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FOLIAR APPLICATION OF SILICON NANOPARTICLES (SiNPs) EFFECTS ON TUBER YIELDS AND CARBOHYDRATE METABOLISM IN FOUR SWEET POTATOE (*Ipomoea batatas L*) VARIETIES

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Abstract: Silicon nanoparticles (SiNPs) have been widely utilised in agriculture, however, there are limited reports on sweet potatoes (*Ipomoea batatas L*). In this study, SiNPs were applied as a foliar spray at a concentration of 0.01% (w/v) three times at five-week intervals after planting. Four sweet potato varieties namely 'Karak Bakar', 'Tanjung Sepat', 'V6D215', and 'Pejabat' were tested. Results showed that the foliar application of SiNPs induced changes in the tuber biomass, number, epidermal layer thickness, starch, reducing sugar and invertase levels in four sweet potato varieties. The highest tuber biomass was seen in the 'Pejabat' (392.9 ± 88.1 g/plant) and 'Karak Bakar' (456.6 ± 102.8 g/plant) varieties. SiNPs treatment also reduced the tuber numbers in all varieties except 'Karak Bakar' and did not significantly affect ($p > 0.05$) the starch and reduced sugar content in the tubers of the 'V6D215' variety. For all tested varieties, SiNPs treatment did not significantly alter ($p > 0.05$) the amylase levels and invertase in the tubers of 'Tanjung Sepat' and 'Karak Bakar'. The findings of the study suggested that the effect of foliar application on sweet potatoes is variety-dependent and further study should be carried out to determine the most suitable SiNPs concentration for each variety.

Keywords: Amylase, biomass, epidermal, invertase, starch, sugar.

Introduction

Worldwide, the rapidly rising population, reduction of land for agronomic activity, and stresses due to climate change have restricted crop yield and diminished food production. To cope with the demand for a staple food, tubers are the most appropriate source of carbohydrates. Potato, cassava and sweet potatoes are tuber crops that provide a higher content of carbohydrates. Tang *et al*. (2022) reported that sweet potato production has increased due to the rising population and demand as a source of carbohydrates after rice and wheat. Sweet potatoes belong to the Convolvulaceae family and are rich in fibre, nutrients, and vitamins (Mohamad-Nor *et al*., 2021; Nurul-Afza *et al.,* 2022). The growth of sweet potatoes is largely determined by mineral availability in the soil and uptake by roots (Usman *et al.,* 2014). Therefore, soil types also play a role in sweet potato growth and development. According to Wadas (2022), nutrient-rich soils produce high yields of low-quality roots, on the other hand, nutrient-poor soils such as light sandy soils produce low yields of high-quality roots. In previous reports, Nurul-Afza *et al.* (2022) mentioned that sweet potatoes are produced best in well-drained, light, sandy, loam or silt loam soil. Studies also revealed that the application of trace elements can enhance nutrient uptake and assimilation by plants which leads to higher tuber yield (Usman *et al.,* 2014; Wadas, 2022; Nurul-Afza *et al.,* 2022; 2023).

Silicon (Si) is the second most abundant naturally available mineral on Earth's crust. Nevertheless, it is a non-essential nutrient for plants but it is classified as a beneficial element for plant growth (Luyckx *et al.,* 2017). Therefore, in agriculture, Si is widely applied to food crops as a stimulant or fertiliser, improving

plant growth and mitigating both biotic and abiotic stresses on plants (Ng *et al.,* 2021; Mukarram *et al.,* 2022). Other than silicon-accumulating plant species such as rice, barley and maize (Ng *et al*., 2020), Si also has been applied to non-Si accumulating and tuber crop species such as sunflowers (Mukarram *et al.,* 2022), cucumber (Zhu *et al.,* 2016; Alsaeedi *et al.,* 2019) and potato (Seleiman *et al.,* 2023). Despite the positive effects of bulk Si on plant growth, nanoform silica was reported to be more effective (Noor-Hassim *et al.,* 2021). The activity of the Si nanoparticles (SiNPs) is due to the highly reactive surface-to-volume ratio property of the nanomaterials that ranged from one to 100 nm (Ng *et al.,* 2021). Other than crop growth, SiNPs were also reported to improve seed germination (Sun *et al.,* 2016; Syazli *et al.,* 2022), mitigate water deficit and enhance potato yield and quality traits (Dahal *et al.,* 2019; Seleiman *et al.,* 2023).

In general, Si regulates the physiological, biochemical and molecular responses which resulted in better plant growth and yield of several food crops (Van-den-Berg *et al*., 2021; Noor-Hassim *et al.,* 2021). According to Kelly *et al.* (2022), the Si concentration in plant shoots varies from 1 to 100 mg/g dry wt. which is dependent on Si-uptake ability by roots and soil types. Mitani and Ma (2005) reported that monocotyledons, mostly from the family Graminae and Cyperaceae are high Si-accumulators (up to 10% dry weight), compared to dicotyledons. In addition, Soares *et al.* (2020) reported that Si content in sweet potato tubers varies among the varieties, which ranges from 0 to 3.70 mg/100 g of raw samples. Ostensibly, the higher plant absorbs silicon through the root membrane channels with water in the form of silicic acid (Exley *et al.,* 2020). Maryam and Gul (2022) reported that a few proteins perform as Si transporters in higher plants known as low silicon (Lsi1 and Lsi2) channels. The Lsi1 is an aquaporin membrane protein family. It is a permeable channel from Nod26-like major intrinsic protein (NIP) III for the uptake and distribution of Si in the xylem transfer cell layer while Lsi2 is as an uncharacterised anion transporter family (Yamaji *et al.,* 2015). In shoots and leaves, the silicic acid is spontaneously transformed into solid amorphous silica (SiO_2-nH_2O) called silica bodies and subsequently deposited as biogenic silica in the cell walls, generating structural and mechanical stability of aerial plant parts (Luyckx *et al.,* 2017). As a result, silicic acid application increased the diameter of the sunflower stem (Mukarram *et al.,* 2022), the biomass of cucumber fruits (Zhu *et al.,* 2016; Alsaeedi *et al.,* 2019) and the potato yield (Seleiman *et al.,* 2023). Silicic acid application was also reported to regulate carbohydrate metabolism in tomatoes (Alam *et al.,* 2022) and increase the invertase activity during the growth phase of sugar cane (Singh *et al*., 2021).

To our knowledge, the information on the effects of silicon or silicic acid on sweet potatoes remains limited and poorly understood. The involvement of silicon, in particular its nanoform in the production of tuber crop production, includes the starch accumulation from the source and deposition in sinks such as grains or tubers. In the case of sweet potatoes, foliar application of SiNPs could be a suitable treatment to increase the tuber root yield. The starch accumulation in the tuber is highly dependent on its degradation by amylase and the conversion of sucrose to glucose and fructose catalysed by invertase. Moreover, invertase and amylase enzymes are involved in sucrose-starch metabolism (Wang *et al.,* 2022). The final product of the activities of these two enzymes is glucose and fructose, a reducing sugar species. Therefore, the current study objective is to determine the effects of foliar applications of SiNPs on tuber yield, starch and reducing sugar content, and the levels of amylase and invertase in the tubers of four sweet potato varieties that are commonly cultivated in Malaysia. The findings of this study will offer insight into future understanding of the effect of SiNPs on sweet potatoes and might be useful information for sweet potato growers worldwide.

Materials and Methods

Experimental Sites and Varieties

The experiment was conducted at Kampung Telaga Mas, Kedah, Malaysia (latitude 6.1564° N, longitude 100.4637° E). The temperature ranged from 37°C to 25°C (day and night) with a relative humidity of 62% to 79%. The soil from three locations of planting sites (30 cm deep from the soil surface) was sampled and analysed for homogeneity in a laboratory at the Malaysia Agriculture Department branch in the state of Kedah. In this study, four sweet potato varieties namely 'Pejabat', 'Tanjung Sepat', 'V6D215', and 'Karak Bakar' were obtained from Malaysia Agricultural Research and Development Institute (MARDI) branch Bachok in the state of Kelantan, Malaysia.

Treatments and Yield Assessment

The runners or vines were used as planting material. For each variety, the vines were planted on four ridges (each ridge 3.0 meters in length, 80-90 cm wide and 30-40 cm in height) with 20 vines at a distance of 15 cm from one to another. The experiment used a completely randomised design. Two ridges were as control (untreated) and SiNPs treatment, respectively. The plants were treated with SiNPs solution (Abogen, Advansia Sdn. Bhd.) at 0.01% (w/v), diluted with tap water as suggested by the manufacturer. Treated plants were foliar sprayed with the SINPs solution after five weeks of planting and repeated twice at five weeks intervals. A mixed fertiliser of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) at a ratio of 12:12:17 was applied at the rate of 6 grams per plant as reported by Nurul-Afza *et al.* (2023). All plants were watered every day. Weeds and pests were manually removed during the experiment. After 120 days of planting, the tubers were harvested. The tuber number and fresh weights per plant were measured. A similar-sized tuber (approximately 50 grams) was stored in a chiller before histological and biochemical analysis. The experiment was repeated twice.

Starch and Reducing Sugar Content in Tuber

Starch was isolated from the freshly peeled (1.0 g) sweet potato tuber. Tuber tissues were grounded using a mortar and pestle in distilled water until homogenous. The homogenate was filtered through four layers of cheesecloth and centrifuged at 3000 *x g* for 10 minutes. The white suspension (starch) was collected and dried in a fully ventilated oven at a temperature of 50°C. The starch powder was dispersed in 1.0 ml ethanol, 9.0 ml NaOH, and distilled water with a final volume of 100 ml. 5 ml of the solution was mixed with 0.5 ml of 1.0 M acetic acid and 1.0 ml of iodine solution. The final volume was made up to 50 ml using distilled water. A mixture of acetic acid and iodine was used as a blank, and absorbance readings were taken at 620 nm using a UV-Vis Spectrophotometer (Shimadzu, Japan). Starch content was calculated based on the standard starch curve (0.05 to 1.0 mg/ml) of water-soluble corn starch.

The reduced sugar content was determined using the Somogyi-Nelson assay (Sadeghi *et al.,* 2021). The supernatant (0.2 ml) was mixed with 1.0 ml of Nelson reagent and heated in a boiling water bath for 10 minutes. After chilling to room temperature, 1.0 ml of Arsenomolybdic acid reagents and distilled water were added to 10 ml. Absorbance reading was taken after 10 minutes of reaction at 510 nm using a UV-Vis Spectrophotometer (Shimadzu, Japan). Reducing sugar content in the tuber was calculated based on the standard curve of glucose (0.5 mM stock solution). Triplicates were used for each treatment.

Carbohydrate Degradation Enzymes: Invertase and Amylase in Tuber

Invertase was assayed according to Duman & Kaya (2014) with slight modification. The fresh tuber flesh (3 g) was sliced and homogenised in 10 ml of 50 mM acetate buffer (pH 5) with the addition of 0.8 M sodium sulphate and 0.1 mM ethylenediaminetetraacetate (EDTA) in an ice bath. The homogenate was filtered through four layers of cheesecloth and centrifuged at 5000 *x g* at 4°C for 20 minutes. The supernatant was

collected as an enzyme extract. The extract (0.2 ml) was mixed with 0.8 ml of 50 mM sucrose prepared in 50 mM acetate buffer (pH 4.7). The mixture was incubated in a water bath at 37°C for 30 minutes. Subsequently, 0.1 ml of DNS reagent was added and heated in a boiling water bath for 5 minutes. Absorbance was read using a UV-Vis spectrophotometer (Shimadzu, Japan) at 540 nm. Each analysis was done in triplicate. Invertase activity was expressed as µg/mg protein.

Amylase activity was assayed according to Nandutu *et al.* (2000) with a slight modification. Fresh tuber flesh (3.0 g) was sliced and ground in 10 ml of 20 mM sodium phosphate buffer (pH 6) in an ice bath. The homogenate was filtered through four layers of cheesecloth and the solution was centrifuged at 5000 *x g* for 20 minutes at 4°C. The supernatant was collected as an enzyme extract and kept in an ice bath. Then, 0.5 ml of enzyme extract was mixed with 0.5 ml of 0.1% (w/v) starch dissolved in 100 mM sodium acetate buffer (pH 6). The mixture was incubated at 70°C for 30 minutes. The reaction was stopped with 1.0 ml of 3,5-dinitro salicylic acid (DNS) reagent and heated for 10 minutes in a boiling water bath. After cooling in an ice bath, 8.0 ml of distilled water was added as the final volume. Absorbance readings were taken at 540 nm using a spectrophotometer. Amylase activity was expressed as µg/mg protein. The protein content in the tuber was estimated using the Bradford method (Kalaydzhiev *et al.,* 2018). Bovine serum albumin was used as standard and absorbance was taken at 595 nm using a UV-Vis Spectrophotometer (Shimadzu, Japan).

The Thickness of the Tuber Epidermal Layer

At harvest, tuber root histological analysis was carried out to examine the structure and thickness of the outer skin and the secondary layer of sweet potato tuber also known as the cortex. A fresh sweet potato tuber was taken from the freezer and sliced into cross-sections using a sliding microtome (Leica SM 2000 R) at a thickness of 180 µm. These slices were placed on a glass slide. To prevent the sample from drying out, one drop of distilled water was added to the sliced tuber on the glass slide. This helps maintain the moisture of the sample during the observation. The glass slide with the sliced tuber was observed under a dissecting light microscope (Olympus SXZ7) at a magnification of 1.6x.

Statistical Analysis

The data were analysed using One-way Analysis of Variance (ANOVA) subjected to GraphPad Prism® software. The mean differences between treatments were compared using Tukey's Honest Significant Difference (HSD) test at $p = 0.05$. The results were expressed as mean ± standard error mean (SEM).

Results

Yield: Biomass and Number of Tubers

Results in Figure 1 show the effect of SiNPs on the tuber biomass and tuber number/plant produced by the four sweet potato varieties. Among the treated varieties, 'Pejabat' and 'Karak Bakar' produced tubers with biomass significantly higher ($p < 0.05$) than the control plants, 456.6 ± 102.8 g/plant for 'Karak Bakar' and 392.9 ± 88.1 g/plant for 'Pejabat'. This was 1.46- and 1.29-fold higher than the control plants, respectively [Figure 1 (A)]. Meanwhile, 'Tanjung Sepat' plants that were treated with SiNPs produced the lowest tuber biomass (143.9 ± 71.2 g/plant) among the varieties. This was equivalent to about half the mass of the control plant [Figure 1 (A)]. SiNPs treatment did not significantly affect ($p > 0.05$) the tuber biomass produced by the 'V6D215' variety. Tuber biomass produced by the SiNPs-treated plants and control plants of 'V6D215' were at 275.2 ± 62.3 g/plant and 279.4 ± 10.7 g/plant, respectively. Results in Figure 1 (B) show that SiNPs treatment also influenced the number of tubers produced per plant by the four sweet potato varieties. Among the four varieties, the SiNPs significantly affected the tuber number produced by 'Pejabat'. For this variety, the number of tubers produced by the SiNPs-treated

plants dropped from 4 to 2 per plant. SiNPs did not significantly affect ($p > 0.05$) the number of tubers produced by the other three varieties of plants [Figure 1 (B)]. On average, 'Tanjung Sepat', 'V6D215' and 'Karak Bakar' produced 3 to 4 tubers/plant by both the SiNPs-treated plants and control plants.

Starch and Reducing Sugar Content in Tuber

Results in Figure 2 (A) showed that SiNPs treatment did not significantly affect ($p > 0.05$) the starch content in the tubers of 'Pejabat', Tanjung Sepat, and 'V6D215'. The starch content in 'Karak Bakar' tubers treated with SiNPs significantly decreased ($p < 0.05$) from (450 ± 67 mg/g fresh wt. to approximately 340 ± 22 mg/g fresh wt. [Figure 2 (A)]. Nevertheless, 'Karak Bakar' contains the highest starch content among the tested varieties, although treated with SiNPs. The second highest starch content was in V6D215 (243 ± 78 mg/fresh wt.), followed by 'Tanjung Sepat' (111 ± 26 mg/g fresh wt). The tuber of 'Pejabat' contains the lowest starch content (32 ± 16 mg/g fresh wt.) among the varieties, both SiNPs-treated as well as the control. Results in Figure 2 (B) show that SiNPs treatment significantly increased ($p < 0.05$) the reduced sugar content in the tuber of 'Pejabat' (9.27 ± 1.35 mg/g fresh wt.), 'Tanjung Sepat' (6.55 ± 2.10 mg/g fresh wt.) and 'Karak Bakar' (7.37 ± 0.80 mg/g fresh wt.). This was equivalent to 1.28-, 1.5 and 1.83-fold compared to the control, respectively. SiNPs treatment did not significantly affect the reduced sugar content in the tuber of the 'V6D215' variety [Figure 2 (B)]. Results also showed that among the varieties, the tuber produced by 'Pejabat' treated

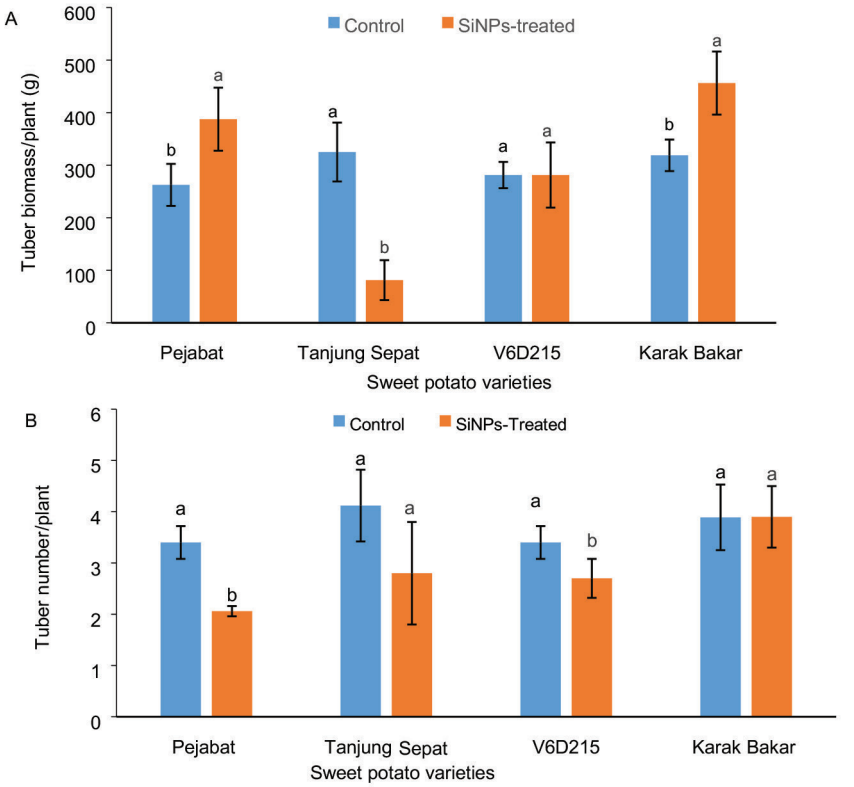

Figure 1: The effect of foliar application of silicon nanoparticle on the tuber biomass (A) and tuber number/plant (B) produced by four sweet potato varieties namely 'Pejabat', Tanjung Sepat, 'V6D215' and 'Karak Bakar'. The error bars indicate the standard error (n = 3) and histograms of the same variety with similar small letters did not significantly differ ($p < 0.05$) as indicated by Tukey's HSD Test

with SiNPs contains the highest reducing sugar content. The reduced sugar content in the tuber of untreated 'Pejabat' plants was similar to the 'Karak Bakar treated with SiNPs and 'V6D215' in both the control and SiNPs-treated plants [Figure 2 (B)].

Invertase and Amylase Levels in Tuber

Results in Figure 3 (A) show that SiNPs treatment significantly increased ($p < 0.05$) the invertase enzyme in the tuber of 'Pejabat' (4.8 ± 0.4 µg/mg protein). This was 1.8-fold higher compared to the control. On the other hand, the invertase levels did not significantly change ($p > 0.05$) in the tuber of 'Tanjung Sepat' (4.9 ± 0.5 µg/mg protein) and 'Karak Bakar' (4.7 ± 0.5 µg/mg protein). Interestingly, the SiNPs treatment significantly decreased ($p < 0.05$) the reduced sugar content in the tuber of 'V6D215' [Figure 3 (A)]. In this variety, the invertase levels in the tuber of SiNPs-treated plants dropped to 5.2 ± 0.1 µg/mg protein. Nonetheless, the highest invertase was in the tubers of 'V6D215' control plants (6.9 ± 0.5 µg/mg protein). The findings also revealed that invertase levels in the tuber

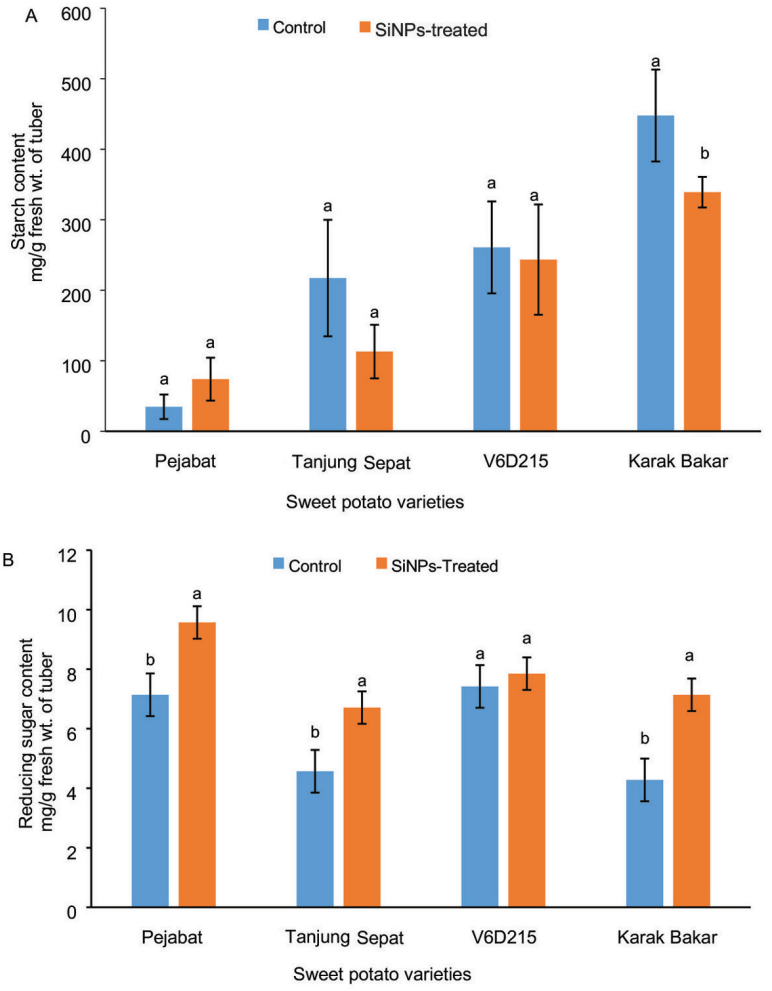

Figure 2: The effect of foliar application of silicon nanoparticle on the content of starch (A) reducing sugar (B) in the tuber sweet potato varieties 'Pejabat', 'Tanjung Sepat', 'V6D215' and 'Karak Bakar'. The error bars indicate the standard error (n = 3) and histograms of the same variety with similar small letters did not significantly differ ($p < 0.05$) as indicated by Tukey's HSD Test

of four varieties treated with SiNPs were almost similar (fluctuating around 5.0 µg/mg protein) to the control 'Tanjung Sepat' and 'Karak Bakar' [Figure 3 (A)]. Results in Figure 3 (B) show that amylase enzyme levels in the tubers were not significantly affected ($p > 0.05$) by the SiNPs treatment. Nonetheless, amylase levels in the tuber of 'Pejabat', (both control and SiNPs-treated plants) were the lowest among the varieties [Figure 3 (B)]. The amylase levels in the three sweet potato varieties, 'Tanjung Sepat', 'V6D215' and 'Karak Bakar' were almost similar, which fluctuated between 0.8 to 1.2 µg/mg protein [Figure 3 (B)].

The Thickness of the Epidermal Layer

The results in Figure 4 show the thickness of the tuber epidermal layer of control and SiNPs-treated plants. The results varied among the four varieties. The SiNPs treatment increased the tuber of the epidermal layer of the 'Pejabat' and 'V6D215' varieties, which were 1.66- and 1.16-fold, respectively. On the other hand, SiNPs treatment decreased the tuber epidermal layer of the 'Tanjung Sepat' and 'Karak Bakar' by approximately 0.8-fold for both varieties.

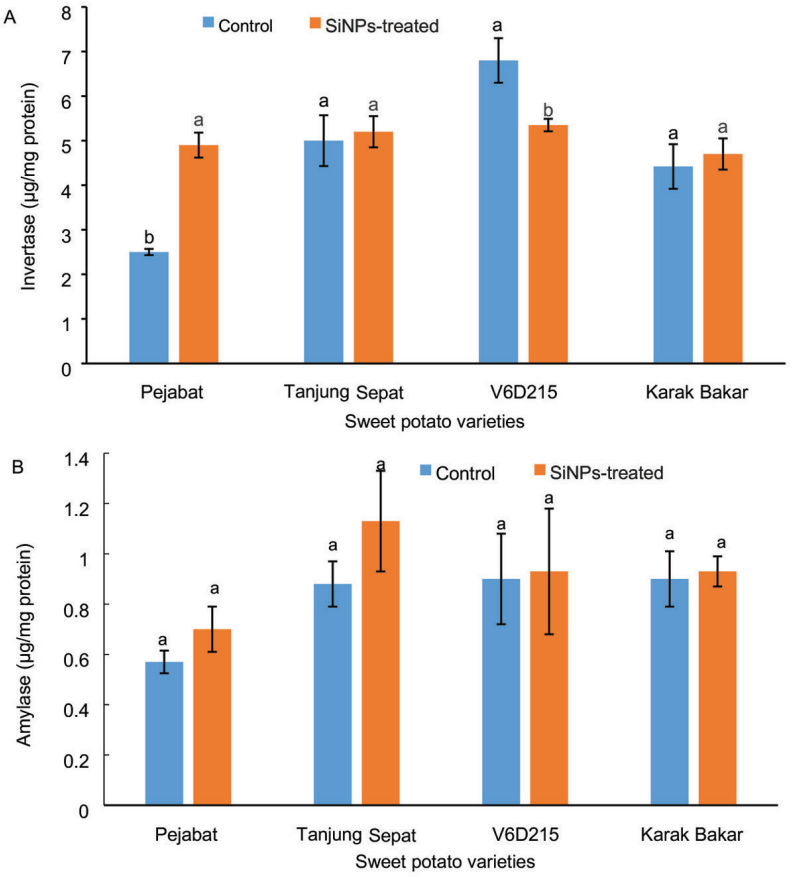

Figure 3: The effect of foliar application of silicon nanoparticle on the levels of invertase (A) and amylase (B) enzymes in the tuber of four sweet potato varieties namely 'Pejabat', 'Tanjung Sepat', 'V6D215' and 'Karak Bakar'. The error bars indicate the standard error (n = 3) and histograms of the same variety with similar small letters did not significantly differ ($p < 0.05$) as indicated by Tukey's HSD Test

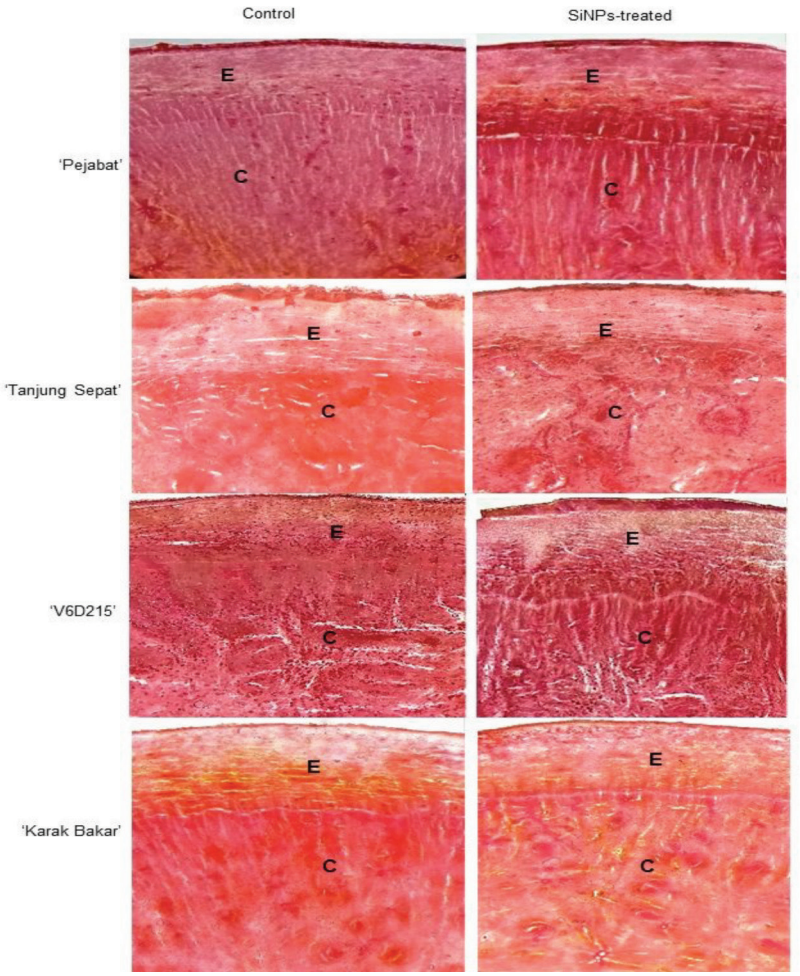

Figure 4: The picture shows the cross-section of tubers from the SiNPs-treated control plants of sweet potato varieties 'Pejabat', 'Tanjung Sepat', 'V6D215' and 'Karak Bakar'. Note: C = cortex, E = epidermal layer

Discussion

Various factors can influence plant growth, development and productivity. These include soil types, mineral availability in the soil and nutrient uptake by the root system or supplied through foliar-influenced tuber yield (Usman *et al.,* 2014). In a report by Nurul-Afza *et al.* (2023), sweet potatoes planted in sandy soil that is rich in organic matter and well-drained produce high tuberous roots. To enhance tuber production, trace elements such as boron are introduced during the growth stage of sweet potatoes (Usman *et al.,* 2014; Wadas, 2022; Nurul-Afza *et al.,* 2023). On the other hand, Si is classified as a non-beneficial element for plant growth and the effect of Si on sweet potatoes remains unknown. However, the nanoparticle form of Si was reported to promote the growth of many crops (Luyckx *et al.,* 2017; Ng *et al.,* 2021; Mukarram *et al.*, 2022; Mahawar *et al.,* 2023). For instance, potatoes (*Solanum tuberosum*) that are grown under limited water conditions (Duman & Kaya, 2014; Dahal *et al.,* 2019; Seleiman *et al.,* 2023).

In the current study, silicon dioxide nanoparticles were applied to the foliage of four sweet potato varieties. The findings

show that the positive effects of SiNPs on sweet potato tuber yield are variety-dependent (Figure 1). One of the possible direct effects of SiNPs on sweet potatoes is in carbohydrate transportation and metabolism. Results of the current study show that SiNPs treatment shifts the physicochemical and eating quality of sweet potato tubers, particularly the tuber biomass [Figure 1 (A)] and sweetness levels in 'Pejabat' and 'Karak Bakar' varieties [Figure 2 (B)]. It is suggested that foliar application of SiNPs on these two varieties might trigger the expression of DNA binding with one-finger proteins (DOF) that play a role in plant growth and tuber development. In long-day crops such as sweet potatoes, the cycling DOF factors (CDFs) are among the DOF proteins that are involved in the photoperiodic control of tuber formations (Carrillo *et al.,* 2023). According to Carrillo *et al.* (2023), DOF protein is also involved in nitrogen assimilation, and C/N balance and regulation, particularly the essential enzymes such as pyruvate kinase, phosphoenolpyruvate carboxylase and glutamate synthase. Whereby, the C/N balance in the source-sink relationship favours the remobilisation of amino acid to support the increased N demand during carbohydrate transportation and accumulation in the tuber (Lawlor, 2002; Carrillo *et al.,* 2023).

Results of the current study also suggested a few possibilities for the reduced sugar content in the tuber of these sweet potato varieties. In higher plants, starch is synthesised by starch synthase enzymes located in amyloplast. Tubers are plant organs that are highly condensed with amyloplast which can be up to 50% tuber tissue dry weight (Muhammad *et al.,* 2000). In amyloplast, sucrose is transported from leaves (sink) through the phloem and is hydrolysed by an invertase enzyme. The hydrolysis process will generate two monosaccharides, glucose and fructose, which are also known as reducing sugars. Tuber starch is two glucose polymers, amylose and branched amylopectin catalysed by starch synthases (SSs; EC 2.4.1.21), starch branching enzymes (SBEs; EC 2.4.1.18) and starch debranching enzymes (DBE; EC 3.2.1.68) which are through the α (1à4) and α (1à6) glycosidic linkages (Nazarian-Firouzabadi & Visser, 2017). High invertase levels in the tuber of 'Pejabat' may contribute to higher sucrose hydrolysis that leads to the accumulation of reducing sugar molecules, glucose and fructose. High reducing sugars in 'Karak Bakar' tubers may be due to lower starch biosynthesis. Although SiNPs treatment decreased the reduced sugar content in 'V6D215', the accumulated starch and invertase levels did not significantly differ (Figures 2 and 3). The findings suggested that the effect of SiNPs on starch and reducing sugar content in the tuber might be associated with water uptake. According to Seleiman *et al.* (2023), SiNPs improves water uptake by plants and contributes to dissolved sugars and starch in the tuber of the tuber potatoes. Moreover, sucrose transportation is highly dependent on water uptake and levels in plant phloem (Nazarian-Firouzabadi & Visser, 2017; Carillo *et al.,* 2023).

The results of the current study agree with the previous studies, where SiNPs regulates carbohydrate metabolisms in the osmotic stress of *Solanum lycopersicum* plants (Alam *et al.,* 2022), cucumber (*Cucumis sativus*) (Zhu *et al.,* 2016; Alsaeei *et al.,* 2019), and potato (*Solanum tuberasum*) (Dahal *et al.,* 2019; Kumar & Ginzberg, 2022; Seleiman *et al.,* 2023). Therefore, the current findings suggest that SiNPs treatment can enhance the characteristics of certain sweet potatoes grown on non-sandy soil types. Moreover, the high-starch sweet potato tubers are suitable sources of flour production while the sweet taste characteristics of tubers high in sugar content are more favourable for fresh consumption (Nurul-Afza *et al.,* 2023). Therefore, the foliar application of SiNPs may benefit sweet potato growers of 'Pejabat' and 'Karak Bakar', which are more suitable to be planted on clay soil (Nurul-Afza *et al.,* 2022).

Additionally, the results also indicate that SiNPs treatment regulates the epidermal layer of tubers of certain sweet potato varieties (Figure 4). The epidermal layer is the second layer after the periderm that acts as a physical

barrier preventing pathogen invasion and water loss. According to Kumar and Ginzberg (2022), the damaged periderm tissues are replaced by the epidermal layer. The thickness of the epidermal layer also plays an important role in the post-harvest quality of sweet potato tubers. Moreover, high Si in the tuber skin of potatoes has resulted in anatomical and compositional changes suggesting delayed skin maturation (Vulavala *et al.,* 2016).

Conclusions

The harvested tuber yield and carbohydrate metabolism in sweet potatoes varied among the four tested varieties. The foliar application of SiNPs can be used as a supplement to increase tuber biomass and reduce sugar levels in the sweet potato tubers, particularly the 'Pejabat' and 'Karak Bakar' varieties. The findings of the current study have enriched the information on the positive effects of silicon, particularly in the nano form, on a tuber crop species. Nonetheless, further studies should be carried out to determine the SiNPs accumulation in tubers, the optimum concentration of SiNPs concentration for each sweet potato variety and the sugar species in the tubers.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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