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Phytoremediation Potential of Cucumber (*Cucumis sativus* L.) For Barium (Ba) Uptake Under a Hydroponic System

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ABSTRACT

This research examined how Cucumber (*Cucumis sativus* L.) responds physiologically, biochemically, and through phytoremediation to barium (Ba) stress in a controlled hydroponic environment. Various metrics were assessed, including seed germination rates, growth factors like root and shoot height, levels of photosynthetic pigments, phytohormones, markers of oxidative stress, antioxidant defenses, and metal accumulation at concentrations of 0 (control), 100, 200, and 300 ppm Ba, using a fully randomized design. The presence of barium significantly reduced the seed germination rate, germination energy, and vigor index by 28.57–60.78%, 30.00–79.00%, and 86.67–88.10%, respectively, compared to the control group. At 300 ppm Ba, both shoot and root lengths decreased by more than 60%, alongside a reduction of over 65% in fresh and dry biomass. The levels of chlorophyll a, chlorophyll b, carotenoids, and SPAD values were markedly lower, with chlorophyll a decreasing by as much as 5.08 times at 300 ppm Ba. Additionally, the concentrations of auxin (IAA) and gibberellic acid dropped by 1.59–3.83-fold and 1.87–3.38-fold, respectively. Ba caused oxidative stress, raising malondialdehyde and hydrogen peroxide levels by up to 75.75% and 39.07%, respectively, while the activities of antioxidant enzymes (SOD, CAT, APX) significantly increased, with SOD activity surging over 24 times at 300 ppm. The bioaccumulation study indicated higher Ba retention in the roots (BAF > 1) but low translocation factors (< 0.5), suggesting a potential for phytostabilization.

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INTRODUCTION

Environmental contamination by heavy metals has become a major global concern due to rapid industrialization, mining, agricultural intensification, and improper waste disposal practices. Among these contaminants, barium (Ba) is increasingly recognized as an environmental pollutant because of its widespread use in oil drilling, ceramics, paints, glass manufacturing, electronics, and medical industries (Tchounwou *et al*., 2012). Although barium naturally occurs in soils and rocks, anthropogenic activities have significantly increased its concentration in terrestrial and aquatic ecosystems, leading to potential ecological and human health risks (Ali *et al*., 2019).

In Nigeria, increasing industrial and agricultural activities have contributed to the accumulation of heavy metals in agricultural soils and water bodies. Industrial effluents, mining operations, drilling activities, and the excessive application of agrochemicals can elevate barium concentrations beyond natural background levels (Abdullahi *et al*., 2020). Elevated Ba concentrations have been reported in contaminated soils and irrigation waters, raising concerns regarding its transfer into food crops and subsequent entry into the food chain. Long-term exposure to excessive barium may adversely affect plant growth, soil microbial communities, and human health (Audu and Lawal, 2016).

Phytoremediation has emerged as a cost-effective and environmentally friendly approach for mitigating heavy metal pollution. The technique utilizes plants to absorb, stabilize, or accumulate contaminants from polluted environments. Among potential phytoremediators, *Cucumis sativus* L. (cucumber) is considered a suitable candidate because of its rapid growth, substantial biomass production, extensive root system, and adaptability to hydroponic cultivation (Mushtaq *et al*., 2022). Hydroponic systems offer controlled conditions that facilitate the evaluation of plant responses to heavy metal stress and allow accurate assessment of metal uptake and translocation (Liu *et al*., 2020).

Despite its potential usefulness in phytoremediation, exposure to elevated concentrations of barium can induce toxicity in plants. Excessive Ba accumulation may interfere with nutrient uptake, particularly calcium and potassium metabolism, resulting in growth inhibition, chlorosis, reduced photosynthetic efficiency, hormonal imbalance, and oxidative stress (Song *et al*., 2023). The generation of reactive oxygen species (ROS) under heavy metal stress can lead to membrane damage, protein oxidation, and disruption of normal cellular functions. Consequently, understanding the physiological, biochemical, and phytoremediation responses of cucumber to barium stress is essential for evaluating its suitability as a phytoremediator (Lairini *et al*., 2017).

MATERIALS AND METHODS

Experimental Design and Hydroponic Setup

The study was executed in a controlled laboratory setting using a hydroponic system to assess the phytoremediation potential of *Cucumis sativus* L. under Barium (Ba) stress. A completely randomized design with treatments in triplicate was employed, featuring heavy metal concentrations of 0 ppm (control), 100 ppm, 200 ppm, and 300 ppm of Ba based on documented toxicity thresholds in plants (Ali *et al*., 2014).

Seed Pre-Treatment and Germination Assay

C. sativus seeds were sterilized and pre-soaked in the corresponding metal solutions for 12 hours, with control seeds soaked in distilled water. The treated seeds were then placed in Petri dishes with moistened filter paper and kept at 22–24 °C under a 16 hours light/8 hours dark photoperiod. Germination was tracked daily over 14 days, with germination percentage, germination rate, vigor index, and inhibition percentage calculated using standard formulas as outlined by Chaudhry *et al*. (2016). These metrics gauged cucumber's early-stage sensitivity to Ba exposure.

Seedling Establishment and Growth Assessment

Uniform seedlings at the four-leaf stage were transferred to hydroponic nutrient solutions with varying metal concentrations (100, 200 and 300ppm). After 42 days of exposure, growth metrics plant height, root length, shoot length, and biomass were evaluated. Plant height was measured from the base to the apical meristem, while roots and shoots were assessed separately using a ruler (Sharma *et al*., 2017). Fresh and dry biomass were noted after oven-drying plant parts at 70 °C until a stable weight was achieved, following Chaves *et al*. (2009).

Physiological and Photosynthetic Measurements

Leaf chlorophyll content was measured non-destructively with a SPAD chlorophyll meter, taking multiple readings per treatment for average values (Sharma *et al*., 2017). Chlorophyll a, b, and carotenoid contents were quantified spectrophotometrically following extraction in 80% acetone, as per methods detailed by Pompelli *et al*. (2013). These parameters assessed the effects of heavy metal stress on photosynthetic efficiency.

Determination of Phytohormonal Activities

Indole-3-acetic acid (IAA) levels were quantified using the Salkowski colorimetric method post-ethanol extraction of root tissues, indicated by a pink hue after incubation and absorbance measured at 530 nm. Gibberellic acid (GA_3) was evaluated using a modified colorimetric method involving zinc acetate and potassium ferrocyanide, measuring absorbance at 254 nm following the protocol by Sharma *et al*. (2018). Hormonal analysis was performed to assess growth regulation under metal stress.

Assessment of Oxidative Stress and Cytotoxicity

Oxidative stress was gauged by measuring malondialdehyde (MDA), hydrogen peroxide (H_2O_2), carbonyl protein content, membrane rupture, and membrane stability index (MSI). MDA levels indicative of lipid peroxidation were measured via the thiobarbituric acid test as described by Li *et al*. (2020). Membrane integrity was inferred through standardized electrolyte leakage protocols, shedding light on cytotoxic damage from Ba exposure.

Antioxidant Defense System Analysis

Spectrophotometric assays were conducted to evaluate the activity of enzymatic antioxidants like superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX). The accumulation of non-enzymatic antioxidants such as reduced glutathione (GSH), phytochelatins, total phenolics, and the free radical scavenging effect were determined following established biochemical methods, including the DPPH radical scavenging assay by Bhagyawant *et al*. (2019).

Heavy Metal Accumulation and Translocation Analysis

Metal concentrations in root and shoot tissues were determined using atomic absorption spectrophotometry (AAS) post-acid digestion. Bioaccumulation factor (BAF) and translocation factor (TF) were calculated using the formular summarized below (Ghaferah *et al*., 2022);

$$BAF = \frac{Heavy\ metals\ on\ plant}{heavy\ metals\ on\ hydroponic\ medium}$$

$$TF = \frac{Conc. of\ heavy\ metals\ on\ shoots}{Conc. of\ heavy\ metals\ on\ roots}$$

Statistical Analysis

Data were analyzed via one-way analysis of variance (ANOVA) using appropriate statistical software. Mean comparisons were executed using Tukey's honest significant difference (HSD) test at $p < 0.05$ to identify significant treatment differences, with results presented as mean ± standard error for statistical reliability.

RESULTS AND DISCUSSION

Effects of Barium on Seed Germination and Early Growth

The effect of Ba on the seed germination indices were determined. Seed germination rates, germination energy, and vigor index were decreased statistically significant ($p < 0.05$) under 100 ppm Ba by 28.57, 30, and 86.67% whereas at 200 ppm of Ba, the seed germination rates, germination energy, and vigor index were affected by 46.42, 50.00, and 80.84% accordingly, compared to the control (Figure 1) The percent at 300ppm decreased statistically significant in seed germination rates (60.78%), germination energy (79.00), and vigor index (88.10%) were recorded under Ba treated group compared to the control. There was a significant germination inhibition (23.41%) especially at highest concentrations (300ppm). The reduction in seed germination and seedling growth observed under increasing Ba concentrations indicates that barium exerts considerable phytotoxic effects on *Cucumis sativus*. The progressive decline in germination percentage, vigor index, shoot length, root length, and biomass suggests that Ba interferes with critical physiological processes required for successful seed germination and seedling establishment. Similar observations have been reported in several crop species where barium toxicity impaired water uptake, enzyme activation, and cellular metabolism during early growth stages (Abdullahi *et al*., 2020).

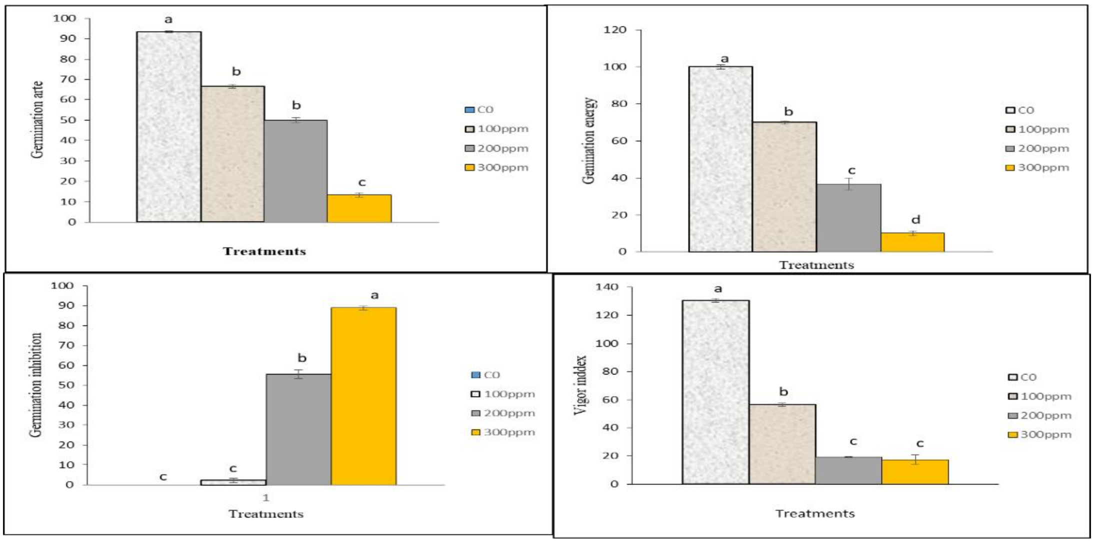

Figure 1: Impact of Barium on the in Vitro Germination Indices Assessment at 100 ppm Exposure

Bars bearing dissimilar letter(s) at $p < 0.05$ for each group symbolize substantial difference, Tukey's HSD test. Data is the triplicate average (n=3). Error bars signify standard error (SE) of three replicates.

Table 1 shows that exposure of *Cucumis sativus* seedlings to increasing concentrations of barium resulted in a significant and progressive reduction in all measured growth parameters. The control seedlings recorded the highest shoot length (5.11 ± 0.03 cm), root length (4.51 ± 0.03 cm), fresh weight (9.40 ± 0.03 g), and dry weight (4.70 ± 0.03 g). At 100 ppm Ba, shoot length and root length declined to 3.24 ± 0.03 cm and 2.54 ± 0.02 cm, respectively. Further reductions were observed at 200 ppm, while the lowest values were recorded at 300 ppm Ba, where shoot length (2.53 ± 0.00 cm), root length (1.63 ± 0.01 cm), fresh weight (3.20 ± 0.01 g), and dry weight (1.50 ± 0.01 g) showed more than 60% reduction compared to the control. These reductions were statistically significant ($p < 0.05$), indicating that barium toxicity negatively affected cucumber seedling growth in a concentration-dependent manner.

Table 1: Growth Parameters of *Cucumis sativus* Seedlings Under Ba Stress

Concentration (ppm)	Shoot length	Root length	Fresh weight	Dry weight
Control	$5.11{\pm}0.03^a$	$4.51{\pm}0.03^a$	$9.40{\pm}0.03^a$	$4.70{\pm}0.03^a$
100	$3.24{\pm}0.03^b$	$2.54{\pm}0.02^b$	$6.70{\pm}0.03^b$	$3.40{\pm}0.02^b$
200	$2.71{\pm}0.01^c$	$2.12{\pm}0.01^c$	$4.50{\pm}0.02^c$	$2.90{\pm}0.03^c$
300	$2.53{\pm}0.00^c$	$1.63{\pm}0.01^d$	$3.20{\pm}0.01^d$	$1.50{\pm}0.01^d$

Numbers sharing similar letter(s) for each parameter do not differ significantly at $p < 0.05$, Tukey's HSD test. Data is the average of 3 replications (n=3). Error bars represent standard error (SE) of triplicates.

The more pronounced reduction in root growth compared with shoot growth may be attributed to direct exposure of roots to the contaminated nutrient solution. Barium accumulation within root tissues can disrupt nutrient absorption and cell division, thereby limiting root elongation and subsequent plant development. The concentration-dependent growth inhibition observed in this study demonstrates that excessive Ba exposure negatively affects overall plant productivity (Akinyemi and Ogunfowokan, 2013).

Photosynthetic Pigment Disruption Under Metal Stress

Chlorophyl (Chl) *a*, *b*, carotenoid (Car.) and SPAD value were determined at dose level of 100 ppm of Ba dose level, the Chl *a* synthesis was inhibited of by 1.84-fold, Chl *b* was decreased by 2.31-fold, Car. decreased by 1.12-fold and SPAD values decreased by 1.31 open exposure to Ba compared to control.

Under 200 ppm Ba the Chl *a* under Ba decrease by 4.16, Chl *b* declined by 3.36, Car. were found to be 3.78-fold and SPAD value in Ba treated group was 3.22 compared to the control (Figure 2).

At 300 ppm Ba spiked water, Chl *a* content decreased by 5.08, Chl *b* by 4.14, Car. by 3.82 and SPAD by 4.38-folds respectively, compared to the control (Figure 2). Photosynthetic pigments were significantly reduced with increasing barium concentrations. The decline in chlorophyll a, chlorophyll b, carotenoids, and SPAD values indicates impairment of the photosynthetic apparatus. Barium toxicity may interfere with chlorophyll biosynthesis and accelerate pigment degradation through oxidative stress mechanisms (Pompelli *et al*., 2013). Heavy metals are known to hinder chlorophyll synthesis by substituting magnesium in the chlorophyll molecule and damaging the chloroplast structure, which consequently limits photosynthetic efficiency and biomass accumulation (Song *et al*., 2023).

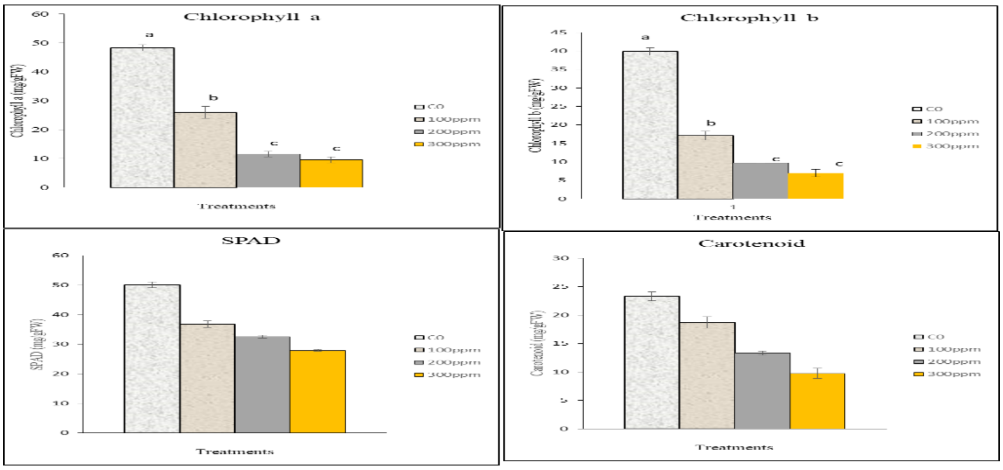

Figure 2: Influence of Barium at 100 ppm Doses on Chlorophyll a, b, Carotenoid and SPAD Content of the *C. sativus* Leaves

Hormonal Activities under Metal Stress

Figure 3 illustrated the impact of 100, 200 and 300 ppm of Ba on hormone (auxin and gibberellic acid) in cucumber seedlings. Auxin (indole-3-acetic acid) was decreasing statistically significant ($p < 0.05$). At 100, 200 and 300 ppm of Ba, IAA decreased significantly by 1.59, 2.03 and 3.83-folds and the fold decrease in gibberellic acids (GAs) under Ba also found to be 1.87, 2.36 and 3.38-folds compared to the control. Phytohormones play a crucial role in regulating plant growth and development under both normal and stressful conditions. The significant reductions in indole-3-acetic acid (IAA) and gibberellic acid (GA_3) observed in this study indicate that barium disrupts hormonal homeostasis in cucumber seedlings. Reduced auxin levels may impair cell elongation, root development, and nutrient acquisition, while decreased gibberellin concentrations can suppress stem elongation and biomass production (Yuan and Huang, 2016).

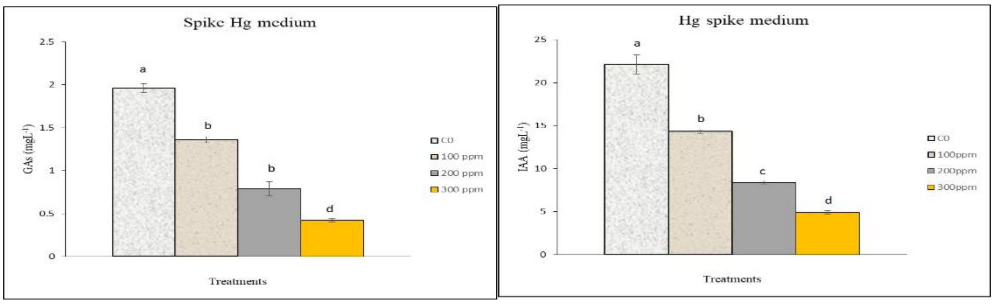

Figure 3: Influence of Barium at 100, 200 and 300 ppm Doses on IAA and GAs Content of the *C. sativus* Leaves

Induction of Oxidative Stress and Cytotoxic Damage

Figure 4 demonstrated the concentrations of MDA under different Ba levels of contamination. The lowest MDA level was observed in control. Reference to the control, at 100 ppm the concentration of MDA increased statistically significant by 46.96 and at 200 ppm, it significantly increases to 70.53 at 300ppm the percent increase to 75.75% compared to the control. Membrane damage might be a result of initiated oxidative stress and the accumulation of “reactive oxygen species” leading to disturbances in membrane configuration (Itri *et al.*, 2014), and oxidation of cell membrane fatty acids (DaCosta and Huang, 2007).

Hydrogen peroxide increased statistically significant by 15.60%, 34.75% and 39.07% for Ba at 100, 200 and 300ppm respectively, comparative to the control (Figure 4). The increase in H_2O_2 due to exposure of heavy metals has been reported by Abdullahi *et al.* (2024) in Spinach and barley by Tamás *et al*. (2010).

The carbonyl concentration indicated the extent of which the protein is oxidized. The percent decrease in carbonyl concentration under 100ppm (26.22%), 200ppm (39.24%) and 44.44% decreased was recorded under Ba at 300ppm comparative to the control (Figure 4). The elevated concentrations of malondialdehyde (MDA) and hydrogen peroxide (H_2O_2) demonstrate that barium exposure induced substantial oxidative stress in cucumber seedlings. Increased MDA content is a clear indication of lipid peroxidation and membrane deterioration, while elevated H_2O_2 levels reflect excessive reactive oxygen species generation. Heavy metal-including Ba induced oxidative stress is commonly associated with disturbances in electron transport processes and cellular metabolism (Mohamed *et al*., 2025).

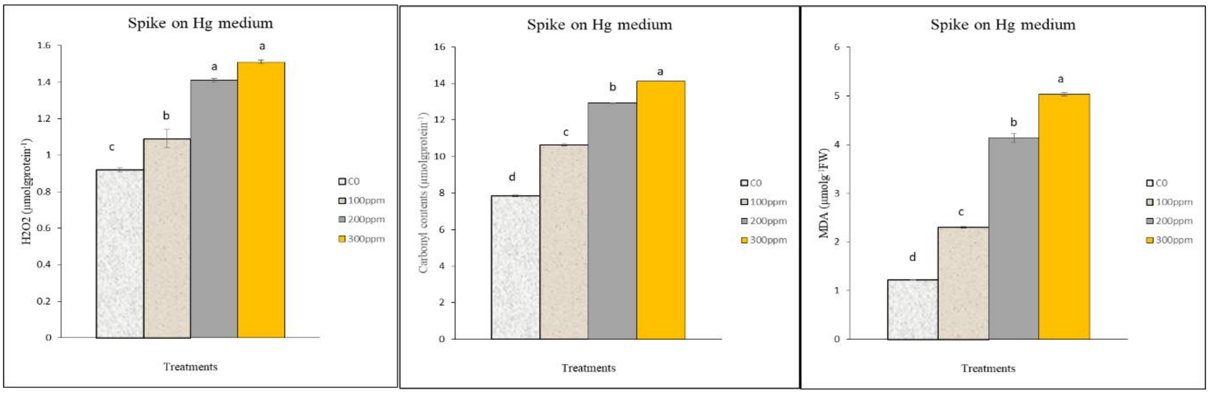

Figure 4: Effect of Ba (100, 200 and 300 ppm) on H2O2, Lipid Peroxidation and Production of Malondialdehyde

Membrane Rupture and Membrane Stability Index of *Cucumis sativus* Seedling at Varying Concentrations

The membrane rupture (MR) and membrane stability index (MSI) were assessed at 100 ppm of Ba as illustrated in Figure 5. The MR increased significantly ($p < 0.05$) under Ba by 1.92-fold and MSI decrease statistically significant by 1.10-fold respectively. At 200 ppm contamination dose, MR increased by significantly by 4.57-fold and MSI was decrease by 1.41 whereas MR were increase substantially by 7.77-fold and MSI increased by 2.22-fold at 300ppm reference to the control.

The increased electrolyte leakage observed at higher Ba concentrations suggests loss of membrane selectivity and disruption of normal cellular functions. Such alterations may adversely affect nutrient transport, water balance, and metabolic activity, thereby contributing to the reduction in plant growth and physiological performance (Demidchik *et al*., 2014). Demidchik and Maathuis (2007) coined out that both membrane electrolytes leakage affected with increase in metal concentration in *Phaseolus vulgaris* plant.

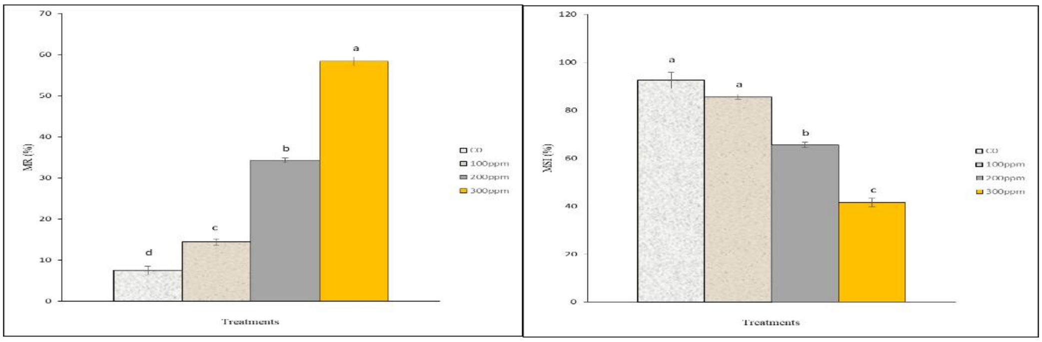

Figure 5: Impact of Ba on MR and MSI at 100-300ppm

Defensive Response Determination of *C. sativus* at Varying Concentrations

Table 2 shows that barium exposure significantly influenced the antioxidant enzyme activities of *Cucumis sativus* seedlings. The control treatment recorded the lowest activities of catalase (CAT: 0.69 ± 0.01), ascorbate peroxidase (APX: 0.90 ± 0.02), and superoxide dismutase (SOD: 0.21 ± 0.01). At 100 ppm Ba, all enzymes showed a marked increase, with CAT rising to 1.15 ± 0.03, APX to 1.22 ± 0.09, and SOD to 1.79 ± 0.03. Further increases were observed at 200 ppm, while the highest enzyme activities were recorded at 300 ppm Ba, where CAT reached 2.28 ± 0.03, APX 2.14 ± 0.03, and SOD 5.23 ± 0.06. These increases were statistically significant ($P < 0.05$), indicating a concentration-dependent induction of antioxidant defense mechanisms in response to barium stress.

The concentration-dependent increase in antioxidant enzyme activities demonstrates the plant's adaptive response to elevated ROS production. However, despite the enhanced antioxidant defense, the persistence of growth inhibition and oxidative damage suggests that the protective mechanisms were insufficient to completely counteract the toxic effects of higher Ba concentrations (Yusuf *et al*., 2015).

Table 2: Enzymatic Activities of *C. sativus* Under Varying Concentrations of Ba

Conc. (ppm)	**Enzymatic activities**		
	CAT	**APX**	**SOD**
C0	0.69 ± 0.01c	0.9 ± 0.02d	0.21 ± 0.01d
100	1.15 ± 0.03b	1.22 ± 0.09c	1.79 ± 0.03c
200	2.13 ± 0.09b	1.78 ± 0.09b	4.19 ± 0.04b
300	2.28 ± 0.03a	2.14 ± 0.03a	5.23 ± 0.06a

Key: CAT; Catalase, APX; Ascorbate Peroxidase, and SOD; Superoxide Dismutase

Non-Enzymatic Defense Activities of *C. sativus* at Varying Concentrations

DPPH of the cucumber seedlings extract were investigated and found to increase by 40.33, 53.33 and 23.27% under 100, 200 and 300 ppm Ba respectively, compared to control (Table 4.2). TAA of the extract increased statistically significant by 18.58, 35.22 and 23.68% upon exposure to Ba at 100, 200 and 300 ppm accordingly, relative to the control. The protein thiol increased substantially by 47.91, 49.05 and 50.53% at various concentration of Ba respectively, comparative to the control. Non-protein thiols (NPT) were found to increase by 65.09, 69.67 and 71.78% under 100, 200 and 300 ppm of Ba respectively, related to the control. A significant increase in glutathione (GSH) and phytochelatin (PC) at 100 ppm (70.49 and 64.86), 200 ppm (72.93 and 70.90) and (73.91 and 73.83) (Table 3).

The increased production of glutathione and phytochelatins suggests an active detoxification strategy aimed at reducing free barium ions within plant tissues. Such responses enhance metal tolerance by limiting oxidative damage and facilitating compartmentalization of toxic ions. Nevertheless, the decline in growth and physiological parameters indicates that prolonged exposure to high Ba concentrations exceeded the detoxification capacity of the plant (Demidchik *et al*., 2014).

Table 3: Impact of Ba at 100, 200 and 300 ppm on Antioxidants Activities

	Parameters					
Ppm	**DPPH**	**TAA**	**PT**	**NPT**	**GSH**	**PC**
C0	29.91±0.20d	3.90±0.06d	1.87±0.03d	0.81±0.01d	0.36±0.01c	0.39±0.04d
100	50.11±0.06b	4.79±0.02c	3.59±0.01c	2.32±0.01c	1.22±0.01b	1.11±0.00c
200	64.06±0.03a	6.02±0.06a	3.67±0.01b	2.67±0.01b	1.33±0.01ab	1.34±0.01b
300	38.97±0.06c	5.11±0.01b	3.78±0.01a	2.87±0.01a	1.38±0.01a	1.49±0.06a

TAA; Total Antioxidant Activity, PT; Protein Thiol, NPT; Non-Protein Thiol, GSH, Glutathione; PCs, Phytochelatins

Bioaccumulation Factor (BAF) and Translocation Factor (TF) of Barium (Ba) in *Cucumis sativus*

Table 4 shows that barium uptake and accumulation in *Cucumis sativus* increased significantly with increasing Ba concentration. At 100 ppm, total uptake (TU) was 69.43 ± 0.02 mg/kg FW, with bioaccumulation factors of 15.22 ± 0.00 in the shoot and 54.21 ± 0.01 in the root, while the translocation factor (TF) was 0.28 ± 0.00. At 200 ppm Ba, TU increased to 141.46 ± 0.02 mg/kg FW, with corresponding increases in shoot BAF (28.24 ± 0.01), root BAF (113.22 ± 0.01), and TF (0.36 ± 0.00). The highest values were recorded at 300 ppm Ba, where TU reached 255.48 ± 0.02 mg/kg FW, shoot BAF increased to 80.17 ± 0.01, root BAF to 175.31 ± 0.01, and TF to 0.46 ± 0.00. These results indicate a concentration-dependent increase in barium uptake and accumulation, with significantly higher retention in roots than shoots ($p < 0.05$).

The higher root bioaccumulation factors and relatively low translocation factors suggest that *Cucumis sativus* primarily immobilizes barium within root tissues. This pattern reduces movement of the metal to aerial parts and indicates that the plant functions mainly as a phytostabilizer rather than a phytoextractor. Root sequestration may represent a protective mechanism that minimizes damage to photosynthetically active tissues while facilitating the stabilization of contaminated environments (Adesodun *et al*., 2014).

Table 4: BAF and TF of Ba at Varying Concentrations

Conc. (ppm)	**TU (mg/Kg FW**	**BAF (Shoot)**	**BAF (Root)**	**BAF (Total)**	**TF (Shoot/Root)**
100	68.72 ± 0.01^{c}	41.61 ± 0.01^{c}	27.11 ± 0.01^{c}	0.69 ± 0.00^{b}	1.54 ± 0.00^{b}
200	138.45 ± 0.02^{b}	87.21 ± 0.01^{b}	51.24 ± 0.01^{b}	0.69 ± 0.00^{b}	1.70 ± 0.00^{a}
300	203.38 ± 0.01^{a}	130.21 ± 0.01^{a}	73.17 ± 0.01^{a}	0.68 ± 0.00^{a}	1.78 ± 0.00^{a}

Key: TU; Total Uptake of Heavy Metals, BAF (Root); Bioaccumulation Factor of Root, BAF (Shoot); Bioaccumulation Factor of Shoot, BAF (Total); Bioaccumulation Factor of Plant and TF; Translocation Factor

CONCLUSION

This investigation assessed the phytoremediation capabilities of *Cucumis sativus* L. in response to Barium (Ba) stress within a controlled hydroponic setup. The results revealed that Barium had a significant impact on seed germination, vegetative growth, photosynthetic capability, and phytohormonal balance in a concentration-dependent manner. The activation of oxidative stress in *C. sativus*, evidenced by elevated malondialdehyde, hydrogen peroxide, and protein carbonyls, indicated that Ba disrupt cellular redox balance. Nevertheless, the plant activated key antioxidant defense mechanisms, including superoxide dismutase, catalase, ascorbate peroxidase, glutathione, phytochelatins, and phenolic compounds, especially at lower to moderate metal concentrations. This response highlights the plant's inherent resilience under metal stress conditions. Analysis of heavy metal accumulation indicated a preferential retention of Ba in root, with limited retention shoot parts. Bioaccumulation factors exceeding one and translocation factors below one affirm that *C. sativus* is more suited for phytoextraction than for phytostabilization.

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