

RESEARCH ARTICLE OPEN ACCESS

Biochar Mitigates Arsenic Phytotoxicity and Improves Crop Performance in Iron-Rich Tropical Soils

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ABSTRACT

The contamination of tropical soils by the highly toxic metalloid, arsenic (As), is a pervasive issue, resulting in declining crop performance due to phytotoxicity. Biochars are gaining popularity as sorbents for contaminants, yet their capacity to ameliorate As phytotoxicity in diverse tropical soil types remains underexplored. This study investigated the interactive effects of biochar and As on the growth and physiology of rice (*Oryza sativa*) and potato (*Solanum tuberosum*) across two distinct tropical Oxisols: agricultural soil and iron-rich soil. While the experimental design focused on biochar × arsenic interactions without a standalone biochar control, results indicated that biochar effectiveness is highly soil-mineralogy dependent. In the Fe-rich soil, biochar significantly mitigated As-induced stress, as evidenced by a 44% increase in potato biomass. Furthermore, biochar application in arsenic-contaminated iron soils significantly improved the maximum quantum yield of Photosystem II (F_v/F_m) by 39% over arsenic-only treatments ($p < 0.001$), restoring absolute F_v/F_m values from a severely stressed state (~ 0.55) to a more physiologically stable range (~ 0.76). In contrast, biochar application in the agricultural soil was less effective and, in some cases, exacerbated growth inhibition. These findings suggest that while biochar is a promising tool for mitigating As-induced phytotoxicity in Fe-rich tropical environments, its application must be soil-specific. Future research should quantify tissue As concentrations to confirm dietary risk reduction.

1 | Introduction

Arsenic (As) contamination is a critical global environmental and public health concern. Inorganic arsenic, primarily ingested through drinking water and food, is especially toxic and poses severe health risks, including cancer and neurological disorders (Mandal and Suzuki 2002). Arsenic contamination in groundwater affects millions of people worldwide (Table 1), with Asia accounting for 94% of the global affected population (Podgorski and Berg 2020). Among the most severely impacted countries is Bangladesh, where naturally occurring arsenic in groundwater has led to chronic exposure among rural populations (Ahmad et al. 2018).

Arsenic enters the food chain mainly through irrigation with contaminated groundwater. Long-term use of such water and arsenic-based agrochemicals leads to persistent soil contamination (Murcott 2012). Paddy fields, due to their flooded anaerobic conditions, promote the mobilization and uptake of the more toxic arsenite [As(III)] form of arsenic, especially by rice, which is a dietary staple and an efficient arsenic accumulator (Takahashi et al. 2004; Zhao et al. 2009). Rice cultivars exhibit significant variability in arsenic uptake, with some translocating less arsenic from root to grain (Meharg and Hartley-Whitaker 2002).

Similarly, potato, widely consumed and cultivated in arsenic-affected areas like Bangladesh and parts of India, shows arsenic

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accumulation in peel and outer tissues (Roychowdhury et al. 2003). Identifying cultivars of rice and potato with low arsenic accumulation potential is therefore essential for reducing dietary exposure and guiding future breeding efforts (Tripathi et al. 2012).

Biochar is a carbon-rich material derived from pyrolyzed biomass and applied to soils for multiple benefits: carbon sequestration, soil fertility enhancement, and pollution remediation. Its properties depend on feedstock type and pyrolysis conditions. Biochars produced from wood at high temperatures (550°C–600°C) tend to have high surface area, porosity, and sorption capacity, making them particularly effective for inorganic contaminant immobilization (Kloss et al. 2012).

In this study, biochar was produced from *Acacia auriculiformis* wood using a Kon-Tiki flame curtain kiln. The resulting biochar featured a high surface area ranging from 250 to 350 m²/g, an alkaline pH of 9 to 10, notable aromatic carbon content with trace amounts of iron (Fe), and a moderate cation exchange capacity (CEC). These combined properties make the biochar suitable for adsorbing arsenic through electrostatic attraction, surface complexation, and co-precipitation. These characteristics make *Acacia*-derived biochar particularly suitable for adsorption of inorganic contaminants such as arsenic through mechanisms like electrostatic attraction, surface complexation, and co-precipitation.

Despite the potential for biochar to sequester As, its performance in tropical soils is inconsistent. The efficacy of biochar in these systems is often governed by the soil's mineralogical composition, particularly the presence of iron (Fe) oxides. Iron oxides have a high affinity for arsenate and arsenite, and the addition of biochar may facilitate the formation of Fe–As complexes or stimulate the development of root iron plaques that act as a barrier to As entry into the plant (Yin et al. 2017; Mohan et al. 2014; Yang et al. 2022). However, the specific mechanisms of biochar-mediated mitigation in Fe-rich vs. low-Fe tropical soils under field conditions remain poorly understood. In this study, we assessed the physiological and growth responses of two staple crops to biochar amendment under arsenic stress. We hypothesize that biochar's effectiveness in reducing As-induced phytotoxicity is contingent upon soil Fe content, with greater efficacy expected in Fe-rich soils due to hypothesized Fe–As–biochar interactions. By evaluating parameters such as biomass and photosynthetic efficiency, we aim to clarify the conditions under which biochar can be reliably used as a strategy for managing crop performance in As-affected tropical regions.

2 | Materials and Methods

2.1 | Study Area

The experimental study was conducted at the nursery of the Department of Forestry and Environmental Science, Shahjalal University of Science and Technology (SUST), Sylhet, Bangladesh (24°55′01.74″ N and 91°49′53.86″ E). The study ran from August 2016 to February 2017, totaling 180 days. The average daily temperature ranged between 25°C and 33°C with relative humidity of 75%–85%. The nursery bed measured 3 m by 15 m, fenced on all sides with bamboo to prevent animal entry, while remaining uncovered to ensure uniform sunlight exposure.

2.2 | Biochar Production and Characterization

Biochar was produced from *Acacia auriculiformis* wood using a Kon-Tiki flame curtain kiln (Figure 1) at approximately 650°C. While proximate analysis was not performed, biochars derived from *Acacia* species at these temperatures are typically characterized by high stability and low to moderate ash content (~3%–5%). The material featured a high surface area (250–350 m²/g) and an alkaline pH (9.0–10.0), which are key determinants of its capacity for electrostatic attraction and surface complexation of inorganic contaminants like arsenic.

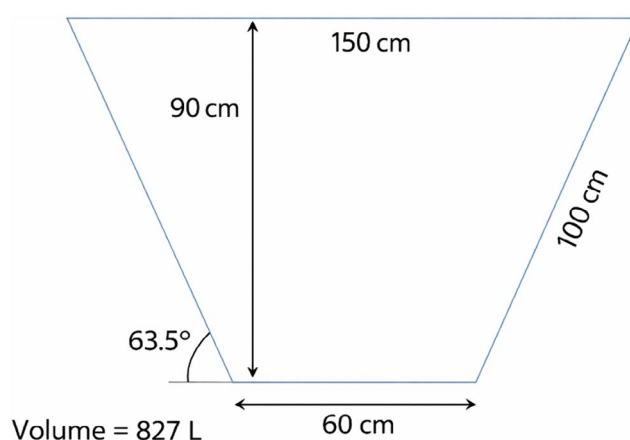


FIGURE 1 | Kon-Tiki kiln design.

TABLE 1 | Number of countries affected by arsenic contamination in groundwater in each continent ($\geq 10 \mu\text{g/L}$) and the proportions of the areas and populations affected. Information source: Podgorski and Berg (2020).

Continent	Countries affected	Proportion of globally affected areas	Proportion of total global affected population
Asia	31	64%	94%
South America	9	14%	1.6%
North America	11	10%	0.6%
Africa	20	9%	3.7%
Oceania	4	2%	0.01%
Europe	31	1%	0.2%

TABLE 2 | Soil properties.

Soil type	Soil properties						
	Soil pH	Moisture (%)	Organic carbon (%)	Total N (%)	Available P (mg/kg)	Available K (mg/kg)	Available Fe (mg/kg)
Agricultural soil	5.2	21.2	9.1	0.11	10.28	0.09	< LOD
Iron soil	6.6	13.45	10.9	0.08	3.14	0.11	26.8

Note: < LOD indicates values were below the analytical Limit of Detection or significantly lower than the Fe-rich soil.

Block	Species	T1: Normal Agricultural Soil (Control)	T2: Normal Iron Soil (Control)	T3: Arsenic Contaminated Agricultural Soil	T4: Arsenic Contaminated Iron Soil	T5: Arsenic Contaminated Agricultural Soil + Biochar	T6: Arsenic Contaminated Iron Soil + Biochar
Block 1	Rice Bina - 32	T1	T2	T3	T4	T5	T6
	BR - 34	T1	T2	T3	T4	T5	T6
	Potato	T1	T2	T3	T4	T5	T6
Block 2	Rice Bina - 32	T1	T2	T3	T4	T5	T6
	BR - 34	T1	T2	T3	T4	T5	T6
	Potato	T1	T2	T3	T4	T5	T6
Block 3	Rice Bina - 32	T1	T2	T3	T4	T5	T6
	BR - 34	T1	T2	T3	T4	T5	T6
	Potato	T1	T2	T3	T4	T5	T6
Block 4	Rice Bina - 32	T1	T2	T3	T4	T5	T6
	BR - 34	T1	T2	T3	T4	T5	T6
	Potato	T1	T2	T3	T4	T5	T6

FIGURE 2 | Experimental units and treatments.

2.3 | Soil Selection and Baseline Characterization

Two distinct tropical soil types (Oxisols) were sourced from Sylhet, Bangladesh: (i) a standard agricultural soil from cultivated fields and (ii) an iron-rich soil from hillocks near SUST. Baseline properties are detailed below (Table 2). Crucially, the agricultural soil served as a low-Fe control compared to 26.8 mg/kg in the iron-rich soil. Both soils were sieved to 2 mm before experimental setup.

2.4 | Arsenic and Biochar Application

The experiment followed a Complete Randomized Block Design (CRBD) with four replicates. The treatment structure evaluated the interaction between soil type, As contamination, and biochar amendment. Sodium arsenate ($\text{Na}_2\text{HAsO}_4 \cdot 7\text{H}_2\text{O}$) was applied at 9 mg kg^{-1} to simulate moderate regional contamination. Biochar was incorporated at a rate of 10 t ha^{-1} (750 g per 2 m^2 plot).

We explicitly note that the study design did not include a biochar-only (non-arsenic) control. Consequently, all observed responses are interpreted as biochar $\times$ arsenic interactions rather than independent biochar effects.

TABLE 3 | Agricultural crop species.

Species name	Scientific name	Family
Amon Bina-32	<i>Oryza sativa</i>	Poaceae
BR-34	<i>Oryza sativa</i>	Poaceae
Potato	<i>Solanum tuberosum</i>	Solanaceae

Sodium arsenate was applied to simulate arsenic contamination at 9 mg kg^{-1} , a concentration typical of moderately contaminated South Asian soils (Meharg and Rahman 2003). Arsenic was dissolved in water and mixed into soil before transplanting. Biochar was applied at a rate equivalent to 10 t ha^{-1} , corresponding to 750 g per 2 m^2 plot based on a soil bulk density of 1.25 g/cm^3 and incorporation depth of 10 cm. Biochar was mixed thoroughly into the topsoil layer to ensure root zone interaction. The layout is shown below (Figure 2).

2.5 | Seedling Preparation and Transplanting

Seeds of rice (Bina-32 and BR-34) were obtained from Ancholic Beej Betan, a commercial nursery, and potato seeds from Sylhet Nursery (Table 3). Germination occurred under

ambient conditions (25°C–30°C) in trays with daily watering. Germination success exceeded 85%. After 30 days, uniform seedlings were transplanted into 2 m × 2 m plots with 3–5 seedlings each and 30 cm spacing. Randomization within blocks was performed to avoid positional bias.

2.6 | Growth and Physiological Monitoring

Growth parameters, including shoot height and leaf area, were recorded weekly. Leaf area for rice was calculated as $LA = L \times W \times 0.75$ (Palaniswamy and Gomez 1974), and for potato using $y = 2.06x - 0.458$ (Firman and Allen 1989). At mid-growth, photosynthetic efficiency was assessed by measuring the maximum quantum yield of Photosystem II (F_v/F_m) using a PAM-2500 fluorometer. Plants were dark-adapted for 30 min prior to measurement to ensure absolute F_v/F_m values reflected the actual physiological stress state of the crops.

At harvest, plant parts (shoots, roots, leaves, reproductive organs) were separated and oven-dried at 65°C for 24 h. Constant weight was confirmed by repeated weighing. Biomass was determined using a precision digital balance.

2.7 | Soil Analysis

Post-harvest soils (100 g per plot) were analyzed at the Soil Laboratory, SUST. Available N was measured via the Kjeldahl method, P by Olsen extraction, K via flame photometry, and Fe by atomic absorption spectrophotometry (AAS) at SRDI, Sylhet. All measurements reflect plant-available forms.

2.8 | Statistical Analysis

All statistical computations were performed in R (v4.3.1). A three-way ANOVA was employed to determine the main and interactive effects of Soil Type (2 levels) × Arsenic (2 levels) × Biochar (2 levels) on growth, biomass, and soil nutrients. Normality and homoscedasticity were verified using Shapiro–Wilk and Levene's tests, respectively. Mean separations were performed using Tukey's HSD test at a significance level of $\alpha = 0.05$.

2.9 | Disclaimer (Artificial Intelligence)

The author(s) declare that generative AI technologies were utilized during the writing and editing process of this manuscript. Specifically, ChatGPT (Academic Researcher, based on OpenAI's GPT-5.2) was used for paraphrasing and refining the text while ensuring clarity and coherence. No part of the research design, data analysis, interpretation of results, or conclusions was generated by this tool, which remained the sole responsibility of the authors. All input prompts provided to the AI were designed to enhance readability without altering the original meaning or integrity of the content. The final manuscript has been reviewed and approved by the author(s) to ensure accuracy and alignment with the research objectives.

3 | Results

3.1 | Crop Growth Responses to Soil Type and Treatments

3.1.1 | Shoot Height

The three-way ANOVA for shoot height revealed highly significant differences between species ($F_{2,54} = 832.6$, $p < 0.001$) and significant effects of treatment ($F_{2,54} = 5.19$, $p < 0.01$). Biochar application in arsenic-contaminated iron-rich soil significantly enhanced shoot height across all crop species ($p < 0.05$) (Table S1). Arsenic contamination reduced shoot height across all crops compared to the control. However, the application of biochar in iron-rich soils significantly mitigated this effect, restoring shoot height to levels nearly equal to the iron-soil control. Among species, BR-34 rice had the tallest shoots, outperforming Bina-32 and potato (Figure 3).

3.1.2 | Root Length

Root elongation was primarily influenced by species ($F_{2,54} = 29.80$, $p < 0.001$) and soil type ($F_{1,54} = 4.44$, $p < 0.05$). A significant three-way interaction (Treatment × Species × Soil) was observed ($F_{6,54} = 3.08$, $p < 0.05$) (Table S2). Root length improved with biochar, particularly in arsenic-contaminated iron soils. Bina-32 showed the greatest root elongation, followed by BR-34 and potato. Biochar enhanced root development in both soil types but was more effective in iron-rich conditions (Figure 4).

3.1.3 | No. of Reproductive Parts

Reproductive output varied significantly by species ($F_{2,49} = 5.90$, $p < 0.01$) and soil type ($F_{1,49} = 5.70$, $p < 0.05$). A highly significant three-way interaction was detected ($F_{6,49} = 4.16$, $p < 0.01$) (Table S3). Reproductive part formation slightly increased with biochar, especially in iron-rich soils. BR-34 consistently produced more reproductive organs than Bina-32 and potato. In contrast, agricultural soil showed minimal response to biochar in this parameter (Figure 5).

3.2 | Biomass Accumulation

3.2.1 | Shoot Biomass

Shoot biomass was predominantly determined by species-specific growth patterns ($F_{2,54} = 73.11$, $p < 0.001$). Although the main effects of treatment and soil were not statistically significant ($p > 0.05$) (Table S4), BR-34 and Bina-32 rice consistently maintained higher biomass levels than potato under all arsenic-stress scenarios. Shoot biomass was highest in Bina-32 rice, followed by BR-34 and potato. Biochar improved shoot biomass under arsenic stress, though control plots still had slightly higher values, suggesting a potential nutrient dilution effect due to higher biomass accumulation (Figure 6).

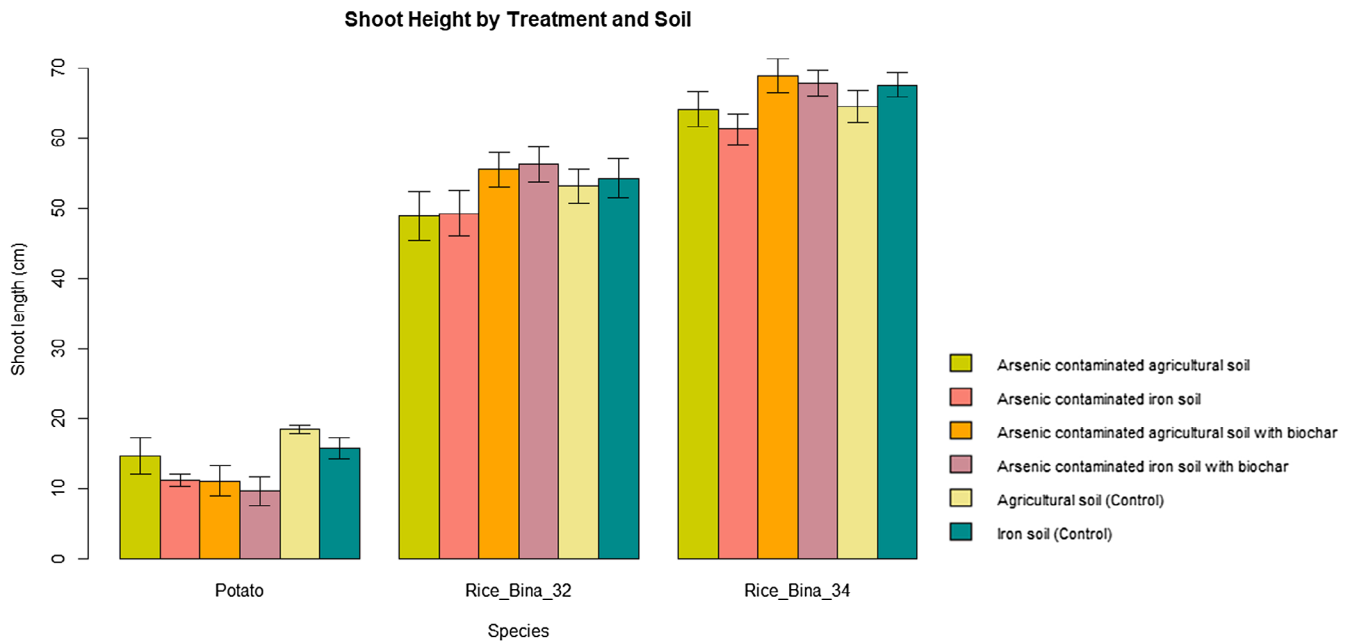


FIGURE 3 | Shoot height.

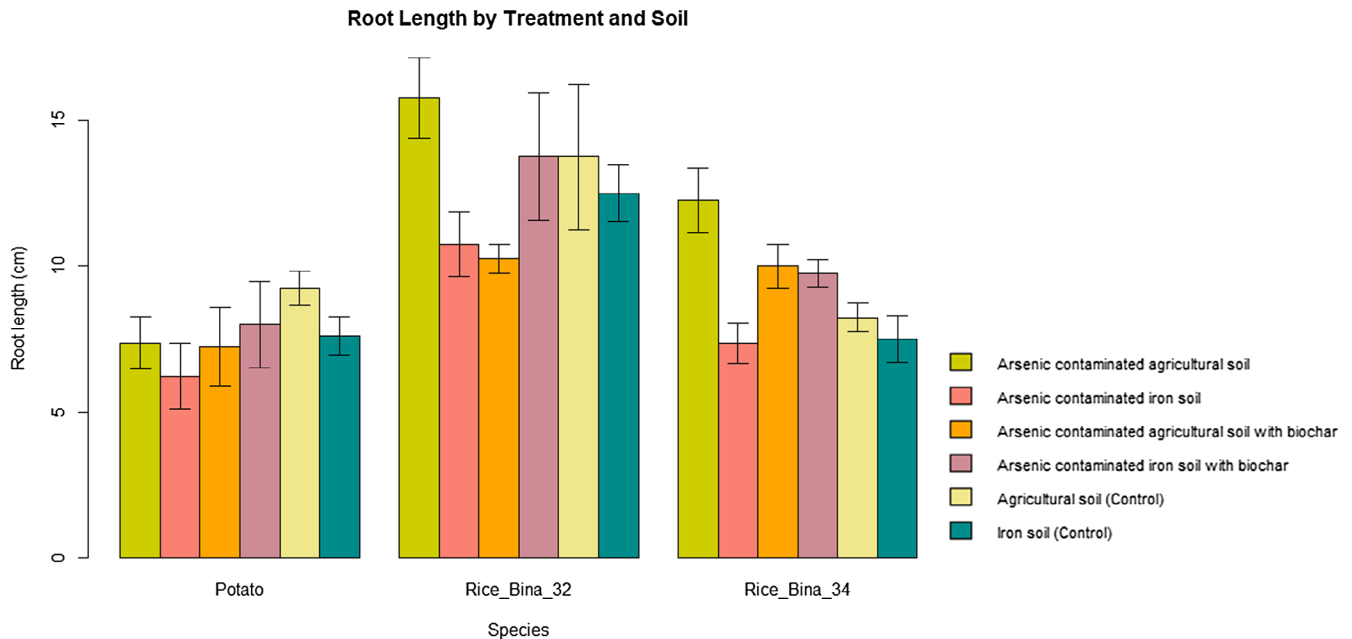


FIGURE 4 | Root length.

3.2.2 | Reproductive Biomass

Reproductive dry weight was highly dependent on species ($F_{2,47}=31.66$, $p<0.001$). The analysis showed a near-significant trend for the main effect of treatment ($F_{2,47}=2.78$, $p=0.07$) (Table S5), suggesting that biochar application has the potential to improve yield components. Bina-32 again led in reproductive biomass, with biochar increasing yield under arsenic conditions most notably in iron-rich soil. This suggests biochar aided reproductive investment despite arsenic stress (Figure 7).

3.2.3 | Root Biomass

Root biomass showed extreme variation between species ($F_{2,54}=110.87$, $p<0.001$). A highly significant three-way interaction ($F_{6,54}=5.18$, $p<0.001$) (Table S6) demonstrated that root dry matter accumulation is a sensitive indicator of the complex interplay between soil iron content, arsenic toxicity, and biochar amendment. Root biomass patterns followed root length, with Bina-32 showing the highest mass. Biochar improved root biomass under arsenic exposure, particularly in iron soils, indicating better below-ground resource acquisition (Figure 8).

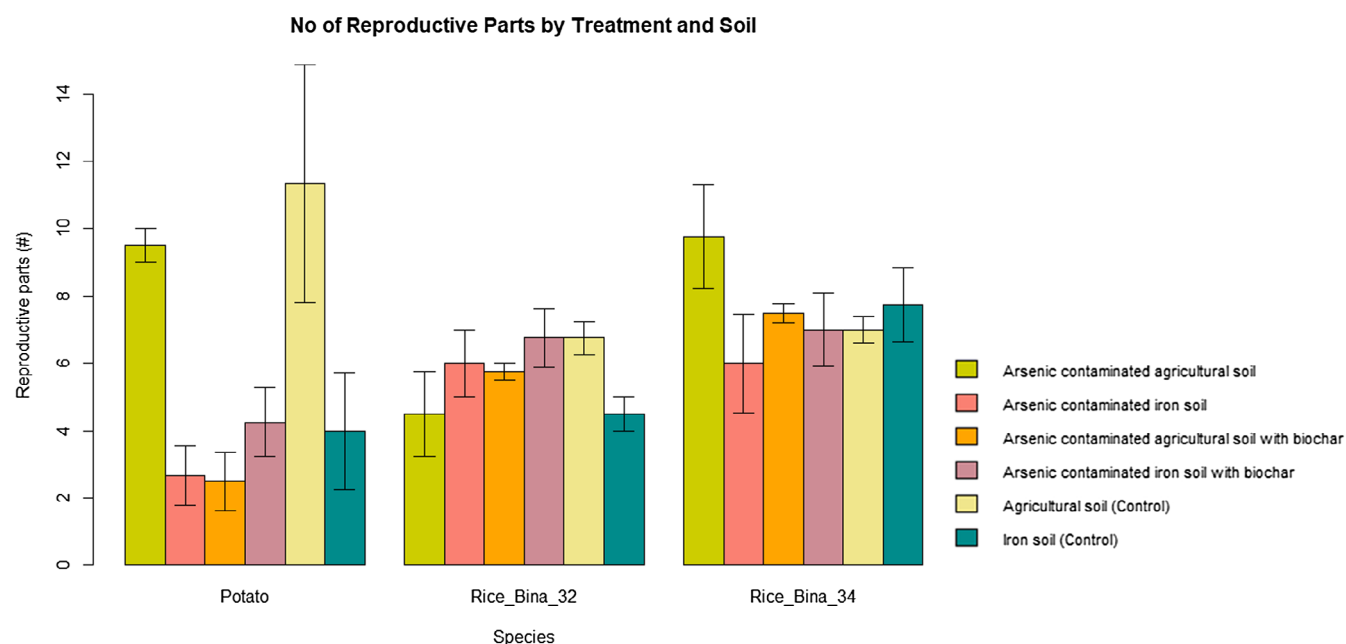


FIGURE 5 | No. of reproductive parts.

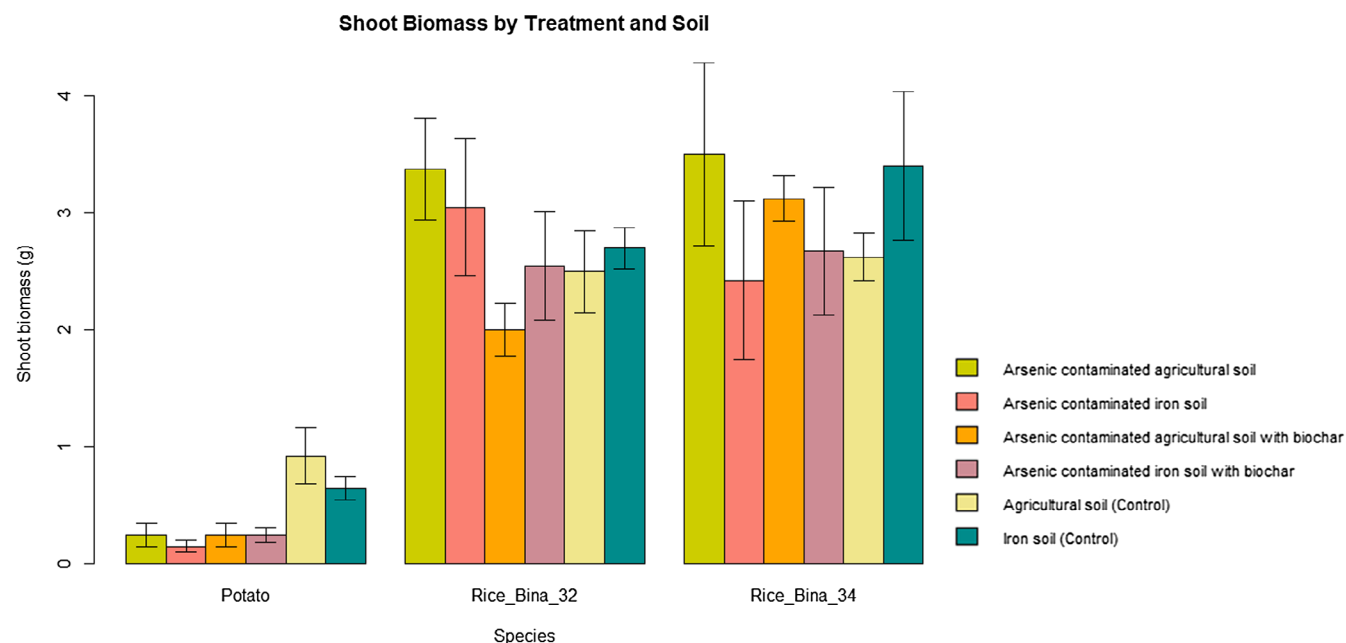


FIGURE 6 | Shoot biomass.

3.2.4 | Leaf Biomass

Leaf biomass was significantly affected by both treatment ($F_{2,54}=8.19$, $p<0.001$) and species ($F_{2,54}=87.22$, $p<0.001$) (Table S7). The strong treatment effect underscores that arsenic contamination significantly reduced foliar dry matter, while biochar application in iron-rich soils successfully recovered leaf weight to levels comparable with non-contaminated control plots for specific varieties. BR-34 had the highest leaf biomass across all treatments. Biochar-amended iron soils demonstrated higher leaf mass under arsenic stress, highlighting biochar's role in maintaining vegetative growth (Figure 9).

3.3 | Leaf Area

Total leaf area was significantly influenced by species ($F_{2,54}=52.34$, $p<0.001$), while treatment and soil effects were not statistically significant ($p>0.05$) (Table S8). This indicates that while biochar improved the density and mass of the leaves (as seen in Figure 9), the physical canopy expansion was governed primarily by the innate developmental traits of the crops rather than the soil amendments. BR-34 rice exhibited the largest leaf area. Biochar application in iron-rich soils under arsenic contamination enhanced leaf area, reinforcing the pattern seen in shoot and leaf biomass (Figure 10).

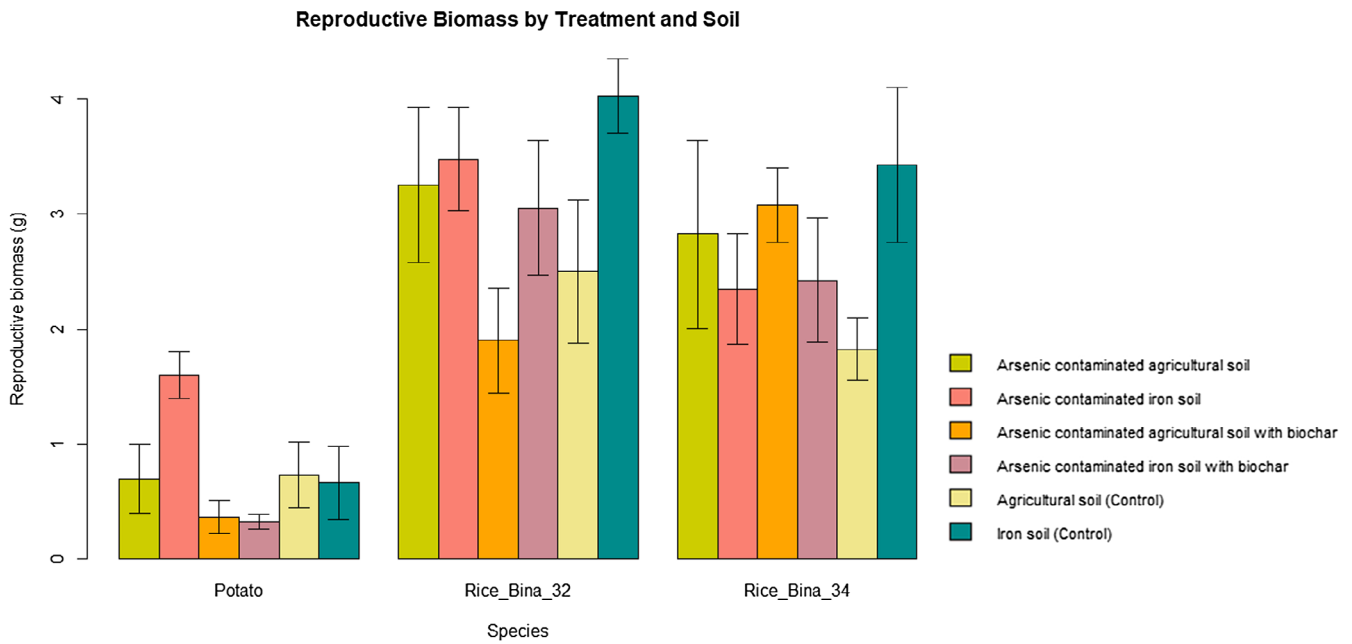


FIGURE 7 | Reproductive biomass.

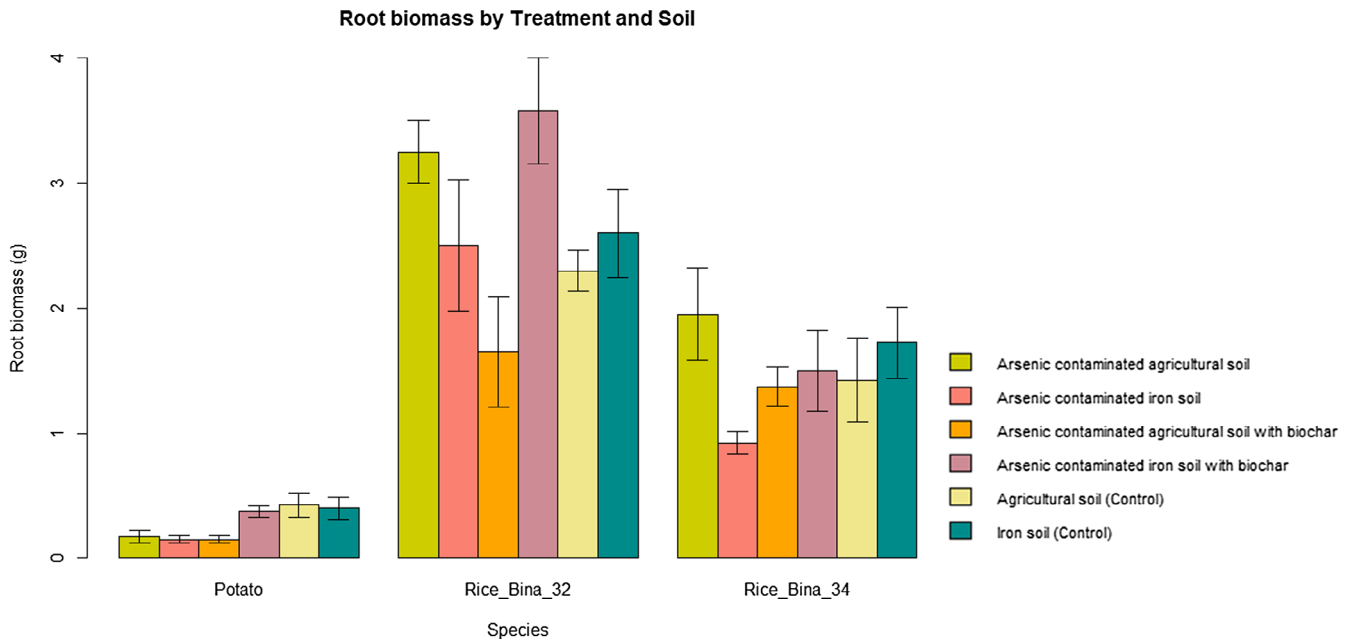


FIGURE 8 | Root biomass.

3.4 | Photosynthetic Efficiency (F_v/F_m)

Application of biochar in arsenic-contaminated iron soils significantly improved the maximum quantum yield of Photosystem II (F_v/F_m) by 39% over arsenic-only iron soil ($F=6.41$, $p<0.001$) (Table S9). This indicates substantial recovery of photosynthetic function due to biochar amendment under arsenic stress (Figure 11). This recovery moved absolute F_v/F_m values from a severely stressed state (≈ 0.55) toward a more physiologically stable range (≈ 0.76), indicating substantial restoration of the photosynthetic apparatus despite the presence of arsenic.

3.5 | Soil Nutrient Dynamics

3.5.1 | Nitrogen

The nitrogen content was highly dependent on soil type ($F=122.66$, $p<0.001$), while the main effects of time ($p=0.065$) and treatment ($p=0.576$) were not statistically significant. Interaction effects, including the three-way interaction of Time $\times$ Treatment $\times$ Soil, also showed no significant impact on nitrogen levels ($p=0.870$) (Table S10). This indicates that soil mineralogical composition, rather than biochar application or duration, was the primary driver of nitrogen variation in this

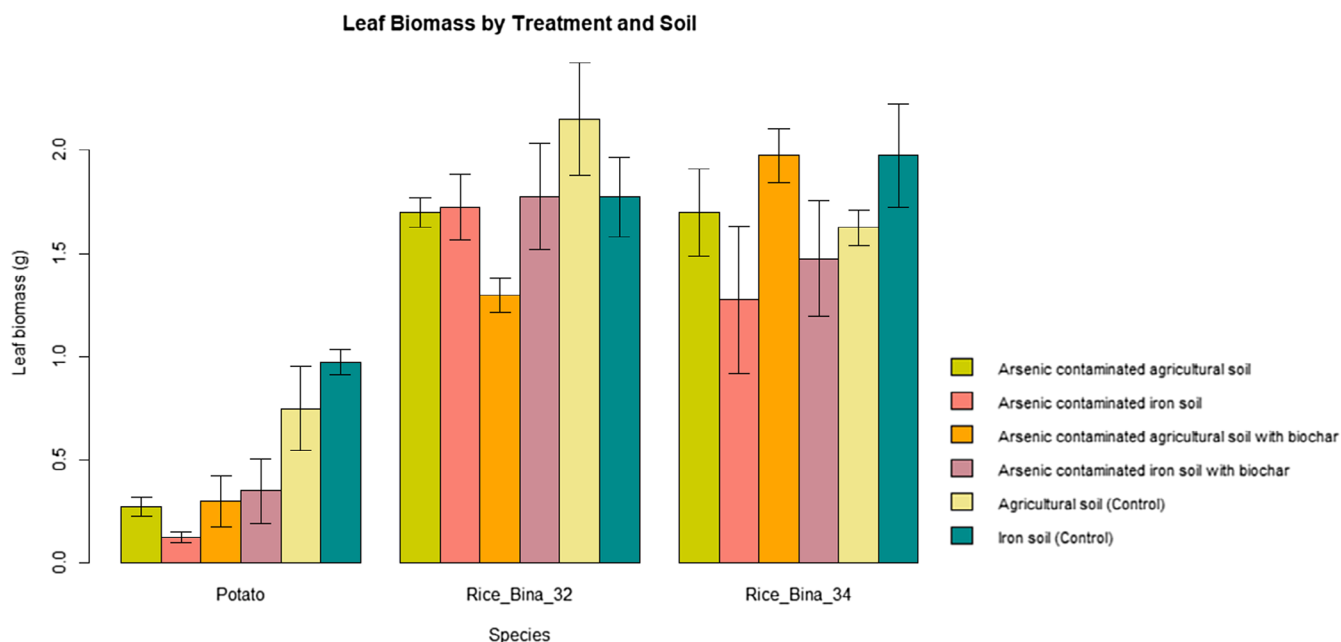


FIGURE 9 | Leaf biomass.

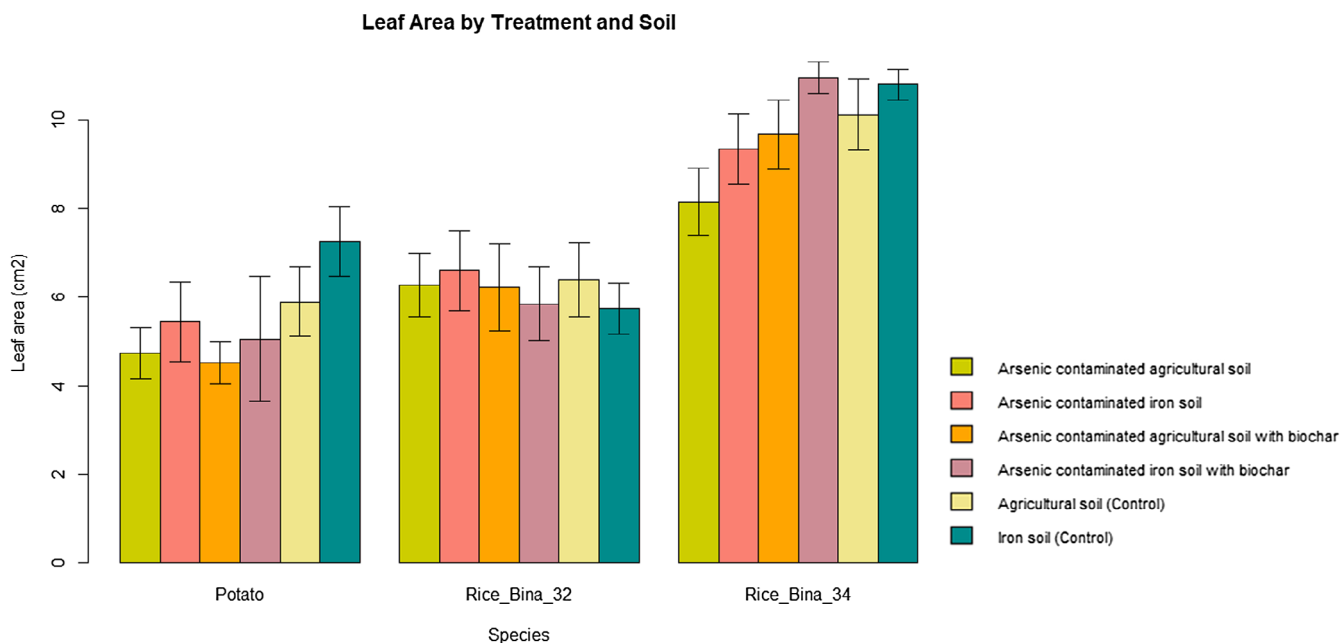


FIGURE 10 | Leaf area.

study. Soil nitrogen levels were consistently higher in agricultural soils compared to iron-rich soils, both before and after the experiment. While treatment effects were minor, time significantly influenced nitrogen availability (Figure 12).

3.5.2 | Potassium

Potassium content was significantly affected by time ($F=13.71$, $p<0.01$) and treatment ($F=5.88$, $p<0.05$), although soil type alone did not show a significant main effect ($p=0.762$). However, a highly significant Treatment $\times$ Soil interaction was observed ($F=14.59$, $p<0.001$) (Table S11), indicating that the influence of biochar on potassium levels varied significantly depending on

whether it was applied to iron-rich or agricultural soil. Biochar application resulted in the most substantial increase in available soil potassium over time, especially in iron-rich soils. This suggests that biochar enhanced potassium retention or availability in challenging soil environments (Figure 13).

3.5.3 | Phosphorus

Similar to nitrogen, phosphorus levels were significantly influenced by soil type ($F=147.20$, $p<0.001$). Neither the treatment ($p=0.215$) nor the time of observation ($p=0.250$) significantly altered phosphorus accumulation. All interaction terms, including Treatment $\times$ Soil ($p=0.334$) (Table S12), remained

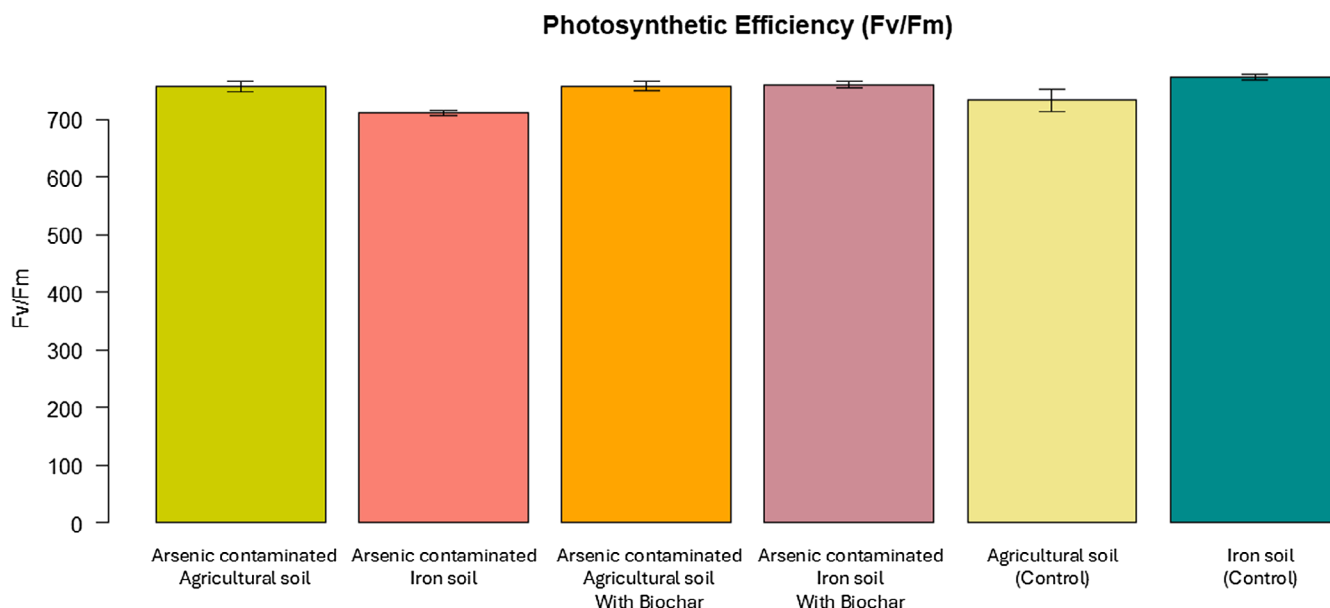


FIGURE 11 | The maximum quantum yield of photo system II (F_v/F_m).

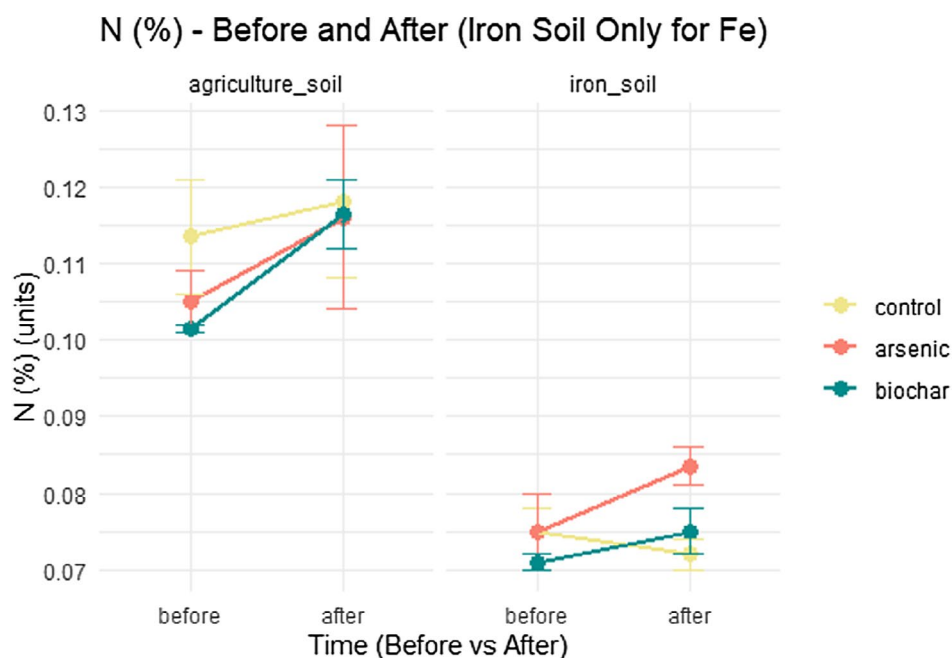


FIGURE 12 | Soil nitrogen (N).

non-significant, suggesting that phosphorus availability was inherently determined by the initial soil properties rather than the experimental amendments. Phosphorus availability was highest in agricultural soils throughout the study. Biochar modestly increased P content in both soil types, indicating its contribution to nutrient availability despite arsenic stress (Figure 14).

3.5.4 | Iron Content

The iron content in plant tissues varied significantly over time ($F=9.79$, $p<0.05$). In contrast, the treatment effect did not reach statistical significance ($p=0.242$), and no significant interaction between time and treatment was detected ($p=0.773$) (Table S13). This suggests that while iron uptake fluctuated during the

growth period, the application of biochar did not significantly shift the total iron accumulation compared to other groups. Soil iron content increased following biochar treatment, particularly in arsenic-contaminated iron soils. This likely reflects Fe–As complexation or stabilization promoted by biochar's surface properties, helping to reduce arsenic mobility (Figure 15).

4 | Discussion

4.1 | Mitigation of As-Induced Physiological Stress

The observed recovery of Photosystem II reaction centers, evidenced by the highly significant effect of the treatment-soil interaction on photosynthetic efficiency (F_v/F_m), indicates a

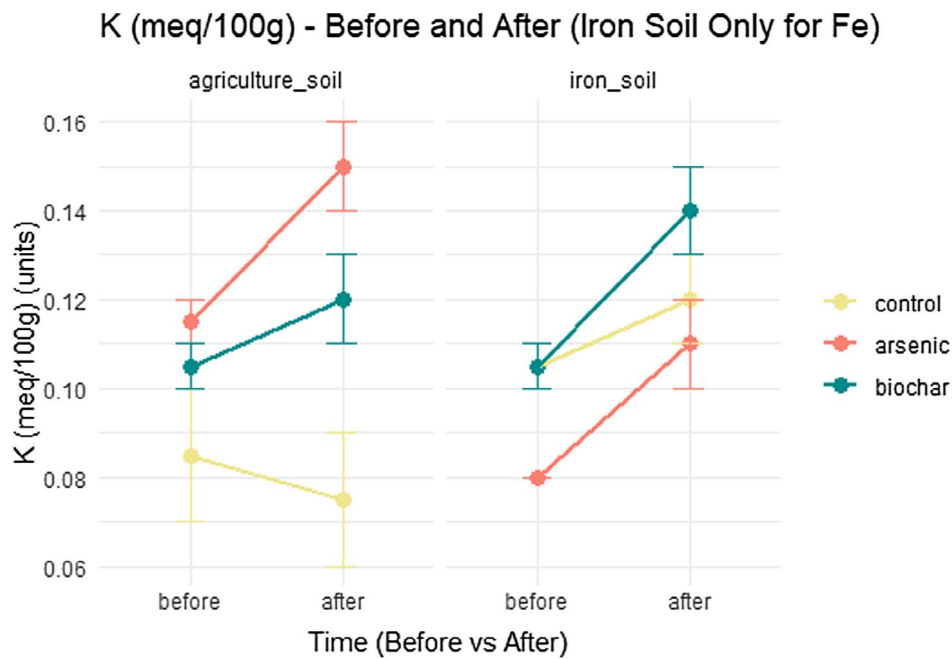


FIGURE 13 | Soil potassium (K).

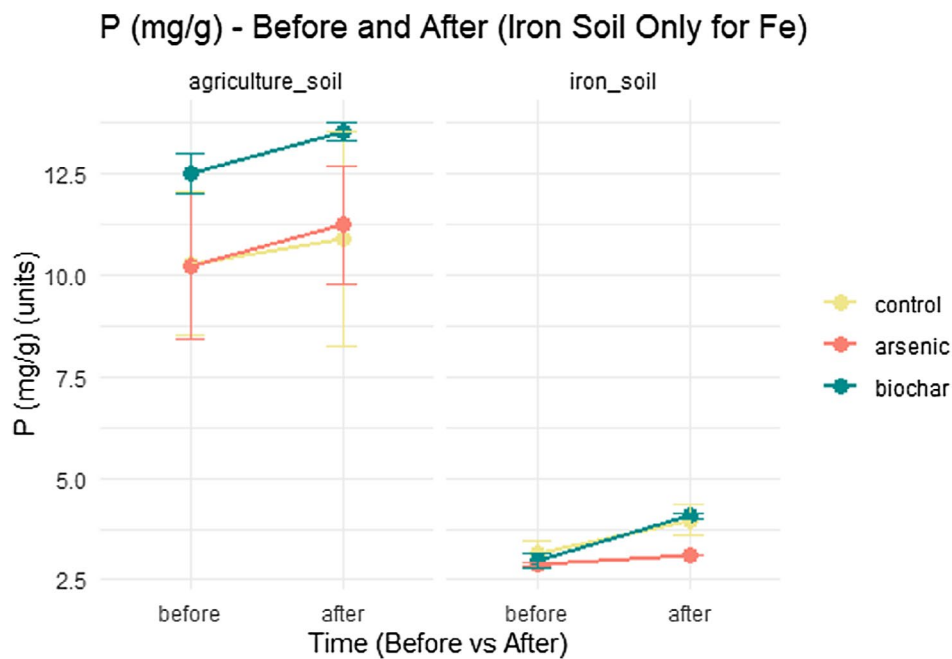


FIGURE 14 | Soil phosphorus (P).

robust physiological rescue. In biochar-treated iron-rich soils, the stabilization of the photosynthetic apparatus suggests that biochar enables the plant to remain functional despite As presence. Similar physiological rescues have been documented where biochar improved electron transport rates in rice under metalloid stress (Zhang et al. 2023). While the absence of a biochar-only control limits the ability to separate direct nutrient effects from stress-mitigation, the contrast between As-only and As + Biochar treatments aligns with findings by Hye et al. (2025) and Shamim et al. (2018) regarding the resilience of rice in Bangladeshi soils.

4.2 | The Role of Soil Iron in Biochar Efficacy

The striking soil-specific efficacy highlights a critical mechanistic interaction, as soil type was a dominant factor for Nitrogen and Phosphorus. We hypothesize that the iron-rich soil environment facilitated the formation of Fe–As–biochar complexes. This is supported by Yao et al. (2021), who demonstrated that iron-modified biochars promote the formation of iron plaques on root surfaces, acting as a “geochemical barrier” sequestering arsenic. Conversely, in the agricultural soil (pH 5.2, low Fe), the alkaline nature of biochar (pH 9–10) may induce a “liming

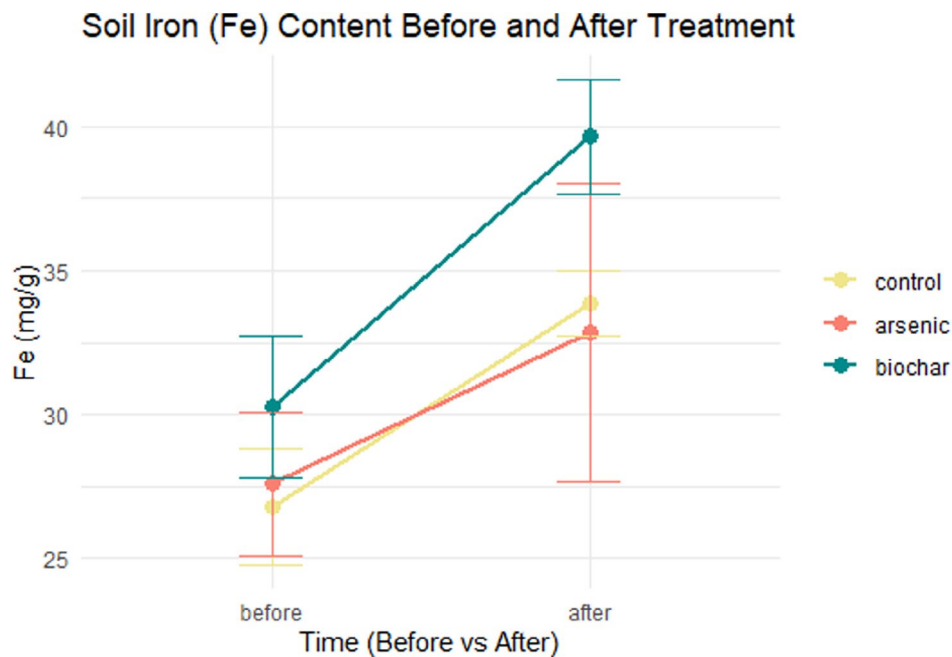


FIGURE 15 | Effect of time and treatment on iron soil.

effect” that increases the solubility of arsenate through hydroxyl (OH-) competition, thereby increasing bioavailability (Verheijen et al. 2010, Karim et al. 2020).

4.3 | Nutrient Synergies and Biomass Gains

Significant biomass increases in Fe-rich soils, specifically a 52.4% increase in root dry weight and a 15.2% increase in leaf dry weight likely resulted from reduced As-stress and enhanced nutrient retention. While Nitrogen and Phosphorus were largely determined by soil mineralogy, Potassium levels showed a highly significant Treatment×Soil interaction. By reducing P-sorption onto free Fe-oxides, biochar likely increased the P:As ratio in the soil solution, a mechanism shown to reduce As-uptake due to the chemical similarity between phosphate and arsenate (Hossain et al. 2020, Zhang et al. 2025). However, improved biomass provides evidence of physiological tolerance rather than confirmed dietary risk reduction (Yin et al. 2017).

5 | Conclusion

This study concludes that *Acacia*-derived biochar is a promising, yet soil-specific, amendment for managing arsenic-affected tropical soils. The most pronounced benefits including significant recovery in photosynthetic efficiency and biomass gains in rice and potato were restricted to iron-rich mineralogies. While total iron and nitrogen levels remained largely determined by soil characteristics and time, biochar amendment significantly optimized potassium uptake and maintained photosynthetic integrity under arsenic stress. This underscores that biochar’s remediation potential is unlocked primarily through interactions with soil iron oxides, acting as a dual-action amendment for both nutritional balance and physiological resilience.

6 | Limitations and Future Directions

The lack of a biochar-only control means the standalone fertilization effect remains undistinguished from As-sequestration. Furthermore, as plant tissue As concentrations were not quantified, findings are limited to growth and physiological resilience; dietary safety remains unverified. Future research should utilize spectroscopic techniques (e.g., XPS or EXAFS) and arsenic speciation analysis to confirm the hypothesized formation of Fe–As–biochar complexes and to track As movement within the soil–plant system. Ultimately, these findings advocate for a targeted, mineralogy-based approach to biochar application in arsenic-endemic regions.

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Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the findings of this study are available within the article and its [Supporting Informations](#). Detailed statistical analyses, including ANOVA tables, are provided in the [S1](#). The results generated during the current study are available to be used, shared, and reproduced without restriction, provided appropriate citation of this work.

References

- Ahmad, S. A., M. H. Khan, and M. Haque. 2018. "Arsenic Contamination in Groundwater in Bangladesh: Implications and Challenges for Healthcare Policy." *Risk Management and Healthcare Policy* 11: 251–261.
- Firman, D. M., and E. J. Allen. 1989. "Estimating Individual Leaf Area of Potato From Leaf Length." *Journal of Agricultural Science* 112, no. 3: 425–426.
- Hossain, M. Z., M. M. Bahar, B. Sarkar, et al. 2020. "Biochar and Its Importance on Nutrient Dynamics in Soil and Plant." *Biochar* 2: 379–420.
- Hye, F. B., N. Saha, M. Shamim, and O. Dutta. 2025. "Assessing Suitable Tree Species for Biochar Production and Their Performance in Enriching Soil Quality and Plant Growth of *Oryza sativa* L. and *Acacia auriculiformis* A. Cunn. Ex Benth." *Asian Journal of Research in Agriculture and Forestry* 11, no. 2: 32–52.
- Karim, M. R., M. A. Halim, N. V. Gale, and S. C. Thomas. 2020. "Biochar Effects on Soil Physiochemical Properties in Degraded Managed Ecosystems in Northeastern Bangladesh." *Soil Systems* 4, no. 4: 69.
- Kloss, S., F. Zehetner, A. Dellantonio, et al. 2012. "Characterization of Slow Pyrolysis Biochars: Effects of Feedstocks and Pyrolysis Temperature on Biochar Properties." *Journal of Environmental Quality* 41, no. 4: 990–1000.
- Mandal, B. K., and K. T. Suzuki. 2002. "Arsenic Round the World: A Review." *Talanta* 58, no. 1: 201–235.
- Meharg, A. A., and J. Hartley-Whitaker. 2002. "Arsenic Uptake and Metabolism in Arsenic Resistant and Nonresistant Plant Species." *New Phytologist* 154, no. 1: 29–43.
- Meharg, A. A., and M. M. Rahman. 2003. "Arsenic Contamination of Bangladesh Paddy Field Soils: Implications for Rice Contribution to Arsenic Consumption." *Environmental Science & Technology* 37, no. 2: 229–234.
- Mohan, D., A. Sarswat, Y. S. Ok, and C. U. Pittman Jr. 2014. "Organic and Inorganic Contaminants Removal From Water With Biochar, a Renewable, Low Cost and Sustainable Adsorbent—A Critical Review." *Bioresource Technology* 160: 191–202.
- Murcott, S. 2012. *Arsenic Contamination in the World*. IWA Publishing.
- Palaniswamy, K. M., and K. A. Gomez. 1974. "Length-Width Method for Estimating Leaf Area of Rice 1." *Agronomy Journal* 66, no. 3: 430–433.
- Podgorski, J., and M. Berg. 2020. "Global Threat of Arsenic in Groundwater." *Science* 368, no. 6493: 845–850.
- Roychowdhury, T., H. Tokunaga, and M. Ando. 2003. "Survey of Arsenic and Other Heavy Metals in Food Composites and Drinking Water and Estimation of Dietary Intake by the Villagers From an Arsenic-Affected Area of West Bengal, India." *Science of the Total Environment* 308, no. 1–3: 15–35.
- Shamim, M., N. Saha, and F. B. Hye. 2018. "Effect of Biochar on Seed Germination, Early Growth of *Oryza sativa* L. and Soil Nutrients." *Tropical Plant Research* 5, no. 3: 336–342.
- Takahashi, Y., R. Minamikawa, K. H. Hattori, K. Kurishima, N. Kihou, and K. Yuita. 2004. "Arsenic Behavior in Paddy Fields During the Cycle of Flooded and Non-Flooded Periods." *Environmental Science & Technology* 38, no. 4: 1038–1044.
- Tripathi, R. D., P. Tripathi, S. Dwivedi, et al. 2012. "Arsenomix: Omics of Arsenic Metabolism in Plants." *Frontiers in Physiology* 3: 275.
- Verheijen, F., S. Jeffery, A. C. Bastos, M. van der Velde, and I. Dias. 2010. "Biochar Application to Soils. A Critical Scientific Review of Effects on Soil Properties, Processes, and Functions." *EUR* 24099, no. 162: 2183–2207.
- Yang, X., M. Hinzmann, H. Pan, et al. 2022. "Pig Carcass-Derived Biochar Caused Contradictory Effects on Arsenic Mobilization in a Contaminated Paddy Soil Under Fluctuating Controlled Redox Conditions." *Journal of Hazardous Materials* 421: 126647.
- Yao, Y., H. Zhou, X. L. Yan, et al. 2021. "The Fe₃O₄-Modified Biochar Reduces Arsenic Availability in Soil and Arsenic Accumulation in Indica Rice (*Oryza sativa* L.)." *Environmental Science and Pollution Research* 28: 18050–18061.
- Yin, D., X. Wang, B. Peng, C. Tan, and L. Q. Ma. 2017. "Effect of Biochar and Fe-Biochar on Cd and As Mobility and Transfer in Soil-Rice System." *Chemosphere* 186: 928–937.
- Zhang, L., L. Chang, H. Liu, M. de Jesús Puy Alquiza, and Y. Li. 2025. "Biochar Application to Soils Can Regulate Soil Phosphorus Availability: A Review." *Biochar* 7, no. 1: 1–20.
- Zhang, L., J. Hu, C. Li, et al. 2023. "Synergistic Mechanism of Iron Manganese Supported Biochar for Arsenic Remediation and Enzyme Activity in Contaminated Soil." *Journal of Environmental Management* 347: 119127.
- Zhao, F. J., J. F. Ma, A. A. Meharg, and S. P. McGrath. 2009. "Arsenic Uptake and Metabolism in Plants." *New Phytologist* 181, no. 4: 777–794.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** ANOVA for shoot height. **Table S2:** ANOVA for root length. **Table S3:** ANOVA for no. of reproductive parts. **Table S4:** ANOVA for shoot biomass. **Table S5:** ANOVA for reproductive biomass. **Table S6:** ANOVA for root biomass. **Table S7:** ANOVA for leaf biomass. **Table S8:** ANOVA for leaf area. **Table S9:** ANOVA for photosynthetic efficiency (F_v/F_m). **Table S10:** ANOVA for nitrogen. **Table S11:** ANOVA for potassium. **Table S12:** ANOVA for phosphorus. **Table S13:** ANOVA for iron content.