82ab	26.74 ± 10.00ab	213.81 ± 88.51
P ₄₀ W ₁₀₀	23.19 ± 3.77a	8 ± 2.03	61.73 ± 17.79a	31.95 ± 11.39a	236.85 ± 111.77
LSD _(0.05)	1.34	ns	7.45	3.77	31.25
F-value	4.21	1.01	4.98	3.31	2.03
P-value	0.0017	0.4148	0.0004	0.0085	0.0820
Season					
Season 1	23.26 ± 3.02a	8 ± 1.41a	55.34 ± 14.31	18.59 ± 6.21b	198.98 ± 80.46b
Season 2	20.44 ± 2.28b	7 ± 1.72b	52.53 ± 13.33	35.82 ± 7.53a	230.96 ± 70.45a
LSD _(0.05)	0.773	0.5097	4.3031	2.1792	18.046
F-value	53.95	22.04	1.34	244.67	5.98
P-value	<0.0001	<0.0001	ns	<0.0001	<0.0001

Means followed by the same letter(s) in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

The significant ($P=0.0459$) interaction between Si-fertiliser, and combined phosphorus and water deficit levels was recorded only on the leaf stomatal conductance (Table 4.2). Compared to $SB_0 \times P_{20} W_{100}$, the $SB_{0.2} \times P_{20} W_{100}$ significantly improved the leaf stomatal conductance by 55%. Li *et al.* (2025) have reported an increase in stomatal conductance, photosynthetic rate, intercellular carbon dioxide concentration, and transpiration under W stress conditions following application of SB on soil. The potential of Si to mitigate the adverse effects of water deficit was also demonstrated by Villa e Vila *et al.* (2024), who reported that, in the first crop cycle of lettuce, the 80% ETc + Si treatment increased yield by 6.3%, while the 60% ETc + Si treatment led to a 7.7% increase compared to the untreated control. These positive results could be related to the role of Si in regulating leaf transpiration and root water absorption (Chen *et al.*, 2018). Hafez *et al.* (2021) observed that foliar spraying of Si, N and P improved the CO₂ assimilation rate in plants by enhancing stomatal conductance in leaves, leading to a decline in water lost through transpiration.

Regardless of the non-significant difference observed, the increase in leaf area and leaf chlorophyll content recorded from $SB_{0.2} \times P_{20} W_{100}$ were 25% and 21% greater than those recorded from $SB_0 \times P_{20} W_{100}$, respectively. Similarly, the $SB_{0.4} \times P_{20} W_{100}$ led to a quantitative increase in leaf area (28%) and leaf chlorophyll content (21%) compared to $SB_0 \times P_{20} W_{100}$. This finding suggests that, in the long term, the $SB_{0.2}$ could have a potentially significant effect. Although further research is needed, these results show the potential of SB in alleviating plant stress. A similar study conducted by Villa e Vila *et al.* (2024) also revealed a non-significant increase in leaf chlorophyll content following application of Si under W deficit conditions.

The interaction effects between SB and cropping season on plant height, number of leaves per plant, leaf area, leaf chlorophyll content, and stomatal conductance were not significant, as illustrated in Table 4.3. Although differences in leaf stomatal conductance were not significant, the leaf stomatal conductance recorded from $SB_{0.2}$ in season 2 was quantitatively higher by 21% than $SB_{0.2}$ compared to season 1. A similar trend was observed for chlorophyll content in season 2, where $SB_{0.2}$ was quantitatively higher by 122% compared to season 1.

Table 4.2: The interaction effect between Si-fertiliser and combined phosphorus and water deficit levels on plant growth parameters, leaf chlorophyll content 63 DAT, and leaf stomatal conductance at 70 DAT.

Fertiliser	PW deficit levels	Plant height (cm)	Number of leaves per plant	Leaf area (cm ²)	Leaf chlorophyll content (CCI)	Stomatal conductance (mmol/m ² s)
SB ₀	P ₂₀ W ₂₅	20.60 ± 2.12	8 ± 1.36	49.84 ± 10.23	28.84 ± 12.68	226.66 ± 70.84b
	P ₄₀ W ₂₅	21.33 ± 3.88	7 ± 1.20	47.52 ± 10.77	27.84 ± 16.38	180.79 ± 12.98b
	P ₂₀ W ₅₀	23.37 ± 1.70	8 ± 1.78	57.91 ± 4.75	21.20 ± 7.89	226.20 ± 49.71b
	P ₄₀ W ₅₀	21.43 ± 2.75	7 ± 2.24	55.88 ± 13.36	25.11 ± 11.15	213.59 ± 44.51b
	P ₂₀ W ₁₀₀	22.86 ± 2.35	9 ± 2.56	49.96 ± 13.26	28.31 ± 13.26	210.95 ± 42.36b
	P ₄₀ W ₁₀₀	23.75 ± 3.39	9 ± 2.73	58.51 ± 9.67	27.81 ± 14.95	207.19 ± 68.24b
SB _{0.2}	P ₂₀ W ₂₅	20.93 ± 1.41	7 ± 1.58	51.95 ± 3.84	30.91 ± 12.39	221.87 ± 31.41b
	P ₄₀ W ₂₅	21.96 ± 4.47	7 ± 1.25	50.40 ± 9.44	25.08 ± 11.48	241.78 ± 65.31ab
	P ₂₀ W ₅₀	20.66 ± 1.85	8 ± 1.03	48.63 ± 7.89	22.92 ± 8.11	217.38 ± 106.37b
	P ₄₀ W ₅₀	20.21 ± 2.70	8 ± 2.33	53.27 ± 13.95	30.28 ± 12.68	242.91 ± 105.98ab
	P ₂₀ W ₁₀₀	23.43 ± 3.43	8 ± 2.22	61.91 ± 14.28	29.74 ± 10.40	266.88 ± 148.71ab
	P ₄₀ W ₁₀₀	21.54 ± 5.32	6 ± 1.16	62.07 ± 26.27	34.76 ± 10.07	351.07 ± 159.98a
SB _{0.4}	P ₂₀ W ₂₅	21.89 ± 3.32	8 ± 1.63	45.65 ± 13.39	19.95 ± 11.19	194.24 ± 34.91b
	P ₄₀ W ₂₅	21.04 ± 3.13	8 ± 1.56	45.65 ± 10.00	30.34 ± 7.68	175.30 ± 23.91b
	P ₂₀ W ₅₀	21.68 ± 3.12	7 ± 1.24	54.89 ± 12.97	27.15 ± 14.27	210.21 ± 80.80b
	P ₄₀ W ₅₀	22.29 ± 2.50	8 ± 1.14	53.94 ± 13.72	27.03 ± 13.83	211.47 ± 63.08b
	P ₂₀ W ₁₀₀	22.21 ± 1.94	8 ± 1.46	60.34 ± 16.15	24.87 ± 10.59	177.76 ± 41.49b
	P ₄₀ W ₁₀₀	23.89 ± 3.57	8 ± 1.63	63.95 ± 14.74	34.86 ± 12.77	204.24 ± 57.61b
SB _{0.6}	P ₂₀ W ₂₅	22.62 ± 2.41	8 ± 0.81	55.72 ± 10.87	25.84 ± 9.62	210.29 ± 42.46b
	P ₄₀ W ₂₅	18.60 ± 1.68	8 ± 1.16	44.88 ± 8.40	24.01 ± 68.78	170.39 ± 67.50b
	P ₂₀ W ₅₀	19.18 ± 2.02	9 ± 1.97	41.82 ± 10.29	27.65 ± 11.34	250.11 ± 52.69ab
	P ₄₀ W ₅₀	21.39 ± 2.23	7 ± 1.77	47.94 ± 7.49	24.94 ± 10.53	175.13 ± 64.85b
	P ₂₀ W ₁₀₀	23.21 ± 2.83	8 ± 1.57	70.56 ± 15.94	24.06 ± 6.14	199.68 ± 72.23b
	P ₄₀ W ₁₀₀	23.60 ± 3.01	8 ± 2.05	62.50 ± 21.59	30.35 ± 8.09	203.94 ± 99.20b
LSD _(0.05)		ns	ns	ns	ns	62.54
F-value		1.55	0.84	1.15	1.59	1.80
P-value		0.1048	0.6344	0.3227	0.0925	0.0459

Means followed by the same letter in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, combined phosphorus and water deficit levels; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

Table 4.3: The interaction effects between Si-fertiliser/combined phosphorus and water deficit levels, and cropping season on plant growth parameters, leaf chlorophyll content at 63 DAT, and stomatal conductance at 70 DAT.

Treatment	Plant height (cm)	Number of leaves per plant	Leaf area (cm ²)	Leaf chlorophyll content (CCI)	Stomatal conductance (mmol/m ² s)
Fertiliser					
Season 1					
SB ₀	23.86 ± 2.29	9 ± 1.58	54.65 ± 8.40	16.78 ± 4.68	205.42 ± 48.56
SB _{0.2}	22.72 ± 3.71	8 ± 1.75	53.88 ± 15.09	20.71 ± 7.12	229.65 ± 125.80
SB _{0.4}	23.86 ± 2.52	8 ± 1.02	57.25 ± 15.31	17.87 ± 8.00	193.46 ± 63.13
SB _{0.6}	22.65 ± 3.33	8 ± 1.04	55.69 ± 17.82	18.95 ± 4.12	168.77 ± 57.36
Season 2					
SB ₀	20.59 ± 2.39	7 ± 2.11	51.89 ± 12.95	36.25 ± 9.54	216.37 ± 53.00
SB _{0.2}	20.19 ± 2.56	7 ± 1.52	55.53 ± 14.16	37.19 ± 7.07	277.56 ± 91.60
SB _{0.4}	20.65 ± 2.35	7 ± 1.42	51.22 ± 13.28	35.86 ± 7.83	197.39 ± 41.12
SB _{0.6}	20.31 ± 1.94	7 ± 1.90	51.51 ± 13.61	33.88 ± 5.16	234.40 ± 65.07
LSD _(0.05)	ns	ns	ns	ns	ns
F-value	0.28	0.62	0.50	0.78	2.48
P-value	0.8379	0.6027	0.6838	0.5054	0.0661
Phosphorus and Water deficit levels					
Season 1					
P ₂₀ W ₂₅	23.18 ± 1.96	8 ± 1.07	53.10 ± 11.27	16.77 ± 5.70	213.40 ± 45.98
P ₄₀ W ₂₅	22.34 ± 3.79	8 ± 0.66	49.08 ± 8.99	17.86 ± 5.53	183.22 ± 65.09
P ₂₀ W ₅₀	22.60 ± 2.29	8 ± 1.02	50.61 ± 11.72	16.72 ± 3.43	208.73 ± 68.32
P ₄₀ W ₅₀	22.68 ± 2.54	8 ± 1.73	52.86 ± 9.09	17.52 ± 4.70	182.40 ± 66.87
P ₂₀ W ₁₀₀	24.37 ± 2.13	9 ± 1.30	61.75 ± 17.28	18.62 ± 4.97	180.81 ± 46.03
P ₄₀ W ₁₀₀	24.33 ± 4.56	9 ± 2.09	64.12 ± 19.47	23.97 ± 9.25	226.28 ± 153.42
Season 2					
P ₂₀ W ₂₅	19.84 ± 1.44	7 ± 1.43	48.48 ± 18.93	36.00 ± 6.72	213.13 ± 48.26
P ₄₀ W ₂₅	19.43 ± 2.69	7 ± 1.44	45.44 ± 9.57	35.26 ± 7.97	199.54 ± 44.69
P ₂₀ W ₅₀	19.85 ± 2.21	8 ± 2.05	51.01 ± 10.44	32.73 ± 8.62	243.22 ± 75.33
P ₄₀ W ₅₀	19.98 ± 1.61	7 ± 1.73	52.65 ± 14.72	36.16 ± 8.09	239.15 ± 68.99
P ₂₀ W ₁₀₀	21.48 ± 2.14	7 ± 2.07	59.64 ± 14.92	34.87 ± 6.38	246.82 ± 109.01
P ₄₀ W ₁₀₀	22.06 ± 2.48	7 ± 1.45	59.08 ± 16.28	39.92 ± 6.86	246.54 ± 58.07
LSD _(0.05)	ns	ns	ns	ns	ns
F-value	0.17	1.30	0.18	0.28	1.48
P-value	0.9718	0.2696	0.9686	0.9221	0.2049

Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns; not significant.

The interaction effects between combined P and W deficit levels and cropping season did not significantly impact plant height, number of leaves per plant, leaf area, chlorophyll content, and stomatal conductance (Table 4.3). Plant height and number of leaves recorded from P₄₀W₁₀₀ in season 1 were generally higher than those recorded in season 2. Contrarily, the leaf chlorophyll content and stomatal conductance were generally lower in season 1 than those recorded in season 2.

Plant height was significantly ($P=0.0052$) influenced by the interaction effect among SB, combined P and W deficit levels, and cropping season. The SB_{0.4}×P₄₀W₁₀₀ significantly ($P<0.0001$) increased the plant height as compared to SB_{0.6}×P₄₀W₂₅ in season 1. Furthermore, plant height recorded from SB_{0.4}×P₄₀W₁₀₀ in season 1 was higher by 48%, 48%, and 47% compared to SB₀×P₄₀W₂₅, SB_{0.6}×P₂₀W₅₀, and SB_{0.2}×P₄₀W₂₅, respectively, in season 2.

The interaction effects among Si-fertiliser, combined P and W deficit levels, and cropping season were not significant for the number of leaves per plant, leaf area, and leaf chlorophyll content (Table 4.4). Generally, in season 1, SB_{0.2}×P₄₀W₁₀₀ gave a higher value of leaf chlorophyll content compared to the other treatments in both seasons, indicating a possible beneficial effect of this treatment on leaf chlorophyll levels. The SB_{0.4}×P₄₀W₁₀₀ interaction in season 1 resulted in the highest leaf area across both seasons, indicating the potential effect of SB_{0.4}×P₄₀W₁₀₀ in improving plant growth. The leaf stomatal conductance was significantly ($P<0.0001$) affected by the interaction among fertiliser, combined phosphorus and water deficit levels, and cropping season (Table 4.4). The SB_{0.2}×P₄₀W₁₀₀ significantly increased the leaf stomatal conductance by 124% in season 1 compared to SB_{0.2}×P₄₀W₁₀₀ in season 2 (Table 4.4). In addition, the SB_{0.2}×P₄₀W₁₀₀ in season 1 was highly significant ($P<0.0001$) in comparison with the other treatments across both seasons, indicating a synergistic effect of SB_{0.2} and combined moderate P application and full irrigation treatment. This synergistic effect trend was also observed on the leaf chlorophyll content (Table 4.4).

Sadiki *et al.* (2025) reviewed the existing literature on the effects of Si-based biostimulants and P application as a mitigating strategy to improve P assimilation, growth and yield of beetroot grown under adverse multi-stress conditions in South Africa. The review explained that abiotic stresses, such as moisture deficit and P deficiency, often co-occur, causing severe consequences for the growth and quality of horticultural species, including beetroot. The findings from the review indicated that the cited research demonstrated increased growth parameters such as potato plant height and leaf area following the application of Si-based biostimulant, and

improved lettuce growth and water stress tolerance. Such findings motivated the eager to consider the use of liquid-based fertiliser containing Si which are readily available in South African retails, for the purpose of this current research. When assessing the performance of SB against the above review findings. Its worthy noting that SB did not have a statistically significant effect on leaf area, number of leaves per plant, chlorophyll content (table 4.4), suggesting a poor performance. The lack of significance by SB could be due to the fact that, when comparing Si-based biostimulant and Si-liquid fertilizer, they differ due to their complex, multi-mode action, which goes beyond merely supplying silicon. While liquid fertilisers offer Si nutrition, Si-based biostimulants typically combine Si with amino acids, humic substances, or other organic compounds that stimulate that plant's natural physiological processes, leading to superior stress tolerance and nutrient uptake (Basar *et al.*, 2025). In brief, Si-based biostimulant is often better because it offers a “synergistic package” that includes improved metabolic stimulation and stress protection, whereas Si-liquid fertiliser usually only provides structural strengthening SiO_2 deposition (Tayade *et al.*, 2022). Additionally, through observations on the conducted research on some biostimulants, is, while these are labelled as fertilizers, in South Africa, they do not perform the function of a fertilizer, neither do they contain the minimum required nutrient levels for them to meet the threshold of being fertilizers. Also, their efficacy is assessed and approved by the AIC under quite vague or dubious experimental conditions. So, when researchers subject them to especially soil, they perform poorly.

Table 4.4: The interaction effect among Si-fertiliser, combined phosphorus and water deficit levels, and cropping season on plant growth parameters, leaf chlorophyll content at 63 DAT, and stomatal conductance at 70 DAT.

Fertiliser	PW deficit levels	Plant height (cm)	Number of leaves per plant	Leaf area (cm ²)	Leaf chlorophyll content (CCI)	Stomatal conductance (mmol/m ² s)
Season 1						
SB ₀	P ₂₀ W ₂₅	22.33 ± 1.37ab	8 ± 0.28	52.59 ± 13.99	18.10 ± 5.40	207.46 ± 62.17c
	P ₄₀ W ₂₅	24.58 ± 1.70ab	8 ± 0.57	54.15 ± 7.62	14.76 ± 1.71	191.60 ± 7.71c
	P ₂₀ W ₅₀	24.25 ± 1.88ab	8 ± 0.86	54.06 ± 2.11	16.86 ± 3.60	226.58 ± 66.66bc
	P ₄₀ W ₅₀	22.50 ± 3.04ab	8 ± 2.29	52.40 ± 3.14	18.30 ± 5.06	189.85 ± 39.04c
	P ₂₀ W ₁₀₀	23.83 ± 0.76ab	9 ± 1.52	49.56 ± 8.36	17.45 ± 3.90	241.96 ± 10.10bc
SB _{0.2}	P ₄₀ W ₁₀₀	25.66 ± 3.78ab	11 ± 1.60	65.15 ± 6.53	15.25 ± 9.17	175.10 ± 73.07c
	P ₂₀ W ₂₅	21.58 ± 1.62ab	8 ± 1.04	54.34 ± 3.99	21.15 ± 5.82	244.58 ± 8.25bc
	P ₄₀ W ₂₅	25.75 ± 2.46ab	8 ± 0.57	56.56 ± 7.96	14.98 ± 1.98	225.55 ± 81.55bc
	P ₂₀ W ₅₀	22.08 ± 0.57ab	7 ± 0.76	44.68 ± 5.25	16.48 ± 3.26	151.83 ± 3.29bc
	P ₄₀ W ₅₀	20.58 ± 3.50ab	8 ± 3.05	50.37 ± 14.11	19.60 ± 7.12	187.58 ± 87.60c
SB _{0.4}	P ₂₀ W ₁₀₀	25.91 ± 2.37ab	9 ± 2.02	62.62 ± 21.73	22.10 ± 8.19	141.28 ± 19.76bc
	P ₄₀ W ₁₀₀	20.41 ± 6.64ab	6 ± 0.76	54.72 ± 29.76	29.95 ± 7.44	525.85 ± 23.40a
	P ₂₀ W ₂₅	24.50 ± 2.00ab	9 ± 1.81	47.79 ± 20.21	10.28 ± 3.53	186.93 ± 51.27c
	P ₄₀ W ₂₅	20.25 ± 1.41ab	8 ± 0.35	40.26 ± 3.11	24.47 ± 10.21	178.07 ± 36.52c
	P ₂₀ W ₅₀	23.83 ± 2.62ab	8 ± 1.44	63.25 ± 12.87	15.65 ± 4.84	234.48 ± 115.13bc
SB _{0.6}	P ₄₀ W ₅₀	24.50 ± 0.25ab	9 ± 0.50	59.78 ± 9.93	16.41 ± 3.80	217.41 ± 84.73bc
	P ₂₀ W ₁₀₀	22.16 ± 2.25ab	8 ± 1.25	56.00 ± 17.04	15.63 ± 1.17	171.51 ± 42.59bc
	P ₄₀ W ₁₀₀	26.75 ± 1.75a	9 ± 0.28	70.75 ± 12.05	27.00 ± 11.65	167.25 ± 29.95bc
	P ₂₀ W ₂₅	24.33 ± 1.75ab	9 ± 0.76	57.68 ± 1.40	17.56 ± 2.75	214.61 ± 50.01bc
	P ₄₀ W ₂₅	18.08 ± 2.12b	8 ± 1.15	42.40 ± 3.29	19.43 ± 4.47	135.96 ± 87.39bc
SB _{0.6}	P ₂₀ W ₅₀	20.25 ± 1.75ab	9 ± 1.25	40.46 ± 9.66	17.91 ± 3.72	222.05 ± 36.95bc
	P ₄₀ W ₅₀	23.16 ± 1.46ab	7 ± 0.76	48.90 ± 6.46	15.76 ± 4.11	134.76 ± 53.39bc
	P ₂₀ W ₁₀₀	25.58 ± 0.52ab	9 ± 0.76	78.81 ± 9.98	19.31 ± 4.23	168.48 ± 32.23bc
	P ₄₀ W ₁₀₀	24.50 ± 4.33ab	9 ± 1.04	65.87 ± 28.42	23.71 ± 3.70	136.78 ± 16.71bc
Season 2						
SB ₀	P ₂₀ W ₂₅	18.87 ± 0.63ab	7 ± 2.12	47.09 ± 6.59	39.59 ± 5.16	245.86 ± 87.04bc
	P ₄₀ W ₂₅	18.08 ± 1.80b	6 ± 1.25	40.89 ± 9.99	40.92 ± 12.46	169.98 ± 3.39bc
	P ₂₀ W ₅₀	22.50 ± 1.19ab	7 ± 2.53	61.76 ± 2.73	25.53 ± 9.30	225.82 ± 41.64bc
	P ₄₀ W ₅₀	20.37 ± 2.51ab	6 ± 2.15	59.35 ± 19.96	31.92 ± 12.10	237.34 ± 41.49bc
	P ₂₀ W ₁₀₀	21.88 ± 3.22ab	8 ± 3.64	50.37 ± 19.21	39.18 ± 8.39	179.94 ± 38.73c

Table 4.4 continues

SB _{0.2}	P ₄₀ W ₁₀₀	21.83 ± 1.59ab	7 ± 1.89	51.87 ± 7.67	40.38 ± 1.12	239.28 ± 56.67bc
	P ₂₀ W ₂₅	20.29 ± 1.04ab	7 ± 2.18	49.56 ± 1.98	40.67 ± 8.01	199.17 ± 29.18c
	P ₄₀ W ₂₅	18.17 ± 0.92b	6 ± 1.32	44.25 ± 6.78	35.18 ± 4.44	258.02 ± 56.78bc
	P ₂₀ W ₅₀	19.25 ± 1.51ab	8 ± 1.15	52.57 ± 9.03	29.36 ± 5.44	282.93 ± 124.04bc
	P ₄₀ W ₅₀	19.83 ± 2.36ab	7 ± 1.62	56.17 ± 16.20	40.96 ± 3.02	298.25 ± 105.92bc
SB _{0.4}	P ₂₀ W ₁₀₀	20.96 ± 2.32ab	7 ± 1.98	61.21 ± 6.03	37.38 ± 5.30	392.47 ± 87.05ab
	P ₄₀ W ₁₀₀	22.67 ± 4.77ab	7 ± 1.28	69.43 ± 26.04	39.58 ± 11.33	234.55 ± 2.08bc
	P ₂₀ W ₂₅	19.29 ± 1.82ab	7 ± 1.25	43.51 ± 5.12	29.62 ± 4.50	201.55 ± 16.05c
	P ₄₀ W ₂₅	21.43 ± 3.88ab	8 ± 2.00	48.32 ± 11.60	33.27 ± 5.39	173.92 ± 22.38c
	P ₂₀ W ₅₀	19.54 ± 1.93ab	7 ± 1.01	46.54 ± 6.77	38.65 ± 9.44	185.94 ± 36.06c
SB _{0.6}	P ₄₀ W ₅₀	20.08 ± 1.01ab	7 ± 1.23	48.11 ± 16.44	37.64 ± 11.22	205.52 ± 51.60bc
	P ₂₀ W ₁₀₀	22.25 ± 2.07ab	8 ± 1.88	64.68 ± 17.47	34.11 ± 4.79	184.01 ± 48.72c
	P ₄₀ W ₁₀₀	21.04 ± 2.10ab	7 ± 1.75	57.16 ± 16.12	42.73 ± 9.28	241.23 ± 57.42bc
	P ₂₀ W ₂₅	20.91 ± 1.66ab	7 ± 0.88	53.75 ± 16.79	34.12 ± 4.30	205.97 ± 44.15c
	P ₄₀ W ₂₅	19.37 ± 0.53ab	8 ± 0.25	47.36 ± 12.13	30.89 ± 10.55	204.81 ± 14.16c
	P ₂₀ W ₅₀	18.12 ± 1.94b	10 ± 2.64	43.18 ± 12.88	37.38 ± 4.87	278.18 ± 56.68bc
	P ₄₀ W ₅₀	19.62 ± 0.94ab	7 ± 2.62	46.99 ± 9.78	34.12 ± 2.77	215.50 ± 52.69bc
	P ₂₀ W ₁₀₀	20.59 ± 1.70ab	7 ± 0.50	62.31 ± 18.21	28.81 ± 2.97	230.87 ± 95.32bc
	P ₄₀ W ₁₀₀	21.06 ± 1.19ab	6 ± 1.75	57.44 ± 12.81	36.98 ± 4.25	271.09 ± 103.89bc
LSD _(0.05)		3.80	ns	ns	ns	88.76
F-value		2.42	0.96	0.97	1.15	5.89
P-value		0.0052	0.4991	0.4930	0.3245	<0.0001

Means followed by the same letter(s) in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha;; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; PW, combined phosphorus and water deficit levels; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

4.2.2 The fresh leaf and dry leaf mass of beetroot

The application of SB had no significant effect on fresh leaf and dry leaf mass of beetroot (Table 4.5). The P and W deficit levels' interaction resulted in a non-significant effect on fresh leaf mass, but a significant effect on dry leaf mass ($P=0.0316$) of beetroot (Table 4.5). Compared to $P_{40}W_{25}$, $P_{40}W_{100}$ significantly increased the dry leaf mass by 26%, indicating that moderate P and full irrigation improve the dry plant matter. This indicates that, even under moderate P supply, the extreme W deficit markedly reduces crop performance. Furthermore, it suggests that W stress can interact with nutrient availability, diminishing the potential benefits of P fertilisation. A similar observation was reported by Kulan & Kaya (2024), who found that water deficit stress significantly suppressed both fresh and dry leaf mass of beetroot. The cropping season effect on fresh leaf and dry leaf mass was significant ($P<0.0001$; Table 4.5). The fresh leaf mass was significantly higher by 271%, while the dry leaf mass was significantly higher by 260% in season 2 compared to season 1.

Table 4.5: The fresh leaf and dry leaf mass of beetroot as affected by the Si-fertiliser, combined phosphorus and water deficit levels, and cropping season.

Treatments	Fresh leaf mass (g/plant)	Dry leaf mass (g/plant)
Fertiliser		
SB ₀	56.46 ± 36.20	6.93 ± 4.54
SB _{0.2}	51.74 ± 35.82	6.84 ± 5.02
SB _{0.4}	55.15 ± 34.93	6.82 ± 4.23
SB _{0.6}	52.19 ± 35.27	6.47 ± 4.31
LSD _(0.05)	ns	ns
F-value	0.73	0.29
P-value	0.5352	0.8309
Phosphorus and water deficit levels		
P ₂₀ W ₂₅	48.86 ± 33.78	6.23 ± 4.40ab
P ₄₀ W ₂₅	48.45 ± 31.48	5.80 ± 3.81b
P ₂₀ W ₅₀	58.61 ± 39.93	7.01 ± 5.05ab
P ₄₀ W ₅₀	51.73 ± 33.90	6.48 ± 4.38ab
P ₂₀ W ₁₀₀	58.12 ± 38.09	7.28 ± 4.30ab
P ₄₀ W ₁₀₀	57.63 ± 35.66	7.82 ± 5.07a
LSD _(0.05)	ns	1.29
F-value	2.09	2.57
P-value	0.0735	0.0316
Season		
Season 1	22.90 ± 7.53b	2.93 ± 1.19b
Season 2	84.92 ± 22.21a	10.55 ± 3.13a
LSD _(0.05)	5.28	0.75
F-value	547.33	418.45
P-value	<0.0001	<0.0001

Means followed by the same letter(s) in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4,

and 0.6 L/ha; P_{20} (20 kg P/ha) and P_{40} (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W_{25} , W_{50} , and W_{100} represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

The interaction effects between Si-fertiliser and combined P and W deficit levels did not significantly affect fresh leaf and dry leaf mass (Table 4.6). The interaction effects between Si-fertiliser and cropping season on fresh leaf and dry leaf mass were not significant (Table 4.7). The interaction effects between combined P and W deficit levels and the cropping season did not significantly affect fresh leaf and dry leaf mass (Table 4.7). As observed in Table 4.7 there was not statistically difference between treatments. However, heteroscedasticity between the two cropping season was observed, where season 2 had quantitatively values than season 1, which may be attributed to seasonal variability factors as indicated in Table 3.1.

Table 4.6: The interaction effects between Si-fertiliser and combined phosphorus and water deficit levels on beetroot fresh and dry leaf mass.

Fertiliser	PW deficit levels	Fresh leaf mass (g/plant)	Dry leaf mass (g/plant)
SB ₀	P ₂₀ W ₂₅	51.16 ± 37.85	7.11 ± 5.88
	P ₄₀ W ₂₅	55.92 ± 37.00	6.92 ± 4.72
	P ₂₀ W ₅₀	63.35 ± 43.55	7.26 ± 5.52
	P ₄₀ W ₅₀	58.02 ± 43.00	5.96 ± 4.93
	P ₂₀ W ₁₀₀	55.64 ± 42.40	7.23 ± 4.72
	P ₄₀ W ₁₀₀	54.68 ± 27.00	7.12 ± 3.03
SB _{0.2}	P ₂₀ W ₂₅	36.98 ± 26.62	4.76 ± 3.21
	P ₄₀ W ₂₅	48.65 ± 35.04	5.77 ± 4.15
	P ₂₀ W ₅₀	61.43 ± 49.04	7.33 ± 5.78
	P ₄₀ W ₅₀	53.76 ± 35.64	7.63 ± 5.81
	P ₂₀ W ₁₀₀	61.62 ± 38.44	6.64 ± 3.07
	P ₄₀ W ₁₀₀	47.24 ± 37.21	8.90 ± 7.74
SB _{0.4}	P ₂₀ W ₂₅	62.11 ± 36.21	6.72 ± 4.48
	P ₄₀ W ₂₅	45.26 ± 28.32	5.03 ± 3.30
	P ₂₀ W ₅₀	54.51 ± 33.88	6.74 ± 4.41
	P ₄₀ W ₅₀	45.67 ± 29.56	6.45 ± 3.21
	P ₂₀ W ₁₀₀	60.22 ± 48.82	7.65 ± 5.62
	P ₄₀ W ₁₀₀	63.14 ± 40.36	8.35 ± 4.53
SB _{0.6}	P ₂₀ W ₂₅	44.48 ± 38.13	6.33 ± 4.51
	P ₄₀ W ₂₅	43.97 ± 32.49	5.49 ± 3.77
	P ₂₀ W ₅₀	55.17 ± 42.57	6.72 ± 5.34
	P ₄₀ W ₅₀	49.47 ± 34.51	5.89 ± 4.18
	P ₂₀ W ₁₀₀	55.01 ± 31.26	7.68 ± 4.63
	P ₄₀ W ₁₀₀	63.75 ± 43.92	6.92 ± 5.03
LSD _(0.05)		ns	ns
F-value		1.08	0.80
P-value		0.3856	0.6752

Values after ± are standard deviation. Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, phosphorus and water deficit levels; P_{20} (20 kg P/ha) and P_{40} (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W_{25} , W_{50} , and W_{100} represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

Table 4.7: The interaction effects between Si-fertiliser/combined phosphorus and water deficit levels, and cropping season on beetroot fresh and dry leaf mass.

Treatments	Fresh leaf mass (g/plant)	Dry leaf mass (g/plant)
Fertiliser		
Season 1		
SB ₀	23.23 ± 6.41	2.96 ± 1.28
SB _{0.2}	21.19 ± 7.43	2.74 ± 1.22
SB _{0.4}	24.74 ± 7.67	3.29 ± 1.16
SB _{0.6}	22.50 ± 8.68	2.75 ± 1.12
Season 2		
SB ₀	89.64 ± 18.03	10.90 ± 2.75
SB _{0.2}	84.09 ± 22.51	10.94 ± 3.87
SB _{0.4}	82.36 ± 25.79	9.99 ± 3.36
SB _{0.6}	83.62 ± 22.87	10.41 ± 2.49
LSD _(0.05)	ns	ns
F-value	0.33	0.50
P-value	0.8023	0.6859
Phosphorus and water deficit levels		
Season 1		
P ₂₀ W ₂₅	20.04 ± 8.53	2.38 ± 0.69
P ₄₀ W ₂₅	19.74 ± 3.47	2.42 ± 0.44
P ₂₀ W ₅₀	22.93 ± 5.86	2.45 ± 0.50
P ₄₀ W ₅₀	21.04 ± 5.36	2.78 ± 1.23
P ₂₀ W ₁₀₀	25.56 ± 6.11	3.79 ± 0.97
P ₄₀ W ₁₀₀	27.83 ± 10.96	3.75 ± 1.82
Season 2		
P ₂₀ W ₂₅	80.31 ± 18.61	10.08 ± 2.76
P ₄₀ W ₂₅	72.74 ± 22.25	8.67 ± 2.88
P ₂₀ W ₅₀	94.30 ± 22.82	11.58 ± 2.76
P ₄₀ W ₅₀	82.42 ± 17.88	10.19 ± 2.94
P ₂₀ W ₁₀₀	90.68 ± 26.16	11.10 ± 3.00
P ₄₀ W ₁₀₀	90.15 ± 20.89	11.90 ± 3.77
LSD _(0.05)	ns	ns
F-value	0.79	0.94
P-value	0.5611	0.4563

Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, respectively; ns, not significant

The interaction effect among SB, combined P and W deficit levels, and cropping season did not significantly affect beetroot fresh and dry leaf mass (Table 4.8). However, although statistically non-significant, the combination of SB_{0.2}×P₄₀W₁₀₀ on dry leaf mass recorded a quantitatively higher value (447%) in season 2 compared to season 1. While SB_{0.2}×P₂₀W₅₀ on fresh leaf mass recorded a higher value (417%) in season 2 compared to season 1, suggesting the SB_{0.2} applications under extreme and moderate P, moderate and full irrigation can be a possible solution affecting both fresh and dry leaf mass. Consequently, these findings indicate that the effects of P supply and W deficit stress on the measured plant traits remain largely

invariant across seasons, suggesting that season-specific modification of combined P and W deficit levels may not be warranted based on the present evidence.

Table 4.8: The interaction effects among Si-fertiliser, combined phosphorus and water deficit levels, and cropping season on beetroot fresh and dry leaf mass.

Treatment		Fresh Leaf Mass (g/plant)		Dry Leaf Mass (g/plant)	
Fertiliser	PW deficit levels	Season 1	Season 2	Season 1	Season 2
SB ₀	P ₂₀ W ₂₅	17.03 ± 1.23	85.29 ± 9.26	2.35 ± 0.67	11.88 ± 4.23
	P ₄₀ W ₂₅	22.80 ± 3.49	89.03 ± 11.05	2.75 ± 0.46	11.09 ± 1.85
	P ₂₀ W ₅₀	25.01 ± 7.60	101.69 ± 16.56	2.31 ± 0.15	12.20 ± 1.72
	P ₄₀ W ₅₀	19.29 ± 1.56	96.76 ± 10.93	1.92 ± 0.12	10.01 ± 3.45
	P ₂₀ W ₁₀₀	24.58 ± 4.41	86.71 ± 39.76	3.77 ± 0.70	10.69 ± 4.41
	P ₄₀ W ₁₀₀	30.95 ± 8.82	78.41 ± 7.49	4.69 ± 2.11	9.55 ± 0.85
SB _{0.2}	P ₂₀ W ₂₅	16.37 ± 2.18	57.59 ± 22.18	2.23 ± 0.61	7.30 ± 2.48
	P ₄₀ W ₂₅	19.84 ± 3.30	77.46 ± 23.87	2.32 ± 0.30	9.23 ± 2.67
	P ₂₀ W ₅₀	19.39 ± 1.64	103.47 ± 26.62	2.37 ± 0.77	12.29 ± 3.04
	P ₄₀ W ₅₀	21.92 ± 11.23	85.60 ± 2.97	2.67 ± 1.65	12.59 ± 2.82
	P ₂₀ W ₁₀₀	28.04 ± 5.59	95.20 ± 16.78	4.14 ± 0.98	9.17 ± 1.88
	P ₄₀ W ₁₀₀	21.56 ± 13.39	85.75 ± 15.37	2.75 ± 2.06	15.05 ± 5.65
SB _{0.4}	P ₂₀ W ₂₅	29.81 ± 11.62	94.42 ± 3.43	2.64 ± 0.50	10.80 ± 0.15
	P ₄₀ W ₂₅	19.75 ± 1.61	58.02 ± 26.18	2.26 ± 0.14	6.42 ± 3.23
	P ₂₀ W ₅₀	27.83 ± 6.58	81.19 ± 26.29	2.95 ± 0.12	10.54 ± 4.23
	P ₄₀ W ₅₀	22.07 ± 1.31	69.27 ± 22.65	4.05 ± 1.27	8.86 ± 2.63
	P ₂₀ W ₁₀₀	18.56 ± 1.82	101.87 ± 27.40	2.86 ± 0.90	2.86 ± 0.90
	P ₄₀ W ₁₀₀	28.77 ± 10.79	97.50 ± 20.34	4.64 ± 1.55	4.64 ± 1.55
SB _{0.6}	P ₂₀ W ₂₅	16.97 ± 8.26	85.75 ± 2.22	2.29 ± 1.19	10.37 ± 0.67
	P ₄₀ W ₂₅	16.58 ± 2.61	71.36 ± 19.56	2.29 ± 0.64	8.69 ± 2.10
	P ₂₀ W ₅₀	19.49 ± 2.59	90.84 ± 26.60	2.17 ± 0.49	2.17 ± 0.49
	P ₄₀ W ₅₀	20.89 ± 4.51	78.05 ± 22.50	2.47 ± 0.63	2.47 ± 0.63
	P ₂₀ W ₁₀₀	31.07 ± 4.65	78.95 ± 26.51	4.40 ± 0.94	12.59 ± 1.95
	P ₄₀ W ₁₀₀	30.03 ± 14.33	97.48 ± 34.72	2.92 ± 1.43	10.93 ± 3.63
LSD _(0.05)		ns		ns	
F-value		1.11		1.43	
P-value		0.3553		0.1511	

Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, combined phosphorus and water deficit levels; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant

4.3 Beetroot yield and quality in response to silicon-based fertiliser application, and combined phosphorus and water deficit levels

4.3.1 Beetroot yield parameters

The effect of application of SB on fresh root mass (FRM), dry root mass (DRM), total fresh biomass (FBM), total dry biomass (DBM), fresh/dry total biomass ratio (F:D ratio), and root diameter (RD) was not significant (Table 4.9). Although not statistically significant, in magnitude, the SB_{0.4} showed potential to improve on FRM (1%), DRM (3%), DBM (2%), and F:D ratio (4%) as compared to the control. The results of FRM, DRM, FBM, DBM, F:D ratio,

and RD as affected by the combined P and W deficit levels are shown in Table 4.9. The $P_{20}W_{25}$ reduced the FRM by 31% compared to $P_{40}W_{100}$. The $P_{40}W_{50}$ reduced the FBM by 37%, while $P_{40}W_{25}$ reduced the DRM by 37% in comparison with $P_{40}W_{100}$.

Similar findings were reported by Elansary *et al.* (2019), who observed significant decreases in root dry weight of 16% and 50% under 70% and 50% W deficit levels, respectively. He *et al.* (2019) reported significant decreases in grain number per cob and grain yield of soya bean plants under combined P and W deficit stress conditions. The $P_{40}W_{25}$ also reduced the DBM by 37% compared to $P_{20}W_{100}$. The F:D ratio and RD were not significantly affected by the combined P and W deficit levels. In contrast to the observed results on RD, Alkahtani *et al.* (2021) observed a significant decrease (41%) in RD of beetroot under W deficit stress compared with the control.

The effect of cropping season on FRM, DRM, FBM, DBM, F:D ratio, and RD was significant (Table 4.9), with season 2 yielding higher values of FRM (331%), DRM (296%), FBM (313%), DBM (285%), F:D ratio (5%), and RD (332%) than season 1. The interaction effect between SB and combined P and W deficit levels did not significantly affect the FRM, DRM, FBM, DBM, F:D ratio, and RD (Table 4.10). In general, $SB_{0.2} \times P_{20}W_{100}$ recorded higher values, which show a potential increase in FRM (71%), DRM (52%), FBM (59%), DBM (42%), and F:D ratio (24%) compared to $SB_0 \times P_{20}W_{25}$.

The interaction between SB and cropping season did not significantly affect the FRM, DRM, FBM, DBM, and RD (Table 4.11). The F:D ratio was significantly ($P=0.0058$) affected by the interaction between SB and cropping season. It is worth noting that the $SB_{0.6}$ improved the F:D ratio in season 2 by 16% compared to that recorded in season 1. The interactive effects of combined P and W deficit levels and cropping season on FRM, FBM, DRM, and DBM were significant (Table 4.11). The FRM, FBM, DRM, and DBM recorded from $P_{20}W_{25}$ in season 1 were significantly reduced by 416%, 387%, 329%, and 346%, respectively, compared to $P_{40}W_{100}$ in season 2. Hamed & Emara (2019) reported that increasing W depletion level from 25% up to 75% negatively affected beet growth traits and decreased root yield by up to 17%. In another study, tomato plants grown with a reduced W supply (30% ETc) showed a significant decrease in their shoot and root fresh weight in comparison to control plants; however, increases in shoot and root dry matter content were observed (Campobenedetto *et al.*, 2021).

Table 4.9: The beetroot yield parameters as affected by the Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

Treatments	FRM (g/plant)	FBM (g/plant)	DRM (g/plant)	DBM (g/plant)	F:D ratio (g/plant)	RD (mm)
Fertiliser						
SB ₀	114.29 ± 77.48	170.75 ± 112.11	16.85 ± 10.75	23.79 ± 14.98	7.05 ± 0.58	10.62 ± 6.69
SB _{0.2}	112.44 ± 83.95	167.32 ± 120.48	16.57 ± 12.08	23.41 ± 16.51	7.07 ± 0.67	10.35 ± 6.95
SB _{0.4}	115.22 ± 88.71	170.02 ± 122.25	17.33 ± 13.06	24.15 ± 16.95	7.36 ± 1.55	10.59 ± 6.59
SB _{0.6}	115.02 ± 93.82	171.12 ± 130.63	16.24 ± 12.33	22.72 ± 16.35	7.23 ± 1.25	10.64 ± 7.28
LSD _(0.05)	ns	ns	ns	ns	ns	ns
F-value	0.04	0.04	0.28	0.31	0.77	0.26
P-value	0.9878	0.9905	0.8390	0.8171	0.5157	0.8574
Phosphorus and water deficit levels						
P ₂₀ W ₂₅	103.56 ± 66.58c	158.86 ± 108.30a	15.96 ± 10.04ab	22.19 ± 14.19ab	6.87 ± 1.05	10.11 ± 6.28
P ₄₀ W ₂₅	96.64 ± 68.05c	145.09 ± 97.56ab	14.18 ± 9.62b	19.98 ± 13.18b	7.35 ± 1.18	10.26 ± 6.60
P ₂₀ W ₅₀	120.55 ± 89.26abc	179.17 ± 127.34ab	17.53 ± 12.48ab	24.54 ± 17.24ab	7.35 ± 0.76	10.78 ± 7.27
P ₄₀ W ₅₀	92.78 ± 65.00c	143.82 ± 98.06b	13.58 ± 8.85b	20.07 ± 12.70b	7.19 ± 1.14	10.00 ± 6.54
P ₂₀ W ₁₀₀	136.20 ± 104.71a	194.32 ± 140.65a	20.04 ± 15.65a	27.33 ± 19.75a	7.35 ± 1.38	11.02 ± 7.26
P ₄₀ W ₁₀₀	135.64 ± 105.12ab	196.47 ± 141.23a	19.35 ± 13.60a	27.18 ± 18.07ab	6.95 ± 0.90	11.13 ± 7.47
LSD _(0.05)	22.01	31.48	3.05	3.87	ns	ns
F-value	5.98	4.40	5.89	5.70	1.22	2.10
P-value	<0.0001	0.0012	<0.0001	0.0001	0.3070	0.0722
Season						
Season 1	43.04 ± 17.28a	65.94 ± 19.45a	6.73 ± 2.77a	9.67 ± 3.21a	6.99 ± 1.31a	3.95 ± 0.83a
Season 2	185.42 ± 63.62b	272.21 ± 84.44b	26.63 ± 8.90b	37.19 ± 11.12b	7.36 ± 0.79b	17.07 ± 2.34b
LSD _(0.05)	12.70	18.17	1.76	2.24	0.31	0.54
F-value	503.59	512.40	510.33	607.42	4.60	2321.94
P-value	<0.0001	<0.0001	<0.0001	<0.0001	0.0346	<0.0001

Means followed by the same letter in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; fresh root mass (FRM), dry root mass (DRM), total fresh biomass (FBM), total dry biomass (DBM), fresh/dry total biomass ratio (F:D ratio), root diameter (RD); Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

Table 4.10: The interaction effects between Si-fertiliser and combined phosphorus and water deficit levels on beetroot yield parameters.

Fertiliser	PW deficit levels	FRM (g/plant)	FBM (g/plant)	DRM (g/plant)	DBM (g/plant)	F:D ratio (g/plant)	RD (mm)
SB ₀	P ₂₀ W ₂₅	95.70 ± 60.79	146.86 ± 97.52	14.46 ± 9.62	21.58 ± 15.28	6.88 ± 0.64	9.81 ± 6.37
	P ₄₀ W ₂₅	102.90 ± 87.94	158.82 ± 124.57	14.97 ± 12.13	21.89 ± 16.80	7.13 ± 0.24	10.26 ± 7.80
	P ₂₀ W ₅₀	139.76 ± 111.82	203.11 ± 155.06	19.23 ± 13.78	26.49 ± 19.29	7.48 ± 0.49	11.58 ± 8.24
	P ₄₀ W ₅₀	112.12 ± 66.80	170.14 ± 108.17	17.07 ± 10.17	23.04 ± 14.51	7.35 ± 0.37	10.58 ± 6.55
	P ₂₀ W ₁₀₀	109.47 ± 82.08	165.12 ± 123.46	16.38 ± 12.10	23.61 ± 16.65	6.73 ± 0.73	10.36 ± 6.94
	P ₄₀ W ₁₀₀	125.77 ± 73.17	180.45 ± 98.47	19.00 ± 10.27	26.12 ± 12.97	6.76 ± 0.59	11.15 ± 7.10
SB _{0.2}	P ₂₀ W ₂₅	96.68 ± 64.68	133.67 ± 90.54	13.77 ± 8.20	18.53 ± 11.23	7.06 ± 0.59	9.48 ± 5.77
	P ₄₀ W ₂₅	99.05 ± 66.50	147.70 ± 97.21	14.38 ± 9.21	20.16 ± 13.00	7.29 ± 0.34	10.45 ± 6.96
	P ₂₀ W ₅₀	127.72 ± 103.91	189.16 ± 148.81	20.12 ± 16.30	27.45 ± 21.48	6.84 ± 0.44	11.18 ± 8.62
	P ₄₀ W ₅₀	89.73 ± 60.97	143.49 ± 95.39	13.85 ± 9.50	21.49 ± 15.19	6.67 ± 0.66	9.46 ± 6.65
	P ₂₀ W ₁₀₀	123.08 ± 80.39	184.70 ± 117.12	18.68 ± 12.56	25.32 ± 15.45	7.12 ± 1.08	10.60 ± 7.24
	P ₄₀ W ₁₀₀	138.37 ± 131.89	205.20 ± 183.96	18.63 ± 17.51	27.54 ± 24.31	7.54 ± 0.68	10.95 ± 9.06
SB _{0.4}	P ₂₀ W ₂₅	110.25 ± 75.41	172.37 ± 110.21	18.42 ± 11.72	25.15 ± 16.14	6.85 ± 0.43	10.85 ± 6.94
	P ₄₀ W ₂₅	87.88 ± 54.32	133.15 ± 81.56	13.65 ± 9.50	18.69 ± 12.40	7.87 ± 2.30	10.35 ± 5.99
	P ₂₀ W ₅₀	102.72 ± 50.85	157.23 ± 83.52	14.84 ± 7.02	21.59 ± 11.89	7.44 ± 1.11	9.87 ± 5.60
	P ₄₀ W ₅₀	84.13 ± 75.63	125.41 ± 106.05	13.40 ± 10.07	19.86 ± 13.11	6.78 ± 1.11	10.23 ± 7.25
	P ₂₀ W ₁₀₀	163.49 ± 144.69	223.71 ± 193.33	22.96 ± 21.99	30.62 ± 27.53	8.54 ± 2.07	11.37 ± 8.70
	P ₄₀ W ₁₀₀	137.67 ± 106.29	200.81 ± 145.12	20.67 ± 15.42	29.03 ± 19.53	6.57 ± 0.96	10.85 ± 7.54
SB _{0.6}	P ₂₀ W ₂₅	111.62 ± 81.00	182.52 ± 149.25	17.17 ± 12.21	23.50 ± 16.64	6.70 ± 2.02	10.31 ± 7.61
	P ₄₀ W ₂₅	96.74 ± 77.77	140.71 ± 108.33	13.70 ± 10.13	19.20 ± 13.66	7.11 ± 0.73	10.01 ± 7.31
	P ₂₀ W ₅₀	111.99 ± 98.94	167.16 ± 140.95	15.92 ± 13.73	22.65 ± 19.03	7.65 ± 0.72	10.50 ± 8.21
	P ₄₀ W ₅₀	83.70 ± 72.17	133.17 ± 105.87	10.08 ± 5.91	15.89 ± 9.75	7.80 ± 1.76	9.73 ± 7.49
	P ₂₀ W ₁₀₀	148.75 ± 118.98	203.76 ± 149.61	22.58 ± 17.84	30.27 ± 22.38	7.00 ± 0.60	11.75 ± 8.06
	P ₄₀ W ₁₀₀	141.78 ± 134.22	199.42 ± 163.49	19.12 ± 14.07	26.04 ± 18.84	7.14 ± 1.16	11.55 ± 8.19
LSD _(0.05)		ns	ns	ns	ns	ns	ns
F-value		0.98	0.85	0.80	1.04	1.63	0.74
P-value		0.4843	0.6175	0.6752	0.4251	0.0803	0.7416

Values after ± are standard deviation; fresh root mass (FRM), dry root mass (DRM), total fresh biomass (FBM), total dry biomass (DBM), fresh/dry total biomass ratio (F:D ratio), root diameter (RD); PW, phosphorus and water deficit levels; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

Table 4.11: The interaction effect between Si-fertiliser application/combined phosphorus and water deficit levels and cropping season on beetroot yield parameters.

Treatments	FRM (g/plant)	FBM (g/plant)	DRM (g/plant)	DBM (g/plant)	F:D ratio (g/plant)	RD (mm)
Fertiliser						
Season 1						
SB ₀	47.03 ± 19.94	70.31 ± 20.81	7.41 ± 2.74	10.37 ± 3.19	6.81 ± 0.59ab	4.17 ± 0.72
SB _{0.2}	40.05 ± 17.22	61.24 ± 20.06	6.20 ± 2.85	8.94 ± 3.45	6.88 ± 0.55ab	3.70 ± 0.89
SB _{0.4}	44.56 ± 16.19	69.30 ± 18.08	6.62 ± 2.85	9.92 ± 2.99	7.59 ± 2.16ab	4.13 ± 0.76
SB _{0.6}	40.61 ± 15.93	63.12 ± 18.73	6.69 ± 2.72	9.45 ± 3.30	6.69 ± 1.15b	3.80 ± 0.89
Season 2						
SB ₀	181.54 ± 48.83	271.19 ± 63.86	26.30 ± 6.44	37.20 ± 8.14	7.29 ± 0.46ab	17.08 ± 1.86
SB _{0.2}	184.83 ± 55.83	273.40 ± 75.19	26.94 ± 8.05	37.88 ± 10.29	7.23 ± 0.74ab	17.01 ± 2.21
SB _{0.4}	181.95 ± 76.06	265.13 ± 99.31	26.90 ± 10.94	36.89 ± 13.72	7.14 ± 0.56ab	16.70 ± 2.24
SB _{0.6}	193.81 ± 74.94	279.13 ± 100.39	26.35 ± 10.19	36.77 ± 12.20	7.78 ± 1.12a	17.48 ± 3.04
LSD _(0.05)	ns	ns	ns	ns	0.64	ns
F-value	0.46	0.17	0.26	0.15	4.45	0.73
P-value	0.7089	0.9163	0.8573	0.9308	0.0058	0.5342
Phosphorus and water deficit levels						
Season 1						
P ₂₀ W ₂₅	45.73 ± 15.35c	65.77 ± 16.68d	7.25 ± 2.13e	9.63 ± 2.11e	6.52 ± 1.11	4.10 ± 0.88
P ₄₀ W ₂₅	36.87 ± 12.04c	56.61 ± 10.81d	5.41 ± 2.07e	7.83 ± 1.93e	7.53 ± 1.71	3.79 ± 0.53
P ₂₀ W ₅₀	41.74 ± 18.16c	64.67 ± 19.43d	6.39 ± 2.40e	8.84 ± 2.65e	7.43 ± 0.93	3.85 ± 0.88
P ₄₀ W ₅₀	39.43 ± 21.64c	60.48 ± 22.78d	6.07 ± 3.10e	8.85 ± 3.37e	6.76 ± 0.70	3.74 ± 0.94
P ₂₀ W ₁₀₀	50.21 ± 18.03c	75.77 ± 19.88d	7.57 ± 3.17e	11.36 ± 3.52e	7.28 ± 1.87	4.18 ± 0.71
P ₄₀ W ₁₀₀	43.75 ± 17.07c	71.58 ± 21.68d	7.59 ± 3.26e	11.34 ± 4.02e	6.33 ± 0.75	4.00 ± 1.00
Season 2						
P ₂₀ W ₂₅	161.40 ± 41.65b	251.93 ± 73.09bc	24.66 ± 6.41bcd	34.75 ± 8.50bcd	7.22 ± 0.89	16.13 ± 1.67
P ₄₀ W ₂₅	147.22 ± 52.05b	219.96 ± 69.98c	21.60 ± 6.63cd	30.27 ± 8.94d	7.20 ± 0.43	16.20 ± 2.57
P ₂₀ W ₅₀	199.36 ± 52.71ab	293.66 ± 70.18ab	28.66 ± 7.04abc	40.24 ± 8.75abc	7.27 ± 0.56	17.71 ± 2.23
P ₄₀ W ₅₀	150.97 ± 40.55b	234.74 ± 56.21c	21.09 ± 5.57d	31.29 ± 7.18dc	7.61 ± 1.36	16.26 ± 1.75
P ₂₀ W ₁₀₀	222.19 ± 80.44a	312.87 ± 101.52a	33.65 ± 11.71a	44.76 ± 14.32a	7.42 ± 0.66	17.85 ± 2.82
P ₄₀ W ₁₀₀	235.89 ± 52.99a	321.35 ± 84.93a	31.12 ± 8.60a	43.03 ± 10.93ab	17.48 ± 0.67	18.25 ± 0.22
LSD _(0.05)	31.15	44.55	4.32	5.48	ns	ns
F-value	5.06	2.50	4.29	3.24	2.18	1.89
P-value	0.0004	0.0359	0.0015	0.0096	0.0635	0.1030

Means followed by the same letter in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; fresh root mass (FRM), dry root mass (DRM), total fresh biomass (FBM), total dry biomass (DBM), fresh/dry total biomass ratio (F: D ratio), root diameter (RD); Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

Table 4.12A: The interaction effects among Si-biostimulant, combined phosphorus and water deficit, and cropping season on beetroot yield parameters.

Fertiliser	PW deficit levels	Fresh root mass (g/plant)		Total fresh biomass (g/plant)	
		Season 1	Season 2	Season 1	Season 2
SB ₀	P ₂₀ W ₂₅	44.59 ± 20.20i-l	146.80 ± 31.56c-l	61.62 ± 19.72f-h	232.09 ± 39.89a-g
	P ₄₀ W ₂₅	26.85 ± 9.63l	178.95 ± 43.52a-g	49.66 ± 9.35g-h	267.99 ± 54.39a-d
	P ₂₀ W ₅₀	40.74 ± 5.10i-l	238.79 ± 42.61a-d	65.75 ± 2.67f-h	340.48 ± 59.16a-c
	P ₄₀ W ₅₀	56.44 ± 32.79f-l	167.79 ± 28.00a-i	75.73 ± 32.19e-h	264.55 ± 38.46a-d
	P ₂₀ W ₁₀₀	53.17 ± 24.99g-l	165.78 ± 81.91a-j	77.76 ± 21.08e-h	252.49 ± 121.52a-e
SB _{0.2}	P ₄₀ W ₁₀₀	60.38 ± 4.41f-l	191.16 ± 23.19a-e	91.33 ± 11.93d-h	269.57 ± 16.49a-d
	P ₂₀ W ₂₅	56.93 ± 14.80f-l	136.44 ± 74.16c-l	73.30 ± 16.80e-h	194.03 ± 96.34b-g
	P ₄₀ W ₂₅	39.81 ± 14.41i-l	158.29 ± 17.87b-k	59.65 ± 13.28f-h	235.75 ± 13.75a-f
	P ₂₀ W ₅₀	34.08 ± 7.11k-l	221.37 ± 25.21a-d	53.47 ± 5.48f-h	324.84 ± 10.02a-c
	P ₄₀ W ₅₀	37.34 ± 19.93j-l	142.12 ± 25.75c-l	59.26 ± 30.23f-h	227.72 ± 23.48a-h
SB _{0.4}	P ₂₀ W ₁₀₀	50.83 ± 21.25g-l	195.34 ± 6.71a-d	78.87 ± 23.18e-h	290.54 ± 12.48a-c
	P ₄₀ W ₁₀₀	21.33 ± 1.68l	255.42 ± 48.83a-c	42.89 ± 13.90h	367.51 ± 73.34a-b
	P ₂₀ W ₂₅	42.56 ± 15.42i-l	177.95 ± 15.23a-h	72.37 ± 10.43e-h	272.37 ± 16.07a-d
	P ₄₀ W ₂₅	38.84 ± 19.07i-l	112.40 ± 48.91d-l	58.59 ± 20.68f-h	170.43 ± 73.38c-h
	P ₂₀ W ₅₀	62.86 ± 17.59e-l	142.59 ± 37.25c-l	90.68 ± 11.04d-h	223.78 ± 63.50a-h
SB _{0.6}	P ₄₀ W ₅₀	34.89 ± 15.94l-k	157.99 ± 64.72c-k	56.97 ± 16.00f-h	228.07 ± 96.69a-h
	P ₂₀ W ₁₀₀	37.34 ± 14.02j-l	289.64 ± 66.36a	55.90 ± 14.46f-h	391.52 ± 93.59a
	P ₄₀ W ₁₀₀	48.98 ± 11.35h-l	226.35 ± 67.26a-d	77.76 ± 16.97e-h	323.86 ± 83.32a-c
	P ₂₀ W ₂₅	38.84 ± 12.46i-l	184.41 ± 18.87a-f	55.81 ± 20.65f-h	309.23 ± 84.16a-c
	P ₄₀ W ₂₅	42.64 ± 5.02i-l	150.84 ± 79.47c-l	59.23 ± 2.56f-h	222.20 ± 97.01a-h
LSD _(0.05)	P ₂₀ W ₅₀	29.29 ± 20.92l-k	194.70 ± 59.29a-d	48.79 ± 18.33g-h	285.54 ± 85.39a-c
	P ₄₀ W ₅₀	29.07 ± 14.69l-k	138.34 ± 62.06c-l	49.96 ± 10.65g-h	216.39 ± 84.48a-h
	P ₂₀ W ₁₀₀	59.51 ± 11.10fg-l	238.00 ± 106.65a-d	90.58 ± 6.45d-h	316.95 ± 132.23a-c
	P ₄₀ W ₁₀₀	44.32 ± 15.52i-l	287.96 ± 18.75a-b	74.36 ± 8.21e-h	324.48 ± 140.85a-c
		62.59		44.55	
F-value		2.21		1.78	
P-value		0.0112		0.0492	

Means followed by the same letter in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; PW, combined phosphorus and water deficit levels; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively.

Table 4.12B: The interaction effects among Si-fertiliser, combined phosphorus and water deficit, and cropping season on beetroot yield parameters.

Fertiliser	PW deficit levels	Dry root mass (g/plant)		Total dry biomass (g/plant)	
		Season 1	Season 2	Season 1	Season 2
SB ₀	P ₂₀ W ₂₅	6.53 ± 3.01e-i	22.39 ± 5.82b-g	8.89 ± 2.34h-k	34.27 ± 9.75a-f
	P ₄₀ W ₂₅	4.39 ± 1.54h-i	25.55 ± 5.44a-d	7.15 ± 1.17j-k	36.64 ± 7.23a-d
	P ₂₀ W ₅₀	6.85 ± 0.91e-i	31.62 ± 3.72abc	9.16 ± 0.95g-k	43.83 ± 5.31a-c
	P ₄₀ W ₅₀	8.42 ± 4.01d-i	25.72 ± 4.28a-d	10.35 ± 3.98g-k	35.73 ± 5.28a-d
	P ₂₀ W ₁₀₀	8.46 ± 2.63d-i	24.29 ± 13.08a-e	12.23 ± 1.93f-k	34.98 ± 17.37a-e
	P ₄₀ W ₁₀₀	9.79 ± 1.30d-i	28.21 ± 2.78abc	14.48 ± 2.80d-k	37.76 ± 2.49a-c
SB _{0.2}	P ₂₀ W ₂₅	8.38 ± 2.31d-i	19.16 ± 8.70b-i	10.61 ± 1.74f-k	26.46 ± 11.13d-k
	P ₄₀ W ₂₅	6.05 ± 1.76f-i	22.71 ± 0.95b-f	8.37 ± 1.49h-k	31.95 ± 1.96a-g
	P ₂₀ W ₅₀	5.62 ± 1.34f-i	34.62 ± 5.64a-b	7.98 ± 0.57i-k	46.91 ± 4.21a-c
	P ₄₀ W ₅₀	5.96 ± 4.22f-i	21.74 ± 4.63b-h	8.64 ± 5.83h-k	34.34 ± 6.93a-f
	P ₂₀ W ₁₀₀	7.89 ± 3.96d-i	29.46 ± 5.46a-c	12.01 ± 4.48f-k	38.63 ± 6.72a-c
	P ₄₀ W ₁₀₀	3.31 ± 1.05i	33.96 ± 7.81a-b	6.06 ± 2.98k	49.02 ± 9.22a-b
SB _{0.4}	P ₂₀ W ₂₅	7.84 ± 1.35d-i	29.01 ± 2.40abc	10.48 ± 0.84g-k	39.82 ± 2.25a-c
	P ₄₀ W ₂₅	4.50 ± 4.80g-i	18.23 ± 7.67b-i	6.76 ± 4.66k	24.66 ± 10.33d-k
	P ₂₀ W ₅₀	9.14 ± 1.43d-i	20.55 ± 4.84b-i	12.09 ± 1.38fg-k	31.09 ± 9.00b-h
	P ₄₀ W ₅₀	5.23 ± 2.14f-i	21.58 ± 6.96b-h	9.27 ± 1.98g-k	30.44 ± 9.47b-i
	P ₂₀ W ₁₀₀	4.34 ± 3.07h-i	41.58 ± 2.65a	7.21 ± 2.40jk	54.03 ± 15.64a
	P ₄₀ W ₁₀₀	8.00 ± 2.46d-i	33.35 ± 10.31ab	12.64 ± 2.84e-k	45.41 ± 11.87a-c
SB _{0.6}	P ₂₀ W ₂₅	6.26 ± 2.05fg-i	28.09 ± 3.39a-c	8.55 ± 3.21h-k	38.46 ± 3.32a-c
	P ₄₀ W ₂₅	6.40 ± 0.26f-i	21.01 ± 9.81b-i	8.69 ± 0.87h-k	29.71 ± 11.62b-j
	P ₂₀ W ₅₀	3.98 ± 2.42hi	27.87 ± 6.16a-c	6.15 ± 2.78k	39.15 ± 9.00a-c
	P ₄₀ W ₅₀	4.67 ± 1.51g-i	15.34 ± 0.20d-i	7.14 ± 0.89j-k	24.65 ± 2.66d-k
	P ₂₀ W ₁₀₀	9.57 ± 0.66d-i	42.10 ± 1.70a	13.98 ± 0.74d-k	54.70 ± 3.66a
	P ₄₀ W ₁₀₀	9.26 ± 3.25d-i	28.98 ± 13.89a-c	12.17 ± 2.03f-k	39.92 ± 17.51a-c
LSD _(0.05)		8.68		7.75	
F-value		2.40		2.34	
P-value		0.0055		0.0070	

Means followed by the same letter in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; PW, combined phosphorus and water deficit levels; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively.

Table 4.13: The interaction effects among Si-fertiliser, combined phosphorus and water deficit, and cropping season on beetroot fresh and dry total biomass ratio, and the root diameter.

Fertiliser	PW deficit levels	Fresh/Dry total biomass ratio (g)		Root diameter (mm)	
		Season 1	Season 2	Season 1	Season 2
SB ₀	P ₂₀ W ₂₅	6.84 ± 0.51abc	6.91 ± 0.88abc	4.03 ± 0.89	15.60 ± 0.65
	P ₄₀ W ₂₅	6.96 ± 0.22abc	7.31 ± 0.05abc	3.33 ± 0.68	17.20 ± 2.76
	P ₂₀ W ₅₀	7.23 ± 0.50abc	7.73 ± 0.42abc	4.06 ± 0.25	19.10 ± 0.55
	P ₄₀ W ₅₀	7.29 ± 0.30abc	7.41 ± 0.49abc	4.63 ± 0.91	16.53 ± 0.70
	P ₂₀ W ₁₀₀	6.20 ± 0.69c	7.26 ± 0.14abc	4.26 ± 0.61	16.46 ± 2.90
	P ₄₀ W ₁₀₀	6.38 ± 0.63c	7.14 ± 0.26abc	4.70 ± 0.27	17.60 ± 1.17
SB _{0.2}	P ₂₀ W ₂₅	6.93 ± 0.76abc	7.19 ± 0.49abc	4.40 ± 0.86	14.56 ± 2.28
	P ₄₀ W ₂₅	7.21 ± 0.44abc	7.38 ± 0.27abc	4.16 ± 0.07	16.73 ± 1.66
	P ₂₀ W ₅₀	6.57 ± 0.46abc	6.94 ± 0.43abc	3.33 ± 0.49	19.03 ± 0.86
	P ₄₀ W ₅₀	6.74 ± 0.53bc	6.73 ± 0.86abc	3.53 ± 1.35	15.40 ± 1.76
	P ₂₀ W ₁₀₀	6.58 ± 0.46bc	7.67 ± 1.34abc	4.06 ± 0.84	17.13 ± 1.61
	P ₄₀ W ₁₀₀	7.65 ± 0.75abc	7.51 ± 0.83abc	2.71 ± 0.57	19.20 ± 1.05
SB _{0.4}	P ₂₀ W ₂₅	6.87 ± 0.57abc	6.84 ± 0.38abc	4.55 ± 0.47	17.16 ± 1.02
	P ₄₀ W ₂₅	9.90 ± 3.62a	6.86 ± 0.58abc	3.82 ± 0.81	14.70 ± 0.72
	P ₂₀ W ₅₀	7.67 ± 1.54abc	7.21 ± 0.75abc	4.91 ± 0.20	14.83 ± 2.20
	P ₄₀ W ₅₀	6.13 ± 0.93c	7.76 ± 0.19abc	3.66 ± 0.42	16.80 ± 1.41
	P ₂₀ W ₁₀₀	9.75 ± 2.48ab	7.34 ± 0.50abc	3.61 ± 0.79	19.13 ± 2.83
	P ₄₀ W ₁₀₀	6.01 ± 0.96c	7.14 ± 0.66abc	4.11 ± 1.10	17.60 ± 2.16
SB _{0.6}	P ₂₀ W ₂₅	5.45 ± 1.84c	7.96 ± 1.44abc	3.43 ± 1.17	17.20 ± 1.15
	P ₄₀ W ₂₅	6.85 ± 0.98abc	7.38 ± 0.43abc	3.86 ± 0.31	16.16 ± 4.50
	P ₂₀ W ₅₀	8.09 ± 0.64abc	7.22 ± 0.57abc	3.10 ± 0.95	17.90 ± 1.90
	P ₄₀ W ₅₀	6.99 ± 0.53abc	8.60 ± 2.35abc	3.13 ± 0.45	19.33 ± 3.09
	P ₂₀ W ₁₀₀	6.59 ± 0.42bc	7.42 ± 0.45abc	4.80 ± 0.10	18.63 ± 4.14
	P ₄₀ W ₁₀₀	6.16 ± 0.38c	8.12 ± 0.58abc	4.48 ± 0.59	18.70 ± 4.20
LSD _(0.05)		1.59		ns	
F-value		1.93		1.66	
P-value		0.0302		0.0729	

Means followed by the same letter(s) in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, combined phosphorus and water deficit levels; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns; not significant

The interactive effect of SB, P and W deficit and cropping season significantly influenced FRM, FBM, DRM, and DBM (Tables 4.12A and 4.12B). The $SB_{0.4} \times P_{20} W_{100}$ increased FRM, FBM, DRM, and DBM by 550%, 535%, 537%, and 508%, respectively, in season 2 compared to $SB_0 \times P_{20} W_{25}$ in season 1. The F:D ratio recorded from $SB_{0.4} \times P_{40} W_{25}$ was significantly increased by 60% compared to $SB_0 \times P_{20} W_{100}$ (Table 4.13).

4.3.2 Beetroot quality parameters

4.3.2.1 Accumulation of macronutrients in leaves

The accumulation of macronutrients P, Na, K, Ca, and Mg concentration were not significantly affected by the application of SB (Table 4.14). Similar results were reported by Artyszak (2022), who explained that foliar application of Si foliar fertiliser had no significant effect on N, P, K concentration in beetroot leaves during harvest. However, Artyszak (2021), demonstrated that foliar application various forms of Si, including (marine calcite, ortho- and polysilicic acids mixtures, and orthosilicic) to beetroot production increased the concentration of Ca and Mg in the leaves during the critical phase of nutrient supply (July) compared to the control, and surprisingly, explained that foliar application of Si generally did not significantly affect the content of NPK in the leaves. Contrarily, Ibrahim *et al.*, (2020) examined the effect of foliar spraying with potassium silicate (K_2SiO_3), potassium humate, and a mixture of both on the nutrient concentrations of beetroot foliage and reported that foliar application of potassium silicate alone increased the macro concentrations (NPK) in beetroot foliage compared to the control treatment. Furthermore, examined the effectiveness of different silicon sources, including K_2SiO_3 (a likely silicon-based liquid fertiliser), on beetroot yield and quality under various irrigation regimes, and reported improved nutrient concentrations in (NPK) compared to control. The lack of a significant difference in these results using SB which contains $Si(OH)_4$ compared to contrary results from studies using K_2SiO_3 , orthosilicic acid, or polysilicic acid is because they are highly depended on environmental context and chemical formula (Laane, 2018). The combined P and W deficit levels had no significant effect on accumulated Na, K, Ca, and Mg concentration (Table 4.14). The $P_{20} W_{25}$ led to a significant decrease in leaf P concentration by 120% compared to $P_{20} W_{100}$, indicating that extreme P and W deficit levels limit P uptake. The cropping season effect was not significant on leaf P, Na, and Mg concentration ($P < 0.0001$). In general, the total macro-nutrient concentration measured in season 1 was quantitatively higher than in season 2.

Table 4.14: Accumulation of macronutrients concentration in leaves as affected by the Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

Treatments	P (%)	Na (%)	K (%)	Mg (%)	Ca (%)
fertiliser					
SB ₀	0.66 ± 0.44	0.63 ± 0.33	2.20 ± 0.74	0.72 ± 0.24	1.18 ± 0.39
SB _{0.2}	0.64 ± 0.43	0.53 ± 0.29	1.80 ± 0.79	0.79 ± 0.46	1.05 ± 0.38
SB _{0.4}	0.66 ± 0.44	0.60 ± 0.31	2.08 ± 0.82	0.96 ± 0.58	1.24 ± 0.42
SB _{0.6}	0.60 ± 0.42	0.57 ± 0.29	1.90 ± 0.81	0.87 ± 0.64	1.11 ± 0.38
LSD _(0.05)	ns	ns	ns	ns	ns
F-value	0.36	1.39	1.70	2.06	1.37
P-value	0.7803	0.2510	0.1718	0.1106	0.2569
Phosphorus and water deficit levels					
P ₂₀ W ₂₅	0.40 ± 0.28c	0.57 ± 0.32	2.00 ± 0.83	0.84 ± 0.48	1.18 ± 0.41
P ₄₀ W ₂₅	0.46 ± 0.28c	0.60 ± 0.33	2.04 ± 0.84	0.87 ± 0.59	1.16 ± 0.43
P ₂₀ W ₅₀	0.61 ± 0.36ab	0.60 ± 0.28	2.14 ± 0.69	0.85 ± 0.51	1.18 ± 0.33
P ₄₀ W ₅₀	0.75 ± 0.45ab	0.6 ± 0.30	2.05 ± 0.83	0.84 ± 0.51	1.18 ± 0.46
P ₂₀ W ₁₀₀	0.88 ± 0.51a	0.55 ± 0.29	1.84 ± 0.86	0.77 ± 0.4	1.09 ± 0.36
P ₄₀ W ₁₀₀	0.74 ± 0.48ab	0.58 ± 0.34	1.90 ± 0.76	0.84 ± 0.58	1.10 ± 0.40
LSD _(0.05)	0.18	ns	ns	ns	ns
F-value	8.33	0.21	0.43	0.13	0.21
P-value	<0.0001	0.9595	0.0844	0.9852	0.9570
Season					
Season 1	0.91 ± 0.44a	0.81 ± 0.28a	2.11 ± 0.89	1.07 ± 0.58a	1.19 ± 0.42
Season 2	0.38 ± 0.21b	0.36 ± 0.36b	1.88 ± 0.68	0.60 ± 0.28b	1.11 ± 0.37
LSD _(0.05)	0.10	0.07	ns	0.15	ns
F-value	101.85	149.46	3.04	43.00	1.36
P-value	<0.0001	<0.0001	0.0844	<0.0001	0.2461

Means followed by the same letter(s) in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant

Table 4.15: The interaction effects between Si-fertiliser, and combined phosphorus and water deficit levels on the accumulation of macronutrient concentration in leaves.

Fertiliser	PW deficit levels	P (%)	Na (%)	K (%)	Mg (%)	Ca (%)
SB ₀	P ₂₀ W ₂₅	0.37 ± 0.23	0.69 ± 0.38	2.46 ± 0.58	0.74 ± 0.17	1.29 ± 0.36
	P ₄₀ W ₂₅	0.48 ± 0.35	0.68 ± 0.44	2.34 ± 0.86	0.79 ± 0.33	1.31 ± 0.49
	P ₂₀ W ₅₀	0.70 ± 0.38	0.71 ± 0.34	2.57 ± 0.22	0.84 ± 0.19	1.33 ± 0.24
	P ₄₀ W ₅₀	0.71 ± 0.35	0.59 ± 0.35	2.10 ± 0.95	0.65 ± 0.32	1.12 ± 0.61
	P ₂₀ W ₁₀₀	1.08 ± 0.66	0.64 ± 0.32	2.08 ± 0.97	0.70 ± 0.22	1.14 ± 0.31
	P ₄₀ W ₁₀₀	0.65 ± 0.21	0.49 ± 0.23	1.61 ± 0.37	0.57 ± 0.15	0.91 ± 0.18
SB _{0.2}	P ₂₀ W ₂₅	0.44 ± 0.46	0.48 ± 0.33	1.73 ± 0.90	0.81 ± 0.61	1.01 ± 0.40
	P ₄₀ W ₂₅	0.50 ± 0.38	0.55 ± 0.41	1.72 ± 1.07	0.79 ± 0.50	1.05 ± 0.58
	P ₂₀ W ₅₀	0.65 ± 0.47	0.57 ± 0.33	2.01 ± 0.88	0.84 ± 0.56	1.15 ± 0.39
	P ₄₀ W ₅₀	0.84 ± 0.58	0.60 ± 0.32	1.89 ± 0.77	0.86 ± 0.56	1.07 ± 0.36
	P ₂₀ W ₁₀₀	0.86 ± 0.34	0.54 ± 0.27	1.83 ± 0.85	0.78 ± 0.36	1.04 ± 0.27
	P ₄₀ W ₁₀₀	0.52 ± 0.34	0.46 ± 0.17	1.64 ± 0.46	0.68 ± 0.30	0.99 ± 0.38
SB _{0.4}	P ₂₀ W ₂₅	0.40 ± 0.19	0.55 ± 0.28	2.10 ± 0.85	0.89 ± 0.52	1.24 ± 0.55
	P ₄₀ W ₂₅	0.47 ± 0.15	0.66 ± 0.29	2.37 ± 0.82	1.03 ± 0.65	1.30 ± 0.16
	P ₂₀ W ₅₀	0.51 ± 0.22	0.60 ± 0.27	2.18 ± 0.92	0.84 ± 0.31	1.17 ± 0.36
	P ₄₀ W ₅₀	0.85 ± 0.50	0.67 ± 0.34	2.17 ± 0.90	1.11 ± 0.71	1.46 ± 0.49
	P ₂₀ W ₁₀₀	0.80 ± 0.38	0.50 ± 0.15	1.70 ± 0.37	0.88 ± 0.64	1.06 ± 0.18
	P ₄₀ W ₁₀₀	0.95 ± 0.76	0.65 ± 0.53	1.94 ± 1.08	1.02 ± 0.78	1.25 ± 0.63
SB _{0.6}	P ₂₀ W ₂₅	0.39 ± 0.26	0.58 ± 0.32	1.71 ± 0.90	0.90 ± 0.59	1.16 ± 0.35
	P ₄₀ W ₂₅	0.39 ± 0.24	0.51 ± 0.20	1.74 ± 0.50	0.86 ± 0.89	0.95 ± 0.36
	P ₂₀ W ₅₀	0.59 ± 0.40	0.52 ± 0.21	1.78 ± 0.33	0.89 ± 0.88	1.06 ± 0.35
	P ₄₀ W ₅₀	0.59 ± 0.30	0.56 ± 0.26	2.02 ± 0.90	0.76 ± 0.34	1.07 ± 0.34
	P ₂₀ W ₁₀₀	0.79 ± 0.68	0.53 ± 0.42	1.74 ± 1.23	0.74 ± 0.38	1.12 ± 0.63
	P ₄₀ W ₁₀₀	0.83 ± 0.44	0.71 ± 0.36	2.39 ± 0.80	1.08 ± 0.78	1.27 ± 0.24
LSD _(0.05)		ns	ns	ns	ns	ns
F-value		0.88	0.74	0.67	0.36	0.55
P-value		0.5833	0.740	0.8105	0.9849	0.9014

Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, combined phosphorus and water deficit levels; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant

Table 4.16: Accumulation of macronutrients concentration in plant leaves as affected by the interaction between Si-fertiliser/combined phosphorus and water deficit levels, and the cropping seasons.

Treatments	P (%)	Na (%)	K (%)	Mg (%)	Ca (%)
fertiliser					
Season 1					
SB ₀	0.93 ± 0.44	0.91 ± 0.24	2.55 ± 0.64	0.82 ± 0.25	1.26 ± 0.38
SB _{0.2}	0.88 ± 0.44	0.73 ± 0.28	1.82 ± 0.88	1.06 ± 0.48	1.06 ± 0.29
SB _{0.4}	0.95 ± 0.49	0.83 ± 0.31	2.17 ± 0.99	1.25 ± 0.61	1.32 ± 0.50
SB _{0.6}	0.87 ± 0.41	0.78 ± 0.27	1.91 ± 0.90	1.17 ± 0.79	1.12 ± 0.45
Season 2					
SB ₀	0.39 ± 0.23	0.36 ± 0.10	1.84 ± 0.67	0.62 ± 0.19	1.11 ± 0.40
SB _{0.2}	0.39 ± 0.27	0.33 ± 0.13	1.79 ± 0.71	0.52 ± 0.24	1.04 ± 0.46
SB _{0.4}	0.40 ± 0.15	0.40 ± 0.12	2.00 ± 0.65	0.70 ± 0.42	1.18 ± 0.32
SB _{0.6}	0.33 ± 0.21	0.36 ± 0.10	1.88 ± 0.73	0.57 ± 0.17	1.10 ± 0.31
LSD _(0.05)	ns	ns	ns	ns	ns
F-value	0.08	0.86	1.41	1.70	0.32
P-value	0.9731	0.4632	0.2459	0.1732	0.8095
PW deficit levels					
Season 1					
P ₂₀ W ₂₅	0.60 ± 0.27	0.82 ± 0.25	2.16 ± 0.86	1.11 ± 0.52	1.26 ± 0.42
P ₄₀ W ₂₅	0.66 ± 0.24	0.84 ± 0.34	2.12 ± 0.94	1.04 ± 0.65	1.15 ± 0.45
P ₂₀ W ₅₀	0.87 ± 0.34	0.79 ± 0.27	2.09 ± 0.89	1.09 ± 0.65	1.16 ± 0.39
P ₄₀ W ₅₀	1.11 ± 0.35	0.84 ± 0.22	2.21 ± 0.86	1.10 ± 0.57	1.22 ± 0.40
P ₂₀ W ₁₀₀	1.18 ± 0.54	0.76 ± 0.27	2.10 ± 1.00	1.00 ± 0.45	1.18 ± 0.42
P ₄₀ W ₁₀₀	1.01 ± 0.52	0.82 ± 0.35	1.99 ± 0.95	1.10 ± 0.73	1.17 ± 0.50
Season 2					
P ₂₀ W ₂₅	0.20 ± 0.09	0.33 ± 0.12	1.84 ± 0.80	0.56 ± 0.21	1.09 ± 0.40
P ₄₀ W ₂₅	0.29 ± 0.17	0.40 ± 0.16	1.97 ± 0.79	0.72 ± 0.52	1.17 ± 0.43
P ₂₀ W ₅₀	0.35 ± 0.11	0.40 ± 0.09	2.18 ± 0.44	0.62 ± 0.14	1.20 ± 0.28
P ₄₀ W ₅₀	0.39 ± 0.18	0.37 ± 0.14	1.89 ± 0.80	0.59 ± 0.26	1.14 ± 0.53
P ₂₀ W ₁₀₀	0.59 ± 0.26	0.34 ± 0.08	1.58 ± 0.63	0.55 ± 0.17	1.00 ± 0.28
P ₄₀ W ₁₀₀	0.46 ± 0.22	0.34 ± 0.08	1.80 ± 0.52	0.58 ± 0.17	1.04 ± 0.28
LSD _(0.05)	ns	ns	ns	ns	ns
F-value	0.93	0.20	0.38	0.09	0.25
P-value	0.4658	0.9608	0.8596	0.9932	0.9396

Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, combined phosphorus and water deficit levels; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant

Table 4.17: The interaction effects among Si-fertiliser, combined phosphorus and water deficit levels, and cropping season on the leaf macronutrient concentration accumulation.

Treatment		Phosphorus (%)		Sodium (%)		Potassium (%)		Magnesium (%)		Calcium (%)	
Fertiliser	PW deficit levels	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
SB ₀	P ₂₀ W ₂₅	0.58 ± 0.13	0.17 ± 0.01	1.01 ± 0.21	0.37 ± 0.09	2.91 ± 0.35	2.02 ± 0.35	0.85 ± 0.12	0.64 ± 0.17	1.38 ± 0.39	1.21 ± 0.38
	P ₄₀ W ₂₅	0.75 ± 0.29	0.21 ± 0.08	0.98 ± 0.45	0.38 ± 0.14	2.67 ± 1.16	2.01 ± 0.43	0.88 ± 0.45	0.70 ± 0.24	1.37 ± 0.56	1.26 ± 0.53
	P ₂₀ W ₅₀	1.01 ± 0.23	0.39 ± 0.14	1.01 ± 0.14	0.40 ± 0.08	2.74 ± 0.11	2.41 ± 0.22	0.97 ± 0.14	0.71 ± 0.13	1.31 ± 0.08	1.29 ± 0.37
	P ₄₀ W ₅₀	1.02 ± 0.42	0.39 ± 0.29	0.86 ± 0.22	0.32 ± 0.20	2.45 ± 0.65	1.76 ± 1.22	0.77 ± 0.32	0.53 ± 0.34	1.23 ± 0.61	1.02 ± 0.72
	P ₂₀ W ₁₀₀	1.47 ± 0.75	0.68 ± 0.23	0.90 ± 0.22	0.37 ± 0.05	2.72 ± 0.56	2.72 ± 0.56	0.87 ± 0.18	0.54 ± 0.07	1.36 ± 0.28	0.93 ± 0.15
SB _{0.2}	P ₄₀ W ₁₀₀	0.79 ± 0.17	0.51 ± 0.15	0.69 ± 0.17	0.30 ± 0.03	1.80 ± 0.39	1.80 ± 0.39	0.56 ± 0.16	0.59 ± 0.17	0.87 ± 0.19	0.94 ± 0.22
	P ₂₀ W ₂₅	0.71 ± 0.55	0.18 ± 0.11	0.73 ± 0.27	0.23 ± 0.12	0.71 ± 0.68	1.75 ± 1.25	1.18 ± 0.68	0.44 ± 0.29	1.09 ± 0.13	0.92 ± 0.60
	P ₄₀ W ₂₅	0.73 ± 0.35	0.27 ± 0.28	0.79 ± 0.43	0.32 ± 0.25	0.76 ± 1.07	1.68 ± 1.30	1.11 ± 0.41	0.48 ± 0.39	1.16 ± 0.47	0.95 ± 0.77
	P ₂₀ W ₅₀	0.91 ± 0.57	0.38 ± 0.11	0.72 ± 0.44	0.42 ± 0.08	1.86 ± 1.34	2.17 ± 0.29	1.09 ± 0.77	0.59 ± 0.07	1.08 ± 0.53	1.22 ± 0.28
	P ₄₀ W ₅₀	1.32 ± 0.33	0.36 ± 0.24	0.85 ± 0.24	0.35 ± 0.15	2.10 ± 0.94	1.68 ± 0.68	1.21 ± 0.59	0.50 ± 0.28	1.13 ± 0.17	0.97 ± 0.51
SB _{0.4}	P ₂₀ W ₁₀₀	1.02 ± 0.32	0.71 ± 0.34	0.73 ± 0.26	0.35 ± 0.08	1.98 ± 1.25	1.69 ± 0.42	1.01 ± 0.35	1.01 ± 0.35	1.04 ± 0.17	1.05 ± 0.40
	P ₄₀ W ₁₀₀	0.58 ± 0.44	0.47 ± 0.29	0.58 ± 0.15	0.34 ± 0.11	1.53 ± 0.66	1.76 ± 0.25	0.76 ± 0.34	0.76 ± 0.34	0.83 ± 0.19	1.16 ± 0.50
	P ₂₀ W ₂₅	0.53 ± 0.14	0.27 ± 0.14	0.74 ± 0.28	0.37 ± 0.15	2.07 ± 1.15	2.13 ± 0.70	1.20 ± 0.58	0.59 ± 0.24	1.34 ± 0.74	1.14 ± 0.41
	P ₄₀ W ₂₅	0.58 ± 0.07	0.42 ± 0.16	1.01 ± 0.16	0.49 ± 0.14	2.86 ± 0.23	2.13 ± 0.94	0.98 ± 0.29	1.06 ± 0.82	1.33 ± 0.20	1.28 ± 0.16
	P ₂₀ W ₅₀	0.66 ± 0.16	0.36 ± 0.16	0.76 ± 0.29	0.44 ± 0.16	2.15 ± 1.19	2.21 ± 0.85	1.04 ± 0.27	0.64 ± 0.22	1.17 ± 0.48	1.18 ± 0.28
SB _{0.6}	P ₄₀ W ₅₀	1.27 ± 0.33	0.44 ± 0.07	0.91 ± 0.29	0.42 ± 0.14	2.31 ± 1.20	2.04 ± 0.73	1.51 ± 0.84	0.71 ± 0.29	1.51 ± 0.49	1.41 ± 0.60
	P ₂₀ W ₁₀₀	1.03 ± 0.43	0.58 ± 0.16	0.62 ± 0.10	0.37 ± 0.06	1.54 ± 0.38	1.87 ± 0.36	1.13 ± 0.89	0.62 ± 0.21	1.00 ± 0.13	1.11 ± 0.23
	P ₄₀ W ₁₀₀	1.53 ± 0.63	0.36 ± 0.09	1.00 ± 0.57	0.30 ± 0.05	2.31 ± 1.53	1.57 ± 0.42	1.56 ± 0.80	0.48 ± 0.10	1.59 ± 0.79	0.91 ± 0.13
	P ₂₀ W ₂₅	0.59 ± 0.23	0.20 ± 0.08	0.82 ± 0.28	0.35 ± 0.13	1.94 ± 0.96	1.48 ± 0.98	1.22 ± 0.72	0.58 ± 0.21	1.21 ± 0.41	0.11 ± 0.37
	P ₄₀ W ₂₅	0.56 ± 0.22	0.21 ± 0.09	0.63 ± 0.22	0.40 ± 0.12	1.44 ± 0.08	2.03 ± 0.61	1.16 ± 1.29	0.55 ± 0.20	0.64 ± 0.03	1.15 ± 0.32
LSD _(0.05)	P ₂₀ W ₅₀	0.90 ± 0.36	0.29 ± 0.09	0.68 ± 0.16	0.36 ± 0.08	1.62 ± 0.39	1.93 ± 0.21	1.24 ± 1.25	0.55 ± 0.11	1.03 ± 0.47	1.10 ± 0.30
	P ₄₀ W ₅₀	0.83 ± 0.20	0.36 ± 0.17	0.75 ± 0.22	0.37 ± 0.12	1.96 ± 1.07	2.09 ± 0.93	0.90 ± 0.40	0.61 ± 0.27	0.96 ± 0.10	1.18 ± 0.49
	P ₂₀ W ₁₀₀	1.19 ± 0.77	0.40 ± 0.32	0.79 ± 0.47	0.27 ± 0.12	2.81 ± 1.56	1.31 ± 0.89	0.99 ± 0.36	0.49 ± 0.24	1.32 ± 0.84	0.92 ± 0.39
	P ₄₀ W ₁₀₀	1.14 ± 0.30	0.52 ± 0.35	1.00 ± 0.29	0.43 ± 0.08	2.34 ± 1.17	2.45 ± 0.49	1.52 ± 0.97	0.64 ± 0.07	1.39 ± 0.26	1.16 ± 0.19
	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
F-value		1.15		0.58		0.37		0.50		0.58	
P-value		0.3272		0.8857		0.9843		0.9372		0.8829	

Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, combined phosphorus and water deficit levels; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant

The accumulation of leaf macronutrient concentrations measured was not significantly affected by the interactive effect of SB and combined P and W deficit levels (Table 4.15), the SB and cropping season interaction, the interactive effect of cropping season and combined P and W deficit levels (Table 4.16), or the three-way interaction effects among SB, combined P and W deficit levels, and cropping season (Table 4.17).

4.3.2.2 Leaf micronutrients concentration

The results on accumulation of leaf micronutrients concentration as affected by the SB application are shown in Table 4.18. The total leaf Mn, Co, Zn, B, and Mo concentration were not significantly affected by the application of the SB. The application of SB_{0.2} significantly reduced leaf Fe concentration by 29%, relative to control, while SB_{0.6} reduced leaf Cu concentration by 128%, relative to control (Table 4.18). Silicon has been reported to ameliorate the abiotic stresses, such as an excess dose of heavy metal, and increase the tolerance of plants against heavy metals (Adrees *et al.*, 2015). Emamverdian *et al.* (2018) reported that Si is accumulated in plants' roots for certain mechanisms, including a physical barrier, reduction of translation, and reduction of heavy metal uptake. Furthermore, Si can increase the chelated ions through stimulation of root exudate, which can limit metal uptake by roots in plants or by decreasing the free metals in plant organs, which reduces the translocation activity in apoplasm (Adrees *et al.*, 2015). The combined P and W deficit levels had no significant effect on the total concentration of Mn, Fe, Co, Zn, Cu, B and Mo. Accumulated leaf micronutrients concentration was significantly influenced by the cropping season, with total micro-nutrient concentration higher in cropping season 1 than in season 2. The ANOVA also showed that the accumulated leaf micronutrients concentration was not influenced by the interaction between SB and combined P and W deficit levels (Table 4.19), the interaction effect of SB and cropping season (Table 4.20). The interaction effect between combined P and W deficit levels and cropping season (Table 4.20) or the interaction effect among SB, combined P and W deficit levels, and cropping season (Table 4.21).

Table 4.18: Accumulation of micronutrients concentration in plant leaves as affected by the Si-fertiliser application, combined phosphorus and water deficit levels and cropping season.

Treatments	Mn (mg/kg)	Fe (mg/kg)	Co (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	B (mg/kg)	Mo (mg/kg)
Fertiliser							
SB ₀	1074.99 ± 358.46	376.18 ± 165.19a	70.09 ± 29.09	221.32 ± 105.12	117.88 ± 98.67a	109.43 ± 43.73	100.38 ± 77.21
SB _{0.2}	913.72 ± 339.37	291.44 ± 122.98b	66.79 ± 31.36	182.17 ± 79.47	89.34 ± 53.91ab	107.50 ± 42.53	84.81 ± 41.70
SB _{0.4}	1074.27 ± 412.52	328.61 ± 126.32ab	67.01 ± 31.45	227.09 ± 86.74	84.63 ± 54.29ab	98.11 ± 32.07	78.41 ± 38.23
SB _{0.6}	987.12 ± 391.82	336.16 ± 146.98ab	67.07 ± 31.57	201.13 ± 87.52	77.88 ± 52.66b	98.20 ± 31.89	74.33 ± 39.96
LSD _(0.05)	ns	53.10	ns	ns	28.59	ns	ns
F-value	1.53	3.14	0.16	2.04	3.06	1.43	2.54
P-value	0.2117	0.0208	0.9217	0.1144	0.0320	0.2382	0.0615
Phosphorus and water deficit levels							
P ₂₀ W ₂₅	966.82 ± 383.15	293.02 ± 121.83	67.63 ± 31.19	208.04 ± 84.43	85.33 ± 57.21	99.20 ± 33.57	77.15 ± 41.34
P ₄₀ W ₂₅	977.36 ± 383.53	326.01 ± 165.10	67.05 ± 30.86	199.12 ± 97.78	83.16 ± 53.06	100.81 ± 32.83	79.37 ± 41.27
P ₂₀ W ₅₀	1021.52 ± 333.79	355.10 ± 163.45	67.30 ± 31.53	215.43 ± 90.69	85.15 ± 54.95	103.67 ± 32.84	81.41 ± 42.78
P ₄₀ W ₅₀	1080.23 ± 414.34	352.18 ± 132.76	68.25 ± 31.21	219.70 ± 107.96	84.70 ± 56.47	101.46 ± 36.35	79.35 ± 44.79
P ₂₀ W ₁₀₀	1017.65 ± 305.01	350.70 ± 135.23	68.23 ± 30.92	206.84 ± 81.96	95.85 ± 65.27	104.06 ± 40.34	84.86 ± 49.04
P ₄₀ W ₁₀₀	1012.83 ± 459.01	321.28 ± 140.42	67.99 ± 31.10	198.19 ± 88.29	123.24 ± 111.77	110.70 ± 51.59	106.56 ± 84.99
LSD _(0.05)	ns	ns	ns	ns	ns	ns	ns
F-value	0.27	1.12	0.01	0.24	1.31	0.49	1.29
P-value	0.9287	0.3553	1.0000	0.9439	0.2679	0.7842	0.2762
Season							
Season 1	1146.86 ± 377.32a	405.58 ± 135.93a	405.58 ± 135.93a	223.43 ± 97.83a	112.87 ± 80.67a	82.47 ± 38.30a	104.49 ± 67.13a
Season 2	884.06 ± 334.68b	263.66 ± 112.97b	263.66 ± 112.97b	192.60 ± 81.29b	73.20 ± 48.87b	53.42 ± 3.23b	65.56 ± 9.39b
LSD _(0.05)	125.34	37.554	7.7659	29.629	20.222	10.284	14.376
F-value	16.99	55.69	52.97	4.50	14.06	58.71	27.45
P-value	<0.0001	<0.0001	<0.0001	0.0365	0.0003	<0.0001	<0.0001

Means followed by the same letter(s) in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

Table 4.19: Accumulation of micronutrients concentration in plant leaves as affected by the interaction between Si-fertiliser, and combined phosphorus and water deficit levels.

Fertiliser	PW deficit levels	Mn (mg/kg)	Fe (mg/kg)	Co (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	B (mg/kg)	Mo (mg/kg)
SB ₀	P ₂₀ W ₂₅	1027.76 ± 392.23	327.96 ± 138.13	70.09 ± 29.09	244.48 ± 124.63	107.02 ± 69.62	113.53 ± 41.37	87.92 ± 48.20
	P ₄₀ W ₂₅	1068.45 ± 437.27	378.20 ± 214.16	66.79 ± 31.36	225.27 ± 145.18	90.44 ± 62.26	111.04 ± 37.65	85.65 ± 49.80
	P ₂₀ W ₅₀	1245.95 ± 386.15	464.45 ± 211.48	67.01 ± 31.45	246.03 ± 114.29	91.51 ± 68.52	110.53 ± 42.88	85.70 ± 55.79
	P ₄₀ W ₅₀	943.26 ± 376	376.56 ± 181.85	67.07 ± 31.57	201.10 ± 92.84	88.55 ± 71.14	99.66 ± 44.75	79.70 ± 60.43
	P ₂₀ W ₁₀₀	1227.28 ± 301.37	375.51 ± 159.23	70.09 ± 29.09	207.58 ± 85.21	106.08 ± 84.42	111.32 ± 58.64	89.58 ± 70.10
SB _{0.2}	P ₄₀ W ₁₀₀	937.20 ± 251	334.44 ± 93.17	66.79 ± 31.36	204.13 ± 106.49	223.69 ± 161.33	110.70 ± 55.32	173.70 ± 132.04
	P ₂₀ W ₂₅	839.93 ± 344.24	260.22 ± 112.05	70.09 ± 29.09	171.99 ± 73.36	80.31 ± 55.49	97.07 ± 32.98	74.88 ± 41.41
	P ₄₀ W ₂₅	897.77 ± 455.39	269.74 ± 139.57	66.79 ± 31.36	174.71 ± 77.42	82.42 ± 53.86	92.02 ± 32.98	78.06 ± 42.38
	P ₂₀ W ₅₀	881.26 ± 321.05	335.86 ± 138.11	67.01 ± 31.45	214.11 ± 77.84	87.83 ± 54.42	101.84 ± 28.24	84.61 ± 41.09
	P ₄₀ W ₅₀	1093.28 ± 365.85	356.60 ± 102.05	67.07 ± 31.57	186.46 ± 101.42	89.45 ± 56.84	108.32 ± 39.70	84.61 ± 43.65
SB _{0.4}	P ₂₀ W ₁₀₀	929.71 ± 250.31	291.46 ± 89.87	70.09 ± 29.09	187.52 ± 73.61	96.44 ± 60.61	108.35 ± 36.57	93.65 ± 47.91
	P ₄₀ W ₁₀₀	840.36 ± 356.62	234.79 ± 152.38	66.79 ± 31.36	153.42 ± 96.89	104.73 ± 69.85	137.39 ± 72.79	96.63 ± 53.24
	P ₂₀ W ₂₅	915.02 ± 332.60	296.99 ± 131.67	70.09 ± 29.09	211.67 ± 66.53	78.21 ± 55.74	93.96 ± 33.05	74.56 ± 41.75
	P ₄₀ W ₂₅	1037.97 ± 202.36	373.43 ± 140.77	66.79 ± 31.36	212.67 ± 66.53	81.50 ± 55.12	100.60 ± 35.24	79.20 ± 39.96
	P ₂₀ W ₅₀	989.27 ± 178.91	294.73 ± 117.46	67.01 ± 31.45	217.58 ± 76.12	82.42 ± 54.97	98.93 ± 33.33	79.31 ± 42.22
SB _{0.6}	P ₄₀ W ₅₀	1297.62 ± 474.15	334.90 ± 128.32	67.07 ± 31.57	295.52 ± 120.57	83.18 ± 54.53	99.81 ± 33.33	78.50 ± 41.31
	P ₂₀ W ₁₀₀	1023.64 ± 211.36	338.19 ± 123.90	70.09 ± 29.09	208.77 ± 75.39	102.57 ± 70.33	104.60 ± 32.74	83.03 ± 41.15
	P ₄₀ W ₁₀₀	1182.13 ± 787.74	298.42 ± 150.62	66.79 ± 31.36	216.92 ± 92.73	79.92 ± 55.34	90.74 ± 37.37	75.87 ± 40.72
	P ₂₀ W ₂₅	1084.57 ± 498.71	286.92 ± 128.38	70.09 ± 29.09	204.01 ± 65.31	75.77 ± 57.05	92.26 ± 30.81	71.26 ± 43.40
	P ₄₀ W ₂₅	905.25 ± 457.06	282.67 ± 167.95	66.79 ± 31.36	188.80 ± 103.29	78.71 ± 57.05	99.57 ± 32.32	74.57 ± 43.39
LSD _(0.05)	P ₂₀ W ₅₀	969.59 ± 373.89	325.36 ± 158.36	67.01 ± 31.45	184.00 ± 102.95	78.85 ± 54.65	103.37 ± 33.55	76.02 ± 41.98
	P ₄₀ W ₅₀	986.75 ± 446.52	310.68 ± 134.65	67.07 ± 31.57	195.72 ± 104.14	77.63 ± 57.41	98.07 ± 35.82	74.25 ± 43.50
	P ₂₀ W ₁₀₀	864.47 ± 396.34	397.64 ± 166.01	70.09 ± 29.09	223.46 ± 108.42	78.32 ± 57.46	91.96 ± 37.09	73.17 ± 43.26
	P ₄₀ W ₁₀₀	1091.65 ± 271	413.67 ± 129.48	66.79 ± 31.36	210.81 ± 64.73	78.44 ± 58.44	103.95 ± 34	76.71 ± 43.12
	F-value	0.68	1.04	0.01	0.50	1.13	0.54	1.03
	P-value	0.7942	0.4217	1.0000	0.9370	0.3455	0.9132	0.4297

Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, combined phosphorus and water deficit levels; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

Table 4.20: Accumulation of micronutrients concentration in plant leaves as affected by the Si-fertiliser application or combined phosphorus and water deficit levels interacting with the cropping season.

Treatments	Mn (mg/kg)	Fe (mg/kg)	Co (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	B (mg/kg)	Mo (mg/kg)
Fertiliser							
Season 1							
SB ₀	1257.52 ± 358.46	455.84 ± 144.06	87.15 ± 33.50	241.10 ± 109.34	130.54 ± 110.55	121.85 ± 52.84	120.26 ± 102.47
SB _{0.2}	1028.46 ± 300.12	351.31 ± 124.79	79.58 ± 40.91	191.33 ± 85.16	119.36 ± 67.30	134.73 ± 45.70	110.46 ± 49.19
SB _{0.4}	1243.78 ± 473.01	393.43 ± 105.95	83.01 ± 40.22	244.42 ± 85.11	103.85 ± 67.41	116.77 ± 36.55	96.81 ± 47.87
SB _{0.6}	1058.12 ± 351.50	420.37 ± 150.33	80.16 ± 41.04	218.03 ± 107.17	97.94 ± 69.64	119.82 ± 32.55	90.66 ± 51.69
Season 2							
SB ₀	892.45 ± 279.56	296.52 ± 148.29	53.04 ± 2.16	200.38 ± 99.35	105.23 ± 86.50	76.57 ± 6.67	80.49 ± 30.57
SB _{0.2}	789.97 ± 345.20	231.58 ± 89.31	54.00 ± 2.23	172.46 ± 74.30	62.66 ± 6.57	80.26 ± 8.03	62.00 ± 8.44
SB _{0.4}	922.61 ± 283.88	274.03 ± 117.93	52.69 ± 5.23	211.58 ± 87.48	67.44 ± 32.11	81.40 ± 13.75	61.95 ± 14.14
SB _{0.6}	920.06 ± 425.40	251.94 ± 82.83	53.98 ± 2.06	184.23 ± 60.66	57.81 ± 2.72	76.57 ± 6.67	58.00 ± 7.07
LSD _(0.05)	ns	ns	ns	ns	ns	ns	ns
F-value	0.67	0.48	0.25	0.04	0.39	1.37	0.24
P-value	0.5719	0.6935	0.8631	0.9910	0.7582	0.2558	0.8686
PW deficit levels							
Season 1							
P ₂₀ W ₂₅	1141.17 ± 271.71	221.94 ± 92.76	81.89 ± 39.85	244.38 ± 79.9	101.85 ± 72.03	119.16 ± 36.51	93.21 ± 53.18
P ₄₀ W ₂₅	1101.41 ± 389.65	264.54 ± 159.76	85.49 ± 38.17	219.07 ± 122.12	110.46 ± 69.91	125.39 ± 33.59	102.41 ± 51.92
P ₂₀ W ₅₀	1121.82 ± 368.04	279.82 ± 142.22	81.39 ± 40.51	217.07 ± 95.60	105.10 ± 72.84	123.61 ± 36.00	97.02 ± 56.49
P ₄₀ W ₅₀	1203.38 ± 367.43	258.79 ± 65.65	82.53 ± 39.82	226.08 ± 97.79	104.45 ± 75.35	122.13 ± 41.77	93.21 ± 53.18
P ₂₀ W ₁₀₀	1141.65 ± 289.48	265.94 ± 87.08	81.85 ± 39.90	219.08 ± 104.72	110.15 ± 78.92	122.05 ± 48.42	101.82 ± 63.51
P ₄₀ W ₁₀₀	1167.49 ± 572.52	290.88 ± 109.28	81.92 ± 39.92	214.52 ± 103.11	151.42 ± 119.82	128.73 ± 60.90	143.14 ± 111.46
Season 2							
P ₂₀ W ₂₅	792.47 ± 408.43	364.10 ± 106.80	53.37 ± 1.56	171.69 ± 75.10	68.80 ± 32.54	79.25 ± 12.44	61.10 ± 13.52
P ₄₀ W ₂₅	872.39 ± 359.68	398.65 ± 146.12	51.44 ± 6.01	180.84 ± 69.30	60.05 ± 7.85	80.01 ± 10.14	59.87 ± 10.91
P ₂₀ W ₅₀	921.22 ± 274.88	430.38 ± 152.55	53.21 ± 2.13	213.79 ± 89.72	65.21 ± 11.78	83.73 ± 9.55	65.80 ± 10.20
P ₄₀ W ₅₀	957.08 ± 436.87	445.58 ± 116.25	53.98 ± 2.67	213.31 ± 121.33	64.95 ± 11.83	80.80 ± 9.33	63.11 ± 9.39
P ₂₀ W ₁₀₀	903.99 ± 283.57	354.44 ± 167.11	54.60 ± 1.74	194.58 ± 52.47	81.55 ± 47.24	86.06 ± 18.74	67.89 ± 19.14
P ₄₀ W ₁₀₀	858.18 ± 246.10	398.65 ± 146.12	54.06 ± 2.19	180.37 ± 69.16	81.55 ± 47.24	94.16 ± 36.45	67.89 ± 19.14
LSD _(0.05)	ns	ns	ns	ns	ns	ns	ns
F-value	0.14	0.90	0.02	0.46	0.08	0.06	0.47
P-value	0.9829	0.4837	0.9999	0.8047	0.9952	0.9972	0.7950

Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, combined phosphorus and water deficit levels; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

Table 4.21: Accumulation of micronutrients concentration in plant leaves as affected by the interaction between Si-fertiliser, combined phosphorus and water deficit levels and cropping season.

Fertiliser	PW deficit levels	Mn (mg/kg)	Fe (mg/kg)	Co (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	B (mg/kg)	Mo (mg/kg)
Season 1								
SB ₀	P ₂₀ W ₂₅	1293.19 ± 386.05	377.29 ± 164.53	87.30 ± 40.81	263.67 ± 151.61	111.87 ± 92.35	134.13 ± 53.52	99.65 ± 72.22
	P ₄₀ W ₂₅	1266.09 ± 494.84	439.23 ± 180.90	85.65 ± 38.40	271.25 ± 179.54	114.64 ± 88.41	137.00 ± 38.14	103.70 ± 71.77
	P ₂₀ W ₅₀	1487.76 ± 171.07	557.16 ± 100.74	87.99 ± 39.95	261.76 ± 101.17	108.40 ± 102.62	129.60 ± 58.77	96.79 ± 85.78
	P ₄₀ W ₅₀	1146.74 ± 379.22	514.47 ± 158.46	89.01 ± 38.49	220.06 ± 62.84	102.36 ± 108.10	113.40 ± 64.41	91.12 ± 91.86
	P ₂₀ W ₁₀₀	1446.72 ± 195.77	482.87 ± 152.73	87.52 ± 40.23	243.16 ± 113.05	109.58 ± 121.39	121.83 ± 88.28	96.20 ± 107.96
	P ₄₀ W ₁₀₀	913.63 ± 233.11	364.06 ± 118.64	85.42 ± 41.07	186.70 ± 107.55	236.39 ± 174.05	81.81 ± 22.33	234.11 ± 167.28
SB _{0.2}	P ₂₀ W ₂₅	1025.20 ± 78.14	317.65 ± 65.81	78.93 ± 49.89	211.96 ± 68.19	103.48 ± 77.95	120.99 ± 30.45	95.09 ± 54.64
	P ₄₀ W ₂₅	1040.47 ± 351.42	352.45 ± 114.94	79.88 ± 48.85	199.64 ± 70.05	106.58 ± 74.06	109.45 ± 39.47	100.54 ± 53.16
	P ₂₀ W ₅₀	975.37 ± 464.79	434.09 ± 106.21	78.37 ± 48.76	179.13 ± 20.94	112.00 ± 75.08	121.87 ± 27.83	105.06 ± 54.30
	P ₄₀ W ₅₀	1231.35 ± 247.81	445.35 ± 47.00	80.78 ± 47.83	210.02 ± 140.62	117.04 ± 76.06	136.97 ± 38.17	108.13 ± 55.91
	P ₂₀ W ₁₀₀	1079.05 ± 165.75	345.37 ± 55.66	79.46 ± 48.27	186.08 ± 102.41	127.89 ± 78.54	133.52 ± 37.51	121.56 ± 57.98
	P ₄₀ W ₁₀₀	819.36 ± 441.66	203.88 ± 200.86	80.08 ± 48.52	161.15 ± 136.00	208.81 ± 0.00	185.62 ± 79.02	176.25 ± 0.00
SB _{0.4}	P ₂₀ W ₂₅	1073.45 ± 364.51	202.09 ± 63.03	80.44 ± 47.07	264.38 ± 45.91	97.29 ± 81.39	110.59 ± 41.85	90.55 ± 58.44
	P ₄₀ W ₂₅	1117.66 ± 109.14	327.90 ± 149.75	104.50 ± 34.61	226.46 ± 130.72	127.79 ± 92.05	133.24 ± 51.32	117.22 ± 55.98
	P ₂₀ W ₅₀	999.10 ± 267.15	259.97 ± 79.80	80.58 ± 48.09	223.74 ± 110.98	100.65 ± 79.82	114.71 ± 42.06	93.97 ± 59.34
	P ₄₀ W ₅₀	1506.81 ± 413.42	270.69 ± 116.86	79.29 ± 50.20	306.87 ± 180.86	100.43 ± 80.15	118.56 ± 41.41	93.21 ± 59.74
	P ₂₀ W ₁₀₀	1079.52 ± 117.19	293.71 ± 131.06	79.19 ± 48.05	187.13 ± 104.48	102.65 ± 76.67	121.62 ± 31.91	69.23 ± 28.34
	P ₄₀ W ₁₀₀	1644.20 ± 927.93	271.89 ± 189.47	81.20 ± 49.60	274.65 ± 102.95	102.30 ± 78.34	107.41 ± 51.09	55.86 ± 6.98
SB _{0.6}	P ₂₀ W ₂₅	1172.84 ± 234.12	369.57 ± 119.51	80.88 ± 47.99	237.50 ± 50.69	94.77 ± 83.92	110.92 ± 35.15	87.55 ± 61.73
	P ₄₀ W ₂₅	986.84 ± 564.48	360.40 ± 212.48	78.25 ± 48.35	181.38 ± 148.47	98.63 ± 79.64	124.50 ± 25.76	93.12 ± 59.82
	P ₂₀ W ₅₀	1034.16 ± 412.91	400.79 ± 203.36	78.61 ± 51.46	203.67 ± 147.60	99.36 ± 80.48	128.25 ± 30.38	92.27 ± 59.84
	P ₄₀ W ₅₀	928.63 ± 330.28	363.32 ± 169.05	81.03 ± 48.41	190.09 ± 134.82	97.98 ± 83.66	119.53 ± 42.45	89.93 ± 62.95
	P ₂₀ W ₁₀₀	871.16 ± 479.68	521.92 ± 109.92	81.23 ± 49.30	259.96 ± 139.98	100.49 ± 82.34	111.25 ± 48.02	92.70 ± 59.30
	P ₄₀ W ₁₀₀	1292.78 ± 222.38	506.22 ± 97.04	80.99 ± 47.33	235.58 ± 79.34	96.45 ± 86.89	124.46 ± 40.93	88.41 ± 64.98
Season 2								
SB ₀	P ₂₀ W ₂₅	762.33 ± 155.61	278.62 ± 115.47	53.65 ± 1.72	225.29 ± 121.41	102.16 ± 59.32	92.93 ± 11.87	76.19 ± 13.43
	P ₄₀ W ₂₅	870.81 ± 340.55	317.17 ± 266.03	52.57 ± 1.77	156.30 ± 63.11	66.24 ± 10.87	85.09 ± 8.27	67.61 ± 8.47
	P ₂₀ W ₅₀	1013.16 ± 425.35	371.73 ± 275.45	52.65 ± 2.56	230.30 ± 147.23	74.62 ± 18.71	91.45 ± 7.29	74.62 ± 7.42
	P ₄₀ W ₅₀	739.78 ± 293.84	238.65 ± 22.62	52.34 ± 2.36	182.13 ± 128.53	74.74 ± 19.89	85.91 ± 17.09	68.29 ± 17.40
	P ₂₀ W ₁₀₀	1007.85 ± 210.45	268.16 ± 74.09	53.85 ± 1.63	243.16 ± 113.05	102.57 ± 55.17	100.81 ± 21.76	82.96 ± 22.31
	P ₄₀ W ₁₀₀	960.78 ± 320.42	304.81 ± 70.66	53.20 ± 4.00	186.70 ± 107.55	210.99 ± 185.17	129.97 ± 66.98	113.30 ± 68.26
SB _{0.2}	P ₂₀ W ₂₅	654.67 ± 432.65	202.78 ± 131.00	52.99 ± 0.97	132.02 ± 63.34	57.15 ± 3.44	73.14 ± 8.72	54.67 ± 8.79

Table 4.21: Continues

SB _{0.4}	P ₄₀ W ₂₅	755.07 ± 577.82	187.03 ± 122.35	55.39 ± 2.07	149.78 ± 90.34	58.27 ± 4.26	74.60 ± 10.63	55.57 ± 12.15
	P ₂₀ W ₅₀	787.15 ± 121.14	237.63 ± 86.37	53.44 ± 2.35	249.09 ± 105.07	63.67 ± 3.75	81.81 ± 4.01	64.16 ± 4.16
	P ₄₀ W ₅₀	955.22 ± 464.79	267.78 ± 12.62	54.53 ± 4.71	162.91 ± 65.40	61.86 ± 3.17	79.67 ± 4.62	61.79 ± 5.24
	P ₂₀ W ₁₀₀	780.36 ± 249.51	228.54 ± 72.25	53.12 ± 0.84	188.95 ± 55.26	65.00 ± 6.95	83.19 ± 6.06	65.75 ± 6.34
	P ₄₀ W ₁₀₀	861.37 ± 348.65	265.70 ± 121.81	54.55 ± 1.34	141.82 ± 10.76	70.04 ± 9.89	89.17 ± 5.03	70.09 ± 5.19
	P ₂₀ W ₂₅	756.59 ± 261.51	202.09 ± 63.03	53.25 ± 1.51	158.96 ± 24.99	59.14 ± 7.23	77.33 ± 12.25	58.57 ± 13.22
	P ₄₀ W ₂₅	998.12 ± 240.68	327.90 ± 149.75	47.06 ± 9.63	204.87 ± 73.88	58.36 ± 9.88	84.27 ± 11.24	60.19 ± 13.13
	P ₂₀ W ₅₀	979.54 ± 91.50	259.97 ± 79.80	52.86 ± 3.21	211.43 ± 45.32	64.20 ± 13.65	83.15 ± 16.15	64.65 ± 17.05
	P ₄₀ W ₅₀	1088.44 ± 509.76	270.69 ± 116.86	54.48 ± 2.32	306.87 ± 180.86	65.92 ± 10.78	81.07 ± 8.86	63.79 ± 7.06
	P ₂₀ W ₁₀₀	967.76 ± 297.63	293.71 ± 131.06	55.82 ± 0.47	230.41 ± 43.46	102.49 ± 80.53	87.58 ± 28.15	69.23 ± 28.34
SB _{0.6}	P ₄₀ W ₁₀₀	720.07 ± 223.12	271.89 ± 189.47	54.57 ± 0.45	159.20 ± 102.95	57.54 ± 3.91	74.07 ± 6.85	55.86 ± 6.98
	P ₂₀ W ₂₅	996.31 ± 737.29	204.27 ± 80.19	53.59 ± 2.61	170.51 ± 68.77	56.77 ± 3.55	73.60 ± 9.68	54.98 ± 10.18
	P ₄₀ W ₂₅	823.66 ± 428.54	204.93 ± 85.10	52.21 ± 2.45	196.22 ± 66.82	57.90 ± 3.54	74.65 ± 9.19	56.01 ± 9.80
	P ₂₀ W ₅₀	905.02 ± 408.02	249.94 ± 65.37	53.90 ± 1.09	164.34 ± 59.61	58.35 ± 2.33	78.49 ± 5.88	59.76 ± 5.70
	P ₄₀ W ₅₀	1044.87 ± 615.82	258.03 ± 91.86	54.59 ± 0.84	201.35 ± 94.04	57.28 ± 0.18	76.57 ± 4.30	58.57 ± 5.56
	P ₂₀ W ₁₀₀	860.00 ± 446.15	273.36 ± 102.35	55.63 ± 2.25	186.96 ± 76.16	56.16 ± 1.03	72.67 ± 4.24	53.64 ± 4.38
	P ₄₀ W ₁₀₀	890.52 ± 114.53	321.13 ± 82.47	53.94 ± 2.45	186.04 ± 48.36	60.44 ± 3.80	83.45 ± 3.38	65.02 ± 3.93
LSD _(0.05)	ns	ns	ns	ns	ns	ns	ns	ns
F-value	0.68	0.52	0.03	0.50	0.07	0.71	0.32	
P-value	0.7995	0.9234	1.0000	0.9343	1.0000	0.7702	0.9920	

Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, combined phosphorus and water deficit levels; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant

4.3.2.3 Root macronutrients concentration

The results on accumulated macronutrients concentration in the root as affected by the SB application are presented in Table 4.22. Phosphorus, Na, K, and Mg content were not significantly affected by the SB application. Root Ca concentration was significantly ($P=0.0009$) affected by the application of SB. The root Ca content was uniformly reduced by 33% across all treatment applications ($SB_{0.2}$, $SB_{0.4}$, and $SB_{0.6}$) relative to the control.

The combined P and W deficit levels did not affect K and Mg (Table 4.22). Contrarily, Hamed & Emara (2019) reported a significant K concentration gradually decreasing with increasing W depletion from 25% up to 75%. These decreases amounted to 3.2% and 11.9% for K in the first and second seasons, respectively. The $P_{20}W_{25}$ led to 50% ($P=0.0016$) decrease in root P concentration compared to $P_{20}W_{100}$, suggesting that extreme P and W deficit stress levels limit P uptake. Similarly, the $P_{20}W_{25}$ significantly ($P=0.0106$) decreased the root Na concentration by 43% relative to $P_{40}W_{25}$, indicating that adding more P-fertilisation without increasing W levels contributes to the decline in root Na concentration. A higher P dose has previously been reported to reduce the Na^+ concentration in common bean plants (Bargaz *et al.* 2016).

The $P_{20}W_{25}$ significantly ($P=0.0076$) decreased the root Mg concentration by 25% relative to $P_{40}W_{25}$. The cropping season effect on P, Na, K, Ca, and Mg concentration (Table 4.24) was significant ($P<0.0001$). In general, the accumulated macronutrient concentration was quantitatively higher in season 1 than in season 2, suggesting a biomass dilution effect, in which increased yield in season 2 led to lower nutrient content due to the distribution of nutrients across greater biomass (Shi *et al.*, 2025). The interaction effect between SB and combined P and W deficit levels on the root P, K, Ca and Mg concentration was significant (Table 4.23). The $SB_{0.4} \times P_{20}W_{25}$ significantly ($P=0.0150$) decreased the root Na concentration by 300%, 267%, and 233% relative to $SB_{0.4} \times P_{40}W_{25}$, $SB_{0.2} \times P_{20}W_{100}$ and $SB_0 \times P_{40}W_{25}$, respectively (Table 4.25).

Table 4.22: Accumulation of macronutrients concentration in the roots as affected by the Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

Treatments	P (%)	Na (%)	K (%)	Mg (%)	Ca (%)
Fertiliser					
SB ₀	0.25 ± 0.10	0.09 ± 0.04	0.54 ± 0.35	0.09 ± 0.03	0.12 ± 0.06a
SB _{0.2}	0.24 ± 0.11	0.09 ± 0.05	0.59 ± 0.45	0.09 ± 0.04	0.09 ± 0.03b
SB _{0.4}	0.26 ± 0.13	0.09 ± 0.06	0.59 ± 0.46	0.09 ± 0.04	0.09 ± 0.04b
SB _{0.6}	0.21 ± 0.12	0.08 ± 0.05	0.56 ± 0.45	0.08 ± 0.04	0.09 ± 0.04b
LSD _(0.05)	ns	ns	ns	ns	0.02
F-value	2.11	1.87	0.38	1.04	6.02
P-value	0.1047	0.1406	0.7704	0.3795	0.0009
Phosphorus and water deficit levels					
P ₂₀ W ₂₅	0.18 ± 0.09b	0.0762 ± 0.05b	0.50 ± 0.44	0.0812 ± 0.04b	0.08 ± 0.03
P ₄₀ W ₂₅	0.24 ± 0.10ab	0.1054 ± 0.07a	0.65 ± 0.50	0.1037 ± 0.04a	0.11 ± 0.04
P ₂₀ W ₅₀	0.27 ± 0.13a	0.0859 ± 0.04ab	0.63 ± 0.45	0.0859 ± 0.03ab	0.10 ± 0.05
P ₄₀ W ₅₀	0.26 ± 0.13a	0.0950 ± 0.05ab	0.58 ± 0.44	0.0891 ± 0.04ab	0.10 ± 0.05
P ₂₀ W ₁₀₀	0.27 ± 0.10a	0.1016 ± 0.05ab	0.55 ± 0.41	0.1000 ± 0.03ab	0.11 ± 0.05
P ₄₀ W ₁₀₀	0.24 ± 0.11ab	0.0925 ± 0.04ab	0.51 ± 0.33	0.0895 ± 0.03ab	0.10 ± 0.04
LSD _(0.05)	0.05	0.02	ns	0.01	ns
F-value	4.26	2.65	1.30	3.35	2.29
P-value	0.0016	0.0279	0.2725	0.0080	0.0524
Season					
Season 1	0.32 ± 0.09a	0.13 ± 0.04a	0.90 ± 0.37a	0.12 ± 0.02a	0.13 ± 0.04a
Season 2	0.16 ± 0.07b	0.05 ± 0.03b	0.26 ± 0.16b	0.06 ± 0.02b	0.08 ± 0.03b
LSD _(0.05)	0.03	0.01	0.08	0.01	0.01
F-value	148.10	258.61	233.99	270.22	71.37
P-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Means followed by the same letter(s) in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant

Table 4.23: The interaction effects between Si-fertiliser and combined phosphorus and water deficit levels on accumulation of macronutrients concentration in roots.

Fertiliser	PW deficit levels	P (%)	Na (%)	K (%)	Mg (%)	Ca (%)
SB ₀	P ₂₀ W ₂₅	0.20 ± 0.06	0.09 ± 0.02ab	0.52 ± 0.31	0.09 ± 0.02	0.10 ± 0.01
	P ₄₀ W ₂₅	0.24 ± 0.10	0.10 ± 0.06a	0.70 ± 0.48	0.10 ± 0.03	0.11 ± 0.03
	P ₂₀ W ₅₀	0.23 ± 0.07	0.08 ± 0.04ab	0.50 ± 0.37	0.08 ± 0.02	0.12 ± 0.07
	P ₄₀ W ₅₀	0.28 ± 0.14	0.10 ± 0.06a	0.52 ± 0.38	0.09 ± 0.04	0.13 ± 0.08
	P ₂₀ W ₁₀₀	0.26 ± 0.07	0.09 ± 0.03ab	0.49 ± 0.31	0.09 ± 0.03	0.13 ± 0.08
	P ₄₀ W ₁₀₀	0.30 ± 0.12	0.11 ± 0.05a	0.51 ± 0.31	0.09 ± 0.03	0.13 ± 0.06
SB _{0.2}	P ₂₀ W ₂₅	0.19 ± 0.13	0.09 ± 0.07ab	0.64 ± 0.64	0.09 ± 0.05	0.09 ± 0.03
	P ₄₀ W ₂₅	0.24 ± 0.11	0.09 ± 0.06ab	0.61 ± 0.53	0.10 ± 0.04	0.10 ± 0.03
	P ₂₀ W ₅₀	0.27 ± 0.12	0.09 ± 0.04ab	0.69 ± 0.46	0.08 ± 0.02	0.09 ± 0.01
	P ₄₀ W ₅₀	0.23 ± 0.14	0.10 ± 0.08ab	0.63 ± 0.53	0.08 ± 0.50	0.08 ± 0.04
	P ₂₀ W ₁₀₀	0.29 ± 0.10	0.11 ± 0.04a	0.48 ± 0.30	0.10 ± 0.04	0.10 ± 0.02
	P ₄₀ W ₁₀₀	0.24 ± 0.10	0.08 ± 0.03ab	0.52 ± 0.33	0.09 ± 0.03	0.09 ± 0.02
SB _{0.4}	P ₂₀ W ₂₅	0.13 ± 0.07	0.03 ± 0.02b	0.28 ± 0.18	0.05 ± 0.02	0.05 ± 0.02
	P ₄₀ W ₂₅	0.25 ± 0.10	0.12 ± 0.11a	0.69 ± 0.60	0.11 ± 0.04	0.12 ± 0.03
	P ₂₀ W ₅₀	0.30 ± 0.20	0.06 ± 0.05ab	0.72 ± 0.59	0.08 ± 0.06	0.08 ± 0.06
	P ₄₀ W ₅₀	0.30 ± 0.15	0.08 ± 0.04ab	0.65 ± 0.52	0.10 ± 0.04	0.10 ± 0.03
	P ₂₀ W ₁₀₀	0.29 ± 0.09	0.11 ± 0.05a	0.65 ± 0.48	0.11 ± 0.03	0.12 ± 0.20
	P ₄₀ W ₁₀₀	0.27 ± 0.09	0.11 ± 0.04a	0.59 ± 0.39	0.09 ± 0.03	0.10 ± 0.01
SB _{0.6}	P ₂₀ W ₂₅	0.18 ± 0.10	0.08 ± 0.05ab	0.56 ± 0.52	0.08 ± 0.04	0.10 ± 0.04
	P ₄₀ W ₂₅	0.22 ± 0.12	0.09 ± 0.07ab	0.60 ± 0.53	0.10 ± 0.06	0.12 ± 0.07
	P ₂₀ W ₅₀	0.27 ± 0.13	0.09 ± 0.04ab	0.62 ± 0.44	0.09 ± 0.03	0.10 ± 0.04
	P ₄₀ W ₅₀	0.22 ± 0.12	0.08 ± 0.05ab	0.53 ± 0.45	0.07 ± 0.03	0.07 ± 0.02
	P ₂₀ W ₁₀₀	0.23 ± 0.14	0.08 ± 0.06ab	0.61 ± 0.57	0.08 ± 0.04	0.08 ± 0.03
	P ₄₀ W ₁₀₀	0.14 ± 0.11	0.06 ± 0.04ab	0.43 ± 0.36	0.07 ± 0.05	0.08 ± 0.05
LSD _(0.05)		ns	0.04	ns	ns	ns
F-value		1.08	2.13	0.90	1.63	1.29
P-value		0.3812	0.0150	0.5647	0.0816	0.2223

Means followed by the same letter(s) in the same column are statistically non-significant at 5% probability level; Means without letters in the same column are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, combined phosphorus and water deficit levels; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

Table 4.24: The effects between Si-fertiliser or combined phosphorus and water deficit levels interacting with cropping season on the accumulation of macronutrients concentration in the roots.

Treatments	P (%)	Na (%)	K (%)	Mg (%)	Ca (%)
Fertiliser					
Season 1					
SB ₀	0.32 ± 0.08	0.13 ± 0.03	0.80 ± 0.31	0.11 ± 0.01a	0.15 ± 0.07
SB _{0.2}	0.33 ± 0.08	0.14 ± 0.02	0.95 ± 0.37	0.12 ± 0.01a	0.11 ± 0.01
SB _{0.4}	0.34 ± 0.11	0.13 ± 0.07	0.93 ± 0.42	0.12 ± 0.04a	0.11 ± 0.03
SB _{0.6}	0.30 ± 0.09	0.12 ± 0.02	0.92 ± 0.39	0.04 ± 0.02a	0.12 ± 0.03
Season 2					
SB ₀	0.19 ± 0.06	0.06 ± 0.03	0.28 ± 0.08	0.07 ± 0.02b	0.09 ± 0.03
SB _{0.2}	0.15 ± 0.07	0.04 ± 0.02	0.23 ± 0.08	0.05 ± 0.02b	0.07 ± 0.02
SB _{0.4}	0.18 ± 0.09	0.05 ± 0.03	0.31 ± 0.28	0.06 ± 0.03b	0.08 ± 0.04
SB _{0.6}	0.21 ± 0.06	0.03 ± 0.03	0.20 ± 0.09	0.04 ± 0.02b	0.06 ± 0.03
LSD _(0.05)	ns	ns	ns	0.01	ns
F-value	0.75	1.18	1.13	2.75	1.98
P-value	0.5267	0.3205	0.3407	0.0470	0.1224
Phosphorus and water deficit levels					
Season 1					
P ₂₀ W ₂₅	0.25 ± 0.07	0.11 ± 0.04b	0.81 ± 0.44	0.11 ± 0.03	0.10 ± 0.03
P ₄₀ W ₂₅	0.32 ± 0.06	0.17 ± 0.05a	1.07 ± 0.36	0.14 ± 0.02	0.15 ± 0.02
P ₂₀ W ₅₀	0.37 ± 0.09	0.12 ± 0.01b	0.98 ± 0.37	0.10 ± 0.01	0.12 ± 0.05
P ₄₀ W ₅₀	0.36 ± 0.08	0.14 ± 0.03ab	0.95 ± 0.35	0.12 ± 0.01	0.13 ± 0.05
P ₂₀ W ₁₀₀	0.34 ± 0.07	0.14 ± 0.02ab	0.85 ± 0.39	0.13 ± 0.01	0.14 ± 0.05
P ₄₀ W ₁₀₀	0.31 ± 0.12	0.12 ± 0.03b	0.77 ± 0.29	0.11 ± 0.03	0.12 ± 0.04
Season 2					
P ₂₀ W ₂₅	0.11 ± 0.05	0.04 ± 0.02c	0.20 ± 0.07	0.04 ± 0.02	0.06 ± 0.03
P ₄₀ W ₂₅	0.17 ± 0.07	0.04 ± 0.03c	0.33 ± 0.33	0.06 ± 0.03	0.08 ± 0.03
P ₂₀ W ₅₀	0.17 ± 0.08	0.05 ± 0.03c	0.28 ± 0.13	0.06 ± 0.03	0.08 ± 0.05
P ₄₀ W ₅₀	0.15 ± 0.08	0.04 ± 0.02c	0.22 ± 0.10	0.05 ± 0.02	0.07 ± 0.03
P ₂₀ W ₁₀₀	0.20 ± 0.07	0.06 ± 0.02c	0.26 ± 0.08	0.06 ± 0.02	0.08 ± 0.02
P ₄₀ W ₁₀₀	0.18 ± 0.05	0.05 ± 0.02c	0.25 ± 0.07	0.06 ± 0.01	0.08 ± 0.02
LSD _(0.05)	ns	0.03	ns	ns	ns
F-value	1.15	3.40	0.86	1.81	0.97
P-value	0.3393	0.0073	0.5102	0.1186	0.0666

Means followed by the same letter in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

Table 4.25: The interaction effect between Si-fertiliser, combined phosphorus and water deficit levels, and cropping season on the accumulation of macronutrients concentration in the roots.

Treatment		Phosphorus (%)		Sodium (%)		Potassium (%)		Magnesium (%)		Calcium (%)	
Fertiliser	PW deficit levels	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
SB ₀	P ₂₀ W ₂₅	0.58 ± 0.13	0.17 ± 0.01	1.01 ± 0.21	0.37 ± 0.09	2.91 ± 0.35	2.02 ± 0.35	0.85 ± 0.12	0.64 ± 0.17	1.38 ± 0.39	1.21 ± 0.38
	P ₄₀ W ₂₅	0.75 ± 0.29	0.21 ± 0.08	0.98 ± 0.45	0.38 ± 0.14	2.67 ± 1.16	2.01 ± 0.43	0.88 ± 0.45	0.70 ± 0.24	1.37 ± 0.56	1.26 ± 0.53
	P ₂₀ W ₅₀	1.01 ± 0.23	0.39 ± 0.14	1.01 ± 0.14	0.40 ± 0.08	2.74 ± 0.11	2.41 ± 0.22	0.97 ± 0.14	0.71 ± 0.13	1.31 ± 0.08	1.29 ± 0.37
	P ₄₀ W ₅₀	1.02 ± 0.42	0.39 ± 0.29	0.86 ± 0.22	0.32 ± 0.20	2.45 ± 0.65	1.76 ± 1.22	0.77 ± 0.32	0.53 ± 0.34	1.23 ± 0.61	1.02 ± 0.72
	P ₂₀ W ₁₀₀	1.47 ± 0.75	0.68 ± 0.23	0.90 ± 0.22	0.37 ± 0.05	2.72 ± 0.56	2.72 ± 0.56	0.87 ± 0.18	0.54 ± 0.07	1.36 ± 0.28	0.93 ± 0.15
SB _{0.2}	P ₄₀ W ₁₀₀	0.79 ± 0.17	0.51 ± 0.15	0.69 ± 0.17	0.30 ± 0.03	1.80 ± 0.39	1.80 ± 0.39	0.56 ± 0.16	0.59 ± 0.17	0.87 ± 0.19	0.94 ± 0.22
	P ₂₀ W ₂₅	0.71 ± 0.55	0.18 ± 0.11	0.73 ± 0.27	0.23 ± 0.12	0.71 ± 0.68	1.75 ± 1.25	1.18 ± 0.68	0.44 ± 0.29	1.09 ± 0.13	0.92 ± 0.60
	P ₄₀ W ₂₅	0.73 ± 0.35	0.27 ± 0.28	0.79 ± 0.43	0.32 ± 0.25	0.76 ± 1.07	1.68 ± 1.30	1.11 ± 0.41	0.48 ± 0.39	1.16 ± 0.47	0.95 ± 0.77
	P ₂₀ W ₅₀	0.91 ± 0.57	0.38 ± 0.11	0.72 ± 0.44	0.42 ± 0.08	1.86 ± 1.34	2.17 ± 0.29	1.09 ± 0.77	0.59 ± 0.07	1.08 ± 0.53	1.22 ± 0.28
	P ₄₀ W ₅₀	1.32 ± 0.33	0.36 ± 0.24	0.85 ± 0.24	0.35 ± 0.15	2.10 ± 0.94	1.68 ± 0.68	1.21 ± 0.59	0.50 ± 0.28	1.13 ± 0.17	0.97 ± 0.51
SB _{0.4}	P ₂₀ W ₁₀₀	1.02 ± 0.32	0.71 ± 0.34	0.73 ± 0.26	0.35 ± 0.08	1.98 ± 1.25	1.69 ± 0.42	1.01 ± 0.35	1.01 ± 0.35	1.04 ± 0.17	1.05 ± 0.40
	P ₄₀ W ₁₀₀	0.58 ± 0.44	0.47 ± 0.29	0.58 ± 0.15	0.34 ± 0.11	1.53 ± 0.66	1.76 ± 0.25	0.76 ± 0.34	0.76 ± 0.34	0.83 ± 0.19	1.16 ± 0.50
	P ₂₀ W ₂₅	0.53 ± 0.14	0.27 ± 0.14	0.74 ± 0.28	0.37 ± 0.15	2.07 ± 1.15	2.13 ± 0.70	1.20 ± 0.58	0.59 ± 0.24	1.34 ± 0.74	1.14 ± 0.41
	P ₄₀ W ₂₅	0.58 ± 0.07	0.42 ± 0.16	1.01 ± 0.16	0.49 ± 0.14	2.86 ± 0.23	2.13 ± 0.94	0.98 ± 0.29	1.06 ± 0.82	1.33 ± 0.20	1.28 ± 0.16
	P ₂₀ W ₅₀	0.66 ± 0.16	0.36 ± 0.16	0.76 ± 0.29	0.44 ± 0.16	2.15 ± 1.19	2.21 ± 0.85	1.04 ± 0.27	0.64 ± 0.22	1.17 ± 0.48	1.18 ± 0.28
SB _{0.6}	P ₄₀ W ₅₀	1.27 ± 0.33	0.44 ± 0.07	0.91 ± 0.29	0.42 ± 0.14	2.31 ± 1.20	2.04 ± 0.73	1.51 ± 0.84	0.71 ± 0.29	1.51 ± 0.49	1.41 ± 0.60
	P ₂₀ W ₁₀₀	1.03 ± 0.43	0.58 ± 0.16	0.62 ± 0.10	0.37 ± 0.06	1.54 ± 0.38	1.87 ± 0.36	1.13 ± 0.89	0.62 ± 0.21	1.00 ± 0.13	1.11 ± 0.23
	P ₄₀ W ₁₀₀	1.53 ± 0.63	0.36 ± 0.09	1.00 ± 0.57	0.30 ± 0.05	2.31 ± 1.53	1.57 ± 0.42	1.56 ± 0.80	0.48 ± 0.10	1.59 ± 0.79	0.91 ± 0.13
	P ₂₀ W ₂₅	0.59 ± 0.23	0.20 ± 0.08	0.82 ± 0.28	0.35 ± 0.13	1.94 ± 0.96	1.48 ± 0.98	1.22 ± 0.72	0.58 ± 0.21	1.21 ± 0.41	0.11 ± 0.37
	P ₄₀ W ₂₅	0.56 ± 0.22	0.21 ± 0.09	0.63 ± 0.22	0.40 ± 0.12	1.44 ± 0.08	2.03 ± 0.61	1.16 ± 1.29	0.55 ± 0.20	0.64 ± 0.03	1.15 ± 0.32
	P ₂₀ W ₅₀	0.90 ± 0.36	0.29 ± 0.09	0.68 ± 0.16	0.36 ± 0.08	1.62 ± 0.39	1.93 ± 0.21	1.24 ± 1.25	0.55 ± 0.11	1.03 ± 0.47	1.10 ± 0.30
	P ₄₀ W ₅₀	0.83 ± 0.20	0.36 ± 0.17	0.75 ± 0.22	0.37 ± 0.12	1.96 ± 1.07	2.09 ± 0.93	0.90 ± 0.40	0.61 ± 0.27	0.96 ± 0.10	1.18 ± 0.49
	P ₂₀ W ₁₀₀	1.19 ± 0.77	0.40 ± 0.32	0.79 ± 0.47	0.27 ± 0.12	2.81 ± 1.56	1.31 ± 0.89	0.99 ± 0.36	0.49 ± 0.24	1.32 ± 0.84	0.92 ± 0.39
	P ₄₀ W ₁₀₀	1.14 ± 0.30	0.52 ± 0.35	1.00 ± 0.29	0.43 ± 0.08	2.34 ± 1.17	2.45 ± 0.49	1.52 ± 0.97	0.64 ± 0.07	1.39 ± 0.26	1.16 ± 0.19
LSD _(0.05)		ns		ns		ns		ns		ns	
F-value		1.15		0.58		0.37		0.50		0.58	
P-value		0.3272		0.8857		0.9843		0.9372		0.8829	

Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, combined phosphorus and water deficit levels; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; not significant.

The interaction effect between SB and cropping season did not significantly affect the root P, Na, K, and Ca concentration (Table 4.24). The beetroot Mg concentration was significantly ($P=0.0470$) increased by 100% following the application of SB_{0.4} in season 1 compared to season 2. The interaction effect between combined P and W deficit levels and cropping season on root P, K, Mg and Ca concentration was not significant (Table 4.24). The beetroot Na concentration was significantly ($P=0.0073$) higher with P₄₀W₂₅ in season 1 than in season 2. The interaction effect among SB, combined P and W deficit levels, and cropping season on P, Na, K, Mg and Ca was not significant (Table 4.25).

4.3.2.4 Root micronutrients concentration

The results on the effect of SB, combined P and W deficit levels, and cropping season on the accumulation of the micronutrients concentration in the roots are presented in Table 4.26. The Mn, Fe, Co, Zn, Cu and B varied significantly as affected by the application of SB. The SB_{0.6} significantly reduced root Cu, B, Zn, Fe and Co concentration by 39%, 34%, 25%, 21%, and 20%, respectively, relative to the control. Furthermore, the SB_{0.6} significantly reduced the root Mn concentration by 21%, relative to SB_{0.4}. The Si accumulators show considerably lower Mn toxicity, as they help reduce more than 90% of Mn in plant cell walls (Mundada *et al.*, 2021). The root Mo content was not significantly affected by the application of the SB.

Phosphorus and W deficit levels had no significant effect on root Co, Zn, Cu, B and Mo concentration. The P₂₀W₂₅ significantly decreased root Mn and Fe concentration by 42% and 35%, respectively, relative to P₂₀W₅₀ treatment, suggesting that moderate W supply improves the Mn and Fe uptake. The root Mo was not significantly affected by the cropping season. Nevertheless, a highly significant difference ($P<0.0001$) in the effect of the cropping season was observed on other micro-nutrient concentration (Cu, Mn, B, Zn, Fe and Co). In general, the accumulated micronutrient concentration measurements in season 1 were quantitatively higher than in season 2.

The interaction effect between SB, and combined P and W deficit levels did not significantly affect Co, Cu and Mo concentration (Table 4.27). The Mn concentration recorded from SB_{0.4}×P₂₀W₅₀ was significantly ($P=0.0001$) higher (87%) than that recorded from SB₀×P₂₀W₂₅. The SB_{0.2}×P₄₀W₂₅ led to a significant ($P=0.0009$) increase (37%) in B content relative to SB₀×P₂₀W₂₅. The root Fe and Zn concentration recorded from SB_{0.4}×P₂₀W₅₀ were higher by 219% and 99%, respectively, than those recorded from SB_{0.4}×P₂₀W₂₅.

Table 4.26: Accumulation of micronutrients concentration in the roots as affected by the Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

Treatments	Mn (mg/kg)	Fe (mg/kg)	Co (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	B (mg/kg)	Mo (mg/kg)
Fertiliser							
SB ₀	145.44 ± 44.84ab	259.42 ± 125.62a	53.11 ± 22.41a	76.58 ± 27.53a	102.07 ± 34.81a	91.57 ± 24.72a	63.77 ± 37.41
SB _{0.2}	138.38 ± 47.54ab	249.99 ± 154.20ab	49.84 ± 20.34a	72.72 ± 29.49a	99.24 ± 52.48ab	92.52 ± 37.77a	64.90 ± 32.20
SB _{0.4}	159.21 ± 98.42a	281.32 ± 198.67a	42.52 ± 8.40b	70.14 ± 31.64ab	81.75 ± 25.81bc	79.08 ± 14.23b	55.80 ± 21.91
SB _{0.6}	131.40 ± 55.06b	214.93 ± 141.54b	44.22 ± 10.68b	61.16 ± 24.83b	73.21 ± 23.94c	68.59 ± 9.17c	47.91 ± 13.85
LSD _(0.05)	17.20	33.26	4.13	7.99	14.21	7.41	ns
F-value	3.76	5.44	11.17	5.29	7.50	18.61	2.59
P-value	0.0134	0.0017	<0.0001	0.0021	0.0002	<0.0001	0.0574
Phosphorus and water deficit levels							
P ₂₀ W ₂₅	119.82 ± 45.55b	200.33 ± 147.95b	45.94 ± 15.86	62.33 ± 26.75	89.33 ± 38.69	79.55 ± 22.26	53.73 ± 30.78
P ₄₀ W ₂₅	149.04 ± 55.70ab	274.17 ± 164.16a	46.43 ± 16.22	75.08 ± 31.57	94.42 ± 59.94	90.07 ± 47.31	53.34 ± 24.03
P ₂₀ W ₅₀	169.62 ± 114.01a	271.06 ± 181.14a	47.22 ± 15.50	73.60 ± 32.77	82.10 ± 23.01	79.00 ± 15.15	56.02 ± 22.33
P ₄₀ W ₅₀	139.33 ± 55.36ab	232.38 ± 149.89a	48.13 ± 18.34	68.81 ± 29.79	85.12 ± 26.66	80.20 ± 19.69	61.12 ± 30.80
P ₂₀ W ₁₀₀	143.66 ± 43.59ab	267.40 ± 149.09a	49.30 ± 19.38	70.55 ± 28.17	92.59 ± 36.75	83.07 ± 17.64	62.34 ± 29.42
P ₄₀ W ₁₀₀	140.17 ± 44.89ab	263.15 ± 153.40a	47.51 ± 17.71	70.52 ± 23.87	89.61 ± 33.46	84.43 ± 21.13	62.09 ± 32.87
LSD _(0.05)	21.07	40.73	ns	ns	ns	ns	ns
F-value	4.62	4.06	0.45	1.63	0.61	1.69	0.49
P-value	0.0008	0.0022	0.8149	0.1589	0.6909	0.1447	0.7839
Season							
Season 1	185.19 ± 61.48a	382.03 ± 113.25a	60.70 ± 15.19a	91.68 ± 20.16a	107.21 ± 39.34a	92.71 ± 30.82a	61.67 ± 36.84
Season 2	103.16 ± 37.85b	124.38 ± 60.39b	34.50 ± 2.00b	49.21 ± 18.58b	71.13 ± 25.93b	73.24 ± 14.61b	54.54 ± 15.63
LSD _(0.05)	12.16	23.51	2.92	5.65	10.05	5.23	ns
F-value	179.91	482.06	312.96	224.55	49.28	56.83	2.15
P-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.1460

Means followed by the same letter(s) in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively.

Table 4.27: The interaction effects between Si-fertiliser and combined phosphorus and water deficit levels on the accumulation of micronutrients concentration in the roots.

Fertiliser	PW deficit levels	Mn (mg/kg)	Fe (mg/kg)	Co (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	B (mg/kg)	Mo (mg/kg)
SB ₀	P ₂₀ W ₂₅	137.95 ± 31.50b	233.34 ± 126.58abcd	55.06 ± 26.34	84.23 ± 18.66a	111.48 ± 41.73	97.98 ± 19.53b	55.45 ± 39.48
	P ₄₀ W ₂₅	153.93 ± 53.13b	279.02 ± 140.79abc	55.76 ± 26.63	89.33 ± 36.99a	86.91 ± 23.39	89.89 ± 20.10bc	53.31 ± 36.34
	P ₂₀ W ₅₀	130.11 ± 35.96b	240.03 ± 98.59abcd	52.31 ± 23.74	64.24 ± 23.19ab	89.28 ± 22.96	84.79 ± 19.82bc	60.90 ± 29.26
	P ₄₀ W ₅₀	145.84 ± 65.60b	267.86 ± 140.31abcd	52.13 ± 22.55	70.40 ± 31.21ab	100.63 ± 33.90	91.51 ± 33.16bc	71.91 ± 46.27
	P ₂₀ W ₁₀₀	150.17 ± 40.67b	275.11 ± 151.50abc	52.34 ± 24.64	71.67 ± 29.87ab	102.81 ± 36.82	86.23 ± 23.27bc	68.92 ± 36.09
	P ₄₀ W ₁₀₀	154.62 ± 49.48b	261.15 ± 141.92abcd	51.05 ± 20.34	79.61 ± 25.55ab	122.28 ± 48.39	97.77 ± 36.63b	73.79 ± 48.77
SB _{0.2}	P ₂₀ W ₂₅	127.73 ± 63.06b	242.60 ± 216.96abcd	41.71 ± 9.06	60.98 ± 31.61ab	99.05 ± 48.78	89.35 ± 27.01bc	70.22 ± 44.81
	P ₄₀ W ₂₅	136.98 ± 46.43b	288.86 ± 193.28abc	42.55 ± 10.15	69.85 ± 31.09ab	139.61 ± 104.30	134.17 ± 87.27a	59.11 ± 24.89
	P ₂₀ W ₅₀	135.72 ± 40.59b	249.36 ± 139.97abcd	47.24 ± 15.97	72.64 ± 23.00ab	86.15 ± 25.26	82.11 ± 11.56bc	60.23 ± 21.60
	P ₄₀ W ₅₀	137.71 ± 62.09b	229.68 ± 161.51abcd	55.11 ± 26.96	73.39 ± 39.54ab	81.65 ± 21.65	79.34 ± 11.72bc	62.32 ± 34.77
	P ₂₀ W ₁₀₀	151.98 ± 48.10b	261.27 ± 144.77abcd	57.85 ± 26.92	80.39 ± 32.62ab	98.03 ± 42.76	88.42 ± 17.93bc	67.64 ± 37.22
	P ₄₀ W ₁₀₀	140.16 ± 38.71b	228.17 ± 110.80abcd	54.59 ± 26.75	79.04 ± 25.90ab	90.94 ± 21.68	88.65 ± 13.27bc	69.87 ± 37.74
SB _{0.4}	P ₂₀ W ₂₅	91.93 ± 27.03b	117.49 ± 63.24d	42.54 ± 9.21	45.74 ± 19.59b	73.70 ± 27.26	67.43 ± 8.22bc	42.76 ± 6.81
	P ₄₀ W ₂₅	152.96 ± 56.41b	295.61 ± 186.80abc	42.28 ± 8.86	73.01 ± 28.56ab	75.20 ± 17.48	77.25 ± 9.92bc	53.24 ± 18.56
	P ₂₀ W ₅₀	258.17 ± 200.17a	374.97 ± 302.57a	43.68 ± 9.75	90.89 ± 54.13a	78.48 ± 20.46	81.67 ± 17.55bc	53.62 ± 26.12
	P ₄₀ W ₅₀	149.25 ± 56.22b	276.68 ± 202.09abc	42.28 ± 8.26	72.24 ± 25.38ab	83.48 ± 20.77	79.24 ± 14.52bc	60.71 ± 23.21
	P ₂₀ W ₁₀₀	152.23 ± 43.71b	310.30 ± 187.78ab	42.32 ± 0.67	72.34 ± 24.74ab	97.02 ± 40.94	86.83 ± 16.83bc	64.82 ± 26.56
	P ₄₀ W ₁₀₀	150.73 ± 35.54b	312.87 ± 156.67ab	42.02 ± 9.51	66.61 ± 18.89ab	82.80 ± 25.77	82.06 ± 13.86bc	60.17 ± 26.31
SB _{0.6}	P ₂₀ W ₂₅	121.68 ± 49.40b	207.89 ± 147.80bcd	44.45 ± 12.61	58.38 ± 25.19ab	73.08 ± 26.63	63.44 ± 9.47c	14.48 ± 14.48
	P ₄₀ W ₂₅	152.17 ± 76.66b	233.21 ± 170.39abc	45.15 ± 13.20	68.13 ± 33.07ab	74.70 ± 27.83	66.27 ± 8.95bc	17.12 ± 17.12
	P ₂₀ W ₅₀	154.48 ± 62.05b	219.87 ± 110.72bcd	45.65 ± 11.95	66.61 ± 20.45ab	74.50 ± 26.18	68.38 ± 8.09bc	13.36 ± 13.36
	P ₄₀ W ₅₀	124.52 ± 48.43b	155.29 ± 75.67cd	43.01 ± 9.70	59.22 ± 27.37ab	74.88 ± 28.08	70.69 ± 8.45bc	13.17 ± 13.17
	P ₂₀ W ₁₀₀	120.25 ± 44.53b	222.92 ± 135.55abcd	44.67 ± 11.76	57.82 ± 27.68ab	74.21 ± 28.01	71.32 ± 10.21bc	15.76 ± 15.76
	P ₄₀ W ₁₀₀	115.17 ± 54.10b	250.41 ± 215.99ab	42.37 ± 8.94	56.83 ± 22.60ab	67.89 ± 15.08	71.46 ± 10.71bc	15.12 ± 15.12
LSD _(0.05)		42.14	81.46	ns	19.59	ns	18.17	ns
F-value		3.45	2.39	1.23	2.01	1.29	2.91	0.20
P-value		0.0001	0.0056	0.2667	0.0222	0.2240	0.0009	0.9995

Means followed by the same letter(s) in the same column are statistically non-significant at 5% probability level; Means without letters in the same column are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, combined phosphorus and water deficit levels; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively.

Table 4.28 shows root micronutrients concentration accumulation as affected by SB and combined P and W deficit levels interacting with the cropping season. The interaction effect between SB and cropping season did not significantly affect the root Mn, Fe, Zn and Mo concentration. The root Co, Cu and B concentration recorded from SB_{0.2} in season 1 were significantly higher by 105%, 93%, and 56%, respectively, relative to SB_{0.2} in season 2. The interactive effect of combined P and W deficit levels and cropping season on the root Mn, Fe, Co, Zn, Cu, and Mo concentration was not significant. The root B concentration recorded from P₄₀W₂₅ was 64% higher in season 1 than in season 2. The P₄₀W₂₅ in season 1 gave root B concentration that was 57% higher than that recorded from P₄₀W₁₀₀ in season 2.

The interaction effects among SB, combined P and W deficit levels and cropping season on root micronutrient concentration are shown in Table 4.29. The root Co, Zn, Cu and Mo concentration were not significantly affected by an interaction between SB application, combined P and W deficit levels and cropping season. The root Fe and Mn concentration recorded from SB_{0.4}×P₂₀W₅₀ in season 1 were 484% and 333% higher, respectively, compared to those recorded from the same treatment in season 2. Furthermore, the root Fe and Mn concentration recorded from SB_{0.4}×P₂₀W₅₀ in season 1 were 345% and 270% higher, respectively, compared to SB₀×P₂₀W₂₅ in season 2. The root B concentration recorded from SB_{0.2}×P₄₀W₂₅ in season 1 was 229% higher compared to that recorded from the same treatment in season 2. Moreover, the root B concentration recorded from SB_{0.4}×P₂₀W₅₀ in season 1 was 156% higher compared to that recorded from SB₀×P₂₀W₂₅ in season 2.

Table 4.28: The interaction between Si-fertiliser or combined phosphorus and water deficit levels and cropping season on the accumulation of micronutrients concentration in the roots.

Treatments	Mn (mg/kg)	Fe (mg/kg)	Co (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	B (mg/kg)	Mo (mg/kg)
Fertiliser							
Season 1							
SB ₀	178.02 ± 31.24	371.39 ± 69.10	71.70 ± 17.37a	94.89 ± 22.55	114.83 ± 24.09ab	98.82 ± 28.28ab	60.57 ± 48.50
SB _{0.2}	178.83 ± 16.52	387.28 ± 90.23	65.70 ± 17.85a	99.42 ± 10.74	133.38 ± 56.01a	113.50 ± 45.30a	76.19 ± 42.33
SB _{0.4}	211.61 ± 115.0	432.72 ± 171.97	50.75 ± 1.63b	89.73 ± 27.25	93.99 ± 19.66bc	86.82 ± 10.53bc	58.35 ± 28.09
SB _{0.6}	173.76 ± 30.56	339.53 ± 86.19	54.10 ± 5.23b	82.57 ± 13.64	86.77 ± 27.92bcd	73.55 ± 10.26dc	51.36 ± 18.82
Season 2							
SB ₀	112.85 ± 30.28	147.44 ± 34.08	34.51 ± 0.52c	58.26 ± 18.50	90.06 ± 39.55bcd	85.18 ± 19.80bc	67.15 ± 21.26
SB _{0.2}	97.93 ± 30.26	112.70 ± 29.99	33.98 ± 0.72c	46.02 ± 12.88	65.09 ± 8.01cd	72.70 ± 8.10dc	53.60 ± 8.53
SB _{0.4}	112.32 ± 46.54	145.85 ± 97.16	35.16 ± 3.73c	52.61 ± 24.50	70.80 ± 26.16cd	72.16 ± 13.72dc	53.68 ± 15.01
SB _{0.6}	89.04 ± 38.83	90.33 ± 30.67	34.33 ± 0.78c	39.75 ± 10.63	59.65 ± 3.39d	63.63 ± 3.96d	44.47 ± 3.92
LSD _(0.05)	ns	ns	5.84	ns	20.11	10.48	ns
F-value	1.28	1.71	11.80	1.75	4.81	8.69	1.49
P-value	0.2849	0.1701	<0.0001	0.1612	0.0037	<0.0001	0.2236
Phosphorus and water deficit levels							
Season 1							
P ₂₀ W ₂₅	154.57 ± 32.60	309.76 ± 135.63	57.71 ± 14.94	82.21 ± 18.91	131.20 ± 77.39	88.86 ± 25.16bc	56.53 ± 41.49
P ₄₀ W ₂₅	193.27 ± 24.70	423.90 ± 49.68	59.59 ± 15.11	99.85 ± 14.00	107.86 ± 36.23	117.00 ± 65.88a	53.29 ± 34.10
P ₂₀ W ₅₀	178.17 ± 25.66	413.46 ± 146.95	59.83 ± 12.46	96.50 ± 26.78	97.80 ± 20.64	86.80 ± 14.63bc	59.23 ± 29.29
P ₄₀ W ₅₀	175.50 ± 30.41	355.37 ± 111.91	61.72 ± 17.35	93.15 ± 18.94	101.47 ± 23.23	87.41 ± 21.31bc	67.75 ± 40.01
P ₂₀ W ₁₀₀	228.65 ± 129.25	397.27 ± 89.95	64.30 ± 17.15	90.92 ± 21.02	105.15 ± 31.12	87.84 ± 12.76bc	64.54 ± 36.15
P ₄₀ W ₁₀₀	181.64 ± 28.82	395.90 ± 94.87	60.96 ± 16.12	88.14 ± 18.10	103.63 ± 28.83	93.52 ± 22.90b	67.96 ± 43.45
Season 2							
P ₂₀ W ₂₅	85.07 ± 25.34	90.90 ± 35.32	34.16 ± 0.59	42.45 ± 16.63	70.79 ± 32.67	70.24 ± 14.62c	50.92 ± 15.32
P ₄₀ W ₂₅	111.62 ± 46.14	147.48 ± 107.96	35.30 ± 4.45	54.12 ± 26.62	66.12 ± 10.06	71.42 ± 10.13c	53.38 ± 11.74
P ₂₀ W ₅₀	110.59 ± 53.60	128.66 ± 52.66	34.61 ± 0.67	50.69 ± 19.59	66.41 ± 11.99	71.84 ± 12.16bc	52.80 ± 12.74
P ₄₀ W ₅₀	97.02 ± 40.90	109.39 ± 38.08	34.55 ± 0.54	44.48 ± 14.34	68.76 ± 19.06	72.98 ± 15.59bc	54.50 ± 16.95
P ₂₀ W ₁₀₀	109.14 ± 26.75	137.53 ± 39.83	34.29 ± 0.47	50.19 ± 17.68	81.08 ± 38.96	78.69 ± 20.75bc	64.54 ± 36.15
P ₄₀ W ₁₀₀	104.84 ± 23.79	130.40 ± 341.90	34.05 ± 0.95	52.91 ± 13.67	103.63 ± 28.83	74.51 ± 14.06bc	67.96 ± 43.45
LSD _(0.05)	ns	ns	ns	ns	ns	12.86	ns
F-value	1.56	0.83	0.50	0.53	1.07	3.97	0.16
P-value	0.1781	0.5338	0.7770	0.7564	0.3796	0.0027	0.9748

Means followed by the same letter(s) in the same column and treatment are statistically non-significant at 5% probability level; Means without letters in the same column and treatment are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

Table 4.29: Accumulation of micronutrients concentration in the roots as affected by the interaction among Si-fertiliser, combined phosphorus and water deficit levels, and cropping season.

Treatments	PW deficit levels	Mn (mg/kg)	Fe (mg/kg)	Co (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	B (mg/kg)	Mo (mg/kg)
Season 1								
SB ₀	P ₂₀ W ₂₅	162.49 ± 25.84b-d	322.73 ± 126.62c-j	75.39 ± 22.25	100.57 ± 6.07	117.22 ± 29.36	106.49 ± 19.59b	39.51 ± 52.73
	P ₄₀ W ₂₅	195.33 ± 19.95b-d	397.58 ± 73.77b-f	76.75 ± 21.25	115.91 ± 3.19	110.13 ± 0.17	108.10 ± 1.87b	47.62 ± 54.05
	P ₂₀ W ₅₀	149.85 ± 20.30b-d	320.62 ± 44.18c-j	70.48 ± 20.46	77.58 ± 17.93	104.87 ± 15.44	93.94 ± 25.20b	61.80 ± 42.27
	P ₄₀ W ₅₀	183.73 ± 53.55b-d	393.76 ± 15.22b-f	69.46 ± 19.25	90.96 ± 29.66	119.02 ± 27.26	99.26 ± 43.64b	77.63 ± 66.81
	P ₂₀ W ₁₀₀	178.54 ± 35.29d-d	404.24 ± 70.66a-e	70.47 ± 23.08	90.14 ± 33.04	106.19 ± 21.84	75.02 ± 6.59b	61.60 ± 44.49
	P ₄₀ W ₁₀₀	198.17 ± 6.74b-c	389.44 ± 25.25b-f	67.69 ± 14.25	94.22 ± 27.65	127.11 ± 41.98	103.64 ± 46.57b	75.30 ± 66.15
SB _{0.2}	P ₂₀ W ₂₅	182.73 ± 23.89b-d	400.02 ± 207.78b-e	49.97 ± 0.60	88.67 ± 13.50	138.81 ± 34.69	112.13 ± 15.71b	93.26 ± 58.25
	P ₄₀ W ₂₅	174.13 ± 24.62b-d	464.59 ± 20.30a-b	51.61 ± 3.25	97.35 ± 10.82	216.54 ± 97.10	228.93 ± 19.69a	66.04 ± 36.95
	P ₂₀ W ₅₀	169.01 ± 8.36b-d	376.43 ± 10.61b-g	60.31 ± 11.19	91.47 ± 2.94	109.10 ± 2.56	91.97 ± 3.74b	67.63 ± 31.13
	P ₄₀ W ₅₀	187.27 ± 10.34b-d	375.44 ± 21.42b-h	75.85 ± 22.97	108.36 ± 8.51	101.16 ± 2.05	88.44 ± 5.18b	73.35 ± 50.78
	P ₂₀ W ₁₀₀	189.74 ± 18.57b-d	387.43 ± 57.59b-f	81.51 ± 11.55	109.08 ± 3.51	127.77 ± 43.14	100.89 ± 15.44b	78.11 ± 55.17
	P ₄₀ W ₁₀₀	170.11 ± 4.48b-d	319.77 ± 72.85c-j	74.98 ± 23.25	101.57 ± 6.84	106.93 ± 14.42	97.13 ± 9.59b	78.77 ± 56.17
SB _{0.4}	P ₂₀ W ₂₅	108.97 ± 3.44b-d	173.50 ± 4.65e-l	50.82 ± 2.60	60.05 ± 14.20	88.72 ± 34.14	72.93 ± 6.54b	42.99 ± 8.97
	P ₄₀ W ₂₅	176.75 ± 4.85b-d	456.04 ± 3.11a-c	50.36 ± 0.24	85.34 ± 3.72	86.35 ± 25.93	84.54 ± 9.56b	45.85 ± 31.33
	P ₂₀ W ₅₀	419.42 ± 134.20a	640.26 ± 102.31a	52.57 ± 0.98	136.11 ± 9.97	90.53 ± 18.75	93.84 ± 7.88b	56.57 ± 36.98
	P ₄₀ W ₅₀	187.09 ± 34.44b-d	428.54 ± 177.04a-d	49.74 ± 1.92	90.83 ± 16.07	95.21 ± 16.90	84.17 ± 13.17b	65.54 ± 30.67
	P ₂₀ W ₁₀₀	183.82 ± 35.56b-d	452.32 ± 165.37a-d	50.20 ± 1.19	83.12 ± 20.37	97.00 ± 17.82	90.63 ± 6.14b	66.13 ± 32.95
	P ₄₀ W ₁₀₀	182.02 ± 12.75b-d	453.45 ± 15.15a-d	50.68 ± 1.15	81.48 ± 14.93	103.60 ± 19.03	94.02 ± 6.91b	68.86 ± 38.73
SB _{0.6}	P ₂₀ W ₂₅	164.10 ± 7.60b-d	345.79 ± 2.26b-i	54.68 ± 9.11	79.57 ± 15.24	86.70 ± 34.64	63.88 ± 14.60b	50.37 ± 21.67
	P ₄₀ W ₂₅	221.36 ± 4.68b	388.12 ± 2.79c-f	56.59 ± 6.58	95.97 ± 14.73	89.81 ± 35.23	69.97 ± 11.95b	51.17 ± 26.09
	P ₂₀ W ₅₀	176.33 ± 6.65b-d	316.51 ± 1.48c-k	55.96 ± 6.14	80.83 ± 14.78	86.70 ± 34.88	69.84 ± 8.93b	50.92 ± 19.09
	P ₄₀ W ₅₀	168.47 ± 7.08b-d	223.73 ± 3.810c-l	51.82 ± 1.52	82.44 ± 15.12	90.50 ± 35.14	77.76 ± 4.96b	54.47 ± 18.85
	P ₂₀ W ₁₀₀	160.59 ± 7.43b-d	345.10 ± 0.98b-i	55.05 ± 4.76	81.36 ± 13.68	90.00 ± 34.84	80.53 ± 2.26b	52.31 ± 23.73
	P ₄₀ W ₁₀₀	151.72 ± 55.98b-d	420.95 ± 169.32a-d	50.50 ± 0.52	75.28 ± 11.31	76.89 ± 18.03	79.31 ± 10.03b	48.92 ± 23.48
Season 2								
SB ₀	P ₂₀ W ₂₅	113.42 ± 2.60f-n	143.95 ± 7.39g-l	34.73 ± 0.40	67.89 ± 5.76	105.74 ± 58.24	89.46 ± 18.72b	71.40 ± 18.81
	P ₄₀ W ₂₅	112.53 ± 38.95f-n	160.46 ± 44.12f-l	34.77 ± 0.12	62.75 ± 35.94	71.44 ± 14.02	77.75 ± 15.94b	59.00 ± 16.82
	P ₂₀ W ₅₀	110.36 ± 40.64f-n	159.43 ± 53.51f-l	34.14 ± 0.51	50.90 ± 22.13	73.69 ± 18.74	78.69 ± 18.12b	60.01 ± 18.73
	P ₄₀ W ₅₀	107.95 ± 59.86i-n	141.96 ± 37.96g-l	34.81 ± 0.55	49.85 ± 16.98	82.24 ± 33.39	83.76 ± 25.77b	66.19 ± 28.11
	P ₂₀ W ₁₀₀	121.80 ± 21.82e-n	145.97 ± 48.63g-l	34.22 ± 0.37	53.20 ± 10.78	106.19 ± 21.84	93.70 ± 29.19b	76.24 ± 33.41
	P ₄₀ W ₁₀₀	111.07 ± 19.67f-n	132.86 ± 18.63i-l	34.41 ± 0.87	65.01 ± 15.07	127.11 ± 41.98	88.98 ± 27.78b	71.53 ± 27.34
SB _{0.2}	P ₂₀ W ₂₅	72.73 ± 17.21-n	85.19 ± 13.26j-l	33.45 ± 0.60	33.29 ± 4.04	59.29 ± 2.04	66.57 ± 4.62b	47.17 ± 5.76

Table 4.29: continues

SB _{0.4}	P ₄₀ W ₂₅	99.83 ± 25.38k-n	113.14 ± 18.47i-l	33.49 ± 0.79	42.36 ± 5.76	62.67 ± 3.30	71.00 ± 6.10b	52.18 ± 6.34
	P ₂₀ W ₅₀	102.43 ± 26.93j-n	122.29 ± 20.74i-l	34.17 ± 0.56	53.81 ± 15.82	63.21 ± 3.17	72.26 ± 5.40b	52.84 ± 5.75
	P ₄₀ W ₅₀	88.14 ± 46.52l-n	83.92 ± 31.96j-l	34.37 ± 0.53	38.41 ± 12.97	62.13 ± 5.11	70.25 ± 8.29b	51.28 ± 8.89
	P ₂₀ W ₁₀₀	114.22 ± 34.09g-m	135.11 ± 36.58i-l	34.19 ± 0.29	51.71 ± 13.40	68.29 ± 7.50	75.95 ± 9.98b	57.17 ± 9.51
	P ₄₀ W ₁₀₀	110.22 ± 32.20g-n	136.58 ± 14.71h-l	34.20 ± 1.28	56.52 ± 10.42	74.94 ± 14.14	80.17 ± 11.52b	60.97 ± 12.99
	P ₂₀ W ₂₅	74.89 ± 30.71m-n	61.47 ± 23.75l	34.27 ± 0.08	31.44 ± 12.01	58.69 ± 3.98	61.93 ± 5.97b	42.54 ± 5.95
	P ₄₀ W ₂₅	141.07 ± 68.77c-k	215.40 ± 180.05d-l	38.24 ± 8.10	66.84 ± 34.68	69.63 ± 12.68	73.61 ± 8.98b	56.94 ± 13.86
	P ₂₀ W ₅₀	96.92 ± 64.53k-n	109.68 ± 85.25i-l	34.80 ± 0.33	45.66 ± 33.08	66.43 ± 16.11	69.51 ± 16.24b	50.68 ± 17.60
	P ₄₀ W ₅₀	111.41 ± 49.19f-n	124.82 ± 39.73i-l	34.83 ± 0.43	53.65 ± 17.76	71.42 ± 19.19	74.30 ± 16.75b	55.88 ± 18.33
	P ₂₀ W ₁₀₀	120.64 ± 22.79e-m	168.28 ± 17.27e-l	34.45 ± 0.80	61.56 ± 27.70	97.05 ± 62.23	83.03 ± 25.04b	63.50 ± 25.94
SB _{0.6}	P ₄₀ W ₁₀₀	119.45 ± 7.70e-m	172.29 ± 43.03e-l	33.36 ± 0.41	51.75 ± 2.57	62.00 ± 0.55	70.10 ± 1.93b	51.48 ± 2.21
	P ₂₀ W ₂₅	79.26 ± 25.39m-n	73.00 ± 4.33l	34.22 ± 0.47	37.20 ± 2.85	59.46 ± 4.07	63.00 ± 3.27b	42.58 ± 3.06
	P ₄₀ W ₂₅	83.26 ± 19.17l-n	78.30 ± 24.20k-l	33.71 ± 0.47	40.28 ± 13.85	59.59 ± 3.21	62.57 ± 4.05b	44.21 ± 3.96
	P ₂₀ W ₅₀	132.63 ± 90.27d-m	123.23 ± 51.27i-l	35.34 ± 0.60	52.38 ± 14.85	62.30 ± 7.10	66.92 ± 8.79b	47.69 ± 8.60
	P ₄₀ W ₅₀	80.57 ± 4.38m-n	86.85 ± 15.88j-l	34.20 ± 0.65	36.01 ± 5.29	59.26 ± 2.37	63.62 ± 2.04b	44.65 ± 2.50
	P ₂₀ W ₁₀₀	79.91 ± 4.62m-n	100.75 ± 34.07j-l	34.30 ± 0.57	34.28 ± 8.16	58.42 ± 1.01	62.10 ± 0.98b	43.63 ± 0.93
	P ₄₀ W ₁₀₀	78.63 ± 13.33m-n	79.88 ± 26.72k-l	34.24 ± 1.21	38.38 ± 11.33	58.88 ± 0.32	63.61 ± 1.30	44.06 ± 1.58
LSD _(0.05)		59.75	115.51	ns	ns	ns	25.888	ns
F-value		4.68	2.60	1.11	1.53	0.99	4.42	0.24
P-value		<0.0001	0.0027	0.3569	0.1098	0.4697	<0.0001	0.9984

Means followed by the same letter(s) in the same column are statistically non-significant at 5% probability level; Means without letters in the same column are not significantly different from each other; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; PW, combined phosphorus and water deficit levels; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

4.3.2.5 Correlation matrix among the accumulation of macro and micronutrients concentration in plant leaves

The estimated correlation matrix describing the relationships between the accumulation of leaf macro and micronutrients concentration interacting during two distinct cropping seasons as affected by the combined P and W deficit levels, and SB application is presented in Table 4.30. The observed significant and positive associations were between Cu and Mo ($r=0.99$), B and Mo ($r=0.86$) content in season 1, showing a possible uptake and metabolic association (Maillard *et al.*, 2016). Significant and strong positive correlations were observed between Na and Co ($r=0.88$), Na and Fe ($r=0.80$), Mn and Fe ($r=0.85$), Mn and Na ($r=0.87$), Zn and Na ($r=0.85$), Zn and Mn ($r=0.80$), and Ca and Zn ($r=0.80$) concentration in season 1. Strong and negative correlations were observed between Ca and Mo ($r=-0.60$), and Ca and Cu ($r=-0.57$) content, suggesting an antagonistic relationship with Ca, and Mo and Cu in season 1. This observed predominance of strong positive inter-micro-nutrient correlations may suggest that under combined P and W stress, and SB application such as $SB_{0.2} \times P_{20}W_{25}$, the plants' uptake mechanisms or transport pathways favoured internal homeostasis of trace elements. The nutrient crosstalk or non-specific transporter upregulating under stress has been reported (Etienne *et al.*, 2018). The interactions between nutrients may display synergistic or antagonistic behaviour, depending on relative concentration or ionic competition (Rietra *et al.*, 2017).

In season 2, significant and positive correlations were observed between B and Mo ($r=0.99$), B and Cu ($r=0.96$), and Cu and Mo ($r=0.95$) concentration, showing a relationship like that observed in season 1 (Table 4.22). This shows a consistent interdependency association among B, Mo and Cu across seasons. It is noteworthy that this relationship between B, Mo and Cu may indicate a strong biochemical or transport linkage and suggests that under combined P and W deficit level ($P_{20}W_{25}$), the plant may channel these micronutrients together (Zhao *et al.*, 2016; Fan *et al.*, 2021). Calcium content was significantly and positively correlated with Na ($r=0.85$) and K ($r=0.82$). Magnesium content was significantly and positively correlated with Ca ($r=0.86$), Na ($r=0.80$), and Zn ($r=0.75$) content. A negative and significant correlation was observed between K and Cu ($r=-0.56$) in season 2. The correlation analysis suggested that under combined P and W stress and SB application, leaf nutrient dynamics shift over seasons, and this finding also agrees with the cropping season results (Table 4.18), showing that season 1 manifested more widespread synergistic associations among micro-nutrients relative to season 2.

Table 4.30: Correlation analysis between the accumulation of macro and micronutrients concentration in beetroot leaves of cropping seasons one and two, in response to combined phosphorus and water deficit levels, and Si-fertiliser application.

Variables	Mo	Cu	B	P	Co	Fe	Na	Mn	Zn	Ca	K	Mg
Season 1												
Mo	1											
Cu	0.99	1										
B	0.86	0.89	1									
P	0.23	0.26	0.38	1								
Co	0.37	0.43	0.70	0.60	1							
Fe	-0.19	-0.14	0.12	0.67	0.68	1						
Na	-0.00	0.06	0.41	0.52	0.88	0.80	1					
Mn	-0.12	-0.06	0.16	0.68	0.68	0.85	0.87	1				
Zn	-0.27	-0.21	0.05	0.24	0.60	0.68	0.85	0.80	1			
Ca	-0.60	-0.57	-0.43	0.04	0.10	0.52	0.52	0.69	0.80	1		
K	-0.29	-0.26	-0.14	-0.13	0.13	0.39	0.43	0.44	0.55	0.70	1	
Mg	-0.26	-0.24	-0.05	0.40	0.29	0.39	0.39	0.46	0.47	0.30	-0.37	1
Season 2												
Mo	1											
Cu	0.95	1										
B	0.99	0.96	1									
P	0.56	0.51	0.57	1								
Co	-0.22	-0.08	-0.21	0.33	1							
Fe	0.52	0.42	0.51	0.42	0.04	1						
Na	-0.02	-0.16	-0.04	-0.06	-0.41	0.23	1					
Mn	0.35	0.31	0.35	0.32	-0.04	0.31	0.57	1				
Zn	0.31	0.16	0.29	0.14	-0.14	0.51	0.50	0.37	1			
Ca	-0.22	-0.40	-0.24	-0.34	-0.51	0.15	0.85	0.29	0.59	1		
K	-0.41	-0.56	-0.43	-0.42	-0.41	0.13	0.69	0.03	0.17	0.82	1	
Mg	0.21	0.04	0.19	-0.05	-0.48	0.53	0.80	0.47	0.75	0.86	0.61	1

Values in bold are different from 0 with a significance level of 5%.

4.3.2.6 Correlation matrix among the accumulation of macro and micronutrients concentration in plant roots

The results of a correlation analysis to explore the relationships between total root nutrient concentration in response to combined P and W deficit levels, and SB application during seasons 1 and 2 are presented in Table 4.31. The observed significant and positive associations were between Mn and Mg ($r=0.94$), and B and Cu ($r=0.86$), Fe and Mg ($r=0.83$), Mn and Ca ($r=0.82$), Mg and Ca ($r=0.82$), Na and Fe ($r=0.81$), Na and Mn ($r=0.80$), Mn and P ($r=0.76$), Fe and Mn ($r=0.75$), Na and K ($r=0.69$), Ca and P ($r=0.66$), Mn and Zn ($r=0.65$), Fe and P ($r=0.63$), Zn and Mn ($r=0.80$) in season 1.

In season 2, P showed strong and positive correlations with Ca, Mg, Mn, Fe, Na, Zn, and Fe (r range: 0.82 to 0.93). Also, P showed moderate associations with B ($r=0.63$) and Mn ($r=0.62$). Mn had a strong and positive correlation with Mg, Fe, Na, and K, and Zn, with coefficients ranging from 0.89 to 0.97 . Moderate associations between Mn and B ($r=0.65$), and Mn and Mo ($r=0.64$) were observed. The observed strong correlation of P with Ca, Mg, Fe, Na, Zn and Fe could suggest that root P uptake and storage interact with cation assimilation, possibly through charge balancing or co-transport mechanisms. Holz *et al.* (2024) indicated that, in conditions of P or W deficit stress, root architecture and exudation patterns may shift, altering mass flow characteristics that affect multiple ions or nutrient diffusion. Calcium had strong and positive correlations with Mn, Mg, Fe, Na, K, and Zn (range: 0.92 to 0.99). Magnesium had strong and positive correlations with Fe ($r=0.92$) and K ($r=0.97$) and moderate associations with B ($r=0.61$), and Mo ($r=0.60$). Iron also showed a strong and positive association with Na, K, and Zn (range: 0.87 to 0.93), and a moderate association with B ($r=0.59$) and Mo ($r=0.58$). Sodium had a strong and positive relationship with K and Zn, with correlation coefficients ranging from 0.93 to 0.96 , and moderate association with B ($r=0.66$), Mo ($r=0.65$), and Cu ($r=0.57$). Strong and positive correlations were also observed between Zn and K ($r=0.92$), B and Cu ($r=0.97$), and Mo and Cu ($r=0.97$).

The results showed that under combined P and W deficit stress, and SB application, the root nutrient concentration responded in a highly coordinated manner that most of the nutrient content co-varied strongly and suggested linked acquisition, translocation or storage processes. Other studies show that the nutrient-to-nutrient interactions are well documented in plant biology, where the uptake of one ion can co-regulate that of the other via chelation or alteration of root physiology (Romera *et al.*, 2021; Singh *et al.*, 2024).

Table 4.31: Correlation analysis between the accumulation of macro and micronutrients concentration in plant roots of cropping season one and two, under combined phosphorus and water deficit level, and Si-fertiliser application.

	P	Ca	Mn	Mg	Fe	Na	K	Zn	Co	Cu	B	Mo
Season 1												
P	1											
Ca	0.66	1										
Mn	0.76	0.82	1									
Mg	0.64	0.80	0.94	1								
Fe	0.63	0.68	0.75	0.83	1							
Na	0.66	0.67	0.80	0.82	0.81	1						
K	0.38	0.22	0.52	0.54	0.51	0.69	1					
Zn	0.39	0.40	0.65	0.56	0.46	0.54	0.38	1				
Co	-0.14	-0.10	-0.17	-0.32	-0.27	-0.23	-0.39	0.48	1			
Cu	-0.01	0.07	-0.06	-0.04	0.13	0.13	-0.11	0.34	0.43	1		
B	-0.01	0.02	-0.01	0.03	0.26	0.19	0.03	0.41	0.34	0.94	1	
Mo	0.42	0.11	0.07	0.13	0.32	0.34	0.01	0.21	0.21	0.34	0.38	1
Season 2												
P	1											
Ca	0.90	1										
Mn	0.93	0.95	1									
Mg	0.91	0.99	0.94	1								
Fe	0.92	0.92	0.90	0.93	1							
Na	0.93	0.93	0.95	0.92	0.91	1						
K	0.92	0.98	0.97	0.97	0.93	0.96	1					
Zn	0.86	0.93	0.89	0.95	0.87	0.93	0.92	1				
Co	0.26	0.35	0.38	0.36	0.19	0.33	0.40	0.39	1			
Cu	0.52	0.44	0.55	0.49	0.47	0.57	0.44	0.61	0.11	1		
B	0.63	0.55	0.65	0.61	0.59	0.66	0.56	0.71	0.13	0.97	1	
Mo	0.62	0.54	0.64	0.60	0.58	0.65	0.55	0.70	0.14	0.97	1.00	1

Values in bold are different from 0 with a significance level of 5%.

4.3.2.7 Principal component analysis (PCA) for the accumulation of leaf macro and micronutrients concentration

The PCA for the five principal components accounted for most of the total leaf nutrient concentration variability. In season 1, the observation (PC1; 30%) showed a significant positive cluster of nutrients, Co (0.820), Na (0.733), Mn (0.725), B (0.648), P (0.642), Fe (0.629), Zn (0.566) and (0.530) loadings. In addition, PC2 (27%) showed a strong association between Ca (0.846) and K (0.719), and a strong negative loading of Cu (-0.687) and Mo (-0.712). Furthermore, PC3 (18%) showed a positive loading for Mg (0.867). However, PC4 (9%) showed weaker loading (0.472), and Cu (0.349) and PC5 (7%) did not significantly contribute (Table 4.23).

In season 2, PC1 (30%) was repeatedly dominated by Mo (0.735), B (0.727), Cu (0.696), and Fe (0.675) in relation to the observation in season 1; however, there was an additional contribution to the cluster by Zn (0.544) and P (0.512) as positive loadings. The PC2 (27%) showed a positive, strong loading for the basic cations K (0.789), Mg (0.731), Ca (0.752), and Na (0.646), suggesting the uptake dynamics for macro-nutrients which are associated with ionic regulation, cell wall structure and osmotic balance. The variability in PC3 (18%) showed a strong positive loading only for Co (0.728), and also negative loading for Mg (-0.571), Mo (0.531), and B (0.527). Furthermore, PC4 (9%) was influenced by Zn (0.555), and PC5 (7%) showed Mn (0.577) and P (0.544) loadings.

The PC biplot results showed that leaf Cu, B, Co, Ca, and P concentration were strongly associated with $SB_{0.2} \times P_{20} W_{100}$ and $SB_{0.6} \times P_{40} W_{100}$ and in season 1 (Figure 4.1). In addition, $SB_{0.4} \times P_{40} W_{50}$ and $SB_{0.6} \times P_{20} W_{25}$ were strongly associated with leaf K, Ca, and Zn concentration in season 1.

Table 4.32: Principal component analysis for the accumulation of macro and micronutrients concentration of beetroot leaves as affected by combined phosphorus and water deficit level, and Si-fertiliser application.

	PC1	PC2	PC3	PC4	PC5
Eigenvalue	7.11	6.46	4.42	2.05	1.58
Variability (%)	29.64	26.92	18.42	8.55	6.57
Cumulative (%)	29.64	56.56	74.98	83.52	90.10
Eigenvectors and (Factor loadings)					
Season 1					
P	0.241 (0.642)	-0.039 (-0.099)	0.193 (0.406)	0.087 (0.124)	0.248 (0.312)
Na	0.275 (0.733)	0.147 (0.373)	0.201 (0.422)	0.036 (0.052)	-0.290 (-0.365)
K	0.138 (0.367)	0.283 (0.719)	-0.188 (-0.395)	-0.236 (-0.337)	-0.185 (-0.232)
Mg	0.017 (0.046)	0.071 (0.180)	0.413 (0.867)	0.240 (0.344)	0.196 (0.246)
Ca	0.086 (0.230)	0.333 (0.846)	0.109 (0.229)	-0.191 (-0.274)	0.054 (0.068)
Mn	0.272 (0.725)	0.183 (0.465)	0.211 (0.443)	-0.044 (-0.062)	0.027 (0.034)
Fe	0.236 (0.629)	0.162 (0.411)	0.218 (0.458)	-0.104 (-0.149)	0.022 (0.027)
Co	0.308 (0.820)	-0.020 (-0.051)	0.168 (0.352)	0.099 (0.142)	-0.283 (-0.356)
Zn	0.212 (0.566)	0.246 (0.625)	0.184 (0.386)	-0.034 (-0.049)	-0.116 (-0.146)
Cu	0.199 (0.530)	-0.270 (-0.687)	-0.127 (-0.267)	0.244 (0.349)	-0.085 (-0.107)
B	0.243 (0.648)	-0.187 (-0.476)	-0.037 (-0.078)	0.330 (0.472)	-0.261 (-0.328)
Mo	0.183 (0.487)	-0.280 (-0.712)	-0.140 (-0.294)	0.239 (0.343)	-0.050 (-0.063)
Season 2					
P	0.192 (0.512)	-0.173 (-0.440)	-0.100 (-0.210)	0.052 (0.075)	0.433 (0.544)
Na	-0.036 (-0.097)	0.254 (0.646)	-0.239 (-0.503)	0.247 (0.353)	0.299 (0.376)
K	-0.166 (-0.444)	0.314 (0.789)	-0.117 (-0.245)	0.055 (0.078)	0.016 (0.020)
Mg	0.082 (0.218)	0.288 (0.731)	-0.272 (-0.571)	0.171 (0.244)	0.014 (0.017)
Ca	-0.067 (-0.179)	0.296 (0.752)	-0.203 (-0.426)	0.316 (0.453)	-0.044 (-0.056)
Mn	0.184 (0.490)	0.128 (0.325)	-0.068 (-0.144)	0.151 (0.216)	0.459 (0.577)
Fe	0.253 (0.675)	0.171 (0.436)	-0.090 (-0.190)	-0.145 (-0.208)	0.082 (0.103)
Co	0.064 (0.172)	-0.092 (-0.235)	0.346 (0.728)	0.074 (0.105)	0.272 (0.341)
Zn	0.204 (0.544)	0.152 (0.386)	-0.168 (-0.353)	0.388 (0.555)	-0.134 (-0.168)
Cu	0.261 (0.696)	-0.124 (-0.316)	-0.178 (-0.374)	-0.303 (-0.434)	0.098 (0.123)
B	0.273 (0.727)	-0.099 (-0.252)	-0.251 (-0.527)	-0.231 (-0.331)	0.064 (0.080)
Mo	0.275 (0.735)	-0.090 (-0.229)	-0.253 (-0.531)	-0.228 (-0.326)	0.052 (0.065)

Values in bold correspond for each variable to the factor for which the squared cosine is the largest.

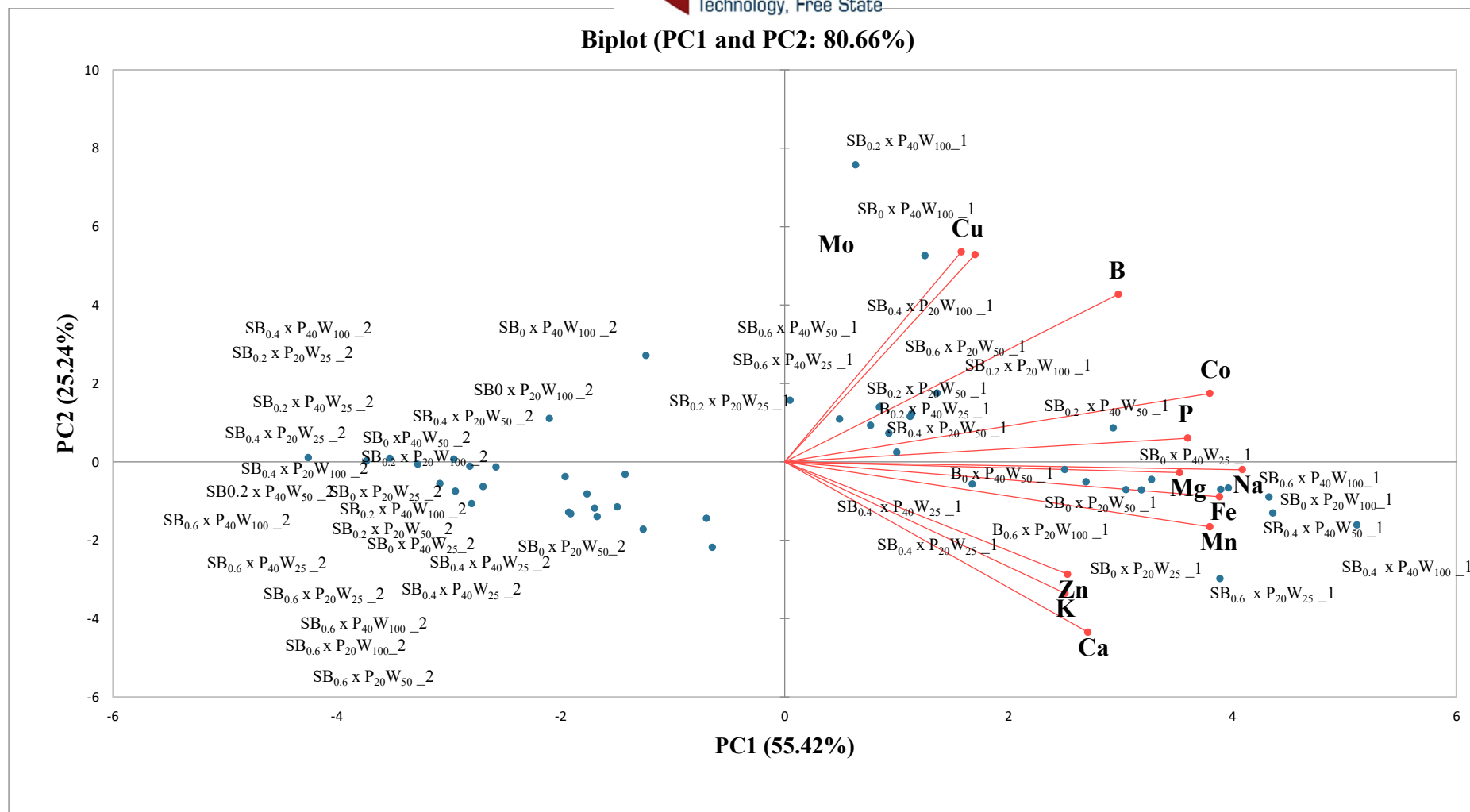


Figure 4.1: Principal component analysis biplot to identify the associations among the accumulation of macro and micronutrients concentration and Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

4.3.2.8 Principal component analysis for the accumulation of macro and micronutrient concentration in plant roots

The principal component analysis revealed that the first five PCs were the most significantly important (Table 4.33) and contributed to a total variation of 90.41% in leaf total nutrient concentration. In this study, during season 1, the observed Principal Component (PC1; 44% total variance) showed the positive loading for Co (0.608), Cu (0.572), and Zn (0.485) for the root micro-nutrient. In addition, PC2 (23%) showed a positive loading by Mg (0.946), Mn (0.920), Na (0.894), Fe (0.848), Ca (0.765), P (0.742), Ca (0.765), and Zn (0.530). Furthermore, PC3 (11%) showed positive loading for Cu (0.731) and B (0.669). The PC4 (7%) showed weaker positive loading for Ca (0.444), and a negative (-0.419), and PC5 (6%) showed a positive loading for (0.586) (Table 4.33).

In season 2, PC1 (30%) showed a highly positive loading dominated by nutrient correlations for almost all root total nutrient content, including P (0.904), Na (0.942), K (0.924), Mg (0.933), Ca (0.913), Mn (0.926), Fe (0.892), Zn (0.950), Cu (0.713), B (0.825), and Mo (0.810), indicating a nutrient uptake that could have been facilitated by the applied SB.

The comparison between seasons displayed a nutrient grouping for Co and Zn and Cu, Mo and B on PC1 in season 1, whilst PC1 in season 2 was dominated by both macro- and micro-nutrient concentration. Furthermore, in season 1, PC2 was dominated by both macro- and micro-nutrient concentration, whilst in season 2, weaker loading or less contribution was observed. In general, PC1 in season 2 demonstrated more grouping of almost all nutrients, showing an improved environmental condition or, rather, a well-functioning plant physiological interaction.

To explore the major patterns of variation in root nutrient concentration, the principal component analysis was applied, and the principal component analysis biplot accounted for 85% of the total variation (Figure 4.2). Beetroot Ca, Mg, K, Na, P, Fe, Zn, and Mn concentration were strongly and positively associated with $SB_{0.4} \times P_{20}W_{50}$ in season 1.

Table 4.33: Principal component analysis for the accumulation of macro and micronutrients concentration in beetroot leaves in response to combined phosphorus and water deficit level, and Si-fertiliser application.

	PC1	PC2	PC3	PC4	PC5
Eigenvalue	10.45	5.52	2.68	1.66	1.40
Variability (%)	43.53	22.99	11.16	6.91	5.82
Cumulative (%)	43.53	66.52	77.68	84.59	90.41
Eigenvectors and (Factor loading)					
Season 1					
P	0.094 (0.305)	0.316 (0.742)	-0.039 (-0.064)	0.145 (0.187)	-0.241 (-0.284)
Na	0.071 (0.228)	0.381 (0.894)	0.070 (0.115)	-0.124 (-0.160)	-0.033 (-0.039)
K	-0.081 (-0.263)	0.307 (0.721)	-0.019 (-0.032)	-0.273 (-0.352)	0.236 (0.280)
Mg	0.028 (0.089)	0.403 (0.946)	-0.027 (-0.044)	0.042 (0.054)	0.008 (0.009)
Ca	0.081 (0.263)	0.326 (0.765)	0.013 (0.021)	0.344 (0.444)	-0.073 (-0.086)
Mn	0.072 (0.234)	0.392 (0.920)	-0.126 (-0.206)	0.133 (0.171)	0.078 (0.092)
Fe	0.075 (0.241)	0.361 (0.848)	0.099 (0.163)	-0.093 (-0.120)	-0.135 (-0.159)
Co	0.188 (0.608)	-0.160 (-0.375)	0.028 (0.046)	-0.001 (-0.001)	0.343 (0.405)
Zn	0.150 (0.485)	0.225 (0.530)	-0.014 (-0.024)	-0.116 (-0.150)	0.496 (0.586)
Cu	0.177 (0.572)	-0.032 (-0.075)	0.446 (0.731)	-0.025 (-0.032)	0.247 (0.292)
B	0.160 (0.517)	0.007 (0.018)	0.409 (0.669)	-0.207 (-0.267)	0.280 (0.331)
Mo	0.096 (0.311)	0.087 (0.205)	0.284 (0.464)	-0.325 (-0.419)	-0.348 (-0.411)
Season 2					
P	0.280 (0.904)	-0.058 (-0.137)	-0.138 (-0.227)	-0.082 (-0.105)	-0.216 (-0.255)
Na	0.291 (0.942)	-0.014 (-0.034)	-0.135 (-0.220)	-0.075 (-0.096)	-0.082 (-0.097)
K	0.286 (0.924)	-0.027 (-0.064)	-0.191 (-0.313)	-0.146 (-0.188)	-0.029 (-0.035)
Mg	0.289 (0.933)	-0.055 (-0.130)	-0.139 (-0.228)	-0.127 (-0.163)	0.035 (0.041)
Ca	0.282 (0.913)	-0.049 (-0.114)	-0.164 (-0.268)	-0.174 (-0.224)	0.013 (0.016)
Mn	0.287 (0.926)	-0.043 (-0.101)	-0.159 (-0.260)	-0.051 (-0.066)	-0.143 (-0.169)
Fe	0.276 (0.892)	-0.055 (-0.129)	-0.099 (-0.161)	-0.178 (-0.229)	-0.168 (-0.199)
Co	0.096 (0.311)	0.009 (0.021)	-0.406 (-0.664)	0.375 (0.483)	0.305 (0.361)
Zn	0.294 (0.950)	-0.041 (-0.097)	-0.093 (-0.152)	-0.023 (-0.029)	0.145 (0.171)
Cu	0.221 (0.713)	-0.047 (-0.111)	0.261 (0.427)	0.383 (0.493)	-0.082 (-0.097)
B	0.252 (0.815)	-0.051 (-0.120)	0.247 (0.404)	0.293 (0.377)	-0.054 (-0.064)
Mo	0.251 (0.810)	-0.049 (-0.116)	0.248 (0.405)	0.303 (0.390)	-0.054 (-0.064)

Values in bold correspond for each variable to the factor for which the squared cosine is the largest.

4.3.2.9 The heatmap for non-targeted phenolic content in the roots

In this study, the response of beetroot to combined P and W deficit levels and SB application was assessed by measuring the non-targeted phenolic compounds as one of the root quality indicators. The measurements of phenolic content in roots during seasons 1 and 2 are presented in Figures 4.3 and 4.4, respectively. The results showed that the untargeted phenolic profiling identified the presence of betanin and isobetanin in season 1 (Figure 4.3), whereas in season 2 (Figure 4.4), no compound was identified.

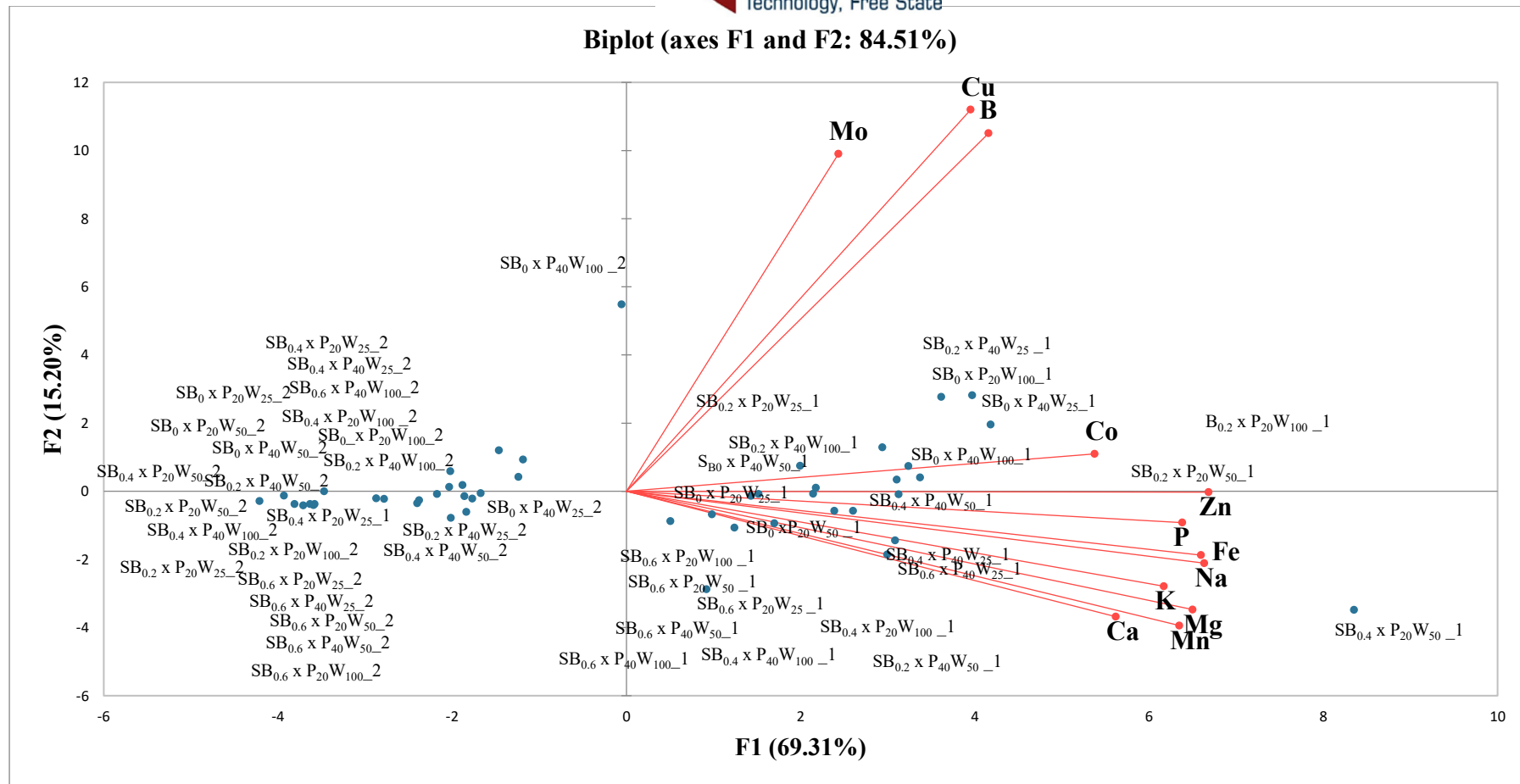


Figure 4.2: Principal component analysis biplot to identify the associations among the accumulation of macro and micronutrients concentration and Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

The abundance of betanin in season 2 might have been influenced by the environmental conditions, such as temperature and relative humidity (Table 3). The vegetable production guideline of KwaZulu-Natal Department of Agriculture and Environmental Affairs, of South Africa, explains that field temperatures in the ranges of 25-29⁰ C generally represents a moderately high environment for beetroot production, as the optimal growth temperature for maximum pigmentation synthesis is lower 15-18⁰C (KZN-DAEA, 2001). While the beetroot is fairly tolerant to heat if moisture is sufficient, higher temperature within this range can lead to a reduction in total betalain content and a change in the ratio of betacyanins to betaxanthins, resulting in a less, intense, more orange-red colour (Sokolova, 2022). The presence of betacyanins in season 1 is in agreement with other recent beetroot studies showing that betanin and isobetanin are the principal pigments or phenolics in mature beetroot tissues under favourable conditions. For instance, Hernández-Aguirre *et al.* (2021) investigated the extraction and stabilisation of betalains from beetroot wastes using deep eutectic solvents and found that betalains (including betanin and isobetanin) can be preserved under certain conditions, however, they are sensitive to light, pH, temperature, and storage time. Furthermore, under suboptimal conditions, betalain concentration declines (Sokolova *et al.*, 2022).

In a study conducted by Kayın *et al.* (2019), focusing on beetroot juice concentrate, increasing storage temperature (25, 35 and 45°C) and light exposure accelerated degradation of betalains and lowered the total phenolic content. Thus, pigment compounds are sensitive to environmental stressors even post-harvest. Other possible hypotheses to explain why betanin and isobetanin were found in season 1 but not in season 2 could be that, under severe P and W deficit levels, plant metabolism often relocates resources away from secondary metabolites (such as betalains and phenolics) to maintenance processes, which means that less phenolic compound might be have been synthesised in roots under combined P and W deficit conditions in season 2. Therefore, it can be concluded that the detection of betanin and isobetanin in season 1 confirms that beetroot roots retain characteristic betalain pigments under moderate stress, and that these can serve as root quality indicators.

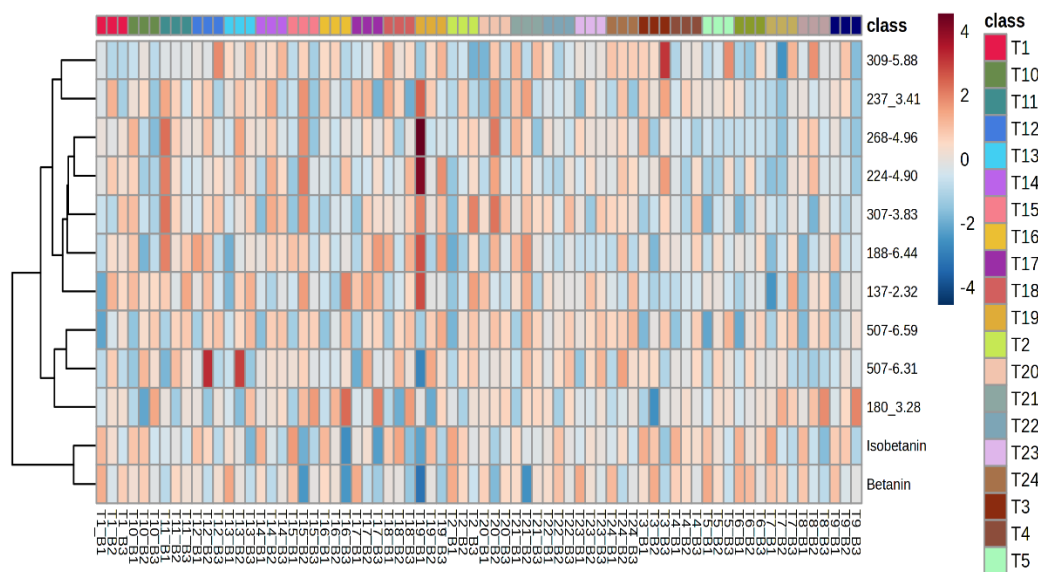


Figure 4.3: Heatmap showing the variations between untargeted beetroot phenolic content and treatments during season 1. T1, SB0×P40W100; T2, SB0×P20W100; T3, SB0×P40W50; T4, SB0×P20W50; T5, SB0×P40W25; T6, SB0×P20W25; T7, SB0.2×P40W100; T8 SB0.2×P20W100; T9, SB0.2×P40W50; T10, SB0.2×P20W50; T11, SB0.2×P40W25; T12, SB0.2×P20W25; T13, SB0.4×P40W100; T14 SB0.4×P20W100; T15, SB0.4×P40W50; T16, SB0.4×P20W50; T17, SB0.4×P40W25; T18, SB0.4×P20W25; T19, SB0.6×P40W100; T20 SB0.6×P20W100; T21, SB0.6×P40W50; T22, SB0.6×P20W50; T23, SB0.6×P40W25; T24, SB0.6×P20W25.

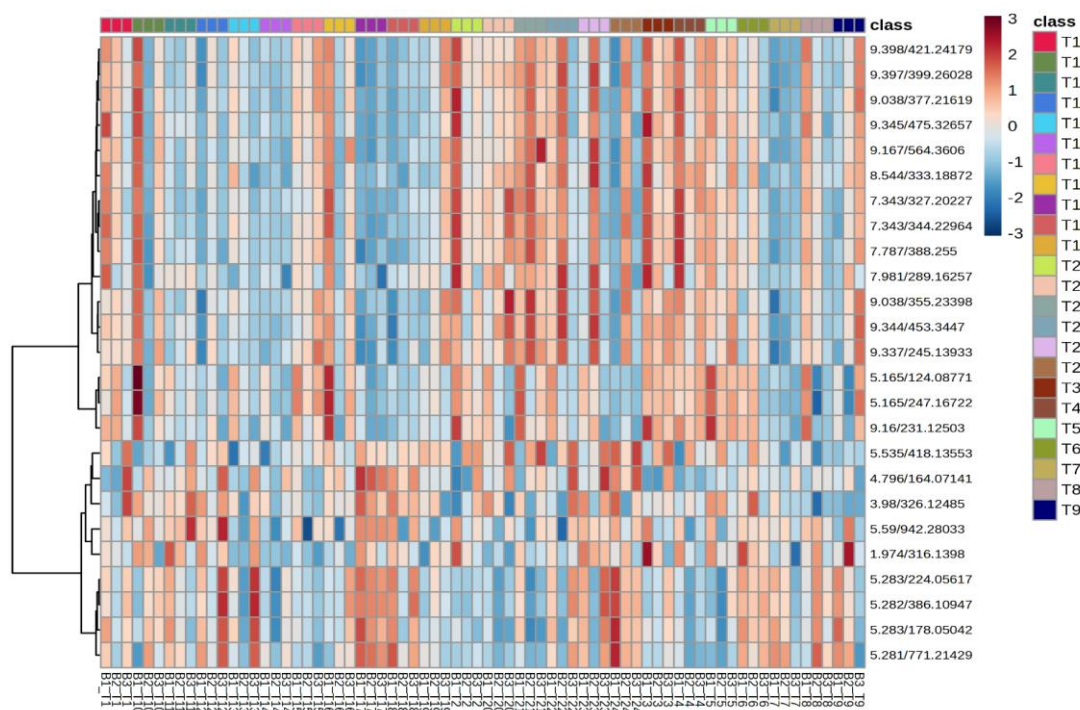


Figure 4.4: Heatmap showing the variations between untargeted beetroot phenolic content and treatments during season 2. 1, SB0×P40W100; T2, SB0×P20W100; T3, SB0×P40W50; T4, SB0×P20W50; T5, SB0×P40W25; T6, SB0×P20W25; T7, SB0.2×P40W100; T8 SB0.2×P20W100; T9, SB0.2×P40W50; T10, SB0.2×P20W50; T11, SB0.2×P40W25; T12, SB0.2×P20W25; T13, SB0.4×P40W100; T14 SB0.4×P20W100; T15, SB0.4×P40W50; T16, SB0.4×P20W50; T17, SB0.4×P40W25; T18, SB0.4×P20W25; T19, SB0.6×P40W100; T20 SB0.6×P20W100; T21, SB0.6×P40W50; T22, SB0.6×P20W50; T23, SB0.6×P40W25; T24, SB0.6×P20W25.

4.4 Collected postharvest soil quality parameters in response to silicon-based fertiliser application and combined P and W deficit levels at crop harvest

4.4.1 Postharvest soil quality parameters

The effect of SB on soil Ca, Na, K, Mg, and pH (KCl) was not significant (Table 4.34). This finding is not in agreement with that of Artyszak *et al.* (2025), who reported significant effects of SB application on the concentration of Ca, Mg, P, and K. As shown in Figure 4.5, the application of SB significantly affected the soil pH (H₂O) ($P=0.0188$) and EC ($P=0.0008$). The SB_{0.4} significantly increased pH (H₂O) by 4.6% as compared to the control. This could imply that SB improved soil pH by reducing soil acidity. The EC was highly reduced by 33% at SB_{0.2} and SB_{0.4}, and 14% at SB_{0.6} applications. This suggests that Si application improves soluble salt concentrates in the soil. Similar results were reported by Karapouloutidou & Gasparatos (2019), who reported that soil pH values were slightly increased and EC values decreased after the application of SB.

Table 4.34: Postharvest soil chemical properties as affected by Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

Treatments	Ca (mg/kg)	Mg (mg/kg)	K (mg/kg)	Na (mg/kg)	P (mg/kg)	pH (H ₂ O)	pH (KCl)	EC (mS/cm)
Season 1	191.12 ± 62.70a	75.93 ± 8.55a	64.96 ± 10.50b	54.71 ± 1.18a	27.63 ± 14.64b	5.03 ± 0.22a	4.17 ± 0.26a	0.10 ± 0.02a
Season 2	171.76 ± 37.06b	51.04 ± 13.89b	138.68 ± 68.87a	26.77 ± 11.80b	49.17 ± 17.31a	4.79 ± 0.37b	3.90 ± 0.35b	0.04 ± 0.01b
LSD _(0.05)	17.101	3.6964	14.35	2.4998	4.7027	0.0988	0.1059	0.0058
F-value	5.42	183.50	105.11	500.87	86.09	23.90	27.48	492.30
P-value	0.0220	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
SB	ns	ns	ns	ns	ns	0.0188	ns	0.0008
PW	ns	ns	ns	ns	<0.0001	ns	ns	ns
SBxSeason	ns	ns	ns	ns	ns	ns	ns	ns
PWxSeason	ns	ns	ns	ns	ns	ns	ns	ns
SBxPWxSeason	ns	ns	ns	ns	ns	ns	ns	ns

Means followed by the same letter(s) in the same column are statistically non-significant at 5% probability level; Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; PW, combined phosphorus and water deficit levels; ns, not significant.

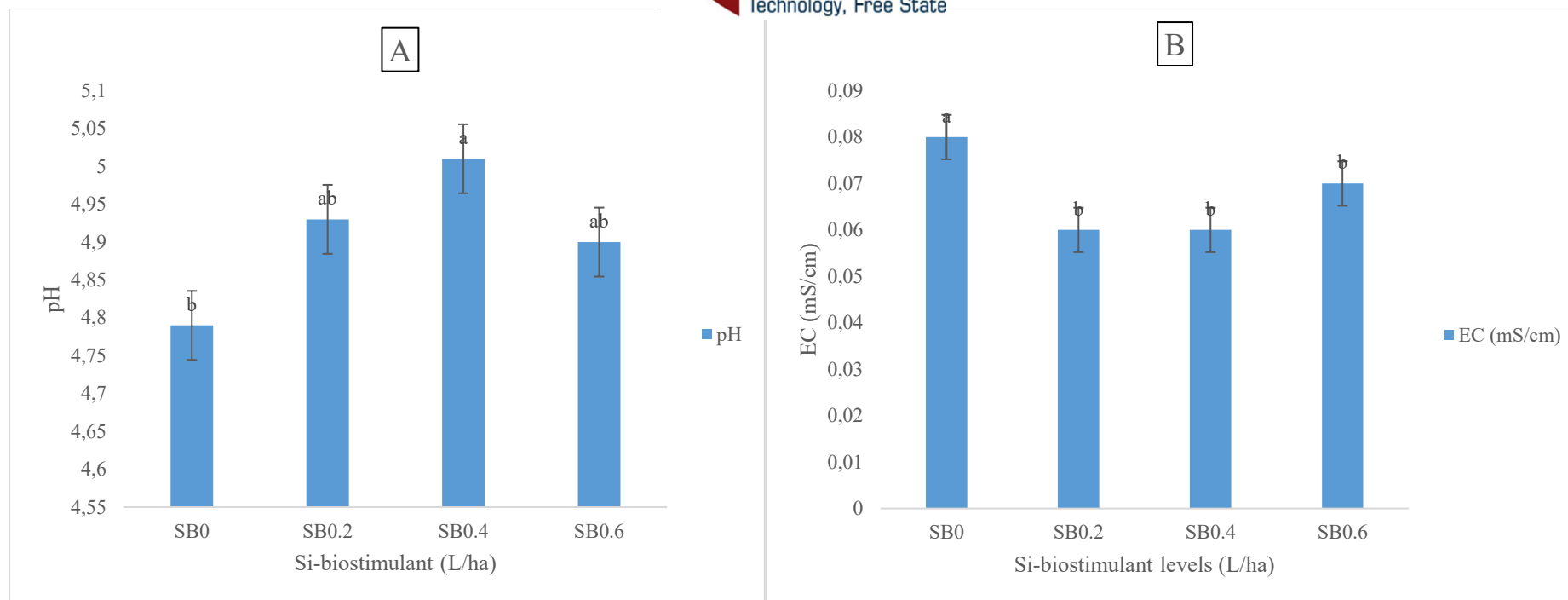


Figure 4.5: Effect of Si-fertiliser on (A) Soil pH-H₂O ($LSD=0.14$; $F=3.49$; $P=0.0188$) and (B) electrical conductivity (EC) ($LSD=0.01$; $F=0.01$; $P=0.0008$). Columns labelled with the same letter for each soil quality parameter are not significantly different at $P \leq 0.05$. Si-fertiliser levels (SB): 0 (control), 0.2, 0.4, and 0.6 L/ha.

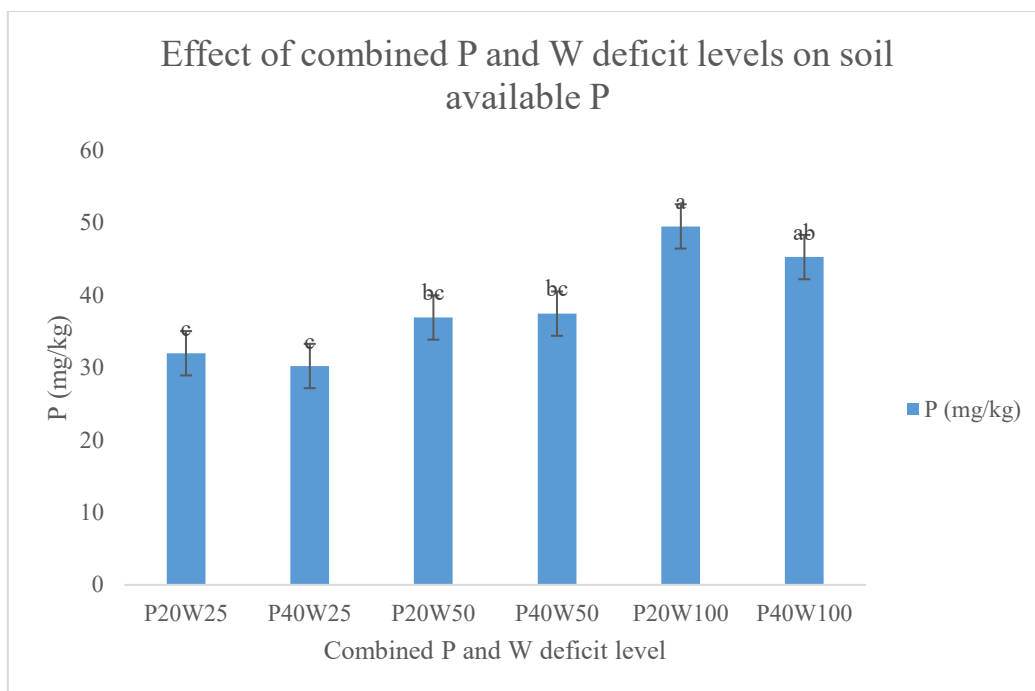


Figure 4.6: Effect of combined P and W deficit levels on soil available P. Columns labelled with the same letter for the collected postharvest soil are not significantly different at $P \leq 0.05$. ($LSD=8.14$; $F=6.68$; $P < 0.0001$). Combined P and W deficit levels where Phosphorus levels (P): 20 kg/ha (extreme deficit), 40 kg/ha (moderate); Water levels (W) 25% ETc (extreme stress), 50% ETc (moderate), 100% ETc (no stress or full irrigation); ETc, evapotranspiration.

Table 4.35: The interaction effects among Si-fertiliser, combined phosphorus and water deficit levels, and cropping season on soil calcium, potassium, magnesium and sodium concentration.

Biostimulant	PW deficit levels	Ca (mg/kg)		K (mg/kg)		Mg (mg/kg)		Na (mg/kg)	
		Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
SB ₀	P ₂₀ W ₂₅	205.82 ± 85.11	168.10 ± 14.81	66.21 ± 10.59	123.83 ± 37.65	76.84 ± 13.56	52.96 ± 13.48	55.19 ± 1.54	27.82 ± 12.54
	P ₄₀ W ₂₅	200.23 ± 82.52	167.73 ± 8.69	74.98 ± 13.10	193.30 ± 35.38	79.33 ± 10.22	51.82 ± 9.97	55.23 ± 0.35	28.28 ± 9.77
	P ₂₀ W ₅₀	160.97 ± 31.75	209.12 ± 30.86	65.33 ± 3.75	115.30 ± 26.55	72.20 ± 1.42	58.20 ± 17.00	54.56 ± 0.82	29.22 ± 15.34
	P ₄₀ W ₅₀	178.58 ± 31.06	177.19 ± 73.11	64.31 ± 4.26	88.94 ± 26.55	74.05 ± 2.28	53.20 ± 19.82	55.50 ± 1.09	35.56 ± 18.03
	P ₂₀ W ₁₀₀	220.74 ± 103.70	148.95 ± 54.93	66.95 ± 9.07	99.80 ± 68.01	79.82 ± 13.05	49.18 ± 16.98	55.36 ± 0.72	26.98 ± 11.98
	P ₄₀ W ₁₀₀	191.36 ± 53.59	184.19 ± 37.26	57.41 ± 6.37	79.09 ± 43.69	73.99 ± 7.63	49.46 ± 18.39	54.49 ± 0.61	25.15 ± 10.24
SB _{0.2}	P ₂₀ W ₂₅	156.85 ± 25.90	172.95 ± 13.26	64.24 ± 13.14	136.70 ± 4.57	73.17 ± 3.68	48.02 ± 10.59	54.39 ± 0.18	28.06 ± 13.81
	P ₄₀ W ₂₅	142.03 ± 48.14	177.00 ± 65.26	63.40 ± 11.65	157.63 ± 45.59	69.60 ± 7.92	54.60 ± 15.67	53.88 ± 0.81	25.20 ± 11.62
	P ₂₀ W ₅₀	167.96 ± 49.99	181.46 ± 52.08	69.84 ± 2.01	120.18 ± 120.56	46.80 ± 21.95	46.80 ± 21.95	55.87 ± 0.11	23.42 ± 14.85
	P ₄₀ W ₅₀	235.53 ± 20.99	173.71 ± 30.90	70.01 ± 7.97	186.48 ± 33.68	45.96 ± 18.94	45.96 ± 18.96	55.01 ± 1.23	24.84 ± 15.08
	P ₂₀ W ₁₀₀	187.22 ± 2.49	174.90 ± 39.77	62.47 ± 8.48	125.66 ± 62.53	76.30 ± 0.81	46.54 ± 23.03	54.40 ± 1.12	26.29 ± 19.04
	P ₄₀ W ₁₀₀	243.14 ± 113.09	160.96 ± 26.98	60.87 ± 2.29	106.63 ± 42.86	81.81 ± 17.66	48.47 ± 16.38	54.70 ± 1.27	26.74 ± 19.35
SB _{0.4}	P ₂₀ W ₂₅	206.43 ± 85.78	197.10 ± 10.60	63.59 ± 2.37	185.85 ± 59.30	76.52 ± 9.39	56.08 ± 10.78	54.73 ± 1.05	25.05 ± 9.56
	P ₄₀ W ₂₅	235.65 ± 69.94	165.38 ± 41.55	68.92 ± 3.45	128.61 ± 61.35	82.42 ± 3.54	57.42 ± 12.33	53.99 ± 0.16	32.87 ± 15.49
	P ₂₀ W ₅₀	249.27 ± 87.07	155.09 ± 13.41	65.85 ± 12.04	99.50 ± 98.05	82.15 ± 9.00	51.50 ± 11.47	55.01 ± 0.21	28.42 ± 12.20
	P ₄₀ W ₅₀	226.87 ± 35.84	158.74 ± 39.78	89.48 ± 9.17	109.99 ± 24.08	85.63 ± 4.34	48.58 ± 16.22	55.90 ± 0.77	24.30 ± 9.72
	P ₂₀ W ₁₀₀	197.52 ± 83.34	163.14 ± 54.95	54.67 ± 7.13	133.03 ± 41.43	76.12 ± 9.98	50.32 ± 13.43	54.83 ± 0.96	26.50 ± 13.61
	P ₄₀ W ₁₀₀	139.93 ± 52.48	181.42 ± 37.47	62.73 ± 12.20	184.98 ± 82.86	71.85 ± 9.15	49.17 ± 19.10	54.15 ± 0.64	25.91 ± 17.40
SB _{0.6}	P ₂₀ W ₂₅	121.67 ± 1.33	185.93 ± 38.64	62.03 ± 18.23	195.61 ± 109.87	61.08 ± 7.90	53.76 ± 19.78	51.99 ± 2.46	22.00 ± 9.31
	P ₄₀ W ₂₅	169.65 ± 36.36	193.15 ± 57.73	64.82 ± 10.19	171.19 ± 60.97	74.36 ± 9.37	52.43 ± 18.67	54.61 ± 1.00	22.64 ± 10.26
	P ₂₀ W ₅₀	169.86 ± 22.36	165.34 ± 31.57	68.75 ± 9.36	81.29 ± 13.05	73.21 ± 1.33	50.87 ± 14.88	54.66 ± 0.41	27.16 ± 16.42
	P ₄₀ W ₅₀	190.72 ± 70.23	144.52 ± 33.97	57.06 ± 13.18	139.85 ± 10.42	74.97 ± 7.85	46.08 ± 13.20	54.08 ± 0.48	22.73 ± 9.29
	P ₂₀ W ₁₀₀	224.96 ± 108.15	162.35 ± 6.03	56.26 ± 7.39	209.82 ± 120.31	74.21 ± 8.19	50.24 ± 11.43	54.66 ± 0.85	25.53 ± 9.26
	P ₄₀ W ₁₀₀	178.88 ± 44.26	163.13 ± 66.17	60.27 ± 7.68	158.48 ± 33.99	76.18 ± 6.12	51.19 ± 19.72	55.65 ± 2.31	29.87 ± 16.26
LSD _(0.05)		ns		ns		ns		ns	
F-value		1.27		1.09		0.48		0.22	
P-value		0.2350		0.3779		0.9472		0.9991	

Values after ± are standard deviation; Treatments description: Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; PW, combined phosphorus and water deficit levels; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

Table 4.36: The interaction effects among Si-fertiliser, combined phosphorus and water deficit levels and cropping season on soil phosphorus content, pH, and electrical conductivity.

Fertiliser	PW deficit levels	P (mg/kg)		pH (H ₂ O)		pH (KCl)		EC (mS/cm)	
		Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
SB ₀	P ₂₀ W ₂₅	29.65 ± 30.36	32.20 ± 13.06	5.06 ± 0.20	4.66 ± 0.15	4.23 ± 0.25	3.73 ± 0.15	0.11 ± 0.01	0.04 ± 0.01
	P ₄₀ W ₂₅	22.45 ± 15.29	35.63 ± 3.86	5.06 ± 0.25	4.66 ± 0.45	4.26 ± 0.35	3.73 ± 0.40	0.11 ± 0.01	0.05 ± 0.01
	P ₂₀ W ₅₀	29.54 ± 17.75	45.70 ± 8.63	4.90 ± 0.10	4.86 ± 0.35	4.13 ± 0.15	3.90 ± 0.36	0.13 ± 0.02	0.06 ± 0.04
	P ₄₀ W ₅₀	28.61 ± 7.92	44.55 ± 15.07	5.00 ± 0.10	4.30 ± 0.10	4.16 ± 0.05	3.46 ± 0.05	0.13 ± 0.02	0.04 ± 0.02
	P ₂₀ W ₁₀₀	23.83 ± 7.91	59.41 ± 27.37	4.86 ± 0.20	4.63 ± 0.11	3.90 ± 0.34	3.53 ± 0.49	0.10 ± 0.01	0.04 ± 0.02
	P ₄₀ W ₁₀₀	28.05 ± 9.80	61.92 ± 16.60	5.06 ± 0.11	4.40 ± 0.51	4.20 ± 0.00	3.86 ± 0.05	0.12 ± 0.01	0.04 ± 0.01
SB _{0.2}	P ₂₀ W ₂₅	15.51 ± 7.31	38.93 ± 19.26	5.10 ± 0.26	4.80 ± 0.36	4.16 ± 0.20	3.90 ± 0.30	0.09 ± 0.02	0.03 ± 0.01
	P ₄₀ W ₂₅	15.25 ± 4.70	36.98 ± 21.12	5.00 ± 0.01	5.03 ± 0.11	4.16 ± 0.15	4.03 ± 0.11	0.09 ± 0.01	0.02 ± 0.01
	P ₂₀ W ₅₀	15.69 ± 7.42	50.59 ± 11.56	4.90 ± 0.10	4.96 ± 0.23	4.10 ± 0.10	4.10 ± 0.26	0.09 ± 0.03	0.03 ± 0.01
	P ₄₀ W ₅₀	32.00 ± 10.64	38.37 ± 16.11	4.86 ± 0.25	4.70 ± 0.40	4.13 ± 0.37	3.76 ± 0.40	0.11 ± 0.01	0.04 ± 0.02
	P ₂₀ W ₁₀₀	39.43 ± 11.90	63.15 ± 3.60	5.10 ± 0.00	4.63 ± 0.41	4.20 ± 0.10	4.20 ± 0.10	0.09 ± 0.01	0.04 ± 0.01
	P ₄₀ W ₁₀₀	28.40 ± 11.22	58.95 ± 23.36	5.03 ± 0.10	4.76 ± 0.49	4.40 ± 0.30	4.40 ± 0.30	0.09 ± 0.01	0.03 ± 0.02
SB _{0.4}	P ₂₀ W ₂₅	28.25 ± 14.51	45.50 ± 22.91	5.36 ± 0.25	5.03 ± 0.50	4.33 ± 0.40	4.23 ± 0.50	0.09 ± 0.01	0.03 ± 0.01
	P ₄₀ W ₂₅	13.07 ± 4.36	38.38 ± 13.96	5.35 ± 0.07	5.00 ± 0.29	4.35 ± 0.07	4.15 ± 0.20	0.12 ± 0.03	0.04 ± 0.03
	P ₂₀ W ₅₀	22.09 ± 10.88	51.96 ± 7.23	5.26 ± 0.32	4.90 ± 0.36	4.46 ± 0.49	4.00 ± 0.34	0.08 ± 0.01	0.03 ± 0.01
	P ₄₀ W ₅₀	20.25 ± 11.40	46.46 ± 20.65	5.06 ± 0.35	5.00 ± 0.30	4.33 ± 0.55	4.06 ± 0.25	0.08 ± 0.01	0.03 ± 0.01
	P ₂₀ W ₁₀₀	32.51 ± 16.38	72.11 ± 14.87	5.03 ± 0.05	4.80 ± 0.34	4.13 ± 0.11	3.83 ± 0.32	0.12 ± 0.01	0.03 ± 0.01
	P ₄₀ W ₁₀₀	30.12 ± 5.33	66.53 ± 9.69	4.86 ± 0.15	4.63 ± 0.55	4.00 ± 0.01	3.76 ± 0.60	0.11 ± 0.01	0.04 ± 0.02
SB _{0.6}	P ₂₀ W ₂₅	32.80 ± 26.53	33.04 ± 17.78	4.90 ± 0.10	5.10 ± 0.36	4.03 ± 0.15	4.23 ± 0.30	0.10 ± 0.01	0.04 ± 0.01
	P ₄₀ W ₂₅	24.43 ± 9.40	47.13 ± 13.84	4.76 ± 0.23	4.90 ± 0.55	3.96 ± 0.25	3.93 ± 0.50	0.09 ± 0.02	0.05 ± 0.01
	P ₂₀ W ₅₀	37.19 ± 7.13	42.60 ± 19.98	4.96 ± 0.15	4.86 ± 0.41	4.03 ± 0.15	4.00 ± 0.36	0.09 ± 0.02	0.03 ± 0.02
	P ₄₀ W ₅₀	33.26 ± 21.05	56.11 ± 7.49	5.13 ± 0.35	4.63 ± 0.40	4.13 ± 0.25	3.76 ± 0.37	0.07 ± 0.01	0.03 ± 0.01
	P ₂₀ W ₁₀₀	47.08 ± 25.44	58.40 ± 20.13	4.96 ± 0.40	4.96 ± 0.40	4.13 ± 0.30	4.13 ± 0.37	0.10 ± 0.01	0.04 ± 0.01
	P ₄₀ W ₁₀₀	28.96 ± 20.80	59.12 ± 7.00	4.66 ± 0.37	4.66 ± 0.37	4.33 ± 0.37	3.83 ± 0.32	0.14 ± 0.02	0.03 ± 0.01
LSD _(0.05)		ns		ns		ns		ns	
F-value		0.56		0.83		0.50		1.34	
P-value		0.9004		0.6407		0.9353		0.1952	

Values after ± are standard deviation; Si-fertiliser levels (SB): 0 - distilled water (control), 0.2, 0.4, and 0.6 L/ha; PW, combined phosphorus and water deficit levels; P₂₀ (20 kg P/ha) and P₄₀ (40 kg P/ha) represent the extreme and moderate P deficit levels, respectively; W₂₅, W₅₀, and W₁₀₀ represent the extreme water deficit level, moderate deficit level, and no deficit level, respectively; ns, not significant.

The combined P and W deficit levels did not affect Na, K, Ca, and Mg, EC, and both pH (H₂O and KCl) (Table 4.34). However, as shown in Figure 4.6, combined P and W deficit significantly ($P < 0.0001$) affected soil available P. Compared to P₄₀W₁₀₀, P₂₀W₂₅ reduced soil available P by 33%. Reduced soil moisture causes a dramatic drop in the phosphate diffusion coefficient in the soil solution, which limits the flow of P from solid phases or fertiliser granules to the surface. In spite of the presence of total P, this lowers plant-available P (Bechtaoui *et al.*, 2021).

The cropping season had significant effects on soil P, Na, Ca, K, Mg, EC, and pH (H₂O and KCl). Sun (2020) reported a decrease in EC among four growing seasons. In season 1, the soil Ca, Mg, Na, EC, and pH (H₂O and KCl) were significantly higher than in season 2. Contrarily, K and P significantly increased by 135% and 78%, respectively, in season 2 relative to season 1. The interactive effect between SB and combined P and water deficit levels on soil properties is presented in Table 4.34. The extractable P, Na, K, Mg, Ca and pH (H₂O and KCl) were not significantly affected by the interaction between SB application and combined P and W deficit levels. The interaction among SB, combined P and W deficit levels, and cropping season on soil quality parameters was not significant (Tables 4.35 and 4.36). In general, the results from this study show that SB did not significantly affect the collected postharvest soil quality parameters such as P, Na, Ca, K, Mg, and further studies should be conducted in the field to make a conclusive observation.

4.4.2 Principal component analysis for the collected postharvest soil quality parameters

The principal component analysis results demonstrated that PC1 (26.15%) and PC2 (20.49%) explained 46.64% of the variation in the measured postharvest soil chemical properties (Table 4.37). In season 1, the PC1 showed a positive loading for Mg (0.887), Ca (0.782), Na (0.723), pH-KCl (0.511), and a moderate pH-H₂O (0.453). The PC2 showed a positive loading for pH-H₂O (0.518), and a negative loading for EC (-0.636). The PC3 showed a moderate contribution for K (0.446). The PC4 showed a positive loading for K (0.671), and PC5 showed a weak to moderate loading. The loading of basic cations (Ca, Mg, K, and Na) with both pH-KCl and H₂O in season 1 aligns with the notion that the base saturation and cation exchange influence soil fertility status as a primary factor (Abdel-Fattah *et al.*, 2021).

Table 4.37: Principal component analysis for postharvest soil quality parameters as affected by combined phosphorus and water deficit level, and Si-fertiliser application.

	PC1	PC2	PC3	PC4	PC5
Eigenvalue	4.19	3.28	2.26	1.67	1.29
Variability (%)	26.15	20.49	14.12	10.45	8.03
Cumulative (%)	26.15	46.65	60.76	71.21	79.24
Eigenvectors and (Factor loadings)					
Season 1					
Ca	0.382 (0.782)	0.109 (0.197)	-0.021(-0.031)	-0.104 (-0.134)	0.402 (0.456)
Mg	0.434 (0.887)	0.099 (0.179)	0.061 (0.092)	0.137 (0.177)	0.292 (0.331)
K	0.141 (0.288)	0.185 (0.336)	0.296 (0.446)	0.519 (0.671)	0.097 (0.110)
Na	0.353 (0.723)	-0.109 (-0.197)	0.167 (0.251)	0.229 (0.296)	0.188 (0.213)
P	-0.077 (-0.158)	-0.200 (-0.361)	-0.303 (-0.456)	-0.282 (-0.365)	0.402 (0.456)
pH(H ₂ O)	0.222 (0.453)	0.286 (0.518)	0.122 (0.183)	-0.456 (-0.590)	-0.145 (-0.165)
pH(KCl)	0.250 (0.511)	0.266 (0.482)	0.254 (0.381)	-0.385 (-0.498)	0.099 (0.112)
EC	-0.047 (-0.096)	-0.351 (-0.636)	0.275 (0.414)	-0.186 (-0.240)	0.166 (0.188)
Season 2					
Ca	-0.332 (-0.680)	-0.066 (-0.119)	0.313 (0.471)	0.014 (0.018)	0.152 (0.172)
Mg	-0.220 (-0.450)	0.008 (0.015)	0.460 (0.691)	-0.248 (-0.321)	-0.015 (-0.017)
K	-0.252 (-0.516)	0.096 (0.174)	-0.063 (-0.095)	-0.020 (-0.026)	0.433 (0.490)
Na	0.184 (0.377)	-0.303 (-0.550)	0.356 (0.535)	-0.220 (-0.285)	-0.185 (-0.210)
P	0.141 (0.289)	-0.173 (-0.314)	-0.386 (-0.580)	-0.234 (-0.302)	0.110 (0.124)
pH(H ₂ O)	-0.229 (-0.468)	0.439 (0.794)	0.042 (0.064)	-0.008 (-0.010)	0.173 (0.196)
pH(KCl)	-0.224 (-0.458)	0.433 (0.784)	0.008 (0.013)	-0.090 (0.116)	0.165 (0.187)
EC	-0.151 (-0.309)	-0.316 (-0.573)	0.205 (0.308)	0.069 (0.089)	0.417 (0.473)

Values in bold correspond for each variable to the factor for which the squared cosine is the largest; PC = principal component; EC, electrical conductivity.

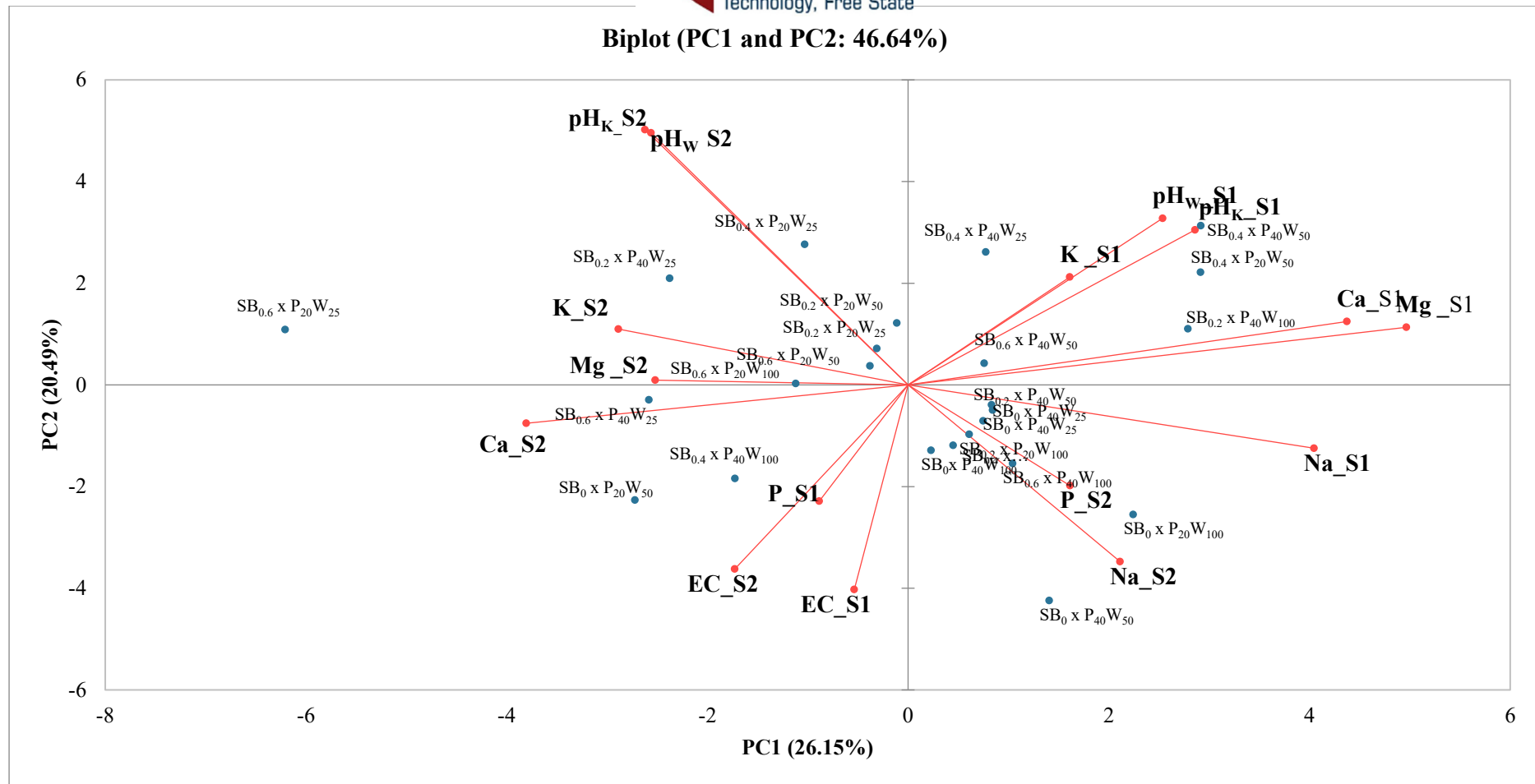


Figure 4.7: Principal component biplot showing the variations between the postharvest soil chemical properties as affected by the interaction among Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

In season 2, PC1 showed high and negative loadings dominated by Ca (-0.680) and K (-0.516). The PC2 showed a strongly positive association between pH-H₂O (0.794) and pH-KCl (0.784) and loaded a negative linkage between Na (-0.550) and EC (-0.573). The PC3 was dominated by Mg (0.691) and Na (0.535). The PC4 and PC5 showed a weak contribution to the total variation. In view of these results, PC1 and PC2 together explained 47% of the variation in these variables (Ca, Mg, K, Na, pH and EC). Similar approaches have been used recently to reduce redundancy in soil quality metrics (Qian *et al.*, 2023). Therefore, it can also be noted that shifting of dominant variables and loading signs between season 1 and 2 highlights that soil chemical relationships are not constant; therefore, soil quality parameters should be monitored over seasons in order to capture the dynamic changes in cation pools.

The principal component analysis biplot shows the association among the soil quality parameters as affected by the interaction of biostimulant application, combined P and W deficit levels, and cropping season (Figure 4.5). Ca and Mg, and pH-(KCl and H₂O) and K clustered strongly, showing positive correlations associated with SB_{0.2}×P₄₀W₁₀, and SB_{0.4}×P₂₀W₅₀, and SB_{0.4}×P₄₀W₂₅, respectively, in season 1. Potassium, Mg and pH-(KCl and H₂O) were positively clustered and linked to SB_{0.4}×P₂₀W₂₅, and SB₀×P₂₀W₅₀ in season 2. Phosphorus and EC were negatively correlated and were associated with SB_{0.4}×P₄₀W₁₀₀ and SB₀×P₂₀W₁₀₀, respectively, in season 1, whereas Ca and EC were negatively correlated and were linked to SB_{0.6}×P₄₀W₂₅ and SB₀×P₂₀W₅₀, respectively, in season 2.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary

Severe soil phosphorus (P) deficit stress, coupled with water (W) stress and imbalanced soil pH, is a major challenge that threatens crop productivity in South Africa. These abiotic stresses disproportionately affect resource-poor farmers, as their use of supplemental irrigation and fertilisation is limited. This calls for investigations into cost-effective and innovative ways to deal with these abiotic stresses. Therefore, this study aimed to assess (i) beetroot growth, yield, and quality, and (ii) soil quality parameters in response to Si-based liquid fertiliser (SB) application and combined P and W deficit levels at crop harvest.

A 90-day experiment was conducted in the net house during the 2023/2024 and 2024/2025 cropping seasons at the Nooitgedacht Research Station in Mpumalanga, South Africa. The 4×6 factorial experiment was arranged in a completely randomised block design with three replications. The treatments consisted of four SB with different concentrations [0 - distilled water as a control (SB_0), 0.2 ($SB_{0.2}$), 0.4 ($SB_{0.4}$), and 0.6 L/ha ($SB_{0.6}$)] and a factorial combination of two P deficit stress levels [20 kg/ha (P_{20}) and 40 kg/ha (P_{40})] and three W deficit levels [25% (W_{25}), 50% (W_{50}), and 100% (W_{100}) of evapotranspiration]: $P_{20}W_{25}$, $P_{40}W_{25}$, $P_{20}W_{50}$, $P_{40}W_{50}$, $P_{20}W_{100}$ and $P_{40}W_{100}$. The W_{25} , W_{50} , and W_{100} represented the extreme water deficit level, moderate water deficit level, and full irrigation of crop water requirement, respectively. The P_{20} and P_{40} represented the extreme and moderate P deficit levels, respectively. The W stress and foliar SB application began at 14 and 28 days after transplanting (DAT), respectively. The SB was applied at 14-day intervals. Data on plant height, number of leaves per plant, leaf area, and leaf chlorophyll content was collected at 63 DAT, while that of stomatal conductance was collected at 70 DAT. Fresh leaf mass, dry leaf mass, fresh root mass, dry root mass, total fresh biomass, total dry biomass, root diameter and beetroot quality parameters were determined at 90 DAT. The soil chemical properties were measured at trial termination. The data were subjected to analysis of variance using PROC GLIMMIX, SAS version 9.4 (PROC GLIMMIX, SAS Institute 2013). Treatment means were separated using Tukey's least significant difference test at the 5% level of significance. Plant and soil data were subjected to multivariate data analysis, using principal component analysis (PCA-XLSTAT 2015) to identify and evaluate the groupings between the variables.

Severe P and W deficit stress ($P_{20}W_{25}$) decreased leaf and chlorophyll content compared to the combination of moderate P and no water deficit stress ($P_{40}W_{100}$), and decreased the leaf P content when compared with severe P and no water deficit stress ($P_{20}W_{100}$). The reduction of

leaf Cu content by up to 78% following SB application indicates the potential of SB to reduce the uptake of heavy metals. The SB_{0.2} was more effective in improving stomatal conductance, while SB_{0.4} and SB_{0.6} resulted in non-significant decreases in stomatal conductance, suggesting a potential hormetic response that justifies further investigation. The increase in stomatal conductance following SB_{0.2} application under P₄₀W₁₀₀ compared to SB₀ with P₂₀W₂₅ in both seasons may lead to improved photosynthetic efficiency, thereby increasing yield. This also showed that the moderate P and optimal irrigation provide a supportive environment for SB_{0.2} to maximise its effectiveness. The SB_{0.4} application showed potential to enhance nutrient content under severe P with moderate water deficit stress (P₂₀W₅₀), and to improve beetroot yield under severe P with full irrigation (P₂₀W₁₀₀). The strong association of nutrient content (Ca, Mg, K, Na, P, Fe, Zn, and Mn) with the SB_{0.4}×P₂₀W₅₀ interaction suggests a synergy between SB application and combined severe P and moderate W deficit stress that enhances the nutrient uptake in beetroot. Neither the SB nor combined deficit stress or their interaction significantly affected the soil chemical properties. However, it was noted that residual extractable P and K content were higher in season 2 relative to season 1.

5.2 Hypotheses Testing

Reporting the null hypotheses of the study: “Using silicon-based liquid fertiliser to improve growth, yield and quality of beetroot (*Beta vulgaris* L.) grown under combined phosphorus and water stress in Mpumalanga”

The results of the ANOVA in “Appendix A” indicate that there are significant and non-significant differences in plant growth, yield and quality among the Si-based liquid fertiliser, combined P and W deficit levels, and cropping season. Therefore, referring from Table 4.1 to 4.7, the null-hypotheses can be rejected or fail to be rejected based on the P values recorded. For instance, if P-value is greater than 0.05 probability level, the null hypotheses are rejected, and vice-versa.

5.3 Implications

- For smallholder farmers: Even without appreciable yield increases, moderate application or use of SB_{0.2} and SB_{0.4} combined with moderate P and full irrigation can support plant health and enhance quality.
- For the agricultural advisor or extension officers: Understanding the impacts of biomass dilution is crucial for agricultural extension since increasing yields may not always

translate into higher nutrient densities. Extension officers should help farmers strike a balance between nutritional quality and yield quantity.

- For research and development: More focused studies are required to determine how SB interacts with various nutrients, especially when different soil types and irrigation schedules are used.
- For smart and climate agriculture: The potential significance of beetroot in climate-resilient vegetable production systems is further supported by the fact that SB_{0.2} and SB_{0.4} can boost the plant's physiological and biochemical resistance under abiotic stress.
- For fertility and nutritional management: The noted enhancement in phenolic content and micronutrient accumulation indicates that SB may be used in organic systems or techniques that aim to produce nutrient-dense crops.

5.4 Conclusion

In conclusion, the results from this study suggest that SB_{0.2} and SB_{0.4} hold potential to improve growth, yield and quality of beetroot under moderate P and full irrigation. Long-term studies focusing on establishing the best SB formulation, dosage, timing and application frequency that suit various development stages of crops in open-field conditions are required. Furthermore, field experiments to test the SB need to be conducted in a range of soil types and agro-ecological zones.

5.5 Recommendations

Based on the findings of this study and the conclusions, the following recommendations can be made to beetroot growers and researchers:

- For beetroot and vegetable farmers: To apply SB_{0.2} and SB_{0.4} to enhance nutritional uptake and increase physiological resilience, especially in the face of moderate P and no water stress. Additionally, avoid extreme stress conditions such P₂₀W₂₅ as they drastically lower nutrient accumulation and reduce yield.
- To agricultural advisors or extension officers: Promote integrated nutrition and water management methods alongside SB utilisation. Inform farmers about the compromise between nutrient density and biomass production (biomass dilution effect). Identify the

most limiting nutrients and inform SB application choices, promote soil, leaf and root testing.

- To scholars and researchers: To find the best SB formulation, dosage, and timing in open-field conditions, conduct long-term field experiments. Examine how SB interacts with various soil types, micro-nutrients (particularly Fe, Mn, and Zn), and stressors (for instance, P and water deficits, acidity, and heat). Examine the processes underlying SB-enhanced phenolic synthesis and any possible connections to its therapeutic or antioxidant qualities.
- To policymakers: Encourage farmers' access, particularly in areas with limited water, or water-scarce and nutrient poor areas, to reasonably priced and properly prepared SB products. Create regulations that support smallholder farmers and encourage the use of sustainable and smart climate resilient inputs like biostimulants.

Future studies should focus on the following:

- Conducting studies that involve validation of SB on field scale in a range of soil types and agro-ecological zones.
- Determining effects of SB at recommended applications and frequencies to suit various stages of crop development.
- To determine the physiological processes underlying the rise of phenolic compounds and nutritional absorption mediated by SB.

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APPENDICES

Appendix A: The summaries of ANOVAs.

Appendix 4.1: Summary of ANOVA for the effect of fertiliser, combined phosphorus and water deficit levels, and cropping season on plant growth parameters, leaf chlorophyll content at 63 days after transplanting, and leaf stomatal conductance at 70 days after transplanting.

Source	df	P-value				
		Plant height	Number of leaves per plant	Leaf area	Leaf chlorophyll content	Leaf stomatal conductance
Model	49	<0.0001 (2.99)	0.0301 (1.58)	0.0761 (1.41)	<0.0001 (6.33)	<0.0001 (3.92)
Factors						
SB	3	0.3522 (1.10)	0.5208 (0.76)	0.9724 (0.08)	0.2966 (1.25)	<0.0001 (8.65)
PW	5	0.0017 (4.21)	0.4148 (1.01)	0.0004 (4.98)	0.0085 (3.31)	0.0820 (2.03)
SB x PW	15	0.1048 (1.55)	0.6344 (0.84)	0.3227 (1.15)	0.0925 (1.59)	0.0459 (1.80)
Season (S)	1	<0.0001 (53.95)	<0.0001 (22.04)	0.2491 (1.34)	<0.0001 (244.67)	0.0013 (11.02)
SB x S	3	0.8379 (0.28)	0.6027 (0.62)	0.6838 (0.50)	0.5054 (0.78)	0.0661 (2.48)
PW x S	5	0.9718 (0.17)	0.2696 (1.30)	0.9686 (0.18)	0.9221 (0.28)	0.2049 (1.48)
SB x PW x S	15	0.0052 (2.42)	0.4991 (0.96)	0.4930 (0.97)	0.3245 (1.15)	<0.0001 (5.98)
R ²		0.61	0.45	0.42	0.76	0.67
CV (%)		10.65	18.81	24.02	24.06	25.22
Root MSE		2.32	1.53	12.95	6.56	54.32
Mean		21.84	8.15	53.93	27.26	215.31

df, degrees of freedom; R², R squared; Root MSE, Root Mean Square Error; CV (%), coefficient of variance; values in parentheses represents the F-value; PW, combined phosphorus and water deficit levels; SB, Si-fertiliser biostimulant; S, cropping season.

Appendix 4.2: Summary of ANOVA for the fresh leaf mass, dry leaf mass and the beetroot yield parameters as affected by the Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

Source	df	P-value							
		FLM	FRM	FBM	DLM	DRM	DBM	F:D ratio	FD
Model	49	<0.0001 (12.37)	<0.0001 (12.51)	<0.0001 (12.10)	<0.0001 (9.71)	<0.0001 (12.82)	<0.0001 (14.58)	0.0044 (1.90)	<0.0001 (48.87)
Factors									
SB	3	0.5352 (0.73)	0.9878 (0.04)	0.9905 (0.04)	0.8309 (0.29)	0.8390 (0.28)	0.8171 (0.31)	0.5157 (0.77)	0.8574 (0.26)
PW	5	0.0735 (2.09)	<0.0001 (5.98)	0.0012 (4.40)	0.0316 (2.57)	<0.0001 (5.89)	0.0001 (5.70)	0.3070 (1.22)	0.0722 (2.10)
SB x PW	15	0.3856 (1.08)	0.4843 (0.98)	0.6175 (0.85)	0.6752 (0.80)	0.2560 (1.24)	0.4251 (1.04)	0.0803 (1.63)	0.7416 (0.74)
Season (S)	1	<0.0001 (547.33)	<0.0001 (503.59)	<0.0001 (512.40)	<0.0001 (418.45)	<0.0001 (510.33)	<0.0001 (607.42)	0.0346 (4.60)	<0.0001 (2321.94)
SB x S	3	0.8023 (0.33)	0.7089 (0.46)	0.9163 (0.17)	0.6859 (0.50)	0.8573 (0.26)	0.9308 (0.15)	0.0058 (4.45)	0.5342 (0.73)
PW x S	5	0.5611 (0.79)	0.0004 (5.06)	0.0359 (2.50)	0.4563 (0.94)	0.0015 (4.29)	0.0096 (3.24)	0.0635 (2.18)	0.1030 (1.89)
SB x PW x S	15	0.3553 (1.11)	0.0112 (2.21)	0.0492 (1.78)	0.1511 (1.43)	0.0055 (2.40)	0.0070 (2.34)	0.0302 (1.93)	0.0729 (1.66)
R ²		0.86	0.86	0.86	0.83	0.87	0.88	0.50	0.96
CV (%)		29.37	33.36	32.21	33.18	31.68	28.61	13.23	15.42
Root MSE		15.83	38.10	54.71	2.24	5.30	6.73	0.95	1.62
Mean		53.91	114.23	169.80	6.77	16.75	23.52	7.18	10.55

df, degrees of freedom; R², R squared; Root MSE, Root Mean Square Error; CV (%), coefficient of variance; values in parentheses represents the F-value; PW, combined phosphorus and water deficit levels; SB, Si-fertiliser; S, cropping season; fresh leaf mass (FLM), dry leaf mass (DLM), fresh root mass (FRM), dry root mass (DRM), total fresh biomass (FBM), total dry biomass (DBM), fresh/dry total biomass ratio (F: D ratio), root diameter (RD).

Appendix 4.3: Summary of ANOVA for the accumulation of macronutrient concentration on plant leaves as affected by the Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

Source	df	P-value				
		P	Na	K	Mg	Ca
Model	49	<0.0001 (3.77)	<0.0001 (3.87)	0.5798 (0.94)	0.0018 (2.02)	0.9838 (0.57)
Factors						
Si-Fertiliser (SB)	3	0.7803 (0.36)	0.2510 (1.39)	0.1718 (1.70)	0.1106 (2.06)	0.2569 (1.37)
Combined P and W deficit levels (PW)	5	<0.0001 (8.33)	0.9595 (0.21)	0.8268 (0.43)	0.9852 (0.13)	0.9570 (0.21)
SB x PW	15	0.5833 (0.88)	0.7407 (0.74)	0.8105 (0.67)	0.9849 (0.36)	0.9014 (0.55)
Season (S)	1	<0.0001 (101.85)	<0.0001 (149.46)	0.0844 (3.04)	<0.0001 (43.00)	0.2461 (1.36)
SB x S	3	0.9731 (0.08)	0.4632 (0.86)	0.2459 (1.41)	0.1732 (1.70)	0.8095 (0.32)
PW x S	5	0.4658 (0.93)	0.9608 (0.20)	0.8596 (0.38)	0.9932 (0.09)	0.9396 (0.25)
SB x PW x S	15	0.3272 (1.15)	0.8857 (0.58)	0.9843 (0.37)	0.9372 (0.50)	0.8829 (0.58)
R ²		0.66	0.66	0.32	0.51	0.23
CV (%)		48.51	37.47	40.42	52.57	37.54
Root MSE		0.31	0.22	0.80	0.44	0.43
Mean		0.64	0.58	1.99	0.83	1.15

df, degrees of freedom; R², R squared; Root MSE, Root Mean Square Error; CV (%), coefficient of variance; values in parentheses represents the F-value.

Appendix 4.4: Summary of ANOVA for the accumulation of micronutrient concentration of plant leaves as affected by the Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

Source	df	P-value						
		Mn	Fe	Co	Zn	Cu	B	Mo
Model	49	0.4582 (1.02)	<0.0001 (2.75)	<0.0001 (3.04)	0.2968 (1.14)	0.0059 (1.84)	0.0001(2.44)	0.0002 (2.38)
Factors								
Si-fertiliser (SB)	3	0.2117 (1.53)	0.0208 (3.14)	0.9217 (0.16)	0.1144 (2.04)	0.0320 (3.06)	0.2382 (1.43)	0.0615 (2.54)
Combined (PW)	5	0.9287 (0.27)	0.3553 (1.12)	1.0000 (0.01)	0.9439 (0.24)	0.2679 (1.31)	0.7842 (0.49)	0.2762 (1.29)
SB x PW	15	0.7942 (0.68)	0.4217 (1.04)	1.0000 (0.01)	0.9370 (0.50)	0.3455 (1.13)	0.9132 (0.54)	0.4297 (1.03)
Season (S)	1	<0.0001 (16.99)	<0.0001 (55.69)	<0.0001 (52.97)	0.0365 (4.50)	0.0003 (14.06)	<0.0001 (58.71)	<0.0001 (27.45)
SB x S	3	0.5719 (0.67)	0.6935 (0.48)	0.8631 (0.25)	0.9910 (0.04)	0.7582 (0.39)	0.2558 (1.37)	0.8686 (0.24)
PW x S	5	0.9829 (0.14)	0.4837 (0.90)	0.9999 (0.02)	0.8047 (0.46)	0.9952 (0.08)	0.9972 (0.06)	0.7950 (0.47)
SB x PW x S	15	0.7995 (0.68)	0.9234 (0.52)	1.0000 (0.03)	0.9343 (0.50)	1.0000 (0.07)	0.7702 (0.71)	0.9920 (0.32)
R ²		0.34	0.59	0.61	0.37	0.49	0.56	0.55
CV (%)		37.25	33.93	34.63	42.72	65.57	29.97	51.02
Root MSE		377.32	113.04	23.46	88.88	60.64	30.95	43.11
Mean		1012.70	333.13	67.74	208.01	92.48	103.26	84.48

df, degrees of freedom; R², R squared; Root MSE, Root Mean Square Error; CV (%), coefficient of variance; values in parentheses represents the F-value; Combined PW, combined phosphorus and water deficit levels; SB, Si-fertiliser; S, cropping season.

Appendix 4.5: Summary of ANOVA for the accumulation of macronutrient concentration or plant root as affected by the Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

Source	df	P-value				
		P	Na	K	Mg	Ca
Model	49	<0.0001 (4.54)	<0.0001 (7.28)	<0.0001 (6.50)	<0.0001 (7.31)	<0.0001 (3.68)
Factors						
Si-fertiliser (SB)	3	0.1047 (2.11)	0.1406 (1.87)	0.7704 (0.38)	0.3795 (1.04)	0.0009 (6.02)
Combined (PW)	5	0.0016 (4.26)	0.0279 (2.65)	0.2725 (1.30)	0.0080 (3.35)	0.0524 (2.29)
SB x PW	15	0.3812 (1.08)	0.0150 (2.13)	0.5647 (0.90)	0.0816 (1.63)	0.2223 (1.29)
Season (S)	1	<0.0001 (148.10)	<0.0001 (258.61)	<0.0001 (233.99)	<0.0001 (270.22)	<0.0001 (71.37)
SB x S	3	0.5267 (0.75)	0.3205 (1.18)	0.3407 (1.13)	0.0470 (2.75)	0.1224 (1.98)
PW x S	5	0.3393 (1.15)	0.0073 (3.40)	0.5102 (0.86)	0.1186 (1.81)	0.4409 (0.97)
SB x PW x S	15	0.3485 (1.12)	0.1911 (1.35)	0.6434 (0.83)	0.2382 (1.27)	0.0666 (1.69)
R ²		0.70	0.79	0.77	0.79	0.66
CV (%)		32.55	34.27	44.03	24.85	33.23
Root MSE		0.07	0.031	0.25	0.02	0.034
Mean		0.24	0.09	0.57	0.09	0.10

df, degrees of freedom; R², R squared; Root MSE, Root Mean Square Error; CV (%), coefficient of variance; values in parentheses represents the F-value; Combined PW, combined phosphorus and water deficit levels; SB, Si-fertiliser; S, cropping season.

Appendix 4.6: Summary of ANOVA for the accumulation of micronutrient concentration of plant root as affected by the Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

Source	df	P-value						
		Mn	Fe	Co	Zn	Cu	B	Mo
Model	49	<0.0001 (7.29)	<0.0001 (12.43)	<0.0001 (8.87)	<0.0001 (6.34)	<0.0001 (2.65)	<0.0001 (5.90)	0.6998 (0.87)
Factors								
Si-Fertiliser (SB)	3	0.0134 (3.76)	0.0017 (5.44)	<0.0001 (11.17)	0.0021 (5.29)	0.0002 (7.50)	<0.0001 (18.61)	0.0574 (2.59)
Combined (PW)	5	0.0008 (4.62)	0.0022 (4.06)	0.8149 (0.45)	0.1589 (1.63)	0.6909 (0.61)	0.1447 (1.69)	0.7839 (0.49)
SB x PW	15	0.0001 (3.45)	0.0056 (2.39)	0.2667 (1.23)	0.0222 (2.01)	0.2240 (1.29)	0.0009 (2.91)	0.9995 (0.20)
Season (S)	1	<0.0001 (179.91)	<0.0001 (482.06)	<0.0001 (312.96)	<0.0001 (224.55)	<0.0001 (49.28)	<0.0001 (56.83)	0.1460 (2.15)
SB x S	3	0.2849 (1.28)	0.1701 (1.71)	<0.0001 (11.80)	0.1612 (1.75)	0.0037 (4.81)	<0.0001 (8.69)	0.2236 (1.49)
PW x S	5	0.1781 (1.56)	0.5338 (0.83)	0.7770 (0.50)	0.7564 (0.53)	0.3796 (1.07)	0.0027 (3.97)	0.9748 (0.16)
SB x PW x S	15	<0.0001 (4.68)	0.0027 (2.60)	0.3569 (1.11)	0.1098 (1.53)	0.4697 (0.99)	<0.0001 (4.42)	0.9984 (0.24)
R ²		0.79	0.86	0.82	0.76	0.587633	0.764541	0.314421
CV (%)		25.59	28.26	18.60	24.36	33.80803	18.78123	49.95746
Root MSE		36.76	71.06	8.82	17.09	30.01995	15.51845	29.01624
Mean		143.61	251.41	47.42	70.15	88.79532	82.62741	58.08189

df, degrees of freedom; R², R squared; Root MSE, Root Mean Square Error; CV (%), coefficient of variance; values in parentheses represents the F-value; Combined PW, combined phosphorus and water deficit levels; SB, Si-fertiliser; S, cropping season.

Appendix 4.7: Summary of ANOVA for postharvest soil chemical properties as affected by the Si-fertiliser application, combined phosphorus and water deficit levels, and cropping season.

Source	df	P-value							
		Ca	Mg	K	Na	P	pH (H ₂ O)	pH (KCl)	EC
Model	4	0.4201 (1.04)	<0.0001 (4.84)	<0.0001 (3.48)	<0.0001 (11.75)	<0.0001 (3.47)	0.0193 (1.65)	0.0954 (1.37)	<0.0001 (11.78)
	9								
Factors									
SB	3	0.6407 (0.56)	0.5500 (0.71)	0.2900 (1.27)	0.6088 (0.61)	0.3182 (1.19)	0.0188 (3.49)	0.0641 (2.50)	0.0008 (6.07)
PW	5	0.9881 (0.12)	0.9885 (0.12)	0.1494 (1.67)	0.9903 (0.11)	<0.0001 (6.68)	0.2345 (1.39)	0.4845 (0.90)	0.6562 (0.66)
SB x PW	1	0.9027 (0.55)	0.9986 (0.23)	0.4077 (1.06)	0.9967 (0.27)	0.9887 (0.34)	0.7769 (0.70)	0.7107 (0.77)	0.0117 (2.19)
	5								
Season (S)	1	0.0220 (5.42)	<0.0001 (183.50)	<0.0001 (105.11)	<0.0001 (500.87)	<0.0001 (86.09)	<0.0001 (23.90)	<0.0001 (27.48)	<0.0001 (492.30)
SB x S	3	0.5675 (0.68)	0.5195 (0.76)	0.1596 (1.76)	0.8233 (0.30)	0.1825 (1.65)	0.1721 (1.70)	0.2098 (1.54)	0.4944 (0.80)
PW x S	5	0.4266 (0.99)	0.6068 (0.72)	0.1360 (1.73)	1.0000 (0.01)	0.1396 (1.71)	0.4692 (0.92)	0.5969 (0.74)	0.4599 (0.94)
SB x PW x S	1	0.2350 (1.27)	0.9472 (0.48)	0.3779 (1.09)	0.9991 (0.22)	0.9004 (0.56)	0.6407 (0.83)	0.9353 (0.50)	0.1952 (1.34)
	5								
R ²		0.352582	0.716258	0.644457	0.859665	0.643886	0.462134	0.416886	0.859942
CV (%)		28.49825	17.63998	42.37001	18.62655	36.85359	6.078692	7.927381	24.14737
Root MSE		51.67063	11.16912	43.36079	7.553492	14.20946	0.298447	0.320123	0.017507
Mean		181.3116	63.31708	102.3384	40.55229	38.55653	4.909722	4.038194	0.072500

df, degrees of freedom; R², R squared; Root MSE, Root Mean Square Error; CV (%), coefficient of variance; *P < 0.05; values in parentheses represents the F-value; PW, combined phosphorus and water deficit levels; SB, Si-fertiliser; S, cropping season.

Appendix 4.8: Silicon-based biostimulant classification information and plant nutrient content.

Name of the product	CibuSil Max
Fertiliser group	2
Specific Gravity	1.4 @ 20 °C
Registration number	Reg. No. B5326 Act. No. 36 of 1947
Plant nutrient content	
Mono Silicic acid [Si(OH) ₄]	448 g/kg
Silicon	138.5 g/kg

**No other nutritional information provided on the product, only Si nutrition.*

Appendix B: Published part of the article extracted from Chapter 1



Phytohormone-Based Biostimulants as an Alternative Mitigating Strategy for Horticultural Plants Grown Under Adverse Multi-Stress Conditions: Common South African Stress Factors

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Abstract

Worldwide, it has been recorded extensively that plants are subjected to severe abiotic and biotic stressors. The scientific research community has widely reported that multi-abiotic stressors cause horticultural crop losses, accounting for at least 50 to 70% of the crop yield and quality losses. Therefore, this review focused on the detrimental effects caused by abiotic stress factors occurring in single-, combined- and multi-cell stresses on horticultural plants worldwide, along with the best production systems practices for mitigation during and post-single and combined abiotic or multi-stress damages. A conclusion and recommendation could be reached using the pool of research material, which constituted research articles, reviews, book chapters, thesis, research short communications and industrial short communications from at least twenty-five years ago. Findings showed that some of the leading abiotic stresses are single- and combined abiotic stressors like water deficit, salinity, soil pH, phosphate deficiency, wounding, soil density and pot size. Established commercial and smallholder farmers are globally adapting to plant growth regulators and biostimulants as part of their production systems. However, as much as the effectiveness of biostimulants containing humic acids, algal extracts, plant growth-promoting microorganisms and phytohormones has been reported to promote plant development under multi-stress, only a few studies are focusing on organic phytohormone-based biostimulants on horticultural crops grown under adverse multi stress factoring. In conclusion, the review recommends alternative solutions for emerging South African farmers and growers who cannot afford agricultural insurance options and energy alternatives on the common single- and combined abiotic- or multi-stress-factors.

Keywords: abiotic stress; moisture stress; plant growth regulators; salinity stress; wounding stress

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INTRODUCTION

Environmental factors such as salinity, drought, cold, moisture stress, and a variety of biotic stresses, including herbivory, are estimated to lower plant growth and crop yield by up to 50%

worldwide (Khetsha, 2020; Habib et al., 2021; Turan et al., 2021; Ramzan and Younis, 2022). According to Franzoni (2020), only 3.5% of the worldwide geographical area is unaffected by

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Appendix C: Published part of the article extracted from Chapter 2

Using silicon-based biostimulant and phosphorus application as an alternative solution for beetroot (*Beta vulgaris* L.) grown under multi-stress in South Africa: a short review

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Abstract

Adverse environmental stressors such as moisture deficit, soil acidity, and nutrient deficiency, particularly phosphorus (P) due to climate change as single and combined multi-stress, are gradually threatening food security globally. Therefore, modern agriculture faces pressing challenges where novel strategies must be developed for sustainable food production and security, particularly in developing countries like South Africa. The authors conducted a desktop review on various vegetables and other commercial crops. At most, the authors maintained 15 years of research material, constituting research articles, review articles, book chapters, theses, research short communications, and industrial short communications. Abiotic stress as a leading stress factor tends to co-occur, causing severe consequences for plant growth and the quality of horticultural species such as beetroot (*Beta vulgaris* L.), and this has been more prevalent in South Africa recently, where multi-stress factors are a problem to the emerging farmers. Beetroot is well-known as the second most crucial sugar-producing crop after sugarcane (*Saccharum officinarum* L.), contributing to about 40% of world sugar production. However, successful beetroot production has been recorded widely depending on agronomic and environmental factors such as moisture deficit and P-deficiency. These are considered critical limiting factors reducing the beetroot yield from 5 to 30% globally. In South Africa, it has been further observed that a combination of soil moisture stress and P assimilation are contributing significantly to the losses in the production yields of beetroot, particularly in Highveld areas such as the Mpumalanga Province; thus, multi-stress remains a challenge for emerging and subsistence farmers in South Africa. Therefore, this review focuses on developing the mitigating strategy using a combination of silicon-based biostimulant and the P application to improve the P assimilation, growth, and yield of beetroot grown under adverse multi-stress in South Africa.

Keywords: environmental stress factors, horticulture, phosphate, plant stress, vegetables

INTRODUCTION

Moisture deficit and phosphorus (P) deficiency under unbalanced soil pH conditions remain the most detrimental abiotic stresses that limit crop production to smallholder farmers in South Africa. A similar statement was mentioned by Asiwe et al. (2021), stating that "Crop yields are declined due to low soil fertility, insufficient soil water availability and poorly managed cropping systems in Limpopo province of South Africa". Depending on the sensitivity of each specific crop, the occurrence of abiotic stress as a single stress or multi-stress affects plant growth, metabolism and other functions depending on the stress level. Moisture deficit refers to the situation when the plant water requirements can be fully met to the desired levels, and the functionality of the plant is affected (dos Santos et al., 2022).

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Appendix D: Poster presented at the national conference as extracted from Chapter 3 - 4

