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The Growth and Biochemical Responses of *Capsicum frutescens* L. (Chilli Pepper) in Soil Obtained from a Coal Mining Environment in Ugiamwen Community, Edo State, Nigeria

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Abstract

Ugiamwen, a fertile region in Edo State, relies heavily on agriculture, and *Capsicum frutescens* L. (pepper) is a key economic crop. However, coal mining near farmlands has raised concerns about soil contamination and its effects on crop growth. This study assessed heavy metal concentrations in soils and evaluated the metal induced stress responses of *C. frutescens* grown under contaminated conditions. Soil samples were collected from two primary sites: coal mining soil (CMS) and adjacent farmland soil (FS), while control soil (CS) was obtained 160 m away from the mining activities. Soil physical properties and concentrations of copper (Cu), chromium (Cr), arsenic (As), and lead (Pb) were analyzed; cadmium was below the detection limit. To assess plant responses, percentage germination, plant height, leaf number, chlorophyll content, antioxidant enzyme activities, and metal accumulation in roots, stems, and leaves were determined. Results showed significantly elevated Cu concentrations in CMS and FS soils. Although, Cu was elevated, Pb, Cr, and As remained below the permissible limits established by the Canadian Council of Ministers of the Environment (CCME) agricultural soil quality guidelines. Lead and Cr accumulated predominantly in leaves, while Cu was higher in roots and As in stems. Germination, growth, and leaf production were markedly reduced in contaminated soils, and plants failed to fruit, unlike control plants, which flowered at 72 days after planting. Visible symptoms included chlorosis and stunted growth. Reduced chlorophyll content and increased antioxidant enzyme activities further indicated oxidative stress. Overall, mining-derived soil contamination significantly impaired the growth and productivity of *C. frutescens.*

Keywords: *Capsicum frutescens* L., coal mining soil, farmland soil, heavy metal, soil contamination, Ugiamwen

Introduction

Communities in mining areas have raised concerns about soil and agricultural land contamination. Mining activities can alter the chemical and biological properties of soils by releasing and redistributing potentially toxic metals. Metals such as lead (Pb), copper (Cu), cadmium (Cd), chromium (Cr), arsenic (As), and zinc (Zn) can enter agricultural soils through mineral weathering, mine wastes, atmospheric deposition, and drainage. Their effects on crops depend not only on total metal concentrations but also on chemical speciation, bioavailability, and interactions with soil properties such as pH, organic matter content, clay content, and cation exchange capacity, which regulate metal mobility and plant uptake (Ali et al., 2021; Huang et al., 2024).

Heavy metal phytotoxicity is both metal and concentration dependent. Essential elements such as Cu and Zn are required for normal plant metabolism but become toxic when their concentrations exceed physiological requirements. In contrast, Pb has no recognized essential metabolic function and may be harmful

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at relatively low bioavailable concentrations. Excess Cu can disrupt cellular redox balance, whereas Pb can interfere with membrane integrity, mineral nutrition, enzyme activity, and cellular metabolism. Although different metals may induce common stress responses, their modes of toxicity can differ considerably (Khan et al., 2021; Wang et al., 2026).

Metal toxicity begins at the soil-root interface, where plants regulate metal uptake, transport, and sequestration through membrane transport systems. Transporter families, including natural resistance-associated macrophage proteins (NRAMPs), zinc-iron permeases (ZIPs), metal tolerance proteins (MTPs), ATP-binding cassette (ABC) transporters, and heavy-metal ATPases (HMAs), contribute to metal homeostasis. Some toxic metals can exploit transport pathways normally used for essential nutrients because of similarities in their chemical properties. Heavy metal ATPases are particularly important in regulating metal distribution, with different members contributing to processes such as root-to-shoot translocation, vacuolar sequestration, and Cu homeostasis (Liu et al., 2024). Consequently, plant responses to metal contamination depend on the balance among metal uptake, intracellular sequestration, translocation, and detoxification.

Once accumulated in plant tissues, toxic metals can disturb cellular redox homeostasis and stimulate the production of reactive oxygen species (ROS), including superoxide radicals and hydrogen peroxide. Excessive ROS can damage proteins, nucleic acids, pigments, and membrane lipids. Plants respond through enzymatic and non-enzymatic antioxidant systems involving superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), ascorbate, glutathione, flavonoids, and phenolic compounds (Sharma et al., 2022). SOD converts superoxide radicals to hydrogen peroxide, which CAT, POD, and other H_2O_2-scavenging enzymes then detoxify. Changes in SOD, CAT, and POD activities therefore serve as useful indicators of oxidative stress and the plants' capacity to maintain redox balance under metal exposure (El-Sappah et al., 2024).

Heavy metals can also impair photosynthesis through distinct physiological mechanisms. Pb can interfere with chlorophyll and carotenoid biosynthesis, chloroplast structure, and components of the photosynthetic electron transfer system, while also contributing to stomatal dysfunction and reduced carbon assimilation (Gupta et al., 2024). Although Cu is essential for photosynthetic electron transport at low concentrations, it can become phytotoxic at high levels, causing chloroplast and thylakoid membrane disruption, reduced photosynthetic pigments, and impaired photosystem II activity (Chen et al., 2025; Zeng et al., 2022). Together with ROS-induced membrane damage and disruption of nutrient acquisition, these effects can ultimately reduce plant growth and biomass production.

Metal contamination can further alter soil biological functioning by affecting microbial communities and the enzyme activities involved in organic matter decomposition and nutrient cycling. A metal analysis showed that Pb, Zn, Cd, Cu, and As contamination generally reduced soil enzyme activities, although the magnitude of inhibition varied among enzymes and was influenced by soil properties such as clay content and soil depth (Aponte et al., 2020). More recent evidence indicates that Pb, Cu, and Cr can modify soil microbial biomass, community structure, and nutrient cycling processes, with pH, organic matter, and soil texture influencing the severity of these effects (Campillo-Cora et al., 2025).

The agricultural consequences of metal contamination therefore depend on interactions among soil characteristics, metal availability, plant uptake, and physiological tolerance. Increased metal availability can promote tissue accumulation, disrupt nutrient acquisition and membrane stability, stimulate oxidative stress, impair photosynthesis, and ultimately reduce crop growth and productivity.

In Ugiamwen farmland, Uhunmwode Local Government Area, Edo State, Nigeria, two years of coal-mining activities have been associated with reduced crop yield and quality. Farmers have also reported premature foliar chlorosis and

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necrosis, locally described as burn symptoms, which persist until crop maturity. Although these symptoms may involve disturbances in chlorophyll metabolism, photosynthesis, membrane stability, and oxidative stress, their specific causes require empirical investigation.

Despite previous studies on the environmental and socioeconomic consequences of coal mining in Nigeria, limited information is available on the integrated relationships among soil metal contamination, metal accumulation in food crops, and crop physiological responses in areas surrounding active coal mining sites in southern Nigeria. This knowledge gap is particularly important in agrarian communities where crops are cultivated near mining sites and then enter local food systems. Therefore, this study investigated concentrations of selected heavy metals in soils and in *Capsicum frutescens* L. cultivated near the Ugiamwen coal mining environment in Uhunmwonde Local Government Area, Edo State, Nigeria. The study evaluated the growth and developmental responses of *C. frutescens* grown in soil obtained from the mining environment and determined the concentrations of selected metals in plant tissues. By integrating soil metal concentrations, plant accumulation, and growth responses, this study provides evidence on the agricultural suitability of mining-affected soils and the environmental management of coal mining activities in agrarian communities.

Materials and methods

Planting material

Seeds of *C. frutescens* were purchased from the National Horticultural Research Institute (NIHORT), Ibadan, Nigeria.

Soil Collection and Preparation of Experimental Pots

Soil samples were collected from two locations: coal mining soil (CMS) and farmland soil (FS). Control soil (CS) was collected 160 m from the coal mining area, where no mining activity had occurred. Within each sampling area, six sampling points, spaced 10 m apart, were established for soil collection using a clean stainless steel shovel at a depth of 0–15 cm. Each sampling point was treated as an independent replicate for subsequent analyses and was not pooled into a composite sample. Each experimental pot contained 4 kg of soil.

Viability Test and Sowing of Seeds

Seed viability was determined using a standardized germination test. The procedure involved replicating optimal germination conditions, counting and recording germinated seeds, and calculating the germination percentage. Ten seeds were sown in each experimental pot, with four replicate pots per treatment.

Physiochemical properties

We applied a conversion factor of 1.724 to the measured organic carbon (OC) content to estimate soil organic matter (SOM). Calcium (Ca) and magnesium (Mg) concentrations were determined using the ethylenediaminetetraacetic acid (EDTA) titration method described by Lanyon and Heald (1982). Calcium carbonate ($CaCO_3$) content was quantified using the acid neutralization method following Hesse (1971). Potassium (K) and sodium (Na) concentrations were measured using a Systronics Flame Photometer-128 after digesting samples in a diacid mixture of perchloric acid ($HClO_4$) and nitric acid (HNO_3) in a 4:1 ratio, following Bhat et al. (2014). Total nitrogen (TN) was determined using the Kjeldahl digestion and distillation method described by Bremner and Mulvaney (1982). Available phosphorus (P) was quantified following extraction with sodium bicarbonate according to the Olsen method (Olsen et al., 1954), and its concentration was measured using a Spectrophotometer-2202.

Heavy metal analysis

Five grams of homogenised soil were finely ground and oven dried at 70 °C for 72 hr to

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achieve constant weight. Subsequently, 0.1 g of the dried sample was subjected to acid digestion by adding 9 ml of concentrated hydrochloric acid (HCl) and 3 ml of concentrated nitric acid (HNO_3) in a beaker. The beaker was covered with a watch glass and heated on a hot plate at 110 °C for 3 hr. After digestion, the samples were allowed to cool, and 20 ml of 20% HNO_3 was added. The resulting solution was cooled, filtered through Whatman filter paper, and diluted to a final volume of 100 ml with double distilled water, following the procedures of Hseu et al. (2002) and Chen and Ma (2001).

The instrumental detection limit of the atomic absorption spectrophotometer (AAS; model AA320N; Hangzhou West Tune Trading Co., Ltd., China) was 0.001 mg/kg for Pb, Cr, Cu, As, and Cd. A reagent blank was prepared by subjecting the same digestion reagents—concentrated HCl, concentrated HNO_3, and 20% HNO_3—to the same digestion, cooling, filtration, and dilution procedures without soil. Appropriate analytical precautions, including clean laboratory glassware, reagent grade acids, double distilled water, and filtration of digested samples, were used to minimize contamination during sample preparation and analysis.

Measurement of Vegetative Parameters

The measured parameters were germination percentage, plant height, and leaf number. Germination was recorded daily for 12 days after sowing. The total number of germinated seeds per pot was quantified, and the germination percentage was calculated accordingly. Plant height was measured weekly using a ruler. The number of leaves per plant was counted and recorded weekly.

Determination of Peroxidase Activity

Peroxidase (POX) activity was determined using the method described by Bergmeyer (1974). In this assay, the rate of hydrogen peroxide decomposition by peroxidase, in the presence of guaiacol as a hydrogen donor, was quantified spectrophotometrically at 470 nm and 4 °C. A 0.5 g fresh tissue sample was homogenised in 0.5 ml of phosphate buffer using a pre-chilled pestle and mortar. The homogenate was filtered and centrifuged at 10,000 rpm for 20 min and 4 °C. Peroxidase activity was estimated spectrophotometrically using guaiacol. In the presence of hydrogen peroxide, peroxidase catalyzes the conversion of guaiacol to tetraguaiacol, which was measured at 470 nm. Peroxidase activity in each sample was determined from the increase in absorbance at 10 sec intervals over 60 sec.

Determination of Superoxide Dismutase Activity

Superoxide dismutase (SOD) activity was determined according to Kakkar et al. (1984). The reaction was initiated by adding 0.2 ml NADH and incubated at 30 °C for 90 sec. The reaction was terminated by adding 1.0 ml glacial acetic acid. Subsequently, the mixture was vigorously shaken with 4.0 ml n-butanol, allowed to stand for 10 min, and then centrifuged to facilitate phase separation. Enzyme activity was expressed as units per gram fresh weight per minute (ΔOD per min/g FW).

Determination of Catalase Activity

Catalase (CAT) activity was determined according to Aebi (1984). The assay monitored the ultraviolet absorbance of hydrogen peroxide at 240 nm. Catalase decomposition of hydrogen peroxide decreases absorbance, and the rate of this decrease was used to calculate enzyme activity. The reaction mixture contained 0.067 M phosphate buffer (pH 7.0) and hydrogen peroxide (2 mM) prepared in the same buffer. For enzyme extraction, a 20% (w/v) homogenate of different *C. frutescens* tissues was prepared in phosphate buffer. The homogenate was centrifuged, and the resulting supernatant was used as the enzyme extract for the CAT assay.

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Chlorophyll Contents

The leaf chlorophyll content was estimated according to the method of Zhang and Qu (2003). Five weeks after planting, leaves of selected plants were harvested, wrapped in aluminium foil, placed in dark polythene bags. A 0.15 g of leaf tissue from each sample and placed in a labelled 50 ml McCartney bottle. Twenty milliliters (20 ml) of 80% acetone were poured into each McCartney bottle for chlorophyll extraction. The bottles were transferred to a dark room and left to stand for 24 hr. After extraction, the extracts were read for absorbance at 665 nm using a spectrophotometer. Chlorophyll content was estimated according to the following formula:

$$Chlorophyll\ a\ (mg/g\ \ FW) = \frac{12.2A_{663} - 0.86\ A_{645}\ \times V}{\alpha\ \times 1000\ \times w}$$

$$Chlorophyll\ b\ (mg/g\ \ FW) = \frac{19.3A_{645} - 3.6\ A_{663}\ \times V}{\alpha\ \times 1000\ \times w}$$

α = length of light path = 1 cm
W = fresh weight of leaf tissue
V = volume of solution

Total chlorophyll content is the sum of chlorophyll a and b. Results were expressed as mg/g FW (fresh weight).

Statistical Analysis

The experiment used a completely randomized design (CRD). Data were expressed as mean ± standard deviation (SD). One-way analysis of variance (ANOVA) was performed using IBM SPSS Statistics version 20.0 to determine whether significant differences existed among treatments. Following a significant ANOVA, treatment means were compared using Duncan's multiple range test (DMRT) at $p \leq 0.05$ (5% level).

Results

Soil Physicochemical Characteristics

Topsoil samples collected from Ugiamwen farmland and adjacent coal mining sites exhibited distinct variations in physicochemical properties (Table 1). Soil pH ranged from acidic (4.12) to neutral (7.01) across sampling locations. The control soil (CS) exhibited a neutral mean pH of 7.00, providing an optimal baseline for nutrient bioavailability to support the growth and physiological performance of *Capsicum frutescens*. Electrical conductivity (EC) ranged from 213.3 to 62.14 µS/cm, reflecting differences in soluble salt concentrations. Soil organic carbon (SOC) ranged from 0.67% to 2.07%, while total nitrogen (TN) ranged from 0.088% to 1.01%. Particle size distribution analysis indicated a predominantly sandy texture across all sites, with sand constituting 70.33%–89.43% of the mineral fraction, silt ranging from 2.10% to 5.50%, and clay ranging from 2.93% to 17.04%.

Heavy Metals Concentrations

Heavy metal concentrations varied significantly across the coal mining soils (CMS), adjacent farmland soils (FS), and the control soil (CS) (Table 2). All sampling locations contained lead (Pb), chromium (Cr), copper (Cu), and arsenic (As), whereas cadmium (Cd) remained below the limit of detection (BDL). Pb, Cr, and As concentrations ranged from 0.120 to 2.700 mg/kg, 0.246 to 2.213 mg/kg, and 0.486 to 3.873 mg/kg, respectively. In contrast, Cu concentrations were substantially higher, ranging from 4.953 to 132.700 mg/kg. Overall, the lowest heavy metal concentrations were generally recorded in the control soil and some farmland soil samples.

Table 3 shows that most investigated heavy metals in the soil were within the Canadian Council of Ministers of the Environment (CCME) agricultural soil quality guidelines. Lead concentrations ranged from 0.120 to 2.700 mg/kg, while Cr ranged from 0.246 to 2.213 mg/kg. None of the samples exceeded the respective CCME agricultural guideline values for Pb and Cr,

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Table 1

Physicochemical Parameters of Topsoil (0-15 cm) Collected from Different Coal Mining Areas

Soil samples	pH	Electrical conductivity	Organic carbon	Total nitrogen	Phosphorus	Potassium	Sodium	Calcium	Magnesium	Particle size analysis (%)		
										Clay	Silt	Sand
CMS1	4.61 ± 0.11 a	103.0 ± 22.6 ab	1.39 ±0.44 abc	3.71 ± 0.65 a	0.16 ± 0.04 a	0.75 ± 0.51 a	1.55 ± 1.43 abc	0.643 ± 0.85 a	17.1 ± 0.10 cde	2.10 ± 0.11 bc	81.2 ± 6.95 a	76.9 ± 9.84 bcde
CMS2	4.63 ± 0.06 a	111.3 ± 5.51 ab	2.07 ± 0.35 c	0.17 ± 0.01 a	4.35 ± 1.17 a	0.13 ± 0.06 a	0.42 ± 0.47 abc	0.643 ± 0.85 a	0.55 ± 0.10 bcd	17.0 ± 1.00 cd	2.19 ± 1.11 a	84.5 ± 3.21 cde
CMS3	4.80 ± 0.20 a	106.0 ± 14.52 ab	1.16 ± 0.26 ab	0.14 ± 0.02 a	2.47 ± 0.73 a	0.13 ± 0.06 a	0.64 ± 0.47 abc	2.50 ± 0.55 bc	0.96 ± 0.22 ef	22.6 ± 0.35 e	2.23 ± 0.17 a	73.6 ± 6.25 ab
CMS4	4.17 ± 0.06 a	62.14 ± 7.937 a	0.99 ± 0.08 a	0.14 ± 0.02 a	2.16 ± 1.04 a	0.13 ± 0.06 a	1.05 ± 0.40 bc	3.21 ± 0.91 abc	1.24 ± 0.48 f	16.5 ± 1.80 cd	2.70 ± 0.10 ab	76.9 ± 9.84 abc
CMS5	4.37 ± 0.25 a	64.66 ± 13.31 a	0.80 ± 0.17 ab	0.07 ± 0.09 ab	3.24 ± 0.76 a	0.83 ± 0.06 b	1.13 ± 0.31 c	2.14 ± 0.30 a	0.77 ± 0.23 de	21.2 ± 1.88 de	2.82 ± 0.17 ab	73.43 ± 3.120 ab
CMS6	4.36 ± 0.31 a	68.66 ± 2.886 a	0.67 ± 0.04 ab	0.35 ± 0.38 ab	2.73 ± 0.30 a	0.07 ± 0.05 a	0.74 ± 0.57 abc	3.00 ± 1.05 abc	0.80 ± 0.12 de	17.9 ± 4.63 de	2.83 ± 0.11 ab	70.33 ± 3.560 a
FS1	4.00 ± 0.00 a	218.7 ± 7.094 c	1.05 ± 0.16 a	0.26 ± 0.05 ab	1.78 ± 034 a	0.14 ± 0.02 a	0.84 ± 0.03 a	4.15 ± 1.45 bcd	0.25 ± 0.09 ab	2.93 ± 0.75 a	2.40 ± 0.77 ab	83.10 ± 7.88 cde
FS2	4.42 ± 0.10 a	187.0 ± 66.0 c	0.85 ± 0.09 ab	0.25 ± 0.04 ab	2.66 ± 0.40 a	0.15 ± 0.05 a	0.63 ± 0.50 abc	7.10 ± 1.62 fg	0.17 ± 0.011 a	6.70 ± 0.11 ab	2.33 ± 0.23 ab	83.3 ± 4.01 cde
FS3	6.47 ± 0.58 bc	111.3 ± 7.76 ab	0.77 ± 0.05 ab	0.15 ± 0.05 a	7.45 ± 6.57 a	0.16 ± 0.04 a	0.34 ± 0.25 ab	5.73 ± 0.56 de	0.32 ± 0.20 abc	7.73 ± 0.31 ab	2.44 ± 0.45 ab	88.22 ± 0.562 de
FS4	6.27 ± 0.93 b	112.0 ± 3.00 ab	0.66 ± 0.05 ab	0.46 ± 0.57 a	13.3 ± 17.3 a	0.16 ± 0.06 a	0.80 ± 0.23 abc	7.59 ± 0.70 f	0.59 ± 0.02 bcd	10.3 ± 0.66 b	3.68 ± 0.49 d	83.9 ± 2.95 cde
FS5	6.74 ± 0.11 bc	188.3 ± 43.68 c	0.97 ± 0.24 ab	0.57 ± 0.37 b	16.6 ± 24.4 a	0.15 ± 0.00 a	0.76 ± 0.14 abc	6.79 ± 1.05 ef	0.79 ± 0.12 de	9.66 ± 0.44 b	3.04 ± 0.16 bc	78.3 ± 1.214 abcd
FS6	6.78 ± 0.11 bc	125.7 ± 22.72 b	0.68 ± 0.05 a	0.12 ± 0.03 a	4.04 ± 0.15 a	0.37 ± 0.44 a	0.43 ± 0.53 abc	4.45 ± 0.70 cd	0.82 ± 0.32 de	10.7 ± 0.37 b	2.73 ± 0.15 ab	83.4 ± 5.78 cde
CS	7.05 ± 0.55c	213.3 ± 45.36 c	1.573 ± 1.3 bc	1.05 ± 0.34 c	34.6 ± 6.26 b	0.33 ± 0.24 a	0.36 ± 0.15 ab	9.61 ± 0.81 g	0.84 ± 0.12 de	4.17 ± 0.54 a	5.50 ± 0.17 c	9.4 ± 1.42 e

Note. CMS = coal mining soil, FS = farmland soil, CS = control soil, values = mean ± S.D. Different letters indicate significant differences using DMRT ($p \leq 0.05$).

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indicating relatively low levels of contamination by these metals. Similarly, As concentration ranged from 0.486 to 3.873 mg/kg, with no sample exceeding the applicable guideline, suggesting that As concentrations were within acceptable agricultural soil limits. In contrast, Cu represented the major metal concern with concentrations ranging from 4.953 to 132.70 mg/kg. Concentrations exceeded the applicable CCME agricultural guideline at CMS1-CMS5 and FS1-FS3, indicating localized Cu enrichment in both coal mining and adjacent farmland soils. The relatively elevated Cu concentrations, particularly in some mining affected locations, suggest that Cu may represent the principal heavy metal constraint in the investigated soil highlighting the need for further monitoring because of its potential implications for soil quality and agricultural productivity.

Table 4 presents the mean percentage

Table 2

Heavy Metal Content of Topsoils (0-15cm) Collected from Different Coal Mining Area

Soil samples	Heavy metal concentration (mg/kg)				
	Pb	Cr	Cu	Cd	As
CMS1	1.083 ± 0.060 abc	0.803 ± 0.528 abc	63.640 ± 5.749 c	BDL	1.226 ± 0.283 abc
CMS2	1.083 ± 0.060 bcd	1.300 ± 0.607 ab	53.620 ± 11.68 c	BDL	0.900 ± 0.420 abcd
CMS3	1.576 ± 0.605 cde	2.000 ± 0.458 abc	70.180 ± 15.79 c	BDL	1.736 ± 1.051 cd
CMS4	2.480 ± 0.495 def	2.070 ± 0.508 cd	100.600 ± 2.398 de	BDL	2.406 ± 0.525 d
CMS5	2.700 ± 0.822 f	2.156 ± 0.548 cd	132.700 ± 10.310 f	BDL	3.696 ± 1.121 d
CMS6	2.543 ± 0.783 ef	2.213 ± 1.601 d	99.380 ± 2.676 de	BDL	3.873 ± 0.130 d
FS1	2.373 ± 0.478 def	2.036 ± 0.064 cd	111.000 ± 9.475 e	BDL	2.240 ± 0.123 cd
FS2	1.283 ± 0.657 bc	1.360 ± 0.360 abc	89.780 ± 12.50 d	BDL	1.646 ± 0.673 abcd
FS3	1.180 ± 0.282 bc	1.623 ± 0.574 abc	70.260 ± 6.628 c	BDL	1.466 ± 0.387 bcd
FS4	1.323 ± 0.011 bc	1.073 ± 0.945 abc	50.200 ± 7.096 bc	BDL	1.440 ± 1.000 abcd
FS5	0.746 ± 0.268 abc	0.583 ± 0.461 a	58.900 ± 22.77 c	BDL	0.643 ± 0.204 ab
FS6	0.573 ± 0.362 ab	0.246 ± 0.151 a	34.050 ± 11.86 b	BDL	0.486 ± 0.444 a
CS	0.120 ± 0.026 a	0.386 ± 0.270 a	4.953 ± 0.626 a	BDL	0.646 ± 0.378 ab

Notes. CMS = coal mining soil, FS = farmland soil, CS = control soil, values = mean ± SD, BDL = below the limit of detection. Different alphabets indicate significant difference using DMRT ($p \leq 0.05$).

Table 3

Comparison of Measured Heavy Metal Concentrations in Topsoil (0–15 cm) with Canadian Council of Ministers of the Environment (CCME) Agricultural Soil Quality Guidelines

Metal	Observed range (mg/kg)	CCME agricultural guideline (mg/kg)	Samples exceeding guideline	Interpretation
Pb	0.120 – 2.700	70	None	Below guideline
Cr	0.246 – 2.213	64	None	Below guideline
Cu	4.953 – 132.700	63	CMS1-CMS5; FS1-FS3	Exceeded at several locations
Cd	BDL	1.4		Not detected
As	0.486 – 3.876	12		Below guideline

Notes. BDL = below the limit of detection. Agricultural soil quality guideline values adapted from Canadian Council of Ministers of the Environment (CCME, 1999).

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germination of *C. frutescens* seeds. No germination was observed in any experimental soils from the coal mining area at five days after planting (5 DAP). Germination was first recorded on day 6 in the control soil (CS). Germination was also observed in farmland soils FS4, FS5, and FS6, located 40 m, 50 m, and 60 m from the mining site, respectively. Germination percentage increased progressively over time across all soil samples. By 12 days after planting (12 DAP), all soil samples showed seed germination. Coal mine soil (CMS) and control soil (CS) recorded the lowest and highest mean germination percentages, respectively (32.50 ± 5.00% and 100.0 ± 0.00%). Notably, CMS5 (50 m from the mining point) exhibited a significant inhibitory effect on seed germination at 12 DAP. Overall, coal mine soil consistently showed delayed and reduced germination. Table 5 presents plant height measurements of *C. frutescens* grown in the different soil samples. A general reduction in growth was observed in plants grown in CMS1–CMS6, corresponding to distances of 10–60 m from the mining soil. Germination was generally higher in the control and farmland soils than in most coal mining soil samples, suggesting that the mining affected soils may have imposed constraints on seed germination.

Table 6 presents the mean number of leaves produced by *C. frutescens* grown in soils collected from the coal mining area. At 5 WAP, plants grown in CMS and FS had a lower mean leaf number than plants grown in control soil. Furthermore, *C. frutescens* cultivated in CMS and FS did not reach the flowering stage during the study period. In contrast, plants grown in control soil flowered at 72 days after planting (72 DAP). Figure 1 illustrates the partitioning of lead (Pb) in the root, stem, and leaf tissues of *C. frutescens* grown in potted soils collected from the coal mining environment. Plants grown in CMS4 (40 m from the mining source) had the highest Pb concentrations in all examined tissues.

Plants cultivated in control soil generally exhibited low Pb concentrations across

Table 4

Percent Germination of Capsicum frutescens Seeds Grown in Different Soil Samples Collected from Coal Mining Area

	Percent germination (%)		
Soil samples	6 DAP	9 DAP	12 DAP
CMS1	2.500 ± 0.500 a	32.50 ± 5.000 bc	60.00 ± 0.000 d
CMS2	-	27.50 ± 5.000 b	62.50 ± 5.000 de
CMS3	-	35.00 ± 5.773 bc	50.00 ± 0.000 c
CMS4	-	25.00 ± 5.773 b	37.50 ± 9.574 b
CMS5	-	15.00 ± 5.773 a	32.50 ± 5.000 a
CMS6	-	30.00 ± 0.000 bc	60.00 ± 0.000 d
FS1	-	32.50 ± 5.000 bc	65.00 ± 5.773 de
FS2	-	45.00 ± 5.773 de	70.00 ± 0.000 ef
FS3	-	50.00 ± 0.000 ef	65.00 ± 5.773 de
FS4	22.50 ± 9.574 bc	55.00 ± 10.00 fg	75.00 ± 5.773 fg
FS5	27.50 ± 9.574 b	62.50 ± 5.000 g	80.00 ± 0.000 g
FS6	22.50 ± 5.000 b	45.00 ± 10.00 cd	87.50 ± 9.574 h
CS	35.00 ± 5.775 c	97.50 ± 5.000 h	100.00 ± 0.000 i

Notes. CMS = coal mining soil, FS = farmland soil, CS = control soil, values = mean ± SD, DAP = days after planting. Different alphabets indicate significant difference using DMRT ($p \leq 0.05$).

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Table 5

Height of Capsicum frutescens Plant Height of Grown in Different Soil Samples Collected from Coal Mining Area

Soil samples	Plant height (cm)			
	2 WAP	3 WAP	4 WAP	5 WAP
CMS1	2.051 ± 0.120 e	2.275 ± 0.170 ef	2.325 ± 0.095 c	2.475 ± 0.170 f
CMS2	2.025 ± 0.206 e	2.325 ± 0.25 ef	2.501 ± 0.374 c	2.725 ± 0.206 ef
CMS3	1.225 ± 0.170 f	1.450 ± 0.129 g	1.450 ± 0.129 c	1.450 ± 0.129 f
CMS4	1.100 ± 0.182 f	1.352 ± 0.238 g	1.400 ± 0.216 c	1.400 ± 0.216 f
CMS5	1.425 ± 0.727 f	1.755 ± 0.670 fg	1.775 ± 0.670 c	1.775 ± 0.670 f
CMS6	2.275 ± 0.125 e	2.750 ± 0.238 e	3.425 ± 0.150 c	3.750 ± 0.100 e
FS1	2.450 ± 0.173 de	3.600 ± 0.244 d	12.900 ± 4.744 b	17.450 ± 0.531 ab
FS2	2.775 ± 0.457 c	3.750 ± 0.420 d	14.370 ± 0.505 ab	15.220 ± 0.590 d
FS3	3.450 ± 0.129 b	4.175 ± 0.125 cd	14.950 ± 0.057 ab	15.720 ± 0.170 cd
FS4	3.775 ± 0.206 bc	4.925 ± 0.492 b	15.850 ± 0.435 a	16.870 ± 0.596 bc
FS5	4.150 ± 0.129 ab	4.725 ± 0.250 bc	15.970 ± 0.050 a	17.500 ± 0.081 ab
FS6	4.125 ± 0.359 ab	5.200 ± 0.725 b	16.710 ± 0.439 a	18.470 ± 0.809 a
CS	4.450 ± 0.310 a	6.975 ± 1.117 a	17.250 ± 2.618 b	21.350 ± 2.802 ab

Notes. CMS = coal mining soil, FS = farmland soil, CS = control soil, values = mean ± SD, WAP = weeks after planting. Different alphabets indicate significant difference using DMRT ($p \leq 0.05$).

Table 6

Leaves of Capsicum frutescens Number of Leaves of Grown in Different Soil Samples Collected from Coal Mining Area

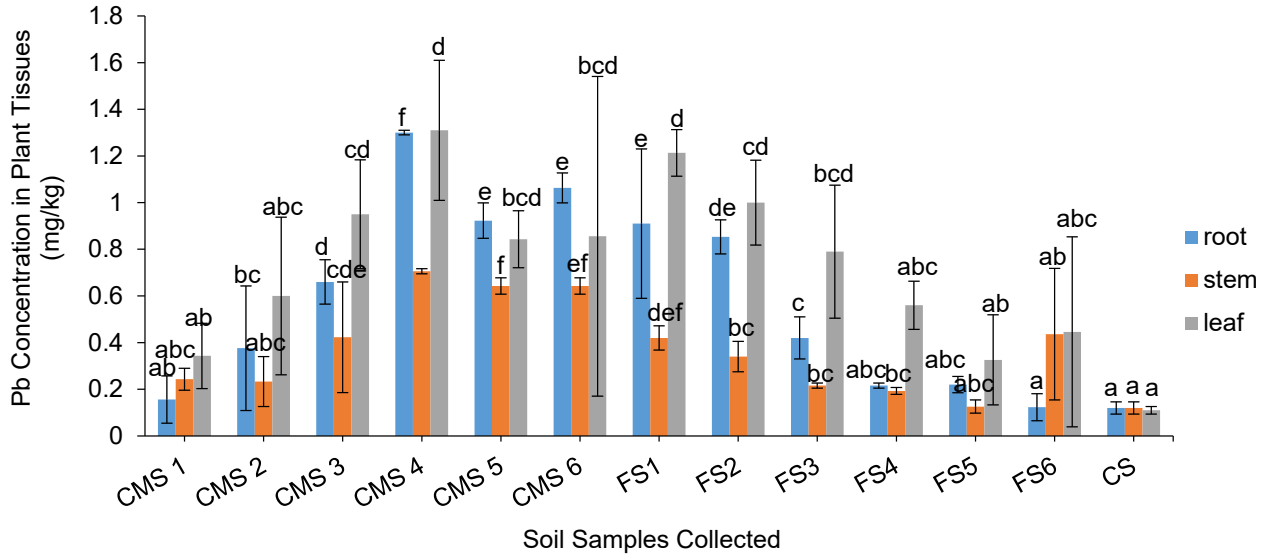
Soil samples	Number of leaves per plant			
	2WAP	3WAP	4WAP	5WAP
CMS1	3.000 ± 0.00 bc	5.000 ± 0.816 b	6.000 ± 0.000 c	7.750 ± 0.500 b
CMS2	2.755 ± 0.500 bcd	4.750 ± 0.500 b	5.000 ± 0.816 def	6.000 ± 0.816 c
CMS3	2.500 ± 0.577 cd	4.000 ± 0.000 b	4.750 ± 0.000 ef	5.750 ± 0.500 c
CMS4	2.000 ± 0.000 d	4.255 ± 0.500 b	5.500 ± 0.577 cde	5.000 ± 0.000 c
CMS5	2.000 ± 0.000 d	4.000 ± 0.000 b	4.750 ± 0.500 ef	5.000 ± 0.000 c
CMS6	3.000 ± 0.816 bc	4.000 ± 0.000 b	4.250 ± 0.577 f	5.000 ± 0.000 c
FS1	2.500 ± 0.577 cd	4.255 ± 0.500 b	5.755 ± 0.957 bcde	7.500 ± 0.577 c
FS2	2.755 ± 0.500 bcd	4.500 ± 0.577 b	5.500 ± 1.290 cde	7.500 ± 1.290 b
FS3	3.500 ± 0.577 ab	4.750 ± 0.500 b	6.755 ± 0.500 b	8.000 ± 1.141 b
FS4	3.000 ± 1.151 bc	4.256 ± 0.957 b	6.255 ± 0.957 bc	8.500 ± 1.290 b
FS5	2.750 ± 0.500 bcd	5.000 ± 0.000 b	6.750 ± 0.500 b	8.750 ± 0.500 b
FS6	2.750 ± 0.000 bc	4.258 ± 0.957 b	6.250 ± 0.957 bc	8.250 ± 0.957 b
CS	4.000 ± 0.000 a	6.255 ± 0.500 a	9.000 ± 0.816 a	12.000 ± 1.825 a

Notes. CMS = coal mining soil, FS = farmland soil, CS = control soil, values = mean ± SD, WAP = weeks after planting. Different letters indicate significant differences using the DMRT ($p \leq 0.05$).

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Figure 1

Lead (Pb) Concentration Capsicum frutescens in Tissues of Grown in Different Soil Samples Collected from Coal Mining Area



Notes. CMS = coal mining soil, FS = farmland soil, CS = control soil. Error bars represent standard deviation. Different letters indicate significant differences using the DMRT ($p \leq 0.05$).

their roots, stems, and leaves. However, Pb concentrations in plants grown in some farmland soil samples, particularly FS6, were statistically comparable to those recorded in the control. Furthermore, some coal mining soil samples also recorded lower Pb concentrations than FS1, indicating that Pb accumulation varied among soil samples and plant tissues rather than following a consistent pattern based solely on proximity to mining activities. Figure 2 presents the chromium (Cr) concentrations in the root, stem, and leaf tissues of *C. frutescens*. Elevated Cr accumulation was observed predominantly in the leaf tissues of plants grown in CMS5 (50 m from the mining source). Leaf Cr concentrations exceeded those in roots and stems in plants grown in CMS5, CMS6, FS1, and FS2 soils (Figure 2). In contrast, roots had the highest Cr concentration in plants grown in CMS4 soil. Figure 3 presents copper (Cu) concentrations in the root, stem, and leaf tissues of *C. frutescens* grown in soils from the coal mining area.

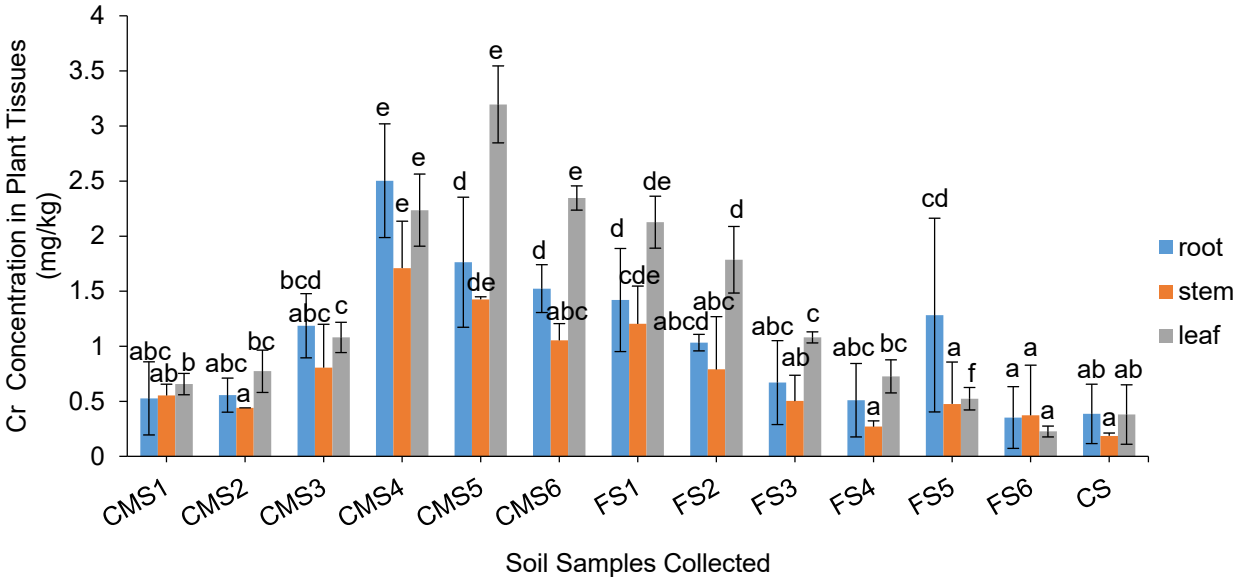
Root tissues had the highest Cu concentrations, while leaf tissues hacd the lowest. Overall, Cu accumulation followed the order root > stem > leaf in both CMS and FS samples. Notably, Cu concentrations increased significantly in FS1 (10 m from the coal mining site), indicating possible lateral metal transfer from the mining area. Figure 4 illustrates arsenic (As) concentrations in the root, stem, and leaf tissues of *C. frutescens*. The highest As concentrations were detected in the stem and leaf tissues of plants grown in CMS samples. However, no clear pattern distinguished the lowest As concentrations in root tissues among the different soil samples. Figure 5 shows peroxidase (POX) activity in tissues of *C. frutescens* grown in the study. Root POX activity was higher in *C. frutescens* plants grown in CMS soils than in those grown in FS soils. Across all soil samples, POX activity was highest in roots, followed by stems and leaves. Plants grown in CS soil exhibited the lowest POX activity in each tissues, whereas those grown in CMS4 soil exhibited the highest activity, indicating 40 m from the coal mining source. Figure 6 illustrates the catalase (CAT) activity in the tissues of *C. frutescens* grown in the various soil samples. The highest CAT activity was predominantly

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observed in stem tissues across all sampling soils, except FS3. Plants grown in the control soil (CS) exhibited the lowest CAT activity across the assessed tissues. Figure 7 presents the superoxide dismutase (SOD) activity in the leaf, stem, and root tissues of *C. frutescens.* The highest SOD activity was recorded in the leaf tissue of CMS4, followed by the corresponding stem tissue from the same sampling location. This suggests that metal distribution within the mining environment was influenced by lateral transport and site specific environmental responses, creating localized zones of higher metal availability. Surface runoff and shallow subsurface movement may distribute particle bound metals downslope, while wind driven movement of contaminated dust may have caused deposition beyond the immediate boundary. Differences in microtopography, drainage pathways, and soil moisture can further determine where contaminants accumulate and become bioavailable. The elevated SOD activity at CMS4 may therefore represent a localized oxidative stress response to increased metal availability. We also detected substantial enzyme activity in the root tissues. In contrast, plants grown in the control soil demonstrated the least SOD activity overall. No statistically significant difference ($\alpha \leq 0.05$) was detected in the mean superoxide dismutase (SOD) activity of roots from plants cultivated in FS5 and FS6, situated 50 m and 60 m, respectively, from the coal mining soil (CMS). Chlorophyll content of the leaves is presented in Figure 8. The results indicate that chlorophyll concentration in *C. frutescens* was markedly reduced in plants grown in coal mining soil (CMS). Potted *C. frutescens* grown in control soil (CS) showed higher chlorophyll content than those grown in CMS and farmland soils (FS). Furthermore, mean chlorophyll values in plants grown in FS were significantly higher than those in CMS ($p \leq 0.05$).

Figure 2

Chromium (Cr) Concentration Capsicum frutescens in Tissues of Grown in Different Soil Samples Collected from Coal Mining Area

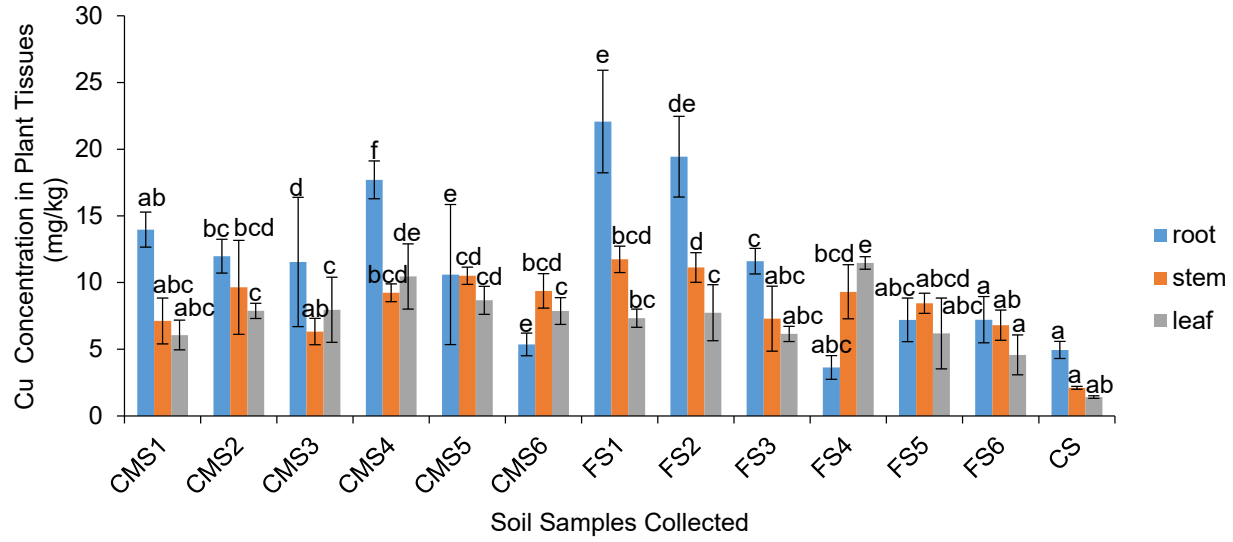


Notes. CMS = coal mining soil, FS = farmland soil, CS = control soil. Error bars represent standard deviation. Different letters indicate significant differences using the DMRT ($p \leq 0.05$).

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Figure 3

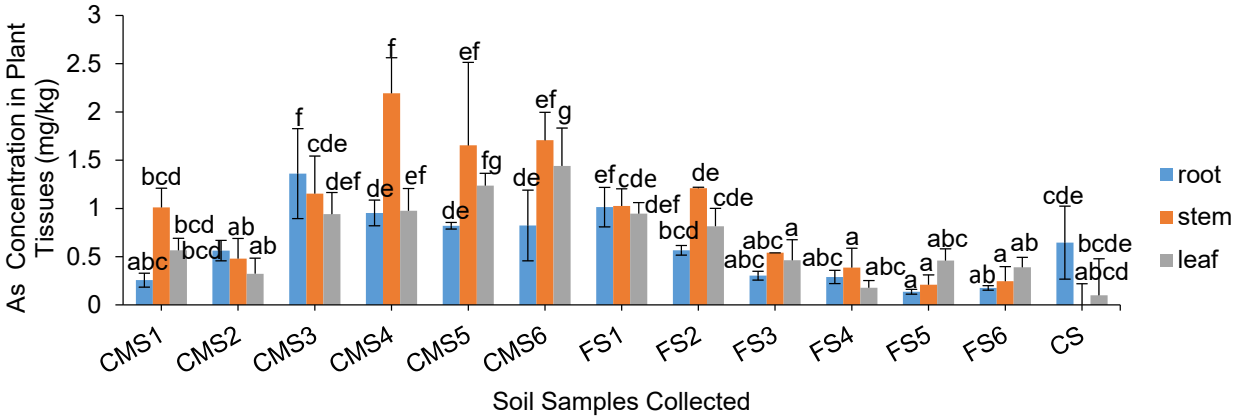
Copper (Cu) Concentration Capsicum frutescens in Tissues of Grown in Different Soil Samples Collected from a Coal Mining Area



Notes. CMS = coal mining soil, FS = farmland soil, CS = control soil. Error bars represent standard deviation. Different letters indicate significant differences using the DMRT ($p \leq 0.05$).

Figure 4

Arsenic (As) Concentration Capsicum frutescens in Tissues of Grown in Different Soil Samples Collected from Coal Mining Area

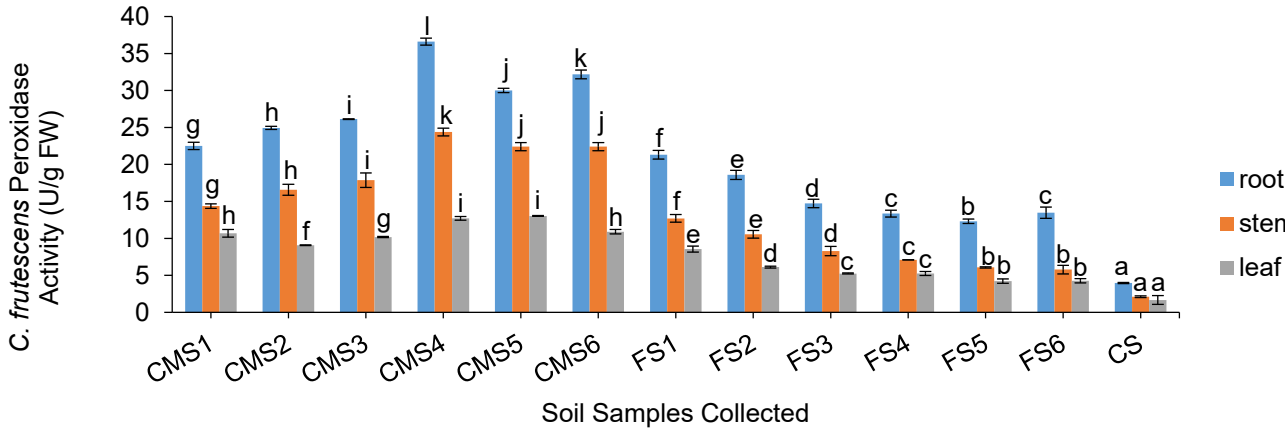


Notes. CMS = coal mining soil, FS = farmland soil, CS = control soil. Error bars represent standard deviation Different letters indicate significant differences using the DMRT ($p \leq 0.05$).

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Figure 5

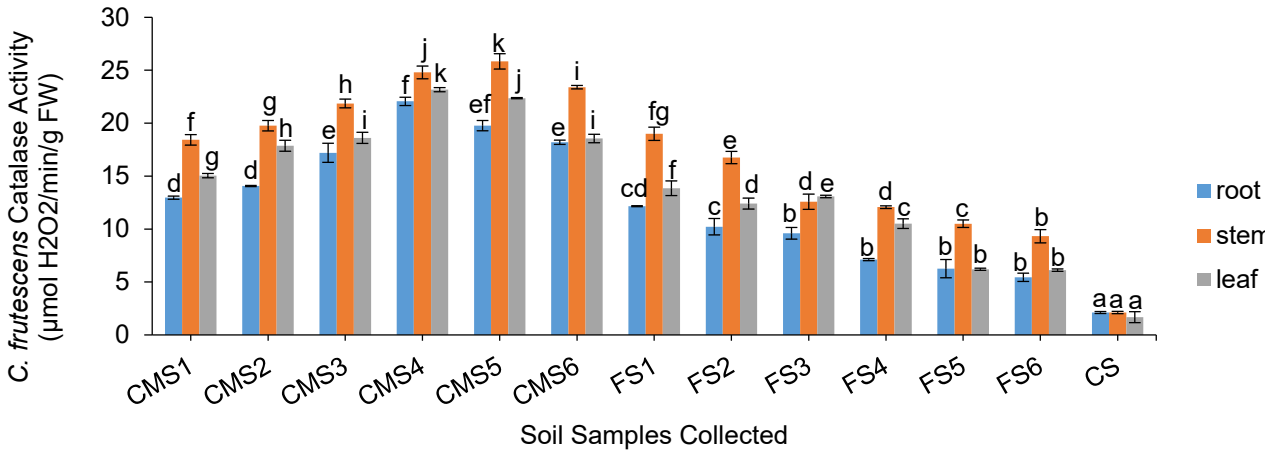
Peroxidase (POX) Activity Capsicum frutescens in Tissues of Grown in Different Soil Samples Collected from a Coal Mining Area



Notes. CMS = coal mining soil, FS = farmland soil, CS = control soil. Error bars represent standard deviation. Different letters indicate significant differences using the DMRT ($p \leq 0.05$).

Figure 6

Catalase (CAT) Activity Capsicum frutescens in Tissues of Grown in Different Soil Samples Collected from Coal Mining Area

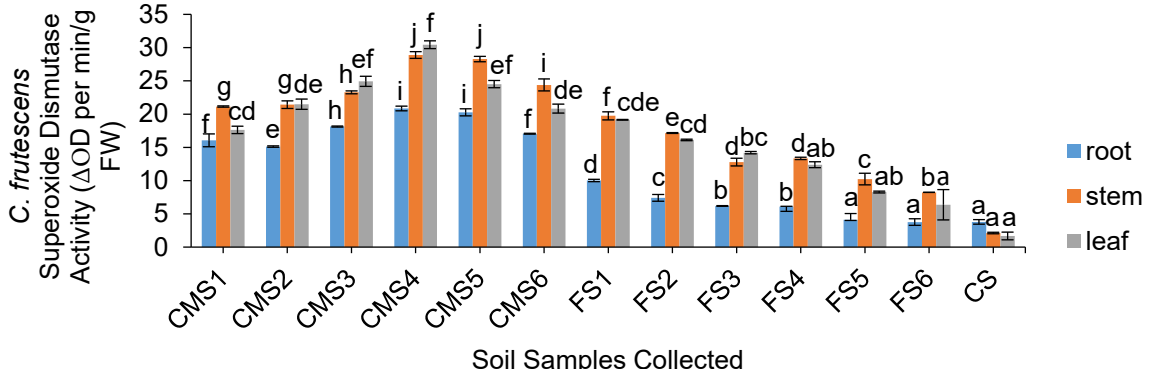


Notes. CMS = coal mining soil, FS = farmland soil, CS = control soil. Error bars represent standard deviation. Different letters indicate significant differences using the DMRT ($p \leq 0.05$).

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Figure 7

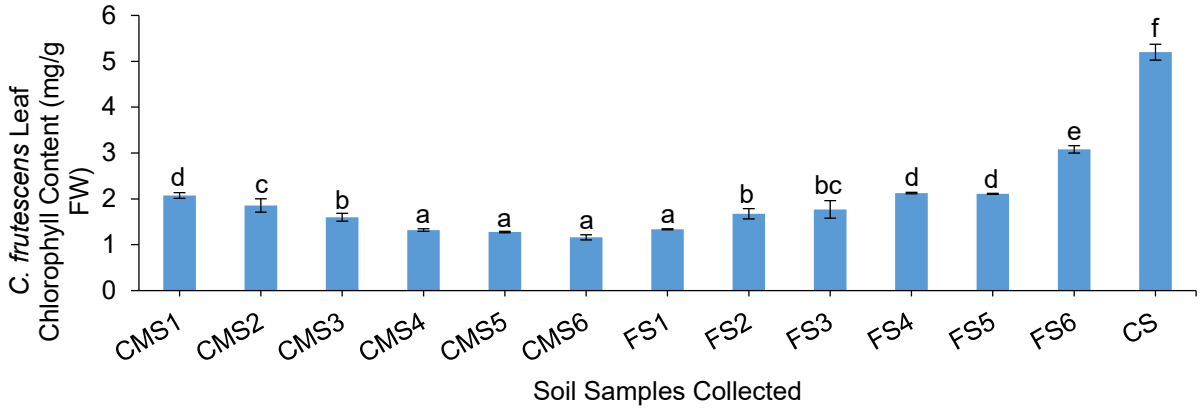
Superoxide Dismutase (SOD) Activity Capsicum frutescens in Tissues of Grown in Different Soil Samples Collected from Coal Mining Area



Notes. CMS = coal mining soil, FS = farmland soil, CS = control soil. Error bars represent standard deviation. Different letters indicate significant differences using the DMRT ($p \leq 0.05$).

Figure 8

Chlorophyll Content in Capsicum frutescens Leaves of Grown in Different Soil Samples Collected from Coal Mining Area



Notes. CMS = coal mining soil, FS = farmland soil, CS = control soil. Error bars represent standard deviation. Different letters indicate significant differences using the DMRT ($p \leq 0.05$).

Discussion

Table 1 presents the physicochemical properties of soil samples collected from the coal mining environment. Textural analysis revealed that the coal mining soil (CMS) contained elevated sand and clay fractions, yielding a sandy clay texture generally unfavorable for plant root development. The control soil had a lower clay content (4.17%) than all CMS soils (16.5%–22.6%) and FS2-FS6 soils (6.7%0–10.7%), but a higher clay content than FS1 soil (2.93%). Soils characterized by high sand fractions and low clay retention typically display elevated permeability, increasing their susceptibility to nutrient and contaminant leaching (Wang et al., 2022). Consistent with this mechanism, the sandy texture of CMS and FS likely promoted trace-metal mobilisation.

Furthermore, CMS soils had pH values of 4.17–4.80, indicating extremely to very strongly acidic conditions. While circumneutral to slightly

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alkaline conditions are considered optimal for *Capsicum frutescens* cultivation, substrate acidification impairs nutrient availability and root growth. Mining activities and associated anthropogenic deposition frequently drive soil acidification through the oxidation of sulfide minerals and the displacement of basic cations (Huilin et al., 2020). The higher phosphorus and calcium concentrations in CS suggest a comparatively more favourable status for these nutrients than in CMS and FS soils. However, this advantage did not extend consistently to organic carbon, total nitrogen, potassium, magnesium, and electrical conductivity, indicating that difference among soil samples were property specific rather than evidence of uniformly poorer soil quality in CMS and FS. Although, mean pH values were lower in CMS and FS soils than CS, the variation among samples highlights the need to consider each sampling locations rather than treating either soil group as chemically uniform. Based on these properties, these findings indicate variations in soil chemical properties among the locations, however, they are insufficient to classy all CMS and FS soils are degraded

Distinguishing general edaphic degradation from metal-specific phytotoxicity is critical when interpreting plant responses. The acidic pH, excessive sand content, and acute macro-nutrient deficiencies in CMS and FS constitute baseline agronomic constraints that inhibit seedling establishment independently of contamination, consistent with previous reports on nutrient depleted sandy soils (Aboyeji et al., 2021). Consequently, the poor growth of *C. frutescens* reflects the interactive pressures of deteriorated physicochemical properties and heavy metal exposure.

Among the quantified elements, concentrations of Pb, Cr, As, and Cd generally complied with the Canadian Council of Ministers of the Environment (CCME) agricultural soil quality guidelines. In contrast, Cu represented the principal contaminant of concern, exceeding the CCME agricultural soil guideline in selected samples (CMS1, CMS3–CMS6 and FS1–FS3). The concentrations in these samples ranged from 63.64 to 132.70 mg/kg, corresponding to approximately 1.01–2.11 times the guideline value. The distribution of elevated Cu in adjacent agricultural plots suggests that mining derived particulates disperse well beyond the primary excavation boundary. Although Cu is an essential micronutrient, excess concentrations provoke acute phytotoxicity by impairing root elongation, interrupting photosynthetic electron transport, compromising membrane integrity, and inducing excessive reactive oxygen species (ROS) formation (Kafle et al., 2022; Mitra et al., 2021; Wang et al., 2024). The highest Cu concentrations were recorded in CMS4 and CMS5, pointing to localized deposition, surface runoff, and metal redistribution around active extraction zones (Li et al., 2023).

Lead (Pb) concentrations were relatively elevated in CMS4, CMS5, and CMS6 corresponding to distances of 40, 50, and 60 m from the primary mining point, respectively. The highest concentration was recorded in CMS5, followed by CMS6 and CMS4, indicating a peak at 50 m rather than consistent increase with distance. Elevated Pb near mining hubs typically originate from explosive residues, fugitive dust, and heavy transport vehicle emissions (Freitas et al., 2004; Ogbonna et al., 2012). While Pb can disrupt mineral nutrition and cellular respiration at toxic thresholds (Johnson & Eaton, 1980), concentrations here remained below CCME criteria, suggesting that Pb was a secondary contributor relative to Cu toxicity and edaphic limitations.

Similarly, arsenic (As) and chromium (Cr) showed localized hotspots in CMS5, CMS6, and FS1. The spatial distribution of As is consistent with the dispersal of blasting agents and combustion emissions (Zhou et al., 2007), whereas Cr patterns likely reflect surface water transport and leaching from coal transfer areas (Yao et al., 2013). Because both As and Cr remained below regulatory agricultural ceilings, their contribution to growth impairment likely contributed to a cumulative contamination burden rather than primary phytotoxic drivers.

The biological consequences of these soil conditions were evident in the bioassay. Germination was delayed in CMS2-6 (20–60

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m from the excavation site) and FS1-3 (10–30 m from the mining boundary), as no seed emergence was recorded in these soil samples at 6 DAP. However, germination occurred in all samples by 9 DAP. The delayed germination in these soils may be associated with the combined effects of high sand content, low pH, nutrient limitations, and elevated Cu concentrations. In treatments where seedlings established, *C. frutescens* exhibited significant reductions in plant height, leaf number, and foliar chlorophyll concentrations relative to CS controls, alongside complete suppression of flowering.

In surviving plants, the detection of Pb, Cr, Cu, and As in roots, stems, and leaves confirmed that trace metals were bioavailable and successfully translocated into vegetative organs. Internalized metals triggered systemic oxidative stress, a hallmark of metal toxicity in crops (Zulfiqar et al., 2022). To counteract this stress, *C. frutescens* mounted a coordinated antioxidant defense response, evidenced by marked upregulation of superoxide dismutase (SOD), catalase (CAT), and peroxidase (POX) activities across tissues (Hasanuzzaman et al., 2020). Organ-specific enzymatic partitioning was apparent: POX activity was predominantly localized in root tissues—the initial site of metal interception—whereas SOD activity was higher in aerial stems and leaves, and CAT activity peaked in stem tissues. Together, SOD dismutated superoxide radicals to hydrogen peroxide (H_2O_2), which was subsequently detoxified by CAT and POX. While this coordinated upregulation mitigated lethal cellular damage, the metabolic cost of persistent antioxidant defense, combined with nutrient starvation, severely suppressed vegetative vigour (Adrees et al., 2022).

These findings hold direct implications for agronomic management and regulatory oversight in near mining landscapes. Cultivating food crops in these transition zones requires pre-planting soil quality screening. For policymakers, routine monitoring and targeted soil remediation—specifically addressing Cu stabilisation and pH correction—are necessary to mitigate ecological risks and protect local agricultural food chains.

Conclusions

This study evaluated the physicochemical properties and heavy metal concentrations of coal mining soil (CMS), farmland soil (FS), and control soil (CS), along with their effects on the growth and physiology of *Capsicum frutescens*. Mining impacted soils showed degraded physicochemical profiles—high sand content, acidic pH, and severe macronutrient depletion—alongside significant Cu contamination that exceeded CCME agricultural guidelines. These combined stressors were associated with delayed and reduced germination in mining affected and proximal farmland soils compared with control, although germination eventually occurred in all samples by 12 DAP. The stress conditions also suppressed vegetative development and chlorophyll synthesis in surviving plants and induced systemic oxidative stress, as reflected by changes in SOD, CAT, and POX activities. Because Cu was the only heavy metal that exceeded the CCME agricultural soil guideline, with exceedances recorded in CMS1-CMS5 and FS1-FS3, it represents the principal metal related contamination in the investigated landscape. Remediating these mining affected agricultural zones requires integrated soil management focusing on acidity neutralisation, organic matter replenishment, and Cu stabilisation. Future investigations should prioritize assessing Cu stabilisation, chemical speciation, and translocation into edible fruits to fully evaluate dietary exposure and food safety risks.

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