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SOIL SCIENCE

Influence of Silicon on Translocation, Compartmentation and Uptake of Lead in Leafy Vegetables

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ABSTRACT

Lead (Pb) has phytotoxic and toxic effects on plants and animals. Leafy vegetables accumulate this element resulting in enrichment along the food chain. Silicon has beneficial effects in enhancing plants' tolerance to biotic and abiotic stresses including heavy metals such as Pb. The study was carried out under greenhouse and field conditions aiming at determining the effects of silicon on transfer, mobility, and uptake of lead by leafy vegetables (spinach, kale, and amaranths). The greenhouse experiment was carried out as a split-plot arranged in Completely Randomized Design (CRD). The vegetable species were allocated to the main plots whereas the treatments (Pb, Pb+Si, Si, and Control) were assigned to the subplots. The field experiment was sited in polluted soils, and treatment included control and Si, applied to spinach, kale, and amaranths. Data was collected on Pb concentrations in roots, stems, and leaves, transfer factor, mobility index, and uptake of lead by leafy vegetables. Lead concentration was highest in roots, intermediate in stems, and least in leaves. Silicon application reduced concentration, transfer factor, mobility, and uptake of lead by 20, 40, 15, and 24%, respectively. The lead transfer factor and translocation index was less than one. Pearson correlation coefficient indicated a strong positive correlation between lead concentrations in soils and plant tissues of leafy vegetables. Application of silicon on polluted soils reduced transfer and mobility of lead in edible tissues of leafy vegetables. The study recommends silicon application to reduce the concentration of lead on vegetable tissues, however, it recommends against vegetable production for human consumption on polluted soils.

HIGHLIGHTS

- Leafy vegetables accumulate lead (Pb) resulting in enrichment along the food chain.
- Lead concentration was highest in roots than in stems and leaves.
- Silicon application reduced concentration, transfer factor, mobility, and uptake of lead in leafy vegetables.

Keywords: Lead, Spinach, Kale, Amaranths, Soil pollution, Environment

Leafy vegetable production and consumption have the potential of creating employment, providing nutrients, antioxidants, phytochemicals, dietary fiber, and providing income (Chagomoka *et al*. 2015; Ngugi *et al*. 2021). However, vegetable consumption in most African countries remains low below the recommended level, negatively impacting the nutrition condition of the population (Lans *et al.* 2012). Vegetable production around urban areas to meet demand especially during dry weather has intensified though associated with risks of

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wastewater and unsafe pesticide use (Chagomoka *et al*. 2015). The use of treated sewage water in crop irrigation in arid areas is greatly advocated for in many countries but the risk in the quality of water used remained unresolved (Su *et al*., 2014). Soil contamination with lead resulting from polluted irrigation water poses a great risk to healthy vegetable production (Kioko, 2015). Leafy vegetables growing in lead-contaminated soils show toxicity symptoms including chlorosis, reduced root growth, and stunted growth (Gweyi-Onyango and Osei-Kwarteng, 2011). Lead phytotoxic effects are due to interference with hormones, membrane structure and permeability, osmotic balance, and inhibition of photosynthesis in a plant (Sharma and Dubey, 2005; Nasar *et al*., 2021). Inhibition of enzymatic activities alters metabolic processes such as chlorophyll synthesis, carbon (iv) oxide fixation, sugar metabolism, and protein hydrolysis. Vegetables have the potential of taking up heavy metals ions and accumulating them in edible plant tissues resulting in enrichment along the food chain (Kumar *et al*. 2020). Their consumption, especially in urban areas, poses a high health risk to both humans and animals (Kiende 2012).

Silicon promotes tolerance through altering the structure of the cell wall via transport control, promoting activities of antioxidant enzymes, and the complexation of metal ions (Emamverdian *et al*. 2018). The antioxidant enzymes scavenge Reactive Oxygen species enhancing plant tolerance against oxidative stress, which has negative morphological, biochemical, and physiological effects on the plant. It also enhances non-enzyme antioxidant activities, which reduce transport in plants. In addition, silicon protects the plant via the accumulation of polysialic acid in plant cells (Emamverdian *et al*. 2018).

Silicon reduces the apoplastic translocation of metals to shoots through the reduction of free metal ions in the plant tissues (Nyawade *et al*. 2020; Ngugi *et al*. 2021, 2022; Parecido *et al*. 2021). It enhances apoplastic barriers in roots: exodermis, epiblema, and endodermis reducing metals ions translocation (Emamverdian *et al*. 2018). Silicon also reduces the symplastic transport of metal ions (Bhat *et al*. 2019).

MATERIALS AND METHODS

Study site description

The field experiments were carried out at the faculty of agriculture, Kenyatta university research farm, which lies 1°10′50.0″S, 36°55′41.0″E and at an elevation of 1608 m above sea level (Ochieng' *et al*. 2021). The average annual rainfall is 1001 mm and the soils were Orange Brown Gritty Loam. The experiments were carried during short rains (October-December, 2019) and long rains (March-May, 2020). The treatments in the field experiment were silicon and control and were randomly assigned to kales, spinach, and amaranths. The experiment was arranged in a Randomized Complete Block Design (RCBD).

The greenhouse experiment was carried out as a pot experiment as a split-plot arranged in Completely Randomized Design (CRD). The subplots constituted: Pb, Pb+Si, Si, and Control, while the main plots were composed of spinach, kale, and amaranths. The soils used to fill the pots were analyzed and homogenized. The soils were spiked with Lead Nitrate $Pb(NO_3)_2$.

Soil analysis

The soil samples from the field were collected as outlined by (Okalebo *et al*. 2002). The soil cores series were collected at 0-20 cm and 21-40 cm using the Transverse method. The cores were mixed to form a composite sample, dried, ground, sieved, and used for analysis. The soil properties determined included pH, organic matter (colorimetric method), and Phosphorous (Bray 3 method). The amount of phosphorous and organic matter was quantified using Equation 1 and 2 respectively (Okalebo *et al*. 2002).

$$\text{Concentration (mg/kg)} = \frac{(a-b)*v*f*1000}{1000*w} \quad \ldots(1)$$

Where, a = concentration in the solution, b-concentration of the blank, v = final volume of the digestion process, w= weight of the sample used and f = the dilution factor.

$$\text{Organic Carbon \%} = \frac{(a-b)*0.10}{w} \quad \ldots(2)$$

Where, a = concentration of Cr^{3+} in the sample, b = concentration of Cr^{3+} in the sample, and w = weight of soil sample.

Determination of lead in soil

One gram of homogenized dry soil was digested by the addition of 150 ml HCl and 5 ml HNO_3. The samples were put on a sandy bath for one hour, and 5 ml HCl and 50 ml deionized water were added after cooling the solution (Al-Hamzawi and Al-Gharabi, 2019). The solution was filtered, and filtrate absorbance was determined using atomic absorption spectrophotometer (AAS) calibrated for the lead at 283.31 nm wavelengths. The actual concentrations were computed using Equation 1.

The concentration of lead in plant tissues

The vegetable samples were harvested at an interval of 10 days, after 35days post-transplanting. The whole plant was uprooted and washed with fresh water to remove adhering dirt and later with deionized water. The plants were portioned into roots, stems, and leaves. The portioned plant samples were oven-dried at 60°C until there was no change in weight, and later dry weight was recorded. The dry samples were ground and stored in labeled zip lock polythene bags for analysis. 0.3 g of the plant sample was digested with 2.5 ml of digestion mixture, Selenium-Sulphuric acid mixture, for two hours at room temperature. The sample digest was heated at 110°C for 1 hour, cooled and 30% H_2O_2 added, and later heated at 330°C until the digest became colorless or light yellow color. The contents were topped to a 50ml volumetric flask mark with deionized water. The sample absorbance was determined using atomic absorption spectrophotometer calibrated for lead 283.31 nm wavelengths. The concentrations were determined using Equation 1 (Okalebo *et al*. 2002).

Transfer factor

The transfer factor (TF) index, was computed as a ratio of the lead concentrations in the plant tissues to their respective concentration in the soils, using Equation 3. It was used to quantify the amount of lead that the plants absorbed from the growth medium.

$$\text{Transfer factor (TF)} = \frac{\text{C plant (mg/kg)}}{\text{C soil (mg/kg)}} \quad \ldots(3)$$

Where C plant and C soil is the concentration.

Mobility index

The mobility index was computed as the ratio of lead and cadmium in the root to the stem and leaf concentration. It was used as a measure of the amount of lead translocated by the plant to above-ground biomass, from the roots. It was calculated using Equation 4.

$$\text{Mobility index} = \frac{\text{C shoot (mg/kg)}}{\text{C root (mg/kg)}} \quad \ldots(4)$$

Where *C* shoot and *C* root is the concentration

Uptake

The uptake of lead by leafy vegetables was calculated using Equation 5. It indicates the total amount of lead absorbed by vegetables from soils.

$$\text{Uptake (kg/ha)} = \frac{\text{(Biomass * Concentration)}}{100} \quad \ldots(4)$$

Where Biomass is the dry weight of leafy vegetables (Kg/ha) and concentration percentage (%) of lead in plant tissues

RESULTS

Soil characteristics

The concentration of lead in the screened field experiments soil was 86.70 mg/kg, it was more than the WHO allowable limits of 85 mg/kg in agricultural soil (Fortin 2009; Kinuthia *et al*. 2020). Soils in both greenhouse and field experiments had low amounts of organic carbon and phosphorous (Ochieng' *et al*. 2021). The soil was acidic with a pH range of 4.5-5.4 (Table 1).

Shoot length and biomass

Lead pollution had significant (P<0.001) inhibition on the height and biomass of leafy vegetables. Spiking soils with lead in the greenhouse experiment decreased the shoot length by 16.75% and 10.59% in amaranths and kale respectively (Fig. 1). Lead treatment reduced above-ground biomass significantly with 47.93, 32.61, and 26.98% in amaranths, kale, and spinach respectively when compared with control. Silicon amendment resulted in the highest shoot length alleviation in amaranths with 24.85%. The application of silicon

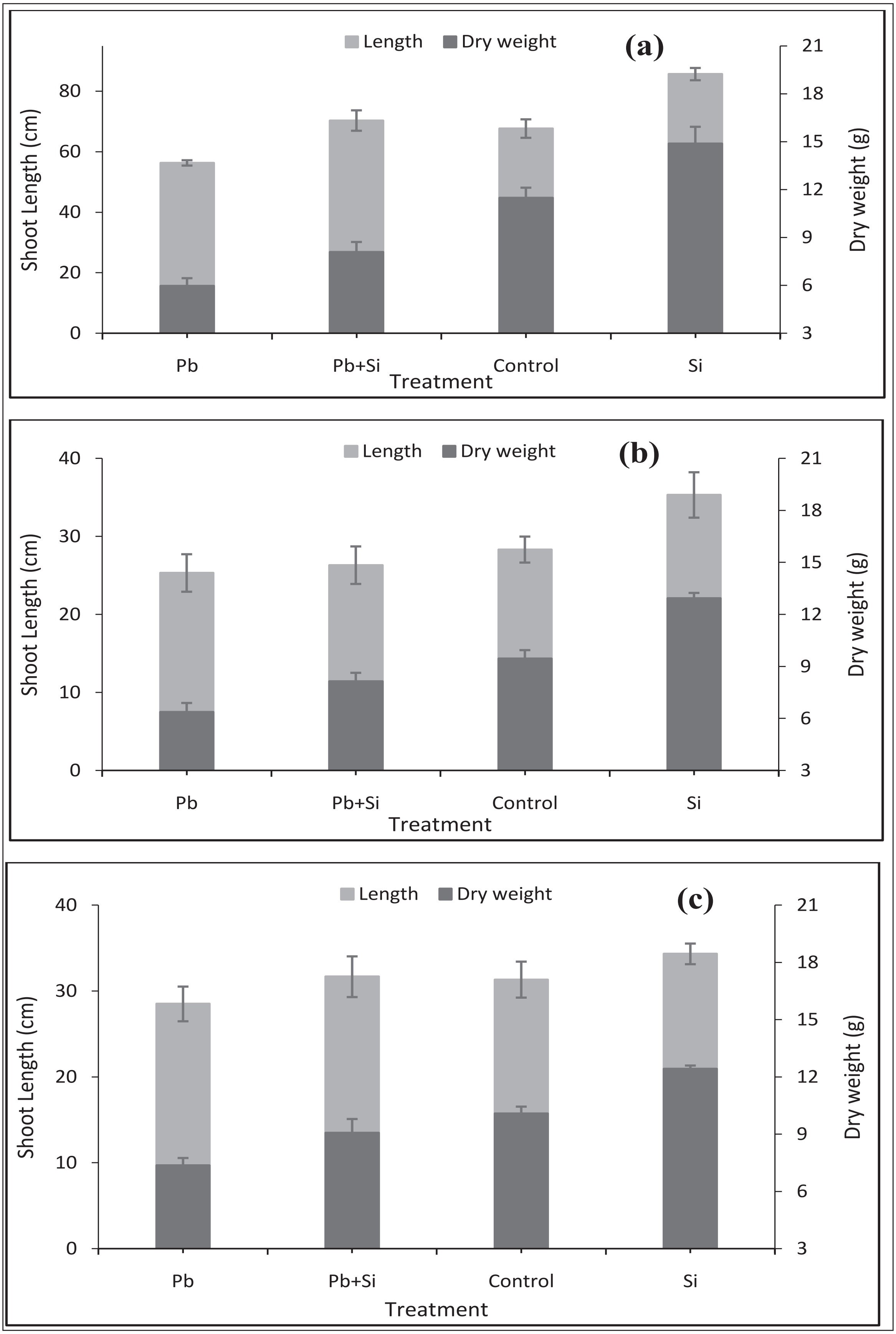

Fig. 1: Shoot length and biomass as ameliorated by silicon amendment in spinach **(a)**, kale **(b)** and amaranths **(c)**

alleviated above-ground biomass tolerance with 35.54, 27.88, and 23.08% in amaranths, kale, and spinach respectively.

Table 1: Soil characteristics in greenhouse and field experiments

Parameter	Greenhouse	Field experiment
$pH_{(water)}$	5.31	5.37
$pH_{(CaCl2)}$	4.52	4.87
Organic Carbon (%)	0.60	0.80
Phosphorous (mg/kg)	25.67	29.85
Lead (mg/kg)	Nd	86.57
Cadmium (mg/kg)	Nd	0.50
Lead- Spiked (mg/kg)	89.90	*
Pb-Irrigation water (mg/l)	Nd	4.00

*Nd- not detected, *- not applicable.*

Root length and biomass

Lead significantly (P<0.001) reduced root length and biomass of the leafy vegetables. The inhibition was highest in spinach for the root length and amaranth for root biomass. Lead treatment reduced root length with 41.65, 32.30, and 25.61% in spinach, kale, and amaranths respectively when compared with control (Fig. 2). Spiking soils with lead reduced root biomass to control with 50.34, 41.49, and 53.94% in spinach, kale, and amaranths respectively. Silicon application alleviated root length highest in spinach among the leafy vegetables. Soil amendment with silicon in lead spiked soils, increased root biomass with 27.92, 39.21, and 48.62% in spinach, kale, and amaranths respectively.

Growth tolerance indices

Results showed treatments had significant effects on root biomass, shoot biomass, and root length tolerance. The leafy vegetables had differential tolerance to lead contamination. Spinach had the highest root biomass tolerance while kale had the highest shoot biomass tolerance (Table 2). Application of silicon on lead spiked soils increased root biomass tolerance index of vegetables with 37.72, 40.62, and 46.72% amaranth, spinach, and kale respectively.

Leaf, stem, and root concentration

Lead concentration in leafy vegetable tissues was highest on the spiked soils. The concentration in tissues increased as plants continuously grew on the polluted soils. Results showed roots had the highest concentration in all the leafy vegetables, however, vegetables had a differential lead concentration in tissues (Fig. 3 and 4). Silicon application on spiked soils reduced concentration highest in leaves, with 51.25, 53.76, and 47.61% in spinach, kale, and amaranths respectively. The concentration of lead was higher during short rains than long rains in the field experiment (Fig. 4). Silicon amendment in the field experiment reduced concentration by 28% and 30% in leaves and stem of vegetables. Silicon application on spiked soils reduced concentration in edible leaves to within WHO allowable limits, however, it was beyond allowed limits in greenhouse spiked soils and field experiments.

Table 2: Leafy vegetables' growth Tolerance Indices as Alleviated by Silicon Fertilization

Vegetable		Root			Shoot
	Treatment	Dry weight	Length	Length	Dry weight
Amaranths	Pb	49.20^{e}	74.39^{c}	83.30^{a}	52.06^{d}
	Pb + Si	79.00^{de}	80.49^{bc}	103.9^{a}	70.50^{bcd}
	Si	184.7^{ab}	137.8^{a}	126.6^{a}	129.62^{a}
Kale	Pb	58.50^{e}	67.69^{cd}	89.40^{a}	93.06^{b}
	Pb + Si	109.8^{cd}	75.38^{c}	92.90^{a}	93.06^{b}
	Si	141.0^{bc}	129.2^{a}	124.7^{a}	93.06^{b}
Spinach	Pb	78.50^{de}	46.67^{e}	91.00^{a}	66.44^{cd}
	Pb + Si	132.2^{c}	54.67^{de}	101.1^{a}	81.77^{bc}
	Si	220.9^{a}	94.67^{b}	109.6^{a}	121.1^{a}
	p value	<0.001	<0.001	0.054	<0.001

Means followed by different superscript letters differ significantly at p ≤ 0.05 by Tukey's test.

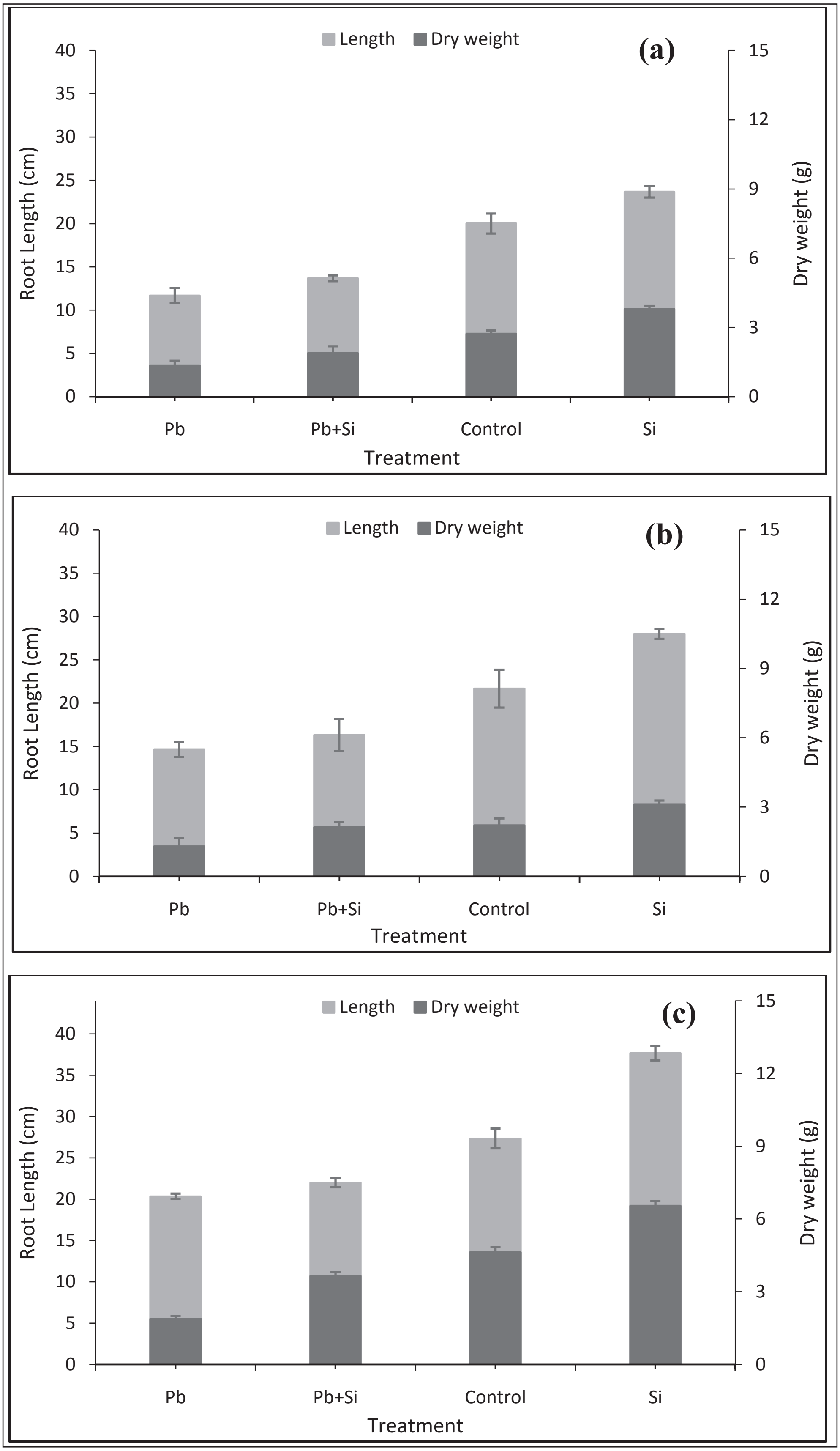

Fig. 2: Root length and dry weight as ameliorated by silicon amendment in spinach **(a)** kale **(b)** and amaranths **(c)**

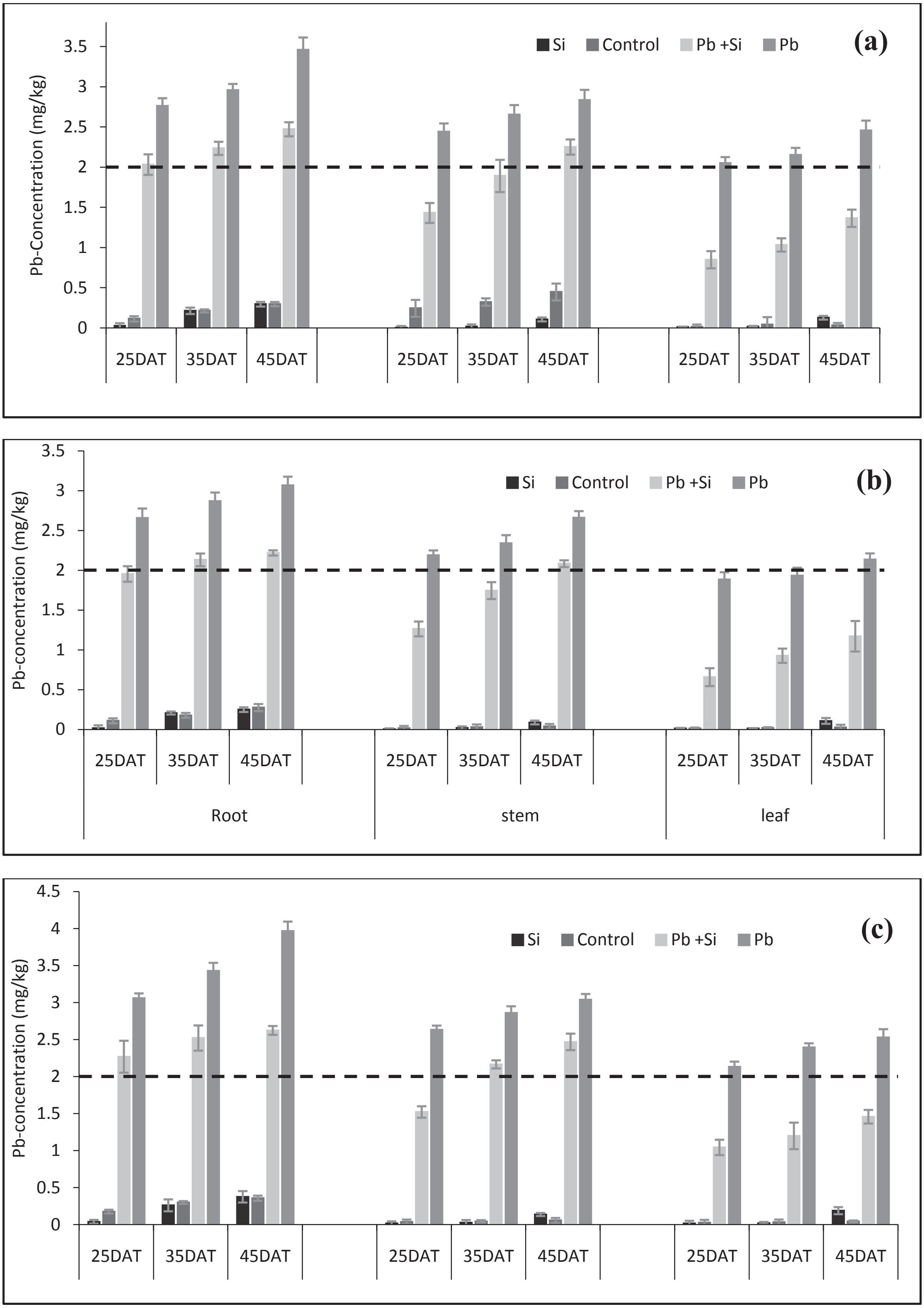

Fig. 3: Root, stem, and leaf concentration of lead in spinach **(a)** kale **(b)**, and amaranths **(c)** as alleviated by silicon application in the greenhouse experiment

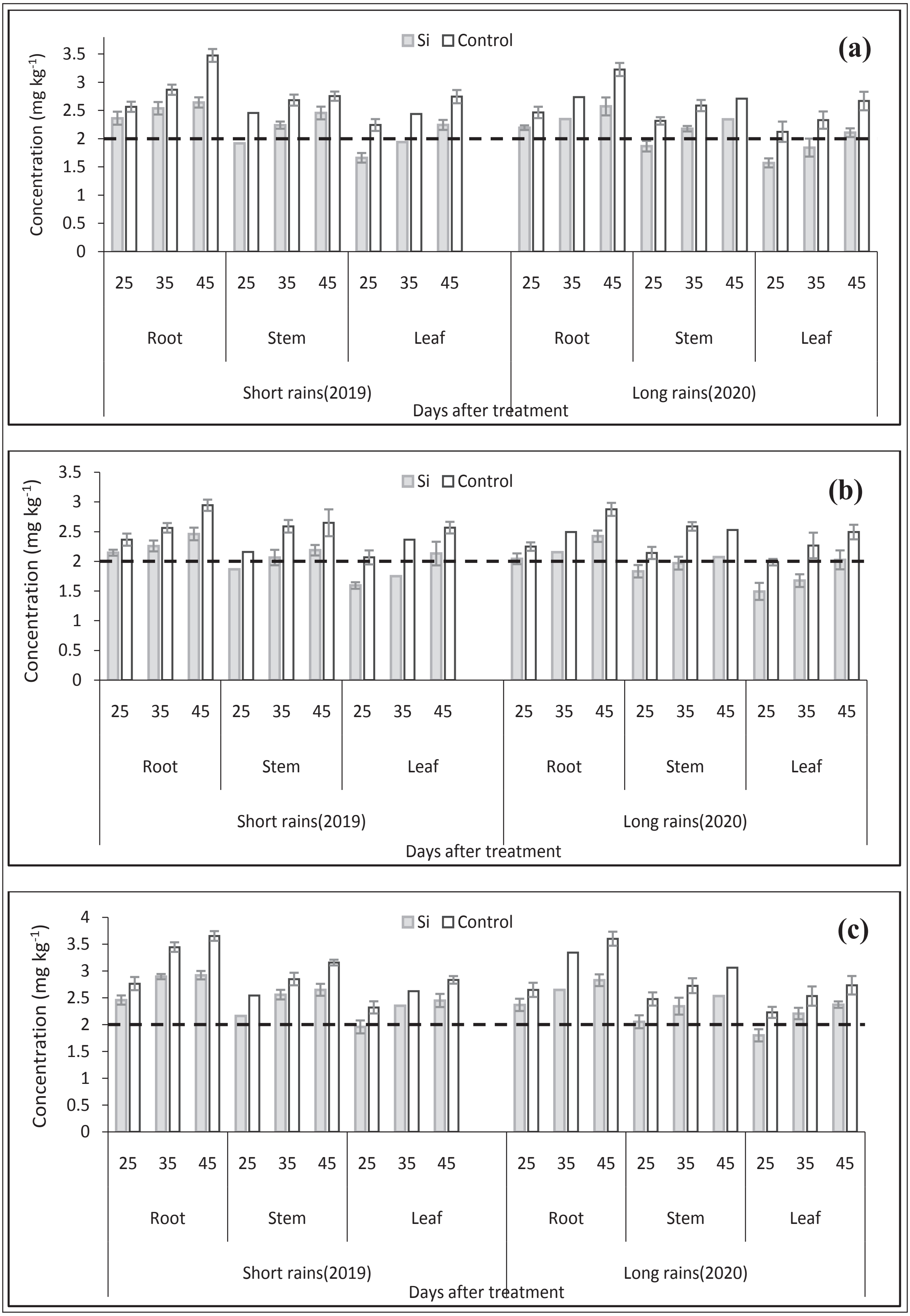

Fig. 4: Root, stem, and leaf concentration of lead in spinach **(a)** kale **(b)**, and amaranths **(c)** as alleviated by silicon application in the greenhouse experiment

Transfer Factor

Leafy vegetables had a differential transfer of lead from the soil, however, the transfer factor was less than one (TF<1) in all the leafy vegetables. The roots had the highest transfer factor when compared with stems and leaves (Fig. 5 and 6). The transfer factor was higher during short rains than long rains in the field experiment (Fig. 6). Soil spiked with lead had the highest transfer of lead ions to the plant, indicating the transfer was influenced by the concentration of the metal ions in the soil. The transfer increased as the vegetables continued to grow on contaminated soils. Silicon application reduced transfer to leaves by 51.26, 53.77, and 47.62% in spinach, kale, and amaranths.

Mobility Factor

Silicon application had a significant ($P<0.001$) reduction in lead translocation to leaves and stems of leafy vegetables. The vegetables had a differential translocation index; nevertheless, translocation was higher to stem than leaves in all the vegetables (Table 3 and Fig. 7). The mobility index was highest in spiked soils. However, the mobility index was less than one in all the leafy vegetables. The translocation index was higher during the short rains than long rains in the field experiment (Fig. 7). Silicon amendment in spiked soils reduced stem mobility during early stages of vegetable growth with 20.31, 21.56, and 21.78% in spinach kale and amaranths respectively. Silicon application reduced translocation to leaves by 35.12, 37.38, and 28.29% in spinach, kale, and amaranth respectively.

Uptake

Spiked soils resulted in the highest lead uptake by leafy vegetables. Amaranths had the highest uptake of lead among the vegetables (Fig. 8 and 9). Silicon application reduced root uptake with 20.27 and 35.80% and with shoot uptake 23.85 and 20.90% in spinach and kales respectively. Silicon amendment reduced stem uptake by 17.93% and leaves uptake with 28.97% in amaranths.

Relationship between growth parameters and Lead concentration in plant tissues

The results indicated a strong negative correlation

Table 3: Mobility of lead to stem and leaves of leafy vegetables as influenced by silicon amendment in the greenhouse experiment

Vegetable	Treatment	Stem mobility			Leaf mobility		
		Days after treatment					
		25	35	45	25	35	45
Spinach	Control	0.1541^{c}	0.0575^{c}	0.0287^{c}	0.1200^{c}	0.2009^{c}	0.1077^{d}
	Si	0.1680^{b}	0.0731^{b}	0.3606^{b}	0.3858b	0.0731^{c}	0.4318^{c}
	Pb +Si	0.7045^{a}	0.8465^{a}	0.9107^{a}	0.4182^{b}	0.4624^{b}	0.5525^{b}
	Pb	0.8841^{a}	0.8976^{a}	0.8199^{a}	0.7434^{a}	0.7277^{a}	0.7106^{a}
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Kale	Control	0.1286^{c}	0.1488^{b}	0.1319^{d}	0.1063^{c}	0.1051^{c}	0.0935^{d}
	Si	0.1717^{c}	0.0824^{c}	0.3479^{c}	0.6153^{a}	0.0555^{d}	0.4273^{c}
	Pb +Si	0.6463^{b}	0.8188^{a}	0.9389^{a}	0.3360^{b}	0.4342^{b}	0.5275^{b}
	Pb	0.8240^{a}	0.8156^{a}	0.8671^{b}	0.7094^{a}	0.6728^{a}	0.6955^{a}
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Amaranths	Control	0.2078^{d}	0.1446^{b}	0.1539^{d}	0.1387^{c}	0.1119^{c}	0.1148^{d}
	Si	0.3994^{c}	0.0964^{c}	0.3615^{c}	0.3898^{b}	0.0704^{c}	0.5006^{c}
	Pb +Si	0.6725^{b}	0.8597^{a}	0.9408^{a}	0.4606^{b}	0.4758^{b}	0.5551^{b}
	Pb	0.8598^{a}	0.8338^{a}	0.7658^{b}	0.6964^{a}	0.6985^{a}	0.6382^{a}
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means followed by different superscript letters (down the column within the same vegetable species) differ significantly at $p \leq 0.05$ by Tukey's test.

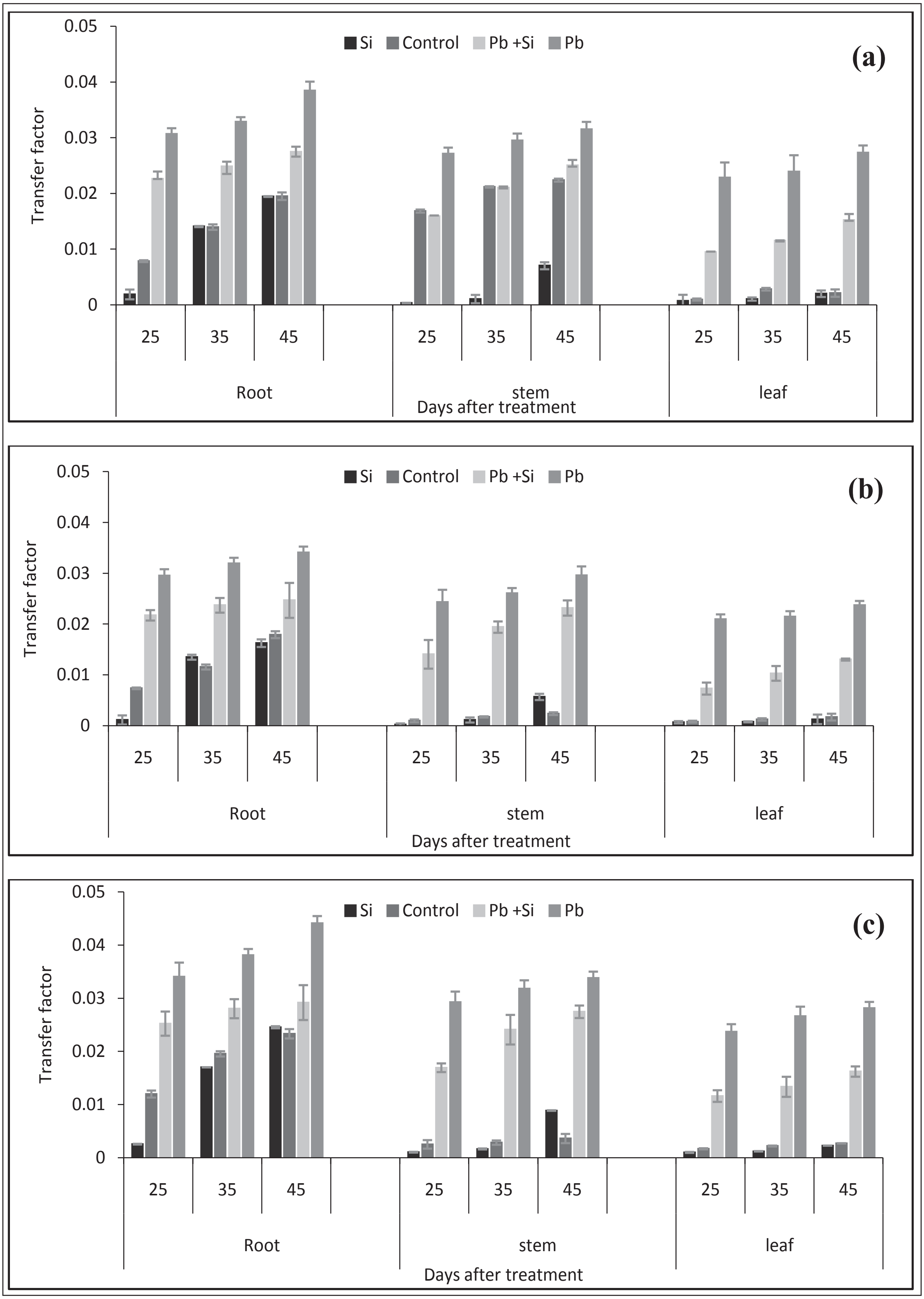

Fig. 5: Transfer factor of lead to in spinach **(a)** kale **(b)** and amaranths **(c)** tissues as ameliorated by silicon amendment in the greenhouse experiment

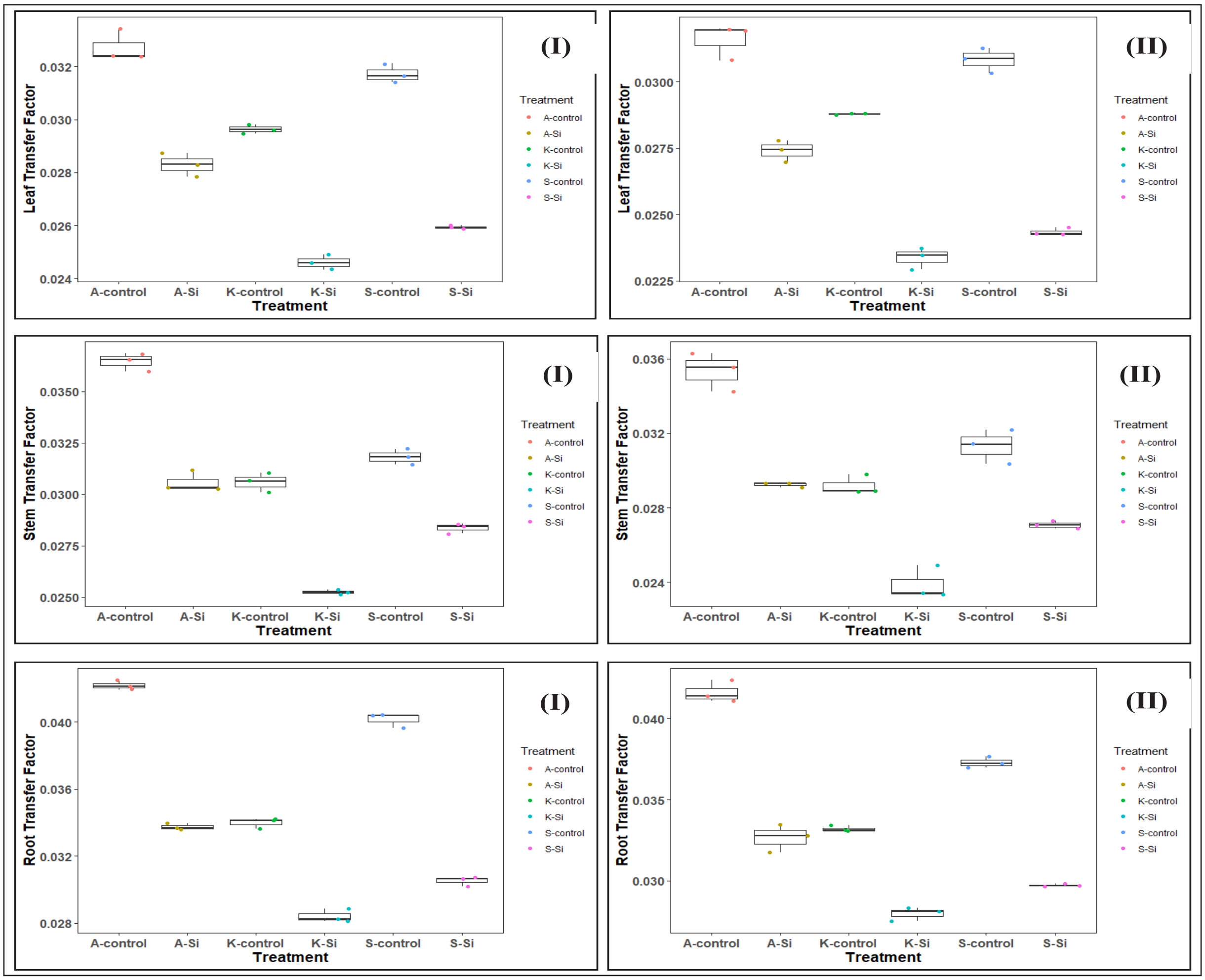

Fig. 6: Transfer factor of lead to leafy vegetable tissues as ameliorated by silicon amendment during short rains **(I)** and long rains **(II)** in the field experiment

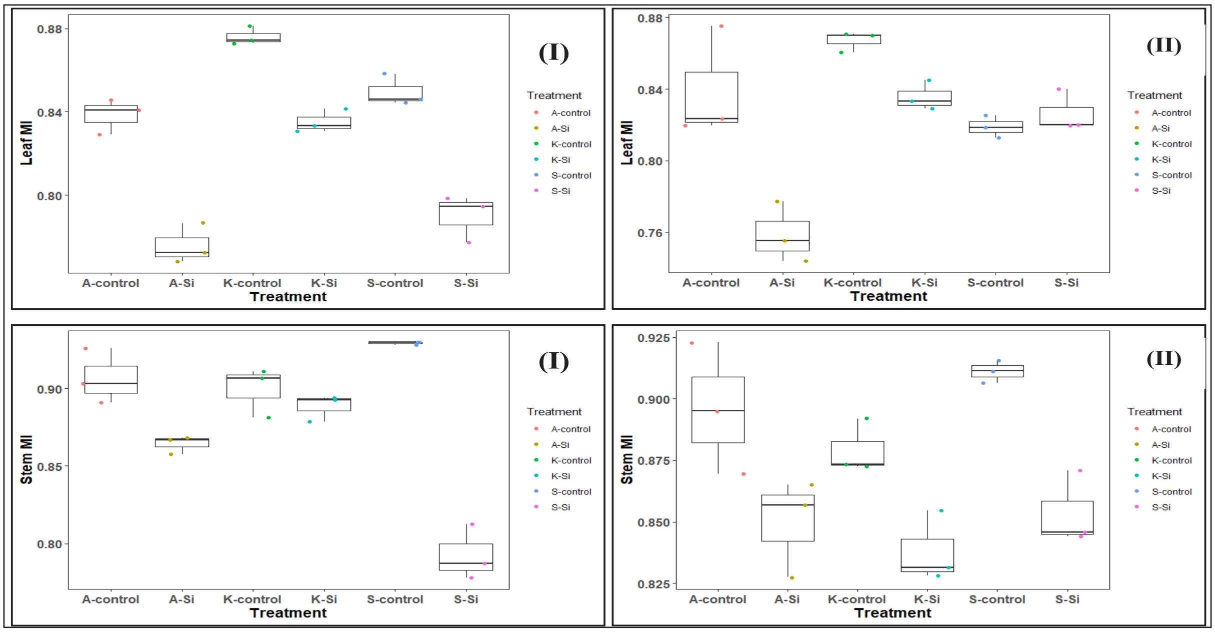

Fig. 7: Mobility of lead to stem and leaves of leafy vegetables as influenced by silicon amendment during short rains **(I)** and long rains **(II)** in the field experiment

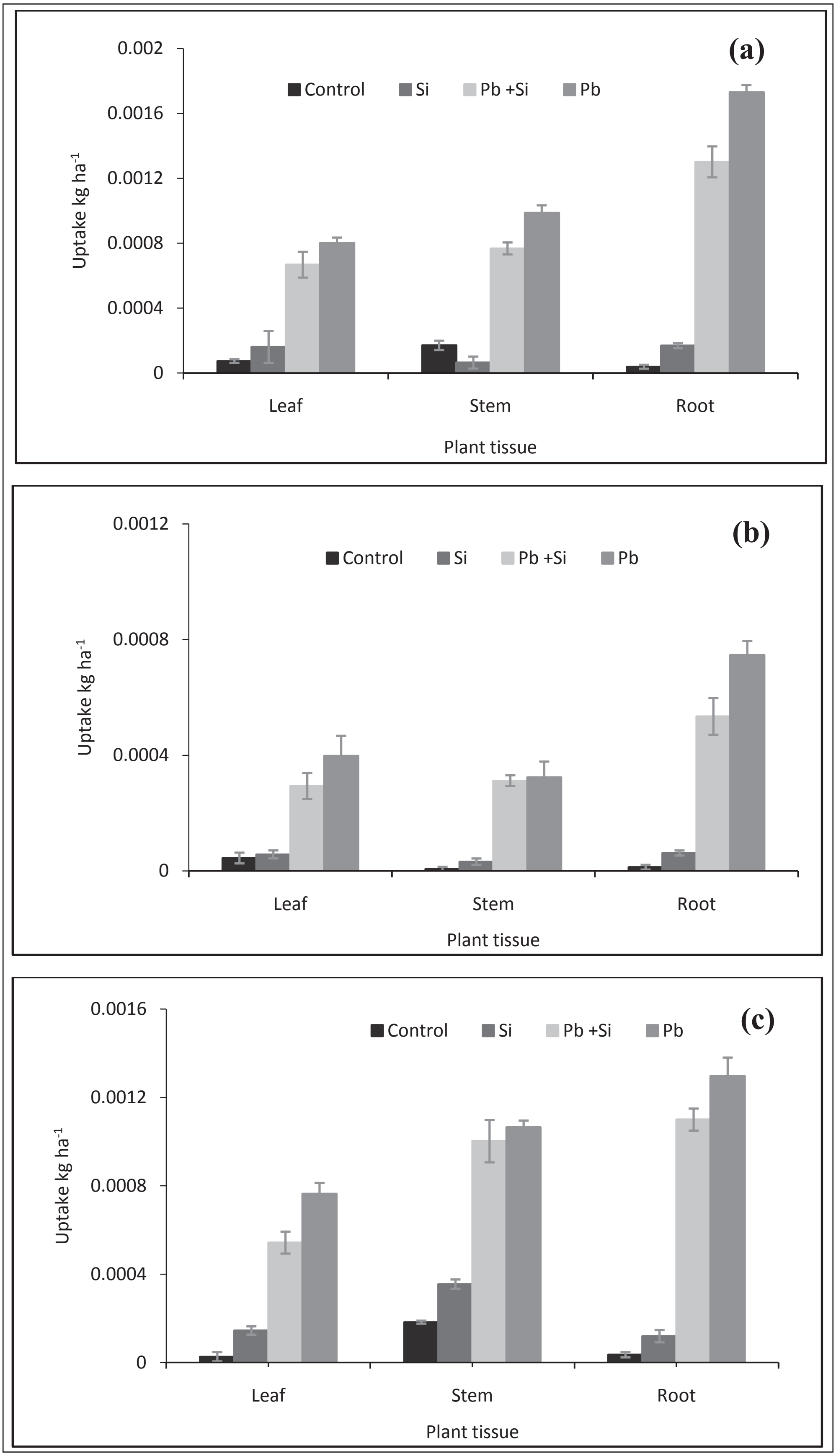

Fig. 8: Lead uptake by spinach **(a)** kale **(b)** and amaranths **(c)** in the greenhouse experiment as influenced by silicon application

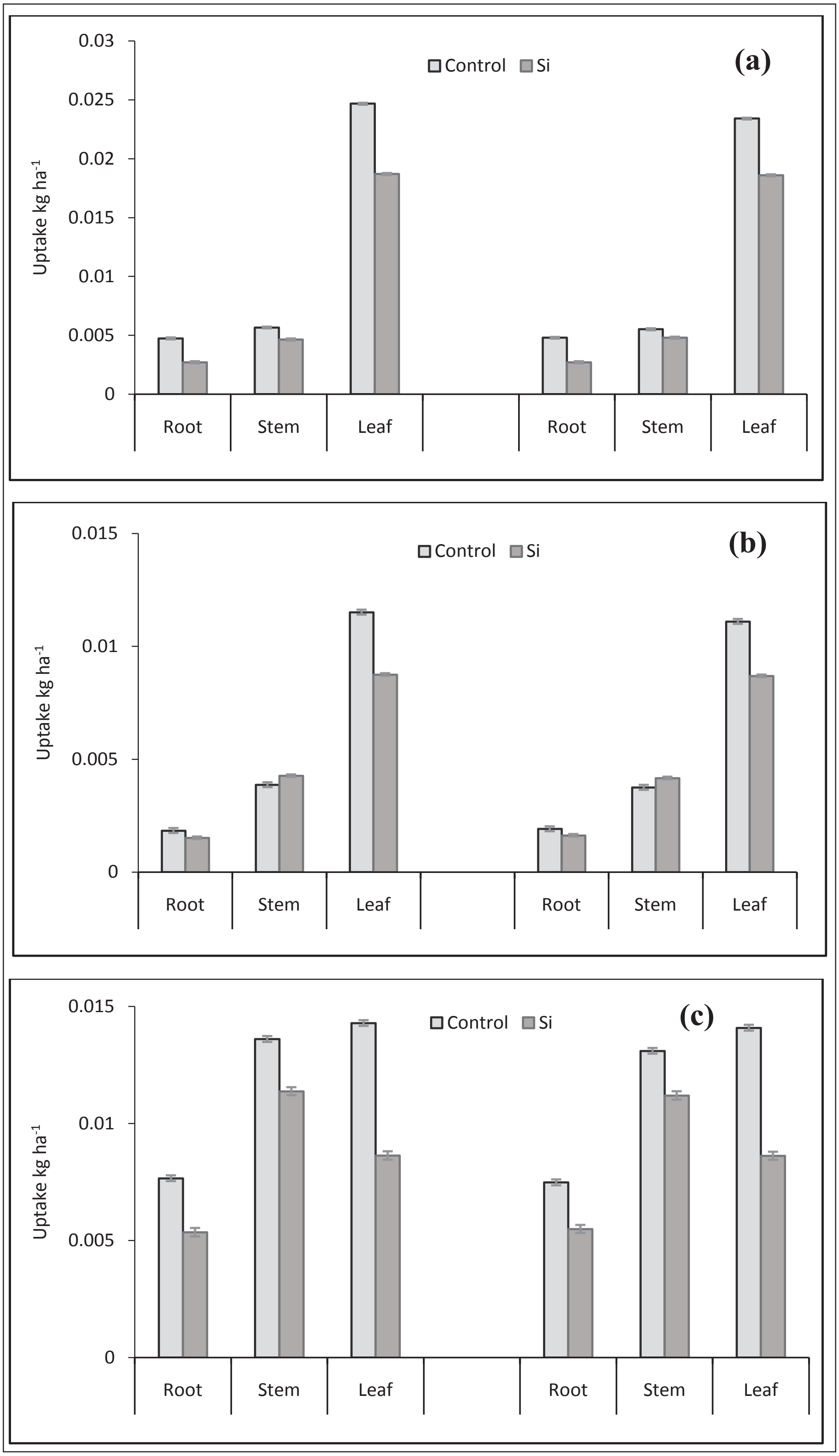

Fig. 9: Lead uptake by spinach **(a)** kale **(b)** and amaranths **(c)** in the field experiment as influenced by silicon application

between lead concentrations and measured growth parameters (Fig. 10). The root length of spinach had the strongest negative linear correlation with a lead concentration in tissues. Amaranths had a little linear relationship between measured growth parameters and lead concentration, indicating a

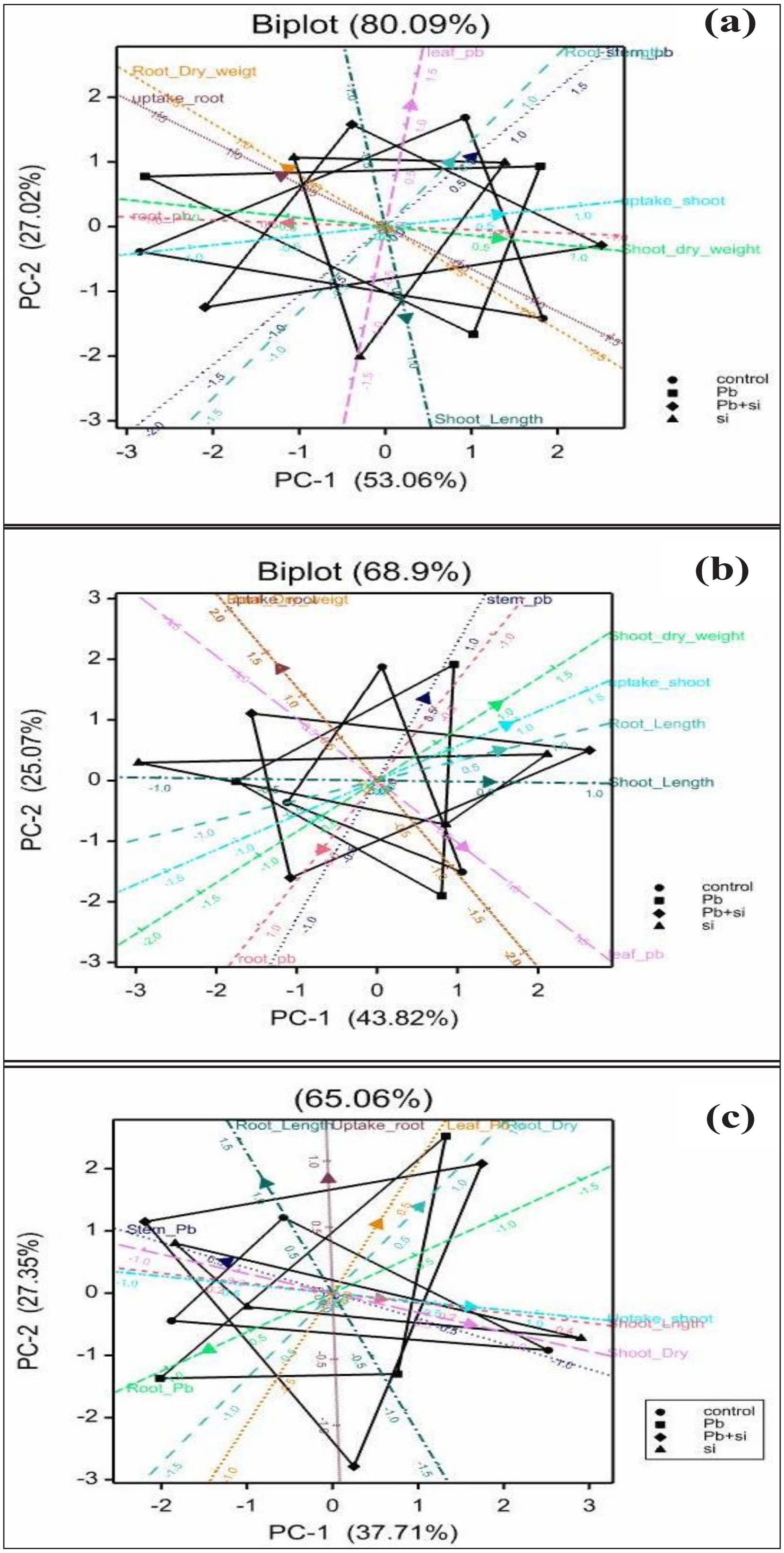

Fig. 10: Relationship among measured growth parameters, and lead concentrations in tissues of leafy vegetables

higher growth tolerance to lead contamination. Results also indicated strong positive linear relationships among measured growth parameters in all the leafy vegetables.

DISCUSSION

Shoot length and biomass

Lead toxicity reduces the rate of photosynthesis through inhibition of chlorophyll synthesis (Sharma and Dubey 2005). It also causes the production of reactive oxygen species causing peroxidation, membrane changes, and oxidative stress (Fahr *et al*. 2013). Lead inhibits enzymatic activities such as photosynthesis and nitrogen metabolism, affects vascular bundle, and induces histological changes in leaves (Nas and Ali 2018). The rate of respiration is also affected by disrupted enzymatic activities (Sharma and Dubey 2005). Lead induces water stress, reduces nitrate reductase activity in shoots, and uptake of nutrients (Feleafel and Mirdad 2013). The induced water stress is by damaging roots and decreasing water uptake and transport to shoots due to reduced transpiration strength (Nas and Ali 2018; Seleiman *et al.* 2021). Lead also reduces the number of dividing cells, and protein-synthesis (Feleafel and Mirdad 2013). Decreased shoot length and biomass were reported by a similar study on tomatoes and maize (Nas and Ali 2018).

Root length and biomass

Lead inhibits cell division at the root tips reducing root elongation (Fahr *et al*. 2013). The toxicity causes leakage of potassium ions from root cells causing mineral deficiency (Sharma and Dubey 2005) and inhibits the development of lateral roots hence a decrease in root biomass (Fahr *et al*. 2013). Lead toxicity causes the development of short, stubby, and swollen roots (Nas and Ali 2018). The higher toxicity in the roots is due to direct contact with contaminated growth medium (Fahr *et al*. 2013). The differential inhibition among the leafy vegetables is due to differences in lead uptake and root-rhizosphere interaction (Fahr *et al*., 2013). Lead inhibited root development was reported by similar studies on wheat and *Sedum alfredii* (Fahr *et al*. 2013), tomatoes and maize (Nas and Ali 2018), and *Tetraena qataranse* (Usman *et al*. 2020).

Growth tolerance indices

Leafy vegetables had differential tolerance indices due to the rooting system since plants with adventitious root systems have a higher tolerance than plants with a primary system (Fahr *et al*., 2013). Less lead is translocated to shoots due to extracellular precipitation and binding of lead on ion exchangeable sites on roots, hence lower toxicity on above-ground biomass (Sharma and Dubey 2005). Plant roots form mechanical barriers such as deposition of callose and forming plagues of iron and manganese on root surface increasing exclusion and reducing the uptake of lead (Fahr *et al*. 2013). The endodermis on the roots also acts as a barrier to lead translocation to shoots (Sharma and Dubey 2005).

Silicon enhances vegetables tolerance via increasing photosynthetic pigments, reduced lead concentration in sap, immobilization in stem and compartmentation, increased root length and girth, and increased nutrient uptake (Adrees *et al*. 2015). Silicon also stimulates enzymatic and non-enzymatic antioxidants, modulation of gene expression, reduced translocation, and precipitation of lead ions (Bhat *et al*. 2019). It also enhances the compartmentation of heavy metals and the expression of metal transport genes (Wu *et al*. 2013). Silicon amendment also raises soil pH, reducing the availability of lead ions for uptake (Bhat *et al*. 2019). It also reduces uptake of lead through chelation and coprecipitation of metal ions (Emamverdian *et al*. 2018), and deposition (Mandlik *et al*. 2020). Enhanced lead tolerance was reported by similar studies on *Lycopersicon esculentum, Ipomoea aquatic*, and beans (Nas and Ali 2018).

Leaf, stem, and root concentration

Spiking of soils with lead leads to an increase in concentration in plant tissues: an increase in soil concentration raised the transfer factor of the lead to plant tissues. The root lead concentration was higher than other plant tissues due to the high transfer factor and less mobility to the shoot.

Silicon application reduced concentrations in roots, stems, and leaves. Silicon reduced the uptake of lead by plants by forming complex compounds with metal ions reducing the amount available for plant uptake. It also regulates the activities of metal transporters in plants. Silicon reduces symplastic and apoplastic transport (Bhat *et al*. 2019). Apoplastic transport is reduced by silicon thickening apoplastic barriers in the plant (Emamverdian *et al*. 2018).

Transfer factor

The acid soil pH and low soil organic carbon influenced the availability and transfer of lead. In acid, soils lead exists in aqueous form $Pb(H_2O_6)^{+2}$ which is more available for the plants' uptake (Kumar *et al*. 2020). The transfer of lead was higher in roots and shoots due to a lower translocation index of lead from root to above-ground biomass. The difference in the transfer factor of lead among vegetables is due to the differential ability of crops to uptake and accumulate metal ions (Tangahu *et al*. 2011; Hassan *et al*. 2020). Higher shoot transfer to shoots of leafy vegetables growing on lead spiked soils is due to high roots lead concentration, which damages the membrane permeability and roots apoplastic barrier resulting in higher translocation index to the shoots (Sharma and Dubey, 2005).

Silicon alters the pH of the soil, reducing lead available for uptake by plants (Emamverdian *et al*. 2018). The rise in soil pH caused the precipitation of lead ions in soils (Kumar *et al*. 2020). It also forms silicates and oxides reducing the availability of metal ions for plant absorption (Bhat *et al*. 2019). Lead transfer factor of less than one (TF Pb<1) was in agreement with a similar study on spinach and amaranths (Jolly *et al*. 2013), leafy vegetables (Roba *et al*. 2015), and spinach (Pal *et al*. 2017).

Mobility index

The lead application resulted in a higher transfer factor and concentrations in the roots. High lead concentrations damaged membrane structure and permeability and also destroyed apoplastic barriers in roots resulting in higher translocation index to the shoot (Sharma and Dubey 2005). The damage to the semi-permeability function of cell membranes and tonoplast results in symplast transport of metal ions (Sharma and Dubey, 2005).

Silicon alters the structure of the cell wall by transport control and reduces lead mobility in the plant (Emamverdian *et al*., 2018; Hassan *et al*., 2020). Lead apoplast transport is reduced by lead binding with carboxyl, galacturonic, and glucuronic acid. It results in metal ion accumulation on root endodermis thus acting as a partial apoplast translocation barrier to the shoots (Kumar *et al*., 2020). Silicon compartmentalizes excess metal ions into cell vacuole and cell walls, leading to higher accumulation in roots and less translocation into the shoots (Bhat *et al*. 2019).

Lead uptake by leafy vegetables

The greenhouse and field experiment soils had low pH and organic carbon, hence more lead availability and uptake by leafy vegetables. In low soil pH lead ions exist in aqueous form $Pb(H_2O_6)^{+2}$ that is readily absorbed by crops. Leafy vegetable species had differential lead transfer factors hence differences in uptake (Fahr *et al*. 2013). Similar studies have shown leafy vegetables have higher lead uptake than other vegetables (Feleafel and Mirdad, 2013). The vegetables on lead treatment synthesis and deposit callose, which act as a barrier to reducing the uptake of lead (Fahr *et al*. 2013). However, high lead concentrations damage the cells and the semipermeable function of the plasma membrane, allowing symplast transport (Sharma and Dubey, 2005). The apoplast and symplast transport caused higher shoot lead uptake in lead treatment.

Silicon reduced lead uptake by forming complex silicon compounds with metal ions. It formed silicates and oxides reducing the availability of lead for uptake by vegetables (Bhat *et al*. 2019). Silicon also raised the soil pH reducing the lead availability. Silicon reduced shoot uptake by decreasing the apoplastic and symplastic transport of lead (Bhat *et al*. 2019). It decreased mobility by enhancing roots apoplastic barriers such as epiblema and endodermis. It also stimulated compartmentation of lead into the cell vacuoles and cell wall, hence higher accumulation in roots than shoots. The results were in agreement with similar studies on silicon ameliorated lead uptake on rice (Liu *et al*., 2015).

Relationship between growth parameters and lead concentration in plant tissues

The lead toxicity was higher in roots due to direct contact with soils and accumulation. Metal ions inhibited cell division at the root tips, reducing root elongation (Alia *et al*. 2015). The lower translocation index to shoots resulted in less inhibition of growth in shoot length than the root length. The reduced inhibition of shoot length in spinach corresponds with a similar study on tomatoes (Rehman *et al*. 2011). Lead negative correlation with root length and leaf area was also reported on tomatoes, radish, and soybeans (Rehman *et al*. 2011).

Leafy vegetables have differential uptake and translocation index of lead. Plants accumulate heavy metals more in roots and translocate poorly to the shoots (Cannata *et al*. 2013). Lead forms stable chelates root deposits easily than cadmium, hence lower mobility (Cannata *et al*. 2013). The lead was translocated to the leaves and stems, however, it was commonly accumulated in roots (Usman *et al*. 2019). The low translocation was also due to apoplastic barriers and precipitation of lead insoluble salts in roots (Usman *et al*. 2019).

CONCLUSION

Lead has significant inhibition on the growth and biomass of leafy vegetables, thus reduced yields in contaminated agricultural soils. However, vegetables have different growth tolerance when produced on a lead-contaminated growth medium. Vegetable transfer and accumulate lead on edible tissues, posing a safety risk for human consumption. Silicon application enhanced growth tolerance, reduced concentration, transfer, mobility to edible tissues, and uptake of lead. The study recommends silicon fertilizer application on polluted soils to enhance yields and reduced lead uptake. The study however recommends against the production of leafy vegetables for human consumption on polluted agricultural lands due to the risk of bioaccumulation and potential of enrichment along the food chain.

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