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Growth and Yield Responses of Brinjal (*Solanum melongena* L.) to Increasing Levels of Soil Arsenic Contamination

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Abstract: Soil arsenic contamination threatens vegetable production in South Asia, yet the dose-dependent response of brinjal (*Solanum melongena* L.) to elevated soil arsenate [As(V)] remains insufficiently quantified. A pot experiment was conducted at Sher-e-Bangla Agricultural University, Dhaka, Bangladesh, using a Completely Randomized Design with four replications to evaluate the effects of sodium arsenate (T_1:0, T_2:25, T_3:50, and T_4:75 mg As kg^{-1} soil) on *S. melongena* cv. BARI Brinjal 5. Arsenate exposure progressively inhibited vegetative growth, root development, biomass accumulation, and reproductive yield, with peak phytotoxicity observed at 75 mg As kg^{-1} soil. Compared with the control, the 75 mg As kg^{-1} treatment significantly reduced root length by 61.7%, root dry weight by 54.2%, plant height by 39.6%, leaf number by 29.2%, and stem diameter by 27.8%, alongside a 32.9% decline in shoot dry weight. Reproductive traits were similarly impaired, reducing individual fruit weight by 34.6% and total fruit yield per plant from ~1.4 kg to ~0.3 kg. These findings demonstrate that soil arsenate severely compromises brinjal productivity; thus, proper soil management and suitable cultivation practices need to be adopted for sustainable vegetable production in arsenic affected areas.

Keywords: Arsenate toxicity; Soil contamination; Vegetative growth; Root development; Fruit yield.

INTRODUCTION

Arsenic (As) is a naturally occurring toxic metalloid that enters agricultural environments through geogenic processes and human activities. In South Asia, particularly Bangladesh and West Bengal, India, arsenic-contaminated groundwater poses a concern because it is widely used for both drinking and crop irrigation (Chowdhury *et al.*, 2001; Bundschuh *et al.*, 2012). Repeated irrigation with arsenic-bearing water can increase arsenic accumulation in agricultural soils, impair crop productivity and facilitate its transfer into the food chain (Meharg and Hartley-Whitaker, 2002; Sandhi *et al.*, 2022). These interconnected effects highlight the need to understand crop responses to arsenic exposure under defined experimental conditions.

The phytotoxicity of arsenic depends on its chemical form and availability, which are influenced by soil redox conditions, pH, texture and phosphate availability, as well as plant species and genotype. Arsenate [As(V)], a structural analogue of phosphate, can enter plant roots through phosphate transport systems and interfere with phosphate-dependent metabolic processes (Abedin and Meharg, 2003). Arsenic exposure can also promote reactive oxygen species formation, damage cellular membranes, disrupt nutrient balance and reduce photosynthetic performance. These disturbances may suppress root and shoot growth and impair reproductive development, although their severity varies with exposure level and growing conditions (Bali and Sidhu, 2021; Yadav *et al.*, 2024; Zaidi *et al.*, 2024).

Brinjal (*Solanum melongena* L.), also known as eggplant, is an economically important vegetable crop in Bangladesh, cultivated during both the *kharif* and *rabi* seasons. It contributes to smallholder income and provides dietary fibre, minerals and antioxidant compounds. In Bangladesh, brinjal cultivation occupied more than 50,000 hectares and produced approximately 378,000 metric tons annually (BBS, 2020). Its importance in local farming

systems and diets makes its response to contaminated soils relevant to agricultural productivity and food safety. Arsenic accumulation and phytotoxic effects in some vegetable crops have been studied, indicating the need for crop-specific assessments (Farid *et al.*, 2003; Shaibur *et al.*, 2009). Although arsenic toxicity has been extensively investigated in rice (*Oryza sativa* L.), comparatively less attention has been given to the growth and reproductive responses of brinjal under controlled soil arsenic application levels (Abedin *et al.*, 2002b; Shah *et al.*, 2004; Alam and Islam, 2011). Evaluating vegetative growth, root development, biomass-related traits and fruit attributes together can help characterize the extent of phytotoxic injury. However, these measurements alone cannot establish arsenic concentrations in edible fruits or determine whether the harvested produce is safe for consumption. The present pot study therefore evaluated the response of brinjal cultivar BARI Brinjal 5 to four nominal soil-applied arsenic levels supplied as arsenate: 0, 25, 50 and 75 mg As kg^{-1} soil. Hence, the main objectives were to assess the growth and yield responses of brinjal (*Solanum melongena* L.) to increasing levels of soil arsenic contamination.

MATERIALS AND METHODS

A. Experimental site and season

The pot experiment was conducted from November 2021 to April 2022 at the Agroforestry and Environmental Science Research Farm of Sher-e-Bangla Agricultural University, Dhaka, Bangladesh (coordinates:23° 46′ 17″ N, 90° 22′ 32″ E; elevation 8.6 m above sea level). The site belongs to the Madhupur Tract (Agro-Ecological Zone AEZ-28) and experiences a subtropical monsoon climate characterized by scanty rainfall and moderate temperatures during the winter (*rabi*) season. During the experimental period, mean monthly minimum and maximum temperatures ranged from 18.17° to 31.60°C.

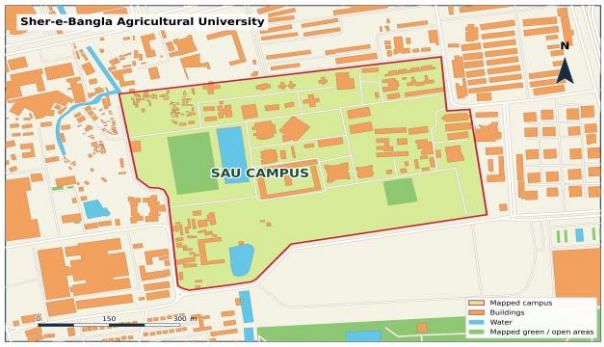


Figure 1. Geographical location of the experimental site at Sher-e-Bangla Agricultural University

B. Soil and planting material

Topsoil (0–15 cm) was collected from the Agronomy Farm of Sher-e-Bangla Agricultural University. The initial soil was air-dried, sieved through a 2 mm mesh to remove crop residues and debris, and thoroughly mixed. Physical and chemical analysis revealed a silty clay loam texture with pH 6.2, electrical conductivity (EC) 2.0 dS m^{-1}, total nitrogen 0.03%, organic carbon 0.45%, organic matter 0.78%, available phosphorus 20 mg kg^{-1}, available sulfur 45 mg kg−1 and exchangeable potassium 0.01 meq 100 g^{-1}. These baseline values were attributed to the Soil Resource Development Institute. BARI Brinjal 5 seeds were obtained from the Genetic Resources Centre of the Bangladesh Agricultural Research Institute, Joydebpur, Gazipur.

C. Pot preparation and crop management

Sixteen plastic pots were used with four replicates per treatment. Each pot was 35 cm in top diameter and 30 cm in height and filled with 14 kg of air-dried soil. Fertilizer doses were calculated based on initial soil test values following the Fertilizer Recommendation Guide (BARC, 2012). Basal fertilizer applications per pot included 7.0 g urea, 7.0 g Triple Superphosphate (TSP), 3.0 g Muriate of potash (MoP) and 2.0 g Gypsum, together with 100 g cow dung. One-third of the urea and the other stated inputs were incorporated with soil before planting; the remaining urea was top-dressed at 25 and 45 days after transplanting (DAT). Healthy, uniform 35-day-old brinjal seedlings (*Solanum melongena* cv. BARI Brinjal 5), raised at the SAU farm nursery, were transplanted into experimental pots in early January 2022 (two seedlings per pot, later thinned to one well-established seedling per pot). Pots were irrigated on alternate days to maintain soil moisture near field capacity. Weeding, mulching, staking and plant-protection practices were undertaken as needed at the pre-flowering stage. Insect pests and viral diseases were managed using preventative applications of Ripcord (2.0 mL L^{-1}), volume Flexi (0.5 mL L^{-1}), and Virtako as required.

D. Experimental Design and Arsenic Treatments

The experiment was laid out in a single-factor Completely Randomized Design (CRD) with four replications. Four arsenic treatments were applied: T_1, control (0 mg As kg^{-1} soil); T_2, (25 mg As kg^{-1} soil); T_3, (50 mg As kg^{-1} soil); and T_4, (75 mg As kg^{-1} soil). Arsenic treatments were prepared using analytical-grade sodium arsenate ($Na_2HAsO_4 \cdot 7H_2O$) dissolved in deionized water and thoroughly incorporated into the pot soil 7 days after seedling transplanting (DAT) to simulate topsoil contamination.

E. Data Collection and Harvesting

Growth parameters were recorded periodically up to 70 DAT and data were collected for plant height, stem diameter, number of leaves, leaf length and breadth, root length after harvest, root weight, shoot weight, number of flowers, number of fruits, fruit length, fruit diameter, individual fruit weight, and fruit yield. Plant height (cm) and stem diameter (cm) measured using a digital vernier caliper at 5 cm above soil line); total leaf count per plant, leaf length (cm), and leaf breadth (cm) were recorded at peak vegetative growth. Reproductive metrics, including flower count per plant, fruit count per plant, fruit length

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(cm), fruit diameter (cm), and individual fruit weight (g), were recorded during harvesting (March 15 to April 30, 2022). Total fruit yield per plant (kg) was calculated as the product of fruit count per plant and mean individual fruit weight. At final harvest, plants were uprooted, and roots were washed in distilled water to determine dry-basis root length (cm), post-harvest root weight (g), and shoot weight (g).

F. Statistical analysis

Data were analyzed using a single-factor CRD model for analysis of variance (ANOVA). Treatment means were separated using the Least Significant Difference (LSD) test at $p \leq 0.05$. The Coefficient of Variation (CV%) was computed to determine experimental precision, with all statistical procedures executed in R software and RStudio.

RESULTS

Vegetative growth and leaf traits

Inorganic arsenate application significantly impacted all measured vegetative growth parameters at 70 DAT (Table 1). Plant height declined continuously with increasing soil arsenate concentrations. The control plants (T_1) were tallest (60.00 cm), followed by T_2 (48.25 cm), T_3 (44.25 cm) and T_4 (36.25 cm). Relative to the control, the T_4 treatment (75 mg As kg^{-1} soil) was 39.6% shorter. The number of leaves decreased from 53.00 per plant in the control to 46.50 in T_2, 37.75 in T_3 and 37.50 in T_4. Stem diameter also declined, from 1.15 cm in T_1 to 0.83 cm in T_4 representing a 27.8% reduction. Treatment T_2 (1.10 cm) maintained a stem diameter comparable to T_1, whereas T_4 exhibited significant thinning relative to the control. Leaf production and expansion were also constrained by arsenic stress. Maximum leaf count per plant was recorded in T_1 (53.00), whereas plants in T_3 (37.75) and T_4 (37.50) exhibited a 29.2% reduction in leaf number. Leaf length decreased numerically from 19.08 cm in the control to 16.00 cm at the highest treatment (T_4), while leaf breadth was significantly decreased from 13.23 to 10.00 cm indicating progressive reduction in leaf photosynthetic area. These results collectively indicate suppression of canopy development under increasing arsenic exposure (Table 1).

Table 1. Vegetative growth and leaf traits of brinjal under different arsenic treatments

Treatment	Plant height (cm)	Stem diameter (cm)	Leaf number	Leaf length (cm)	Leaf breadth (cm)
T_1	60.00 a	1.15 a	53.00 a	19.08 a	13.23 a
T_2	48.25 ab	1.10 a	46.50 ab	19.00 a	12.10 b
T_3	44.25 b	0.98 ab	37.75 b	17.70 a	11.13 b
T_4	36.25 b	0.83 b	37.50 b	16.00 a	10.00 c
CV (%)	12.75	14.06	8.46	11.36	5.44
LSD value	12.64	0.23	12.90	9.00	1.01

Note: In a column having similar letters (s) are statistically similar and those having dissimilar letter (s) differ significantly at 0.05 level of probability. [T_1: Control (No arsenic in the soil); T_2: 25 mg As kg^{-1} soil; T_3: 50 mg As kg^{-1} soil; T_4: 75 mg As kg^{-1} soil applied]

Root length and root/shoot weight

Root length was markedly lower in arsenic-treated plants (Table 2). The control had a root length of 51.50 cm, compared with 23.25 cm at 25 mg As kg^{-1}, 20.50 cm at 50 mg As kg^{-1} and 19.75 cm at 75 mg As kg^{-1}. The reduction between the control and highest treatment was approximately 61.7%. Post-harvest root dry weight decreased and it was highest in the control (12.55 g) and lowest at 75 mg As kg^{-1} (5.75 g), representing a 54.2% biomass reduction. Intermediate treatments T_2 (7.13 g) and T_3 (8.87 g) showed moderate biomass reductions. Post-harvest shoot dry weight similarly declined from 55.57 g in T_1 to 49.41g (T_2), 40.44 g (T_3), and 37.28 g (T_4), reflecting a 32.9% overall biomass loss in top growth under high arsenate stress.

Table 2. Root and shoot biomass of brinjal under different arsenic treatments

Treatment	Root length (cm)	Root weight (g)	Shoot eight (g)
T_1	51.50 a	12.55 a	55.57 a
T_2	23.25 b	7.13 b	49.41 ab
T_3	20.50 c	8.87 ab	40.44 b
T_4	19.75 c	5.75 c	37.28 b
CV (%)	4.64	7.80	12.75
$LSD_{(0.05)}$	2.13	5.34	13.92

Note: In a column having similar letters (s) are statistically similar and those having dissimilar letter (s) differ significantly at 0.05 level of probability. [T_1: Control (No arsenic in the soil); T_2: 25 mg As kg^{-1} soil; T_3: 50 mg As kg^{-1} soil; T_4: 75 mg As kg^{-1} soil applied]

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Flowering and fruit traits

Flower number declined from 2.25 per plant in the control to 1.50, 1.25 and 1.00 in T_2, T_3 and T_4, respectively (Table 3). Fruits number were highest in the control (12.75 fruits plant^{-1}), intermediate in T_2 (9.75 fruits plant^{-1}) and T_3 (6.75 fruits plant^{-1}), and lowest in T_4 (4.00 fruits plant^{-1}). Fruit length decreased from 10.25 cm in the control to 6.38 cm at the highest arsenic treatment. Fruit diameter decreased from 9.63 to 5.88 cm, while identified individual fruit weight decreased from 111.25 to 72.75 g. The highest treatment therefore had 34.6% lower fruit weight than the control. These values indicate an adverse association between arsenic exposure and reproductive development (Table 3). A severe negative impact of arsenic treatments on brinjal fruit yield decreased continuously from T_1 to T_4 (Figure 2). The maximum fruit yield was recorded in the T_1 treatment at approximately 1.4 kg, which steadily declined across the subsequent treatments, reaching the lowest yield of roughly 0.3 kg in the T_4 treatment. Brinjal yield decline strongly suggests that arsenic toxicity severely hampered the normal physiological and reproductive processes of the plants, directly causing the drastic reduction in overall fruit production under higher arsenic stress.

Table 3. Flowering and fruit attributes of brinjal under different arsenic treatments

Treatments	Number of flowers	Number of fruits	Fruit length (cm)	Fruit girth (cm)	Individual-fruit weight (gm)
T_1	2.25 a	12.75 a	10.25 a	9.63 a	111.25 a
T_2	1.50 ab	9.75 b	8.63 b	7.88 b	93.25 b
T_3	1.25 b	6.75 c	7.63 c	7.25 b	85.25 c
T_4	1.00 b	4.00 d	6.38 d	5.88 c	72.75 d
CV (%)	11.43	11.98	6.27	5.58	3.53
$LSD_{(0.05)}$	0.75	2.23	0.82	0.68	5.12

Note: In a column having similar letters (s) are statistically similar and those having dissimilar letter (s) differ significantly at 0.05 level of probability. [T_1: Control (No arsenic in the soil); T_2: 25 mg As kg^{-1} soil; T_3: 50 mg As kg^{-1} soil; T_4: 75 mg As kg^{-1} soil applied]

Brinjal fruit yield

Fruit yield per plant decreased with increasing levels of soil arsenic contamination (Figure 2). The maximum fruit yield was observed in control treatment (T_1) with 1.42 kg plant^{-1}, followed by T_2 (0.91 kg plant^{-1}) and T_3 (0.58 kg plant^{-1}). The lowest yield was recorded in T_4 (75 mg As kg^{-1} soil) with about 0.29 kg plant^{-1}. Fruit yield was reduced by approximately 35.9%, 59.4% and 79.5% in T_2, T_3 and T_4 compared to control. These results show that fruit productivity of brinjal was significantly decreased with the increase of soil arsenic concentration.

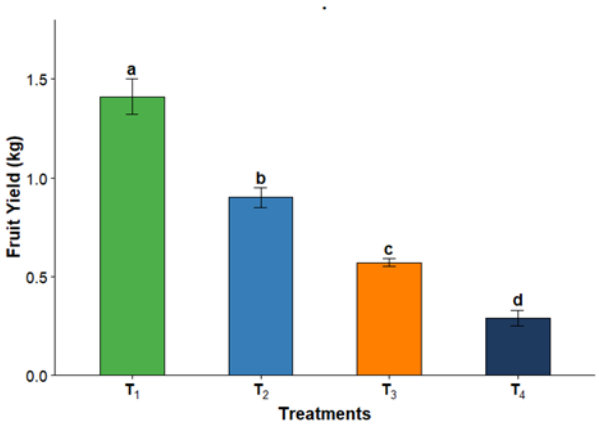


Figure 2. Brinjal fruit yield under different arsenic treatments

Note: In a column having similar letters (s) are statistically similar and those having dissimilar letter (s) differ significantly at 0.05 level of probability. [T_1: Control (No arsenic in the soil); T_2: 25 mg As kg^{-1} soil; T_3: 50 mg As kg^{-1} soil; T_4: 75 mg As kg^{-1} soil applied]

DISCUSSION

In the present study, reductions in plant height, leaf number, stem diameter and leaf breadth show that brinjal growth was negatively associated with increasing arsenic additions. Plant height decreased from T_1 (60.00 cm) to T_4 (36.25 cm), while stem diameter declined from T_1 (1.15 cm) to T_4 (0.83 cm). The strongest numerical response was observed for root length, which fell by approximately 61.7% at the highest treatment compared with the control. These responses agree with reports of inhibited shoot growth and reduced leaf production under arsenic exposure (Abedin & Meharg, 2002; Zaidi *et al*., 2024). However, leaf length remained statistically comparable among treatments. Furthermore, T_2 did not differ significantly from the control for plant height, stem diameter or leaf number, indicating that reductions in these traits were more clearly expressed at higher concentrations, this pattern is consistent with the broader literature showing that arsenic exposure can inhibit root elongation, disrupt nutrient acquisition and impair above-ground growth. Arsenate is chemically analogous to phosphate and may enter roots through phosphate transporters; its uptake can disturb phosphorus-related metabolism and cellular energy processes (Liu *et al*., 2024; Bali & Sidhu, 2021). Arsenic-related oxidative stress is another potential contributor. Recent reviews describe the generation of reactive oxygen species, damage to membranes and photosynthetic machinery, and changes in antioxidant defense as common responses to arsenic exposure (Zulfiqar & Ashraf, 2022; Zaidi *et al*., 2024; Yadav *et al*., 2024). The smaller leaves and shorter plants observed here could be consistent with impaired photosynthesis and cell expansion.

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The pronounced decrease in root length suggests that root growth was particularly sensitive to the arsenic treatments. Root length decreased from T_1 (51.50 cm) to T_2 (23.25 cm), T_3 (20.50 cm) and T_4 (19.75 cm), demonstrating significant inhibition even at the lowest dose (Table 2). This agrees with previous observations of restricted root growth in arsenic-exposed rice seedlings (Abedin & Meharg, 2002; Shri *et al*., 2009). Root dry weight declined from T_1 (12.55 g) to T_4 (5.75 g), although intermediate treatments did not follow a strictly decreasing pattern. Shoot dry weight also declined from T_1 (55.57 g) to T_4 (37.28 g), with significant reductions in T_3 and T_4. The larger proportional reductions in root length and root dry weight than in shoot dry weight suggest a particularly pronounced root response. Likewise, a smaller root system may reduce the capacity to explore soil for water and nutrients, potentially amplifying growth limitations under stress. Root weight also declined numerically at the highest dose. This distinction is important: the observed data support a clear reduction in root length, but they do not establish a statistically significant effect on shoot weight. In addition, the manuscript does not specify whether weights represent fresh or dry biomass, which limits physiological interpretation and comparison with other studies.

The reduction in flower number, fruit number, fruit length, fruit diameter and fruit weight indicates that reproductive traits were adversely associated with increasing arsenic exposure. Fruit weight was 34.6% lower at 75 mg As kg^{-1} than in the control, and fruit number declined from 12.75 to 4.00 fruits per plant. Such responses may reflect the combined effects of reduced vegetative growth, root impairment and stress-related disruption of reproductive development. Yield decreased progressively from T_1 to T_4, with significant differences among all treatments (Figure 2). This indicates that productivity was affected even at the lowest arsenate dose tested. Comparable reductions in crop growth and reproductive output have been reported under arsenic exposure (Abedin *et al*., 2002a; Shri *et al*., 2009). Reviews of arsenic toxicity report broad effects on plant growth and productivity, although response magnitude varies with crop species, genotype, arsenic speciation and soil conditions (Bali & Sidhu, 2021; Yadav *et al*., 2024).

CONCLUSION

The present study demonstrates that soil contamination with inorganic arsenate [As(V)] from 0 to 75 mg As kg^{-1} severely impairs the vegetative growth, root development, biomass accumulation, and fruit yield of brinjal (*Solanum melongena* L., cv. BARI Brinjal 5). The adverse effects generally intensified with the increasing arsenate concentrations and the most pronounced responses observed at 75 mg As kg^{-1} soil. Compared with the control, root length decreased by 61.7%, root weight by 54.2%, plant height by 39.6%, shoot weight by 32.9%, and individual fruit weight by 34.6%. Furthermore, arsenate exposure reduced flower and fruit production, fruit size, and overall fruit yield, indicating that reproductive performance was particularly vulnerable to arsenic-induced stress. These findings highlight the potential for arsenic contamination to compromise brinjal productivity and threaten the sustainability of vegetable cultivation in contaminated soils. Future research might be investigate arsenic accumulation in roots, shoots, and edible fruits to evaluate the potential of food-safety risks, and assess suitable soil remediation strategies and low-accumulating cultivars under field conditions. Such efforts are essential for developing safer and more sustainable brinjal production systems in arsenic-affected agricultural regions.

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Conflict of Interest

The author declares no conflict of interest.

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