FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 10 No. 10, May, 2026, pp 349 – 356
DOI: https://doi.org/10.33003/fjs-2026-1010-5424

Morpho-Physiological and Yield Response of *Capsicum frutescens*L and *Capsicum annuum*L to Nickel (II) Chloride Stress in Loamy and Sandy Soils

Akporobaro Uyoyou Agnes

Department of Biotechnology, Faculty of Science, University of Delta, Agbor, Delta State, Nigeria.

*Corresponding authors' email: agnesuyoyou@gmail.com

ABSTRACT

Nickel (II) Chloride ($NiCl_2$) contamination threatens pepper production by impairing growth metabolism. Yet information on species responses in different soils is limited. This study evaluated the vegetative growth, yield, biomass, and morphological responses of *Capsicum frutescens* (*C. frutescens*) and *Capsicum annuum* (*C. annuum*) exposed to $NiCl_2$ in loamy and sandy soils. A completely randomized design comprising 72 pots with six replicates was used. After direct sowing failed under $NiCl_2$, 20-day-old nursery seedlings were transplanted and treated with cumulative applications of 0, 100, or 250 ppm $NiCl_2$. Data collected up to 3 months after planting (MAP) were analyzed using ANOVA and Duncan's Multiple Range Test ($P \leq 0.05$). At 3 MAP, loamy soil consistently outperformed sandy soil. *C. frutescens* attained the greatest plant height (45.73 cm) at 100 ppm in loamy soil, whereas *C. annuum* declined with increasing Ni concentration. Control *C. frutescens* produced the highest leaves (75.25), branches (9.00), flowers (29.17), fruits (26.17), chlorophyll (4.96), shoot fresh weight (20.83 g), and root fresh weight (6.99 g). Sandy soil markedly reduced growth, with maximum plant heights of 18.37 cm (*C. frutescens*) and 6.30 cm (*C. annuum*). Reduced chlorophyll, biomass, and yield under $NiCl_2$ stress were attributed to disrupted nutrient uptake, and inhibited photosynthesis. Morphological observations confirmed vigorous growth of *C. frutescens* in loamy soil but chlorosis and stunting of *C. annuum*, especially in sandy soil. In general, loamy soil reduced nickel toxicity, while *C. frutescens* exhibited greater tolerance than *C. annuum*.

Keywords: Nickel Toxicity; Soil Texture*; C. Frutescens; C. Annuum;* Species Specific; Metal Tolerance

INTRODUCTION

Excess nickel supplied in the form of $NiCl_2$ causes marked suppression of stem elongation and overall vegetative development (Yu *et al*., 2024). Nickel toxicity restricts growth by disrupting metabolic activities and inhibiting root development, which consequently reduces shoot extension and plant height in several crop species (Mustafa *et al*., 2023). Exposure to excessive $NiCl_2$ reduces leaf initiation and expansion due to disturbances in photosynthesis and nutrient translocation, thereby decreasing the total number of leaves produced by tomato seedlings (Yu *et al*., 2024). Nickel-induced oxidative stress impairs cellular activities and limits foliage development, resulting in reduced leaf production and canopy formation in susceptible plants (Mustafa *et al*., 2023). High concentrations of $NiCl_2$ alter endogenous phytohormone levels and inhibit meristematic activity, leading to reduced lateral shoot development and branch formation (Yu *et al*., 2024). Nickel stress disrupts cell division and assimilate partitioning, adversely affecting the emergence and growth of secondary branches in crop plants (Mustafa *et al*., 2023).

Excessive nickel exposure reduces phytohormone concentrations and limits assimilate availability, thereby suppressing floral initiation and decreasing the number of flowers produced by tomato plants (Yu *et al*., 2024).

Nickel toxicity adversely affects reproductive development through oxidative stress and metabolic disturbances, resulting in poor flowering performance and reduced floral abundance (Mustafa *et al*., 2023). Increasing $NiCl_2$ concentration negatively affects reproductive development and fruit set by disrupting flowering and assimilate partitioning, leading to fewer fruits and lower yield in tomato plants (Yu *et al*., 2024). Nickel accumulation in soil and plant tissues impairs normal fruit development and reduces tomato productivity because of toxicity-induced physiological disorders (Correia *et al*., 2018). Exposure to excess $NiCl_2$ decreases chlorophyll concentration and photosystem activity, resulting in chlorosis and suppression of photosynthesis in tomato seedlings (Yu *et al*., 2024)..Nickel stress disrupts pigment synthesis and reduces chlorophyll accumulation, thereby lowering photosynthetic efficiency in pepper plants (Sardar *et al*., 2022). Nickel toxicity markedly reduces shoot fresh weight and water content, causing a decline in aboveground biomass accumulation in tomato seedlings (Yu *et al*., 2024). Increasing nickel concentration causes substantial reductions in shoot fresh biomass and dry matter production in pepper plants, indicating severe growth inhibition (Sardar *et al*., 2022). Excess $NiCl_2$ inhibits root elongation and significantly reduces root fresh weight through premature differentiation of the root apical meristem and impaired nutrient uptake (Yu *et al*., 2024). Nickel stress causes pronounced reductions in root biomass, with higher nickel concentrations producing greater inhibition of root growth in pepper seedlings (Sardar *et al*., 2022).. Excess $NiCl_2$ induces severe dwarfing, restricts stem elongation, reduces leaf expansion, and promotes the formation of brush-like lateral roots, thereby altering the overall morphology of tomato seedlings (Yu *et al*., 2024). Nickel toxicity negatively affects root architecture, shoot development, and tissue biomass, leading to noticeable changes in plant structure and vigor (Rosatto *et al*., 2021)..

Early investigations demonstrated that toxic nickel concentrations arrested root growth and substantially reduced the height of oat and tomato plants because of impaired absorption of essential nutrients (Knight and Crooke, 1956). Nickel toxicity also produced chlorotic symptoms and necrotic lesions on leaves, accelerating senescence and reducing the number of functional leaves available for growth (Knight and Crooke, 1956). Furthermore, nickel-induced nutritional imbalances and inhibited root growth restricted vegetative proliferation and reduced branching capacity in affected plants (Knight and Crooke, 1956). Toxic nickel

concentrations impaired nutrient uptake and overall plant vigor, which negatively influenced reproductive development and flower production (Knight and Crooke, 1956). Nickel supplied as chloride in nutrient solution caused a progressive decline in fruit number, and the reduction became more pronounced as nickel concentration increased (Balaguer *et at*., 1998) .High nickel concentrations alter leaf physiology and impair pigment formation, which consequently reduced chlorophyll levels and accelerate leaf yellowing (Rosatto *et al*., 2021). Elevated nickel levels caused a gradual decline in shoot fresh biomass in fruit crops, with severe toxicity resulting in substantial reductions in tissue growth (Shafaqat *et al*., 2022). Root biomass also declined considerably under elevated nickel exposure, demonstrating that root tissues are highly sensitive to metal toxicity and constitute the primary target of nickel injury (Rosatto*et al*., 2021). Exposure to increasing nickel concentrations caused visible growth abnormalities, reduced branch length, decreased fresh biomass, and suppressed reproductive structures, resulting in significant morphological deterioration (Rosatto*et al*., 2021). The concentrations of 100 and 250 ppm $NiCl_2$ were selected to simulate moderate and relatively high levels of nickel contamination that may occur in agricultural soils exposed to industrial activities, mining operations, electroplating wastes, sewage sludge application, and excessive disposal of nickel-containing products. These concentrations provide an appropriate range for evaluating the dose-dependent effects of nickel toxicity on plant growth and physiological responses.

Despite extensive reports on nickel toxicity in crop plants, most previous studies have focused on single species, hydroponic systems, and controlled nutrient solutions, with limited comparative information on the morpho-physiological and yield responses of *C. frutescens* and *C. annuum* grown under different soil types. Furthermore, little is known about how loamy and sandy soils influence the severity of $NiCl_2$ toxicity and the relative tolerance of these economically important pepper species. Therefore, the objective of this study was to evaluate the effects of different concentrations of $NiCL_2$ (0, 100, and 250 ppm) on the vegetative growth, yield, chlorophyll content, biomass accumulation, and morphological characteristics of *C. frutescens* and *C. annuum* cultivated in loamy and sandy soils. It was hypothesized that increasing $NiCl_2$ concentrations would significantly suppress plant growth, morphological performance, biomass, and yield, that sandy soil would intensify nickel toxicity because of its lower nutrient-retention capacity, and that *C. frutescens* would exhibit greater tolerance to nickel stress than *C. annuum.*

MATERIALS AND METHODS

Study Area

The experiment was conducted at the Botanic Garden, Department of Plant Biology and Biotechnology, Faculty of Life Sciences, University of Benin, Benin City, Edo State, Nigeria.

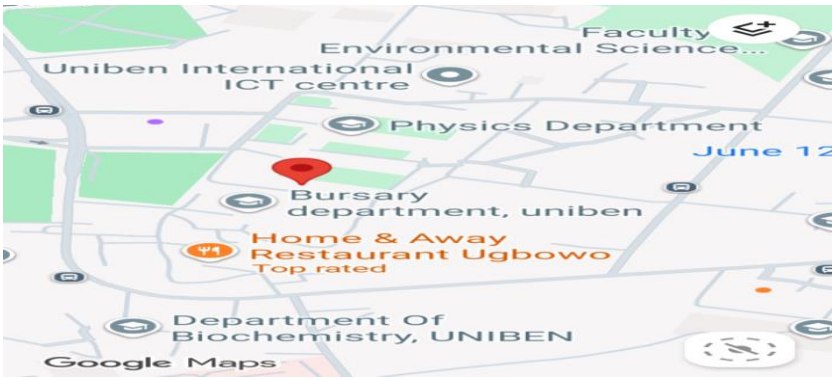


Figure 1: Area of Field Experiment

Plant Materials

Fresh fruits of *C. frutescens* and *C. annuum* were obtained from Mr. Moses Oghre, a gardener who cultivates *Capsicum* species in Odigi Village, Edo State, Nigeria. Seeds were manually separated from the fruits and air-dried at room temperature for 10 days before use.

Soil Collection

Loamy soil (0–13 cm depth) was collected from cultivated farmland in Azuwa Quarters near the Nigerian Institute for Oil Palm Research (NIFOR), Ovia North-East Local Government Area, Edo State, Nigeria. River soil was obtained from a riverbed (drilled from river) at Oluku, located on the outskirts of Benin City, Edo State, Nigeria.

Source of Chemical Reagent

Nickel (II) chloride salt was obtained from the Department of Chemistry, Faculty of Physical Sciences, University of Benin, Benin City, Edo State, Nigeria.

Method- $NiCl_2$ Solution Preparation

Stock solutions of 100 ppm and 250 ppm $NiCl_2$ were prepared using the molecular weight of $NiCl_2$ (129.60 g/mol) and the formula:

Mass (g) = Concentration (ppm) × Volume (L) × Molecular Weight.

The calculated quantity of $NiCl_2$ salt was dissolved in distilled water to prepare 4 liters of each treatment solution.

Seed Viability Test

Eighty seeds of each pepper species were immersed in distilled water for 15 minutes. Seeds that settled at the bottom were considered viable and selected for the experiment.

Initial Sowing and $NiCl_2$ Application

Experimental pots containing 4.50 kg of soil each received a single application of 25 mL of either 100 ppm or 250 ppm $NiCl_2$ solution, while the control pots received no $NiCl_2$ treatment. Two viable seeds were sown at the center of each pot. Irrigation was carried out every Thursday and Friday by applying 1,000 mL of water to each pot. This irrigation regime

was established for the present study to maintain relatively uniform soil moisture throughout the experimental period.

Thirty one days after sowing, seedling emergence was observed only in the control treatment (0 ppm), whereas no germination occurred in either the 100 ppm or 250 ppm treatments. Consequently, this phase of the experiment was terminated, and a revised procedure was adopted.

Nursery Raising Transplanting of Seedlings and $NiCl_2$ Application

Following the unsuccessful direct sowing trial, fresh loamy and river soils were placed into the experimental pots according to their respective treatments. No $NiCl_2$ was applied during nursery establishment.

Eighty seeds each of *C. frutescens* and *C. annuum* were broadcast separately into nursery bowls (18.30 cm diameter) containing either loamy or river soil, resulting in four nursery bowls. The seedlings were maintained under normal growing conditions and irrigated every Thursday and Friday with 2,000 mL of water.

After 20 days, two healthy seedlings were transplanted into each corresponding experimental pot. Immediately after transplanting, the control pots received 5 mL (on Friday) of tap water, whereas the treatment pots received 5 mL of their respective 100 ppm or 250 ppm $NiCl_2$ solutions.

Subsequently, 5 mL of the appropriate treatment solution was applied once every Friday for five consecutive weeks, giving a cumulative application of 25 mL per pot. Control pots received no $NiCl_2$ throughout the treatment period.

Experimental Design

The experiment consisted of 72 pots arranged in a completely randomized design with six replicates per treatment. Pots were spaced 30 cm apart horizontally and 20 cm vertically. Plant growth and yield data were recorded weekly, and monthly cumulative values were used for statistical analysis.

Growth Parameter Assessment

Two plants were maintained in each pot, and their measurements were averaged to obtain one value per replicate. Plant height (cm) was measured using a measuring tape and the number of leaves was recorded at 1, 2, and 3 MAP. The numbers of branches, flowers, and fruits were determined at 2 and 3 MAP.

Leaf chlorophyll content was measured using a hand-held SPAD-502 chlorophyll meter. Ten leaves (five mature and five young leaves) were selected randomly from each pot, and the average SPAD value was recorded, shoots, and roots were harvested separately, and their fresh weights (g) were determined using a top-loading balance at 3 MAP.

MorphologyParameter Assessment

The external appearance, vegetative development, and reproductive structures of plants grown under the different treatments were visually examined and photographed at 3 MAP.

Data Analysis

Data were analyzed using descriptive and inferential statistics. One-way analysis of variance (ANOVA) was performed using IBM SPSS Statistics version 29.0 (IBM Corp., Armonk, NY, USA). Results are presented as mean ± standard deviation. Significant differences among treatment means were determined using Duncan's Multiple Range Test at the 5% probability level. Statistical significance was accepted at $P \leq 0.05$.

RESULTS AND DISCUSSION

Plant height and leaf production generally increased with age but declined with increasing $NiCl_2$ concentration, particularly in *C. annuum*. In loamy soil, *C. frutescens* exhibited little response to $NiCl_2$ during the early growth stage. At 1 MAP, plant height was comparable at 0 ppm (16.17 cm), 100 ppm (15.53 cm), and 250 ppm (16.02 cm), while leaf numbers were 21.50, 28.50, and 48.83, respectively. Similar trends were observed at 2 MAP, where plant heights were 25.92, 25.13, and 22.82 cm, whereas leaf numbers increased to 32.93, 32.58, and 56.25. At 3 MAP, 100 ppm produced a slightly higher plant height (45.73 cm) than the control (45.00 cm), while leaf numbers followed the order 0 ppm (75.25) > 250 ppm (65.75) > 100 ppm (62.08). The slight stimulation observed at 100 ppm may be attributed to the dual role of nickel as both an essential micronutrient and a toxic element, which depends on concentration and plant species. Yusuf *et al*. (2011) reported that the dual character and complicated electronic chemistry of nickel have limited the understanding of its toxicity mechanisms. However, the reduction observed at 250 ppm indicated that excessive nickel exerted toxic effects through impaired nutrient uptake, and inhibition of cell elongation.

In contrast, *C. annuum* exhibited progressive reductions in both plant height and leaf number with increasing $NiCl_2$ concentration. At 3 MAP, plant height declined from 30.30 cm in the control to 19.82 and 17.40 cm at 100 and 250 ppm, respectively, while leaf number declined from 40.00 to 17.83 and 16.50. Similar trends were recorded at 1 and 2 MAP. In sandy soil, both parameters were considerably lower in both species than in loamy soil, reflecting the low nutrient-retention capacity and greater nickel bioavailability associated with sandy soils Table 1b and 2b.

These findings agree with Yu *et al*. (2024), who reported that excessive nickel reduced stem elongation and leaf expansion through disturbances in metabolic and photosynthetic activities. Similarly, Uğurlar and Kaya (2023) observed growth inhibition in pepper plants due to oxidative stress and altered nitrogen metabolism. Altaf *et al*. (2022) and Kováčik (2024). Also reported reduced foliage development and chlorosis under prolonged nickel exposure. However, the ability of *C. frutescens* to maintain growth under 100 ppm nickel stress indicates the existence of adaptive mechanisms that were not fully emphasized in previous studies.

Branch formation and reproductive parameters followed similar trends, with values decreasing progressively as $NiCl_2$ concentration increased. In *C. frutescens*, branch number at 3 MAP declined from 9.00 branches in the control to 7.25 and 6.50 branches at 100 and 250 ppm, respectively. Flower number followed the same pattern, decreasing from 29.17 flowers to 14.00 and 5.92 flowers, while fruit number declined from 26.17 fruits in the control to 12.67 and 5.67 fruits at 100 and 250 ppm, respectively. Similar reductions were observed at 2 MAP. In *C. annuum*, the inhibitory effects were more pronounced. At 3 MAP, branch number decreased from 5.33 branches in the control to 2.33 and 2.00 branches, flower number declined from 13.33 to 3.33 and 1.00, and fruit number decreased from 12.08 to 2.50 and 1.00 fruits at 100 and 250 ppm, respectively as shown in Table 3 - 5.

The progressive decline in these parameters suggests that nickel toxicity impaired meristematic activity and disrupted assimilate of nutrients, thereby suppressing vegetative and reproductive development. The relatively higher branch, flower, and fruit production maintained by *C. frutescens* indicates greater tolerance to nickel stress.

These findings agree with Yu *et al*. (2024), who reported that excessive nickel reduced branch development, floral

initiation, and fruit set. Mustafa *et al*. (2023) also observed that nickel-induced oxidative stress impaired assimilate translocation and reproductive development. Similarly, Balaguer *et al*. (1998) and Correia *et al*. (2018) reported reductions in fruit production under elevated nickel concentrations. Nevertheless, the superior reproductive performance of *C. frutescens* suggests species-specific adaptive mechanisms that have received limited attention in previous studies.

At 3 MAP, chlorophyll content, shoot fresh weight, and root fresh weight generally decreased with increasing $NiCl_2$ concentration, and the reductions were more pronounced in sandy soil than in loamy soil. In loamy soil, *Capsicum frutescens* recorded the highest chlorophyll content (4.96), shoot fresh weight (20.83 g), and root fresh weight (6.99 g) at 0 ppm, followed by 100 ppm with values of 3.21, 10.86 g, and 5.69 g, respectively, while the lowest values were obtained at 250 ppm (2.43, 6.35 g, and 2.85 g, respectively). A similar trend was observed in *C. annuum*, where chlorophyll content declined from 4.20 to 2.54 and 2.37, shoot fresh weight decreased from 6.66 g to 1.34 and 1.00 g, and root fresh weight declined from 3.66 g to 1.06 and 1.08 g at 0, 100, and 250 ppm, respectively. The statistical similarity observed between some nickel-treated groups indicated that both concentrations exerted comparable inhibitory effects on pigment accumulation and biomass production.

In sandy soil, all three parameters were markedly lower than those obtained in loamy soil. In *C. frutescens*, chlorophyll content declined from 1.32 in the control to 0.56 and 0.34 at 100 and 250 ppm, respectively. Likewise, shoot fresh weight decreased from 1.28 g to 0.26 and 0.28 g, whereas root fresh weight declined from 0.57 g to 0.31 and 0.24 g. Similar reductions were observed in *C. annuum*, where chlorophyll content decreased from 1.37 to 0.61 and 0.43, shoot fresh weight declined from 2.03 g to 0.02 and 0.02 g, and root fresh weight decreased from 2.92 g to 0.09 and 0.05 g at 0, 100, and 250 ppm, respectively (Table 6 – 8). The comparable values recorded among some nickel-treated plants suggest that severe damage had already occurred and that further increases in nickel concentration produced similar inhibitory effects. *C. frutescens* maintained higher chlorophyll content and biomass than *C. annuum*, indicating greater tolerance to nickel toxicity. The reductions observed with increasing $NiCl_2$ concentration attributed to impaired chlorophyll biosynthesis, reduced photosynthetic efficiency, inhibition of cell division, poor water uptake, and restricted nutrient absorption. The poorer performance recorded in sandy soil were associated with its low nutrient-retention capacity and greater nickel bioavailability, which intensified toxicity.

These findings agree with Yu *et al*. (2024), who reported that excessive $NiCl_2$ reduced chlorophyll concentration and biomass accumulation through impairment of photosynthetic and metabolic processes. Similarly, Sardar *et al*. (2022) observed that increasing nickel concentration caused severe reductions in chlorophyll content, shoot biomass, and root growth in pepper plants. Rosatto*et al*. (2021) also reported that root tissues constitute the primary targets of nickel injury and that elevated nickel concentrations adversely affect plant architecture and biomass accumulation. Furthermore, Shafaqat *et al*. (2022) attributed reductions in shoot biomass to impaired water relations and oxidative stress. However, the greater chlorophyll retention and biomass accumulation observed in *C. frutescens* suggest the existence of adaptive mechanisms that were not clearly emphasized in previous studies.

Figures 3–8 illustrate visible differences in the appearance of both pepper species under increasing $NiCl_2$ concentrations in loamy and sandy soils. The photographic evidence shows progressive alterations in plant form and foliage with rising nickel levels, with more noticeable changes occurring at higher treatments, particularly in sandy soil. These visual observations are consistent with the measured growth responses presented in Table 1a – 8.

As shown in Figure 3a, *C. frutescens* grown in control (0 ppm) loamy soil exhibited healthy morphological features at 3 MAP, which corresponded with the greater plant height (45.00 cm), leaf number (75.25), and branch number (9.00) recorded in Tables 1a, 2a and 3. In contrast, *C. annuum* (Figure 3b) grown under the same conditions showed slight leaf chlorosis in some pots, although it maintained comparatively lower values of 30.30 cm plant height, 40.00 leaves, and 5.33 branches. These observations indicate that *C. annuum* was inherently less vigorous than *C. frutescens*.

At 100 ppm $NiCl_2$ in loamy soil (Figure 4a), *C. frutescens* maintained healthy and vigorous growth with no obvious morphological deterioration, which agreed with the high plant height (45.73 cm), leaf number (62.08), and branch number (7.25) recorded in Tables 1a, 2a and 3. In contrast, *C. annuum* (Figure 4b) exhibited chlorotic leaves, stunted shoots, and unhealthy appearances, corresponding to the lower plant height (19.82 cm), leaf number (17.83), and branch number (2.33). These findings suggest that 100 ppm nickel concentration exerted little toxic effect on *C. frutescens* but markedly inhibited the growth of *C. annuum.*

Figure 5 showed that plants grown in 250 ppm loamy soil followed the same pattern observed at 100 ppm. Although *C. frutescens* (Figure 4a) still maintained relatively acceptable growth, slight reductions in vigor were evident, corresponding to the lower plant height (40.12 cm), increased leaf number (65.75), and reduced branch number (6.50) recorded in Tables 1a, 2a, and 3. However, *C. annuum* (Figure 5b) exhibited severe chlorosis and stunted growth, which coincided with the marked reductions in plant height (17.40 cm), leaf number (16.50), and branch number (2.00). These observations indicate that high nickel concentration induced toxic effects, especially in *C. annuum.*

Plants grown in sandy soil exhibited poorer morphological characteristics than those grown in loamy soil irrespective of nickel concentration. As shown in Figure 6 (a and b), both *C. frutescens* and *C. annuum* grown in control sandy soil displayed depressed growth, chlorotic leaves, and stunted features at 3 MAP. These observations corresponded with the lower plant heights of 18.37 and 6.30 cm and leaf numbers of 12.92 and 8.58 recorded for *C. frutescens* and *C. annuum*, respectively (Tables 1b and 2b). The poor performance under control sandy soil indicates that low nutrient-retention capacity and poor water-holding ability limited plant growth even in the absence of nickel stress.

Figures 6 and 8 showed that plants grown in 100 and 250 ppm sandy soils followed the same trend observed in Figure 6 (a and b). In both species, severe chlorosis, depressed growth, and stunted shoots became more pronounced as nickel concentration increased. These symptoms corresponded with the reductions in plant height from 12.45 to 10.58 cm and leaf number from 7.42 to 7.17 in *C. frutescens*, and from 6.30 to 5.78 cm and 7.08 to 4.42 leaves in *C. annuum* at 100 and 250 ppm, respectively (Tables 1b and 2b). The poor growth recorded in sandy soil may be attributed to increased nickel mobility and reduced nutrient retention, which intensified metal toxicity. These observations agree with Yu *et al*. (2024) who reported that excess $NiCl_2$ induced dwarfing, restricted stem elongation, and reduced leaf expansion, thereby altering the morphology of tomato seedlings. Similarly, Rosatto*et al*. (2021) observed that nickel toxicity adversely affected shoot

development and plant architecture, leading to visible reductions in vigor. Mosa *et al*. (2023) also reported that nickel-induced oxidative stress caused chlorosis, stunted growth, and morphological deterioration through disturbances in photosynthesis and nutrient metabolism. However, the present study demonstrated that *C. frutescens* maintained better morphological characteristics than *C. annuum* under both moderate and high nickel stress, thereby providing additional evidence of species-specific differences in tolerance that have received limited attention in previous studies. Furthermore, the study revealed that soil type strongly influenced the severity of nickel toxicity, with sandy soil intensifying growth suppression compared with loamy soil.

Table 1: Impacts of $NiCl_2$ Loamy Soil on Plant Height (cm)

	C. frutescens			***C. annuum***		
Duration	0ppm	100ppm	250ppm	0ppm	100ppm	250ppm
1 MAP	16.17 ±0.87^{a}	15.53 ±1.47^{a}	16.02 ±0.91^{a}	9.87± 2.67^{b}	9.33± 3.73^{c}	8.13± 4.16^{d}
2 MAP	25.92 ±5.01^{a}	25.13 ±1.87^{b}	22.82 ±1.48^{c}	19.07 ±5.89^{d}	15.93 ±7.89^{e}	13.55 ±7.99^{f}
3 MAP	45.00 ±11.13^{b}	45.73 ±3.06^{a}	40.12 ±6.83^{c}	30.30 ±5.41^{d}	19.82 ±8.65^{e}	17.40 ±9.72^{f}

Values = mean ± standard deviation; n = 6, mean values with similar superscript in a row are not significantly different, P ≤ 0.05.

Table 2: Impacts of $NiCl_2$ Sandy Soil on Plant Height (cm)

	C. frutescens			***C. annuum***		
Duration	0ppm	100ppm	250ppm	0ppm	100ppm	250ppm
1 MAP	14.42 ±1.24^{a}	8.88± 1.82^{ab}	8.50± 1.12^{ab}	3.48 ±0.77^{bc}	3.35 ±2.17^{bc}	3.63 ±2.49^{bc}
2 MAP	15.82 ±0.62^{a}	11.53 ±3.02^{ab}	10.17 ±2.14^{bc}	5.50 ±1.59^{cd}	4.20 ±2.31^{de}	3.93 ±2.56^{de}
3 MAP	18.37 ±0.97^{a}	12.45 ±3.02^{ab}	10.58 ±2.21^{bc}	6.30 ±1.71^{cd}	6.30 ±2.19^{cd}	5.78 ±2.42^{de}

Values = mean ± standard deviation; n = 6, mean values with similar superscript in a row are not significantly different, P ≤ 0.05.

Table 3: Impacts of $NiCl_2$ Loamy Soil on Number of Leaves

	C. frutescens			***C. annuum***		
Duration	0ppm	100ppm	250ppm	0ppm	100ppm	250ppm
1 MAP	21.50 ±7.18^{cd}	28.50 ±12.13^{c}	47.83 ±20.28^{a}	13.58 ±3.15^{de}	10.00 ±7.81^{ef}	9.42 ±3.61^{f}
2 MAP	32.92 ±17.40^{bc}	32.58 ±12.81^{bc}	56.25 ±23.83^{a}	22.33 ±4.05^{cd}	12.50 ±7.88^{de}	13.42 ±6.21^{de}
3 MAP	75.25 ±48.97^{a}	62.08 ±21.89^{ab}	65.75 ±25.77^{ab}	40.00 ±8.04^{bc}	17.83 ±11.29^{cd}	16.50 ±6.32^{d}

Values = mean ± standard deviation; n = 6, mean values with similar superscript in a row are not significantly different, P ≤ 0.05.

Table 4: Impacts of $NiCl_2$ Sandy Soil on Number of Leaves

	C. frutescens			***C. annuum***		
Duration	0ppm	100ppm	250ppm	0ppm	100ppm	250ppm
1 MAP	4.50± 1.30^{a}	4.25 ±1.44^{a}	4.00± 1.10^{ab}	2.58± 0.58^{bc}	2.92± 0.86^{bc}	2.42± 0.80^{c}
2 MAP	7.08± 2.38^{a}	5.42 ±1.07^{b}	6.08± 1.46^{ab}	5.17± 1.13^{b}	4.42± 1.59^{bc}	4.00± 0.77^{c}
3 MAP	12.92 ±4.74^{a}	7.42 ±1.56^{b}	7.17± 1.47^{b}	8.58± 1.88^{b}	7.08± 2.60^{bc}	4.42± 0.92^{cd}

Values = mean ± standard deviation; n = 6, mean values with similar superscript in a row are not significantly different, P ≤ 0.05.

Table 5: Impacts of $NiCl_2$ Loamy Soil on Number of Branches

	C. frutescens			***C. annuum***		
Duration	0 ppm	100 ppm	250 ppm	0 ppm	100 ppm	250 ppm
2 MAP	5.67 ±3.54^{a}	5.00± 1.87^{ab}	4.08± 1.11^{b}	1.50 ±0.55^{c}	0.83± 0.41^{cd}	0.67± 0.52^{cd}
3 MAP	9.00 ±4.49^{a}	7.25± 1.86^{b}	6.50± 0.95^{bc}	5.33 ±1.75^{c}	2.33± 0.82^{d}	2.00± 0.95^{d}

Values = mean ± standard deviation; n = 6, mean values with similar superscript in a row are not significantly different, P ≤ 0.05.

Table 6: Impacts of $NiCl_2$ Loamy Soil on Number of Flowers

	C. frutescens			***C. annuum***		
Duration	0 ppm	100 ppm	250 ppm	0 ppm	100 ppm	250 ppm
2 MAP	21.50 ±9.27^{a}	12.00 ±5.48^{b}	5.50 ±1.22^{c}	11.00 ±4.36^{b}	2.50 ±2.17^{d}	1.00 ±1.67^{e}
3 MAP	29.17 ±7.45^{a}	14.00 ±5.73^{b}	5.92 ±1.11^{c}	13.33 ±5.49^{b}	3.33 ±3.01^{d}	1.00 ±1.67^{e}

Values = mean ± standard deviation; n = 6, mean values with similar superscript in a row are not significantly different, P ≤ 0.05.

Table 7: Impacts of $NiCl_2$ Loamy Soil on Number of Fruits

	C. frutescens			***C. annuum***		
Duration	0 ppm	100 ppm	250 ppm	0 ppm	100 ppm	250 ppm
2 MAP	9.33 ± 4.18^{a}	4.25 ± 3.08^{b}	2.25 ± 0.88^{c}	6.08 ± 2.25^{ab}	1.08 ± 0.86^{cd}	0.42 ± 0.66^{d}
3 MAP	26.17 ± 7.00^{a}	12.67 ± 5.17^{b}	5.67 ± 1.13^{c}	12.08 ± 4.80^{b}	2.50 ± 2.17^{d}	1.00 ± 1.67^{e}

Values = mean ± standard deviation; n = 6, mean values with similar superscript in a row are not significantly different, $P \leq 0.05$.

Table 8: Impacts of $NiCl_2$ Loamy and Sandy Soil on Chlorophyll Content (m) at 3 MAP

	C. frutescens			***C. annuum***		
Soil type	0ppm	100ppm	250ppm	0ppm	100ppm	250ppm
Loamy	4.96 ± 0.63^{a}	3.21 ± 0.45^{b}	2.43 ± 0.40^{c}	4.40 ± 0.45^{b}	2.54 ± 0.43^{c}	2.37 ± 0.24^{c}
Sandy	1.32 ± 0.26^{a}	0.56 ± 0.16^{b}	0.34 ± 0.12^{bc}	1.37 ± 0.19^{a}	0.61 ± 0.12^{b}	0.43 ± 0.16^{bc}

Values = mean ± standard deviation; n = 6, mean values with similar superscript in a row are not significantly different, $P \leq 0.05$.

Table 9: Impacts of $NiCl_2$ Loamy and Sandy Soil on Fresh Weight (g) of shoots at 3 MAP

	C. frutescens			***C. annuum***		
Soil type	0ppm	100ppm	250ppm	0ppm	100ppm	250ppm
Loamy	20.83 ± 12.26^{a}	10.86 ± 3.72^{b}	6.35 ± 2.31^{c}	6.66 ± 1.38^{a}	1.34 ± 0.43^{b}	1.00 ± 0.33^{bc}
Sandy	1.28 ± 0.30^{a}	0.26 ± 0.19^{b}	0.28 ± 0.08^{b}	2.03 ± 3.66^{a}	0.02 ± 0.01^{b}	0.02 ± 0.01^{b}

Values = mean ± standard deviation; n = 6, mean values with similar superscript in a row are not significantly different, $P \leq 0.05$.

Table 10: Impacts of $NiCl_2$ Loamy and Sandy Soil on Fresh Weight (g) of roots at 3 MAP

	C. frutescens			***C. annuum***		
Soil type	0ppm	100ppm	250ppm	0ppm	100ppm	250ppm
Loamy	6.99 ± 3.19^{a}	5.69 ± 1.27^{b}	2.85 ± 0.69^{c}	3.66 ± 0.48^{c}	1.06 ± 0.17^{d}	1.08 ± 0.47^{d}
Sandy	0.57 ± 0.10^{a}	0.31 ± 0.19^{b}	0.24 ± 0.29^{b}	1.92 ± 3.76^{c}	0.09 ± 0.13^{b}	0.05 ± 0.02^{b}

Values = mean ± standard deviation; n = 6, mean values with similar superscript in a row are not significantly different, $P \leq 0.05$.

A B

Figure 2: Fresh Fruits of *C. frutescens* (a) and *C annuum* (b), from Which Seeds were Extracted and Dried before Planting

A B

Figure 3: Growth of *C frutescens* in the Control (0 ppm $NiCl_2$) Loamy Soil

A B

Figure 4: Growth of *C. frutescens*in the 100 ppm $NiCl_2$-Treated Loamy Soil

A B

Figure 5: Growth of *C. Frutescens* (a) and *C. annuum* (b) at 250 ppm $NiCl_2$ Loamy Soil

A B

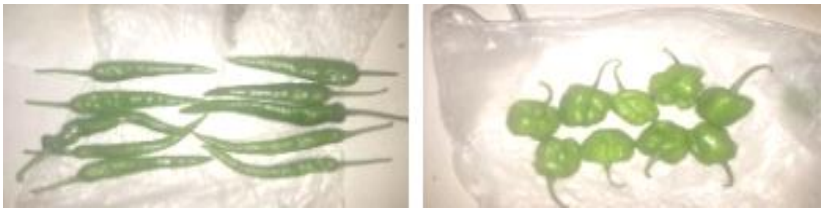
Figure 6: Growth of *C. frutescens* (a) and *C.annuum* (b) in the Control (0 ppm $NiCl_2$) Sandy Soil

A B

Figure 7: Growth of *C.frutescens* (a) and *C.annuum* (b) at 100 ppm $NiCl_2$ sandy soil

A B

Figure 8: Growth of *C. Frutescens* (a) and *C.annuum* (b) at 250 ppm $NiCl_2$ Sandy Soil



A B

Figure 9: Fresh Sample of the Harvested *C. frutescens* (a) and *C. annuum* (b) Fruits from Loamy Soil

CONCLUSION

Nickel toxicity significantly affected the growth, biomass accumulation, chlorophyll content, reproductive performance, and morphological characteristics of pepper plants, with the severity depending on species, soil type, nickel concentration, and growth duration. Although growth parameters generally increased with plant age, increasing $NiCl_2$ concentration progressively reduced plant height, leaf production, branching, flowering, fruiting, chlorophyll content, and shoot and root fresh weights. *C. frutescens* consistently exhibited greater tolerance to nickel stress than *C. annuum*, maintaining better vegetative growth, reproductive performance, biomass accumulation, and healthier morphological characteristics, particularly at 100

ppm $NiCl_2$. Loamy soil supported superior growth and reduced the severity of nickel toxicity, whereas sandy soil intensified toxicity because of its lower nutrient-retention capacity and greater nickel bioavailability. Thus, the study demonstrated that nickel toxicity suppresses pepper growth and productivity, but the degree of damage is strongly influenced by species and soil type, with *C. frutescens* grown in loamy soil showing the greatest tolerance to nickel stress.

REFERENCES

Altaf, M.A., Hao, Y., He, C., Mumtaz, M.A., Shu, H., Fu, H. and Wang, Z. (2022). Physiological and biochemical responses of pepper (*Capsicum annuum* L.) seedlings to nickel toxicity. *Frontiers in Plant Science*, **13**, 950392.

Balaguer, J., Almendro, M.B., Gómez, I., Navarro Pedreño, J. and Mataix, J. (1998). Tomato growth and yield affected by nickel present in the nutrient solution. *Acta Horticulturae*, **458**, 255–262.

Correia, L., Marrocos, P., Montalván Olivares, D.M., Velasco, F.G., Luzardo, F.H.M. and Mota de Jesus, R. (2018). Bioaccumulation of nickel in tomato plants: Risks to human health and agro-environmental impacts. *Environmental Monitoring and Assessment*, **190**, 317.

Knight, A.H. and Crooke, W.M. (1956). Interaction between nickel and calcium in plants. *Nature*, **178**, 220.

Kováčik, J. and Vydra, M. (2024). The impact of nickel on plant growth and oxidative balance. *Physiologia Plantarum*, **176**, e14595.

Mosa, K.A., El-Naggar, M., Abdelsalam, N.R. and Al-Huqail, A.A. (2023). Heavy metal toxicity and plant responses: Physiological, biochemical and molecular mechanisms. *Plants*, **12**, 875.

Mustafa, A., Zulfiqar, U., Mumtaz, M.Z., Radziemska, M., Haider, F.U., Holatko, J., Hammerschmiedt, T., Naveed, M., Ali, H., Kintl, A., Saeed, Q., Kucerik, J. and Brtnicky, M. (2023). Nickel (Ni) phytotoxicity and detoxification mechanisms: A review. *Chemosphere*, **328**, 138574.

Rosatto, S., Mariotti, M., Romeo, S. and Roccotiello, E. (2021). Root and shoot response to nickel in hyperaccumulator and non-hyperaccumulator species. *Plants*, **10**, 508.

Sardar, H., Shahzadi, I., Altaf, M.A., Mumtaz, M.Z., Ashraf, U. and Ali, B. (2022). Physiological and biochemical responses of pepper (*Capsicum annuum* L.) seedlings to nickel toxicity. *Frontiers in Plant Science*, **13**, 950667.

Shafaqat, A., Akbar, A., *et al.* (2022). Comparative morphology and biochemical analysis of nickel toxicity in minor fruit species (*Grewia asiatica* L., *Syzygium cumini* (L.) Skeels and *Tamarindus indica* L.). *Agriculture*, **12**, 323.

Uğurlar, F. and Kaya, C. (2023). Synergistic mitigation of nickel toxicity in pepper (*Capsicum annuum*) by nitric oxide and thiourea via regulation of nitrogen metabolism and subcellular nickel distribution. *Functional Plant Biology*, **50**, 1099–1116.

Yu, H., Li, W., Liu, X., Song, Q., Li, J. and Xu, J. (2024). Physiological and molecular bases of the nickel toxicity responses in tomato. *Stress Biology*, **4**, 25.

Yusuf, M., Fariduddin, Q., Hayat, S. and Ahmad, A. (2011). Nickel: An overview of uptake, essentiality and toxicity in plants. *Bulletin of Environmental Contamination and Toxicology*, **86**, 1–17.