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Assessing Yield Response and Relationship of Soil Boron Fractions with Its Accumulation in Sorghum and Cowpea under Boron Fertilization in Different Soil Series

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Abstract: Boron (B) is an essential micronutrient in the growth of reproductive plant parts. Its deficiency and/or toxicity are widespread in arid and semi-arid soils with low clay contents. This study was planned to determine the response of sorghum (*Sorghum bicolor* L., non-leguminous crop) and cowpea (*Vigna sinensis* L., leguminous crop) to boron (0, 2, 4, and 16 $\mu\text{g g}^{-1}$) on four distinct soil series from Punjab, Pakistan i.e., Udic Haplustalf (Pindorian region), Typic Torrifluvent (Shahdra region), Halic Camborthid (Khurianwala region), and Udic Haplustalf (Gujranwala region). Overall, there was a significant difference ($p < 0.05$) in yield between the sorghum (3.8 to 5.5 g pot^{-1} of 5 kg dry soil) and cowpea (0.2 to 3.2 g pot^{-1} of 5 kg dry soil) in response to B application. The highest yield was observed in both sorghum and cowpea either in control or at 2 $\mu\text{g g}^{-1}$ B application in all four soils. Cowpea showed the same yield trend in all four soils (i.e., an increase in yield at 2 $\mu\text{g g}^{-1}$ B application, followed by a significant decrease at the higher B levels). In contrast, sorghum exhibited greater variability of response on different soils; Udic Haplustalf (Pindorian region) produced the greatest yield at low levels of B application. However, Halic Camborthid produced its lowest yield at that level. Boron concentration in shoots increased with the levels of B application, particularly in sorghum. In cowpea, the plant growth was extremely retarded—and most of the plants died at higher levels of B application even if a lower concentration of B was measured within the shoot. Hot water-extractable B was the most available fraction for cowpea ($R^2 = 0.96$), whereas the easily exchangeable B was most available for sorghum ($R^2 = 0.90$). Overall, these results have implications for micronutrient uptake for both leguminous and non-leguminous crops.

Keywords: Boron; toxicity; sensitivity; soil series; sequential extraction; bioavailability; regression

1. Introduction

Boron (B) is the only metalloid which is not uniformly distributed in the earth's crust, being mainly present in phyllosilicate, borosilicate and borate minerals. Globally, borosilicate minerals are the key source of B in soils [1]. Borate ions ($\text{B}(\text{OH})_4^-$) are mobile in soil and can be leached down from the root zone. However, the release/dissolution of B as borates from these minerals is very slow [2]. Therefore, after intense cultivation, natural B supply from these minerals is inadequate to fulfill the needs of crop plants. In addition, the natural occurrence of B in soil is very low, ranging from 2–200 mg kg^{-1} , most of which is unavailable to plants [1,3]. Brdar-Jokanović [4] reported that soils having a hot water-extractable fraction of $\text{B} < 0.5 \text{ mg kg}^{-1}$ are categorized as B deficient. Boron is also known for its narrow range of deficiency to toxicity. Its deficiency is more common in saline, alluvial and calcareous soils [5]. B soil bioavailability depends on several factors, including soil type, soil temperature, quality of irrigation water, plant species, climatic variations, and agronomic practices [6]. B availability reduces as soil pH increases due to its high adsorption capacity in alkaline conditions. During drought periods when root activity is restricted, B deficiencies are more pronounced—and thus the growth and yield of plants are affected [7,8]. The crops that are susceptible to B deficiency include leguminous and non-leguminous crops, e.g., alfalfa, sugar beets, clovers, and legumes [9].

Boron is an indispensable micronutrient, and its role is as vital as the macronutrients (N, P and K) for agricultural plants [10,11]. It is required for normal plant growth, including reproductive plant parts, cell wall formation and stabilization, membrane integrity, carbohydrate utilization, stomatal regulation, sporogenesis, pollen germination, and development of meristematic tissues and pollen tube growth [12–14]. On the contrary, B deficiency induces a reduction in crop yields, cell enlargement in growing tissues (because of its structural role in the cell wall), male sterility, formation of the hollow stem, browning of curd, and various floral abnormalities [3,4,15,16]. Furthermore, B deficiency mainly affects root morphology, inducing a higher leaf/root ratio due to the accumulation of lignin, amino acids and cellulose in root cells. This consequently restricts nutrient absorption and translocation [1]. A significant reduction has also been observed in antioxidative defense systems, leaf gas exchange attributes, and photosynthesis, all as a result of B deficiency in plants [17]. The occurrence of B toxicity is also an important aspect that limits plant growth in arid and semi-arid environments throughout the world [15]. Higher B concentrations may occur naturally in the soil and groundwater or be added to the soil from mining, fertilizers, or irrigation water [16]. Although of considerable agronomic importance, our understanding of B deficiency and/or toxicity is rather fragmented and limited.

Sorghum (*Sorghum bicolor* L.) is the fifth most important and largest cereal crop grown in the world after maize, wheat, rice and barley. The world produces 57.6 M tons of grains per year as of 2017 [18]. It has been reported that around 70% of world's sorghum production and 90% of sorghum farmlands are based in hot and dry regions of developing countries, including Pakistan [19]. Sorghum grains are important for their nutritional quality and economic significance. For instance, sorghum is used as feed for meat-producing animals and a cheaper source of human nutrition, energy, protein, iron, and zinc compared to fruits, vegetables, meats, eggs, fish, and dairy products [20]. It is considered less sensitive to B deficiency compared to grain legumes [21]. Cowpea (*Vigna sinensis* L.), a major grain legume with significant nutritive value (i.e., rich in energy, protein and minerals) is grown on 14.5 M ha of agricultural farmlands around the world, yielding 6.2 M metric tons [22–24]. B fertilization improved the yield of many crop plants such as *Oryza sativa* L. [25], *Triticum aestivum* L. [26], *Brassica oleracea* L. [27], *Vigna unguiculata* L. [28], and *Zea mays* L. [29]. Because of the narrow window of toxic-to-deficient B concentrations [4], optimum B application rates differ from one soil to another [30].

Like other trace elements, total soil B is distributed among various geochemical fractions, including easily soluble, carbonate adsorbed, oxide bound, organic matter bound and residual fractions [31,32], all of which differ in their chemical behavior toward mobility and bioavailability in soil [33–35]. Moreover, only a small fraction (<5%) of the total B in

the soil is available for plant uptake [33,36]. Recently, Bhupenchandra [6] claimed that B adsorption and desorption in the soil is the mechanism most responsible for regulating soil B supply for plant uptake. Therefore, exploring the chemical pools of B and their relationship with B accumulation in plants would be valuable to understand and predict their role in leaching and soil mobility dynamics. In this study, the interactive effects of different soil series and various B levels on cowpea (*Vigna sinensis* L.) and sorghum (*Sorghum bicolor* L.) were studied. It was hypothesized that in different soils, B fractions would be different, which could impact B availability for different crops. Overall, the research herein aimed to find out how different fractions of B in soil would impact the growth of cowpea and sorghum. The main objectives of this greenhouse study were (i) to evaluate the yield responses of sorghum and cowpea to B fertilizer, (ii) to determine the optimum B level for sorghum and cowpea under four different soil series, and (iii) to examine the relationship of various B fractions and accumulations in both crops.

2. Materials and Methods

2.1. Soil Sampling, Processing, and Characterization

Representative bulk surface soil samples from the top 15 cm were collected from four distinct soil series from the Punjab, Pakistan, namely: Udic Haplustalf (Pindorian series), Typic Torrifuvent (Shahdra series), Halic Camborthid (Khurianwala series), and Udic Haplustalf (Gujranwala series). The taxonomic classes of these soils have already been well described, according to Soil Management Support Service [37]. After collection, soils were air-dried, ground to pass through 2 mm sieve and characterized for basic physicochemical properties. Briefly, soil texture was determined by the hydrometer method, as explained by Day [38], CaCO_3 by the acid dissolution method [39], and organic matter content by following the Ealkely–Black method [40]. Soluble salts were determined by measuring the electrical conductivity in 1:1 soil:water suspension. The same suspension was used to determine soil pH by a calomel-glass electrode assembly using a Beckman pH meter. Plant-available B in soil was determined after hot water extraction, and total B was determined following US-EPA method 3052. Boron concentration was determined using a spectrophotometer (Spectronic 21, Bausch and Lomb) following the azomethane-H procedure [41].

2.2. Greenhouse Study and Growth Conditions

A greenhouse study was conducted to determine the effects of boron on sorghum and cowpea yield, boron uptake and bioaccumulation. Five kilograms of each of the four soils were placed in polyethylene-lined plastic pots and spiked with different boron (H_3BO_3) levels (0, 2, 4 and 16 $\mu\text{g B g}^{-1}$ soil). Each treatment contained 3 replications. Nitrogen (urea), phosphorus (DAP), and potassium (KClO_3) were supplied in the solution forms to maintain the locally recommended doses for sorghum and cowpea. Prior to sowing, soils in all pots were moistened with distilled water, dried, and mixed thoroughly to establish equilibrium. After equilibrium, soil samples were collected from each pot for laboratory analysis.

Overall, 10 seeds of each crop were broadcast in individual pots, and the pots were arranged according to a completely randomized design in the greenhouse [42]. After germination, two uniform plants in each pot were allowed to grow by thinning. During the course of the growth, the moisture content in all the pots was maintained with distilled water at about 60% of the water-holding capacity by weight. The average temperature in the green-house was 30 ± 3 °C during the day and 22 ± 3 °C during the night. Relative humidity dropped to 35% at midday and increased to 85% at midnight. The light intensity varied between 300 and 1400 $\mu\text{mol photon m}^{-2} \text{s}^{-1}$, depending upon the time of day and the cloud conditions.

2.3. Harvesting and Biomass Measurement

Both crops were allowed to grow for two months after germination, and then the shoots were harvested. Plant samples were washed with distilled water, blotted in filter paper sheets, dried to a constant weight at 65 °C in a forced air oven. After drying, the plant shoot samples were weighed to calculate dry biomass and then ground in a Wiley mill fitted with stainless steel blades for further processing and chemical analysis.

2.4. Boron Sequential Extraction

To determine the distribution of B in different soil phases—hot water-extractable (F1), easily exchangeable (F2), bound to carbonates (F3), bound to Fe and Mn oxides (F4), bound to organic matter (F5), and residual (F6)—a modified sequential extraction approach was employed [43]. The only modification to the original method was the inclusion of a hot water extraction step at the beginning of the extraction scheme. After extraction, the B concentration was determined in each extractant using the azomethine-H method [44] on a Spectronic-21 spectrophotometer (Bausch and Lomb).

2.5. Sample Processing for Total B Concentration in Plant and Soil

Fine-ground plant samples were digested with concentrated (98%) nitric acid (HNO₃, 70%) and, after that, with a diacid mixture ((1:4) HNO₃:HClO₄), following the method of Jackson [45]. Bioavailable B in all soil series was extracted via hot water extraction protocol [41]. Total B content of the soils were determined by digesting it with HNO₃:HF:HCl:H₂O₂ with a ratio of 9:3:2:1, respectively (US-EPA 3052). Boron concentration in the extracted solution and digests was determined by the azomethine-H method [44].

2.6. Statistical Analysis

The data collected were subjected to two-way analysis of variance (ANOVA) and the differences between the treatment means were evaluated using Tukey's (HSD) multiple comparison test [42], using SAS 9.2. All graphical works were carried out with Origin-17 pro software. The correlation analysis was carried out using Rstudio software with a standard key.

3. Results

3.1. Physicochemical Properties of Soil

The soils used in the current study were different textures, ranging from sandy loam to clay loam, and originated from different parent materials (Table 1). There were significant differences in the sand, silt and clay contents of the soils; Udic Haplustalf was the sandiest (86.8% sand) and Typic Torrifluvent was the least sandy (46.8% sand). Halic Camborthid was saline (electrical conductivity; EC = 7.8 dS m⁻¹), and rest of the soils were non-saline (EC < 2 dS m⁻¹). Halic Camborthid also had higher sodium adsorption ratio (SAR) value (~40 mmol L⁻¹) than the other soils (0.88 to 5.85 mmol L⁻¹).

Table 1. The basic physicochemical properties of soils collected from different soil series for the current study.

Soil Characteristic	Unit	Soil Series and Regions			
		Udic Haplustalf	Typic Torrifluvent	Halic Camborthid	Udic Haplustalf
Texture		Sandy loam	Silty clay loam	Clay loam	Clay loam
Parent material		alluvial	alluvial	loess	alluvial
Sand	%	86.8	46.8	62.8	60.8
Silt	%	3.3	35.3	20.0	20.7
Clay	%	9.9	17.9	17.2	19.2
pH 1:1 ^a		7.4	7.8	7.7	7.7
EC 1:1 ^a	(dSm ⁻¹)	1.1	1.8	7.8	0.8
SAR	(mmol L ⁻¹) ^{1/2}	0.9	5.9	40.0	1.1
Organic matter	%	1.4	1.5	1.5	1.5
CaCO ₃ equal. ^b	%	1.5	3.5	3.5	6.0
Total B	µg g ⁻¹	26.9	30.1	34.9	39.0

a: 1:1-soil: water ratio; b: Calcium carbonate equivalent by acid dissolution. The soil series were: Udic Haplustalf (Gujranwala region), Typic torrifluvent (Shahdra region), Halic Camborthid (Khurianwala region), and Udic Haplustalf (Pindorian region), respectively.

3.2. Boron (B) Fractionation in Soil

The fractionation of B into six different operationally defined fractions—(hot water-extractable (F1), easily exchangeable (F2), bound to carbonates (F3), bound to Fe and Mn oxides (F4), bound to organic matter (F5), and Residual (F6)—is provided in Figure 1. Total B in the soils ranged from ~ 27 to $\sim 39 \mu\text{g g}^{-1}$ (Figure 1). Overall, a significant proportion of the total B was present in the residual fraction of all the soils (F6, 58 to 66% of the total B). Organic matter-bound (F5) and Fe and Mn oxide-bound (F4) B fractions were insignificant ($<10\%$). A reasonable proportion of the total B was present in carbonate (F3, 7 to 13%) and easily exchangeable fractions (F2, 10 to 17%). Hot water-extractable B was 4–10% of the total B.

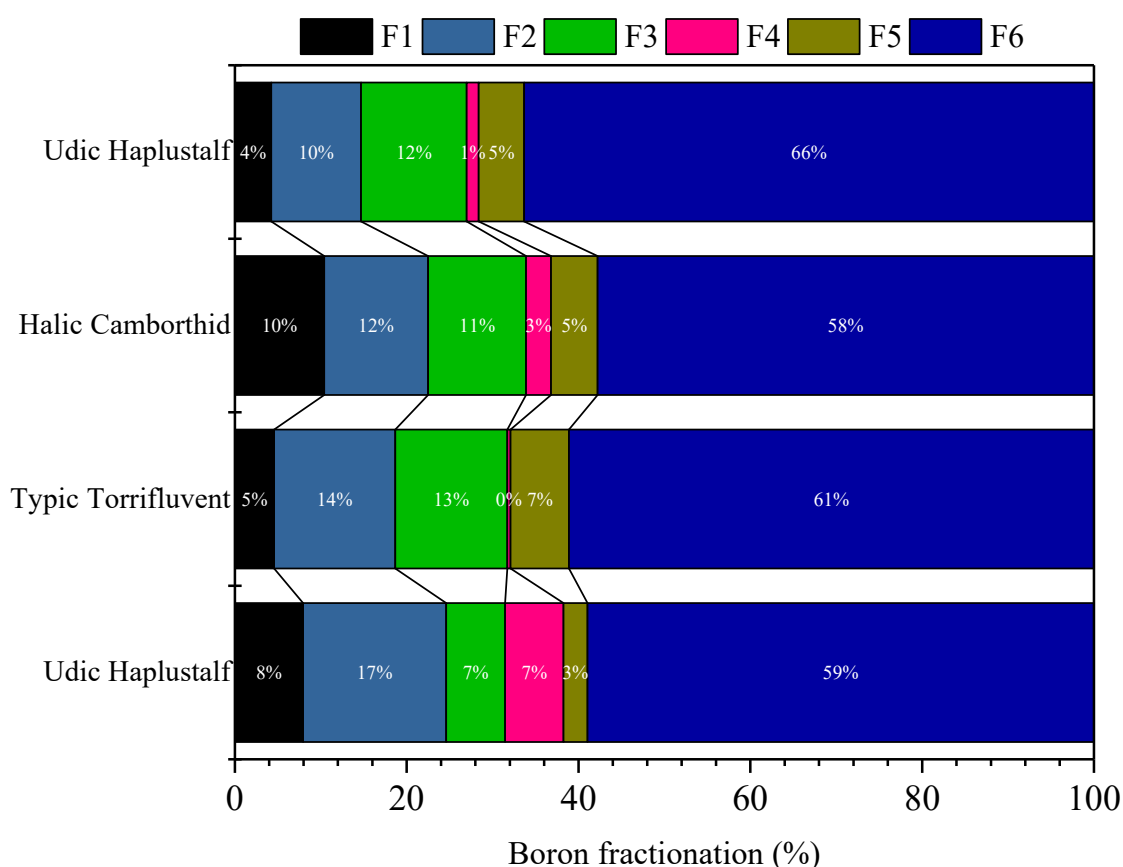


Figure 1. Boron (B) fractionation in soils collected from four different soil series of Punjab, Pakistan. B fractions: hot water-extractable (F1), easily exchangeable (F2), bound to carbonates (F3), bound to Fe and Mn oxide (F4), bound to organic matter (F5), and residual fraction (F6). The soil series were: Udic Haplustalf (Pindorian region), Typic torrifluvent (Shahdra region), Halic Camborthid (Khurianwala region), and Udic Haplustalf (Gujranwala region).

3.3. Effect of B on Yield of Sorghum and Cowpea

The effect of boron on shoot dry matter yield of sorghum and cowpea is shown in Figure 2. Overall, B application levels and soil types had a significant ($p < 0.05$) interactive effect on the shoot dry matter yield of both crops. For sorghum, shoot dry weight was significantly decreased with the application of B in Udic Haplustalf, whereas there was a significant increase in the yield in Halic Camborthid (Figure 2a). Boron level of $2 \mu\text{g g}^{-1}$ achieved optimum sorghum yield in all the soils except Halic Camborthid. For cowpea, shoot dry weight was significantly increased with the application of $2 \mu\text{g g}^{-1}$ B in all the soils (Figure 2b). However, increasing the application of B (i.e., 4 and $16 \mu\text{g g}^{-1}$) significantly reduced the yield and most of the plants showed toxic symptoms and died ($\sim 50\%$). The yield of cowpea showed the same trend on all four soils.

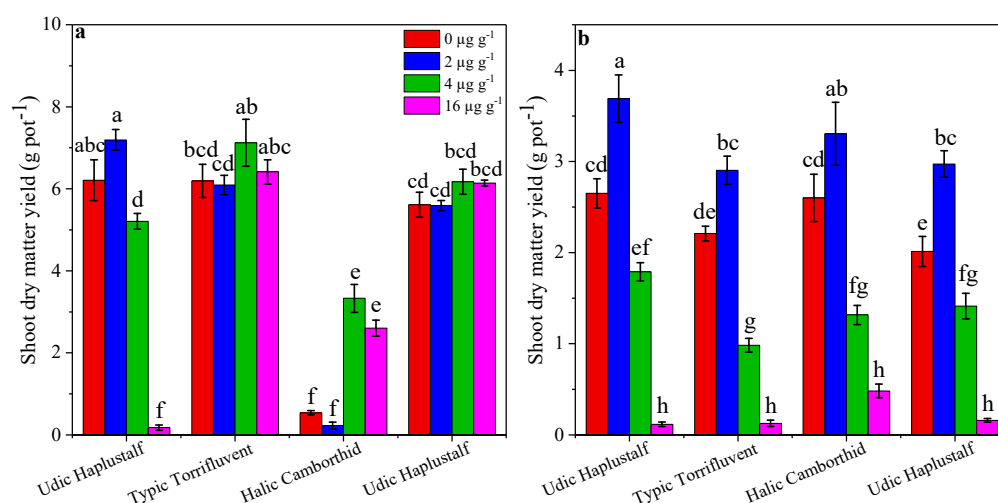


Figure 2. Effect of different boron application levels on shoot dry matter yield (g pot⁻¹) of sorghum (a) and cowpea (b) grown under different soil series of Punjab, Pakistan. The bars sharing different lowercase letters show significant differences among all the soil series, based on Tukey's (HSD) test at 5% probability level ($p < 0.05$). Data is the average of 3 replications ($n = 3$) $\pm$ SD values as error bars. The soil series were: Udic Haplustalf (Pindorian region), Typic torrifluvent (Shahdra region), Halic Camborthid (Khurianwala region), and Udic Haplustalf (Gujranwala region), respectively.

3.4. Effect of B on Its Accumulation in Sorghum and Cowpea

Boron concentration in the shoot of sorghum and cowpea is shown in Figure 3. For sorghum, B concentration significantly increased ($p < 0.05$) with the application of increasing B levels. For cowpea, a significant increase in the B concentration in the shoot was found, but at higher levels of B application (i.e., 4 and 16 µg g⁻¹) the plant growth was extremely retarded, which caused low plant growth and low B uptake. Calculating the B biological accumulation coefficient in both the crops showed that B accumulation in sorghum was directly related to B application (Figure 4a). For cowpea, the biological accumulation of B varied. Due to retarded growth, B accumulation was lower at higher B application levels (i.e., 16 µg kg⁻¹) (Figure 4b).

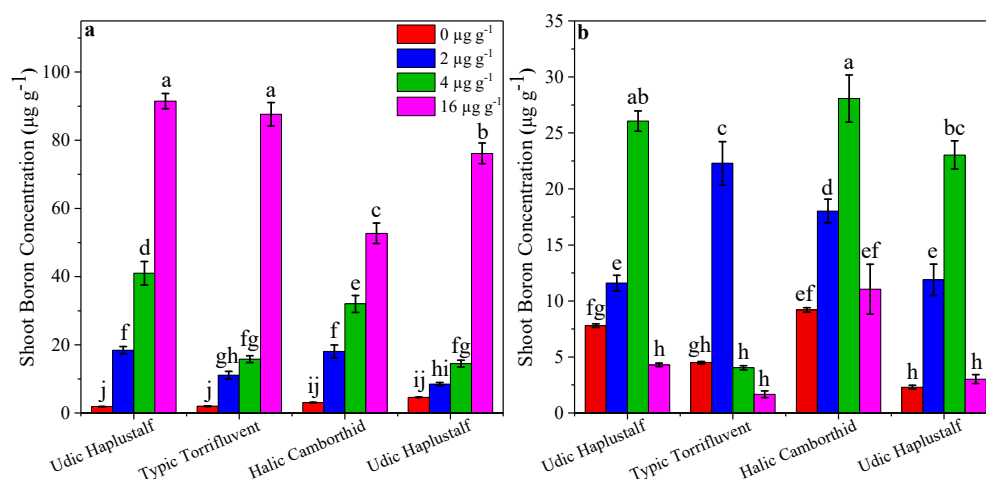


Figure 3. Effect of different boron application levels on shoot boron (B) concentration in sorghum (a) and cowpea (b) grown under different soil series of Punjab, Pakistan. The bars sharing different lowercase letters show significant differences among all the soil series, based on Tukey's (HSD) test at 5% probability level ($p < 0.05$). Data is the average of 3 replications ($n = 3$) $\pm$ SD values as error bars. The soil series were: Udic Haplustalf (Pindorian region), Typic torrifluvent (Shahdra region), Halic Camborthid (Khurianwala region), and Udic Haplustalf (Gujranwala region), respectively.

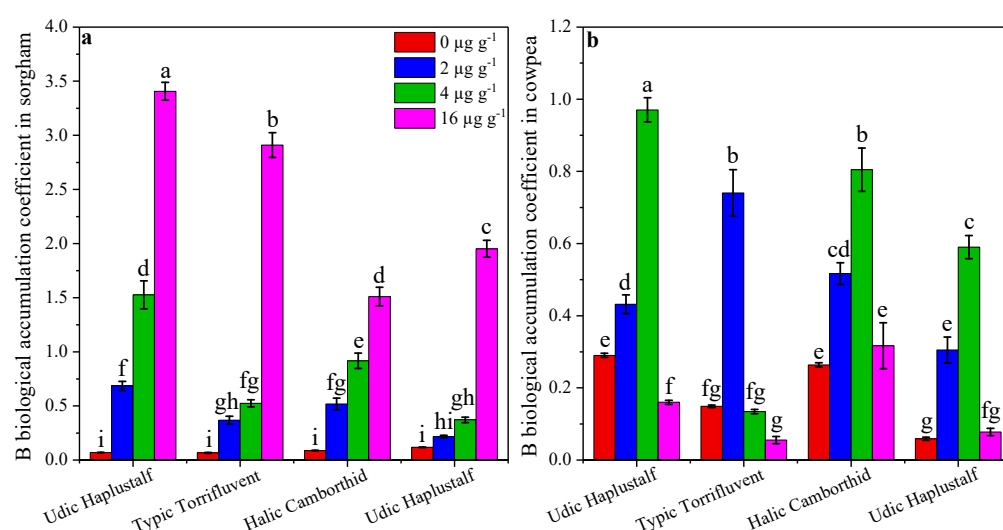


Figure 4. Effect of different boron application levels on biological accumulation coefficient (BAC) of boron in sorghum (a) and cowpea (b) grown under different soil series of Punjab, Pakistan. The bars sharing different lowercase letters show significant differences among all the soil series, based on Tukey's (HSD) test at 5% probability level ($p < 0.05$). Data is the average of 3 replications ($n = 3$) $\pm$ SD values as error bars. The soil series were Udic Haplustalf (Pindorian region), Typic torrifluvent (Shahdra region), Halic Camborthid (Khurianwala region), and Udic Haplustalf (Gujranwala region), respectively.

3.5. Comparison of Shoot Dry Matter Yield in Crops

The results of shoot dry matter yield for both the crops are presented in Figure 2. On average, highest shoot dry matter yield for sorghum was observed at 2 and 4 $\mu\text{g kg}^{-1}$ B application, whereas for cowpea, highest yield was found at 2 $\mu\text{g kg}^{-1}$ B application. For both the crops, there was a significant yield reduction at higher B application.

3.6. Comparison of Different Soil Series

Different soils used in the current study had different total B concentrations (~ 27 to $\sim 39 \mu\text{g g}^{-1}$, Table 1). B sequential extraction showed reasonable differences in the portioning of B into different fractions in different soils (Figure 1). Overall, Udic Haplustalf (Pindorian) appeared to be the best soil for both crops in term of shoot dry weight (Figure 2). For sorghum, two heavy-textured soils—Udic Haplustalf (Gujranwala, non-saline soil) and Halic Camborthid (Khurianwala, saline sodic soil)—exhibited very different behaviors. Udic Haplustalf (Pindorian region) produced relatively higher yield at all the B levels; Halic Camborthid was the lowest-yielding soil for sorghum. For cowpea, Halic Camborthid produced a similar shoot dry matter yield to all the other soils.

3.7. Role of Boron Geochemical Fractions on its Accumulation in Shoot

The relationship between B fractions in soil and accumulation of B in both crops are presented in Figure 5. Overall, the accumulation of B was much higher in sorghum than cowpea, and the response of sorghum was more evident in response to different B fractions in soil. For sorghum, B was exchangeable, and Fe and Mn oxide fractions were positively correlated with B accumulation ($R^2 = 0.90$ and $R^2 = 0.56$). However, the concentration of B in carbonate bound ($R^2 = 0.94$), organic matter ($R^2 = 0.91$), and residual fractions ($R^2 = 0.62$) were negatively correlated with B accumulation in the shoot of sorghum. Interestingly, hot water-extractable B, which is considered more bioavailable, did not show any impact on B accumulation in sorghum ($R^2 = 0.02$). For cowpea, hot water-extractable B showed a positive impact on B accumulation ($R^2 = 0.96$). The rest of the B fractions in the soil did not significantly impact B accumulation in the cowpea crop.

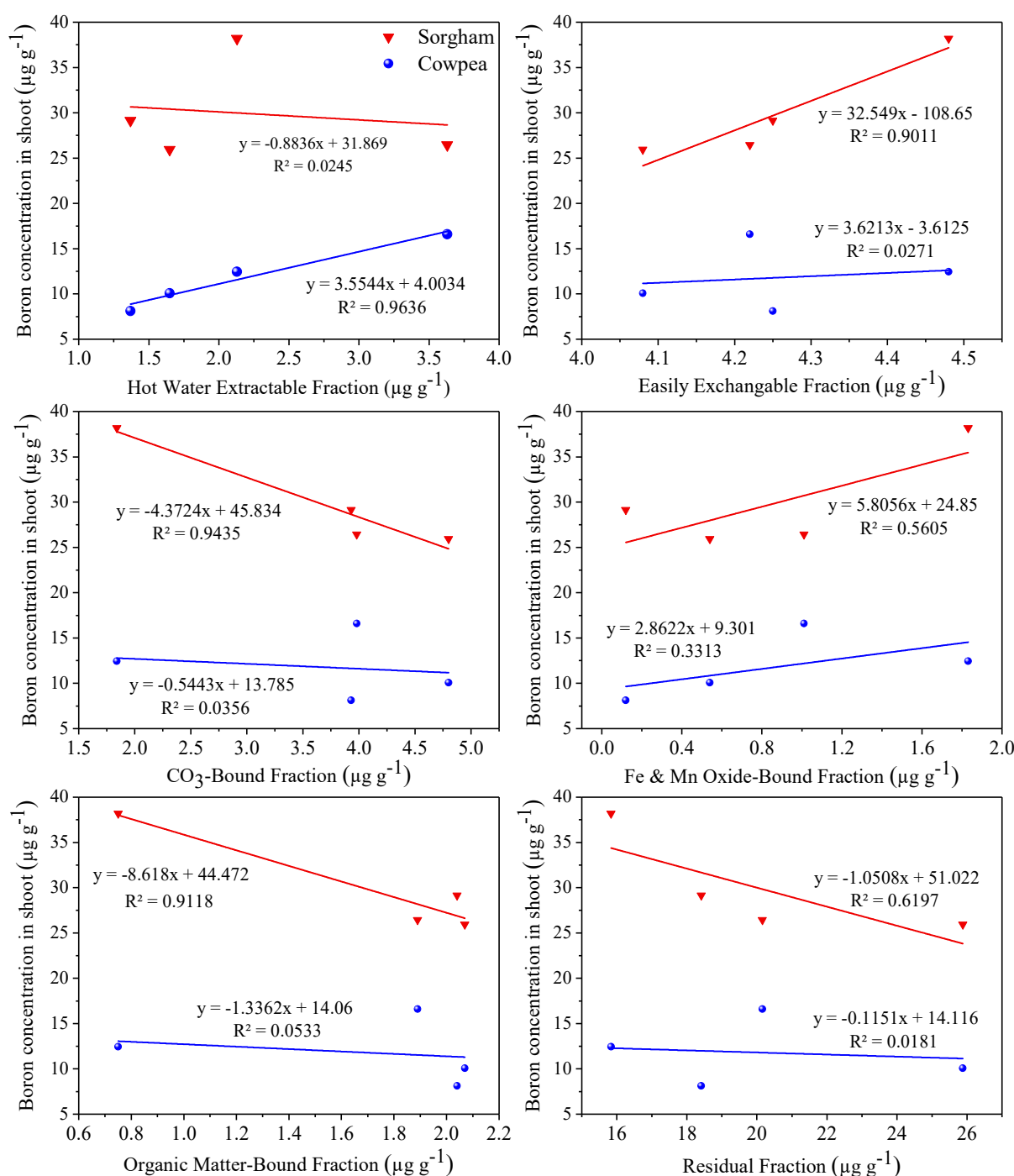


Figure 5. Regression coefficients ($p < 0.05$) between different sequentially extracted fractions of boron and concentrations of boron in the shoots of sorghum and cowpea supplied with various boron application levels.

3.8. Correlation Analysis

The correlations between shoot boron concentration and shoot dry matter yield of sorghum and cowpea grown under various boron application levels are presented in Figure 6. Boron concentration in sorghum shoot showed a significant positive ($r = 0.98$) correlation with the biological accumulation coefficient (BAC); however, it was not strongly ($r = -0.20$) correlated with the sorghum dry matter yield. On the other hand, a strong positive relation ($r = 0.97$) of boron concentration in cowpea shoot was noticed with the

biological accumulation coefficient (BAC), while, for cowpea, a weak correlation ($r = 0.31$) with dry matter yield was highlighted.

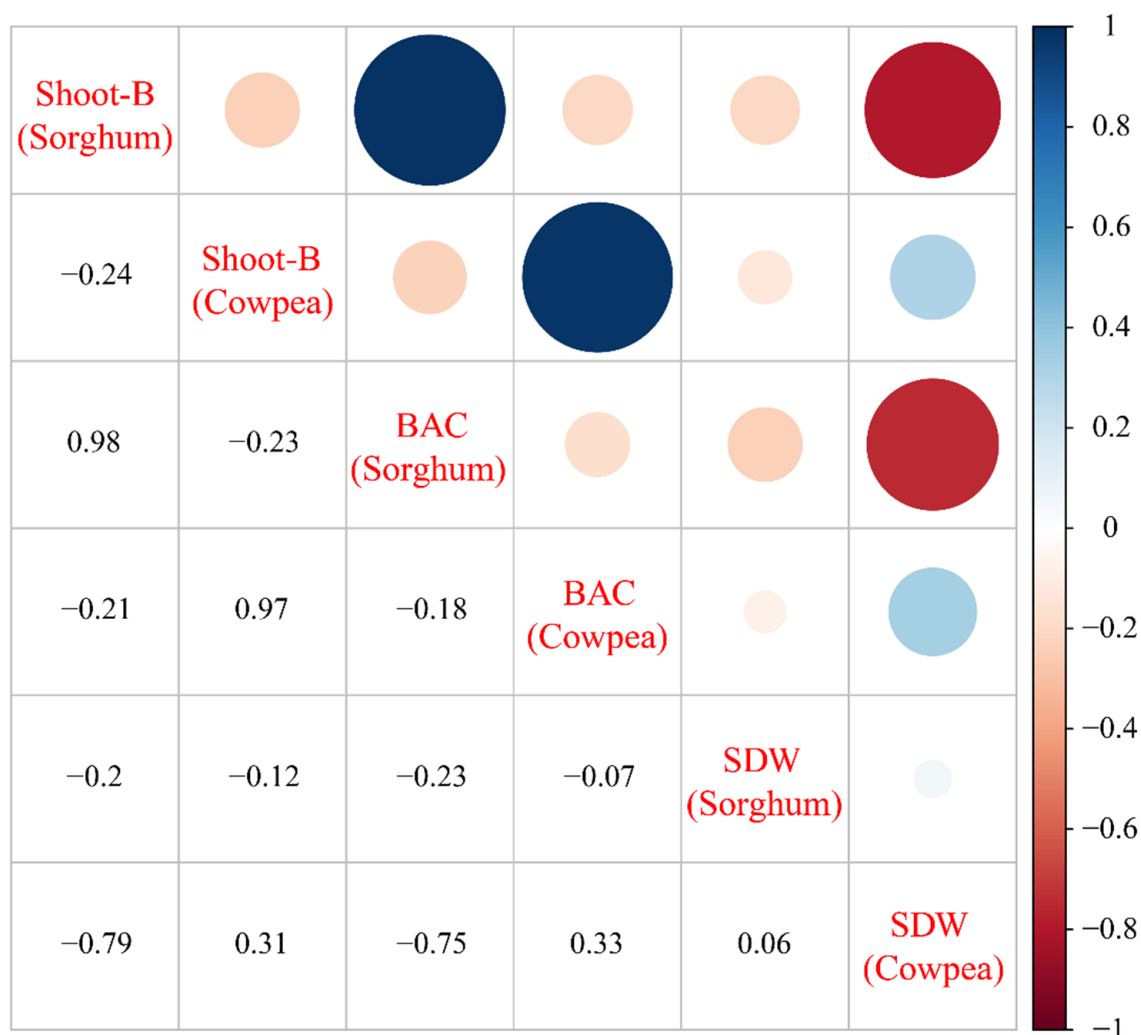


Figure 6. Relationship between shoot boron accumulation and shoot dry matter yield of sorghum and cowpea grown under various boron application levels. The blue and red colors indicate positive (+) and negative (−) correlation, respectively. The size of each circle and color deepness indicate the intensity (stronger or weaker) of correlations at $p < 0.05$, respectively. The abbreviations are as follows: Shoot-B—boron accumulated in the shoot; BA—biological accumulation coefficient of boron; SDW—shoot dry weight.

4. Discussion

Boron is essential for optimal plant growth and productivity. However, there is a very small range between B deficiency and B toxicity. It has been shown that B toxicity and B deficiency limited plant growth and caused variations in the normal growth of plants [46,47]. Results showed that soil boron levels below 1.4 mM could cause crop productivity loss. The negative effects of B toxicity have been found all over the world. It is well-known that in all agricultural areas, the natural B content in soil or irrigation water may cause B toxicity, especially when the water originates near active geothermal areas. B-induced toxicity can adversely affect physiological attributes and yield of crops [48,49]. In addition, high levels of B toxicity occur in arid and semi-arid environments, and high salinity can increase crop stress [50]. However, the optimum doses of B and the cellular processes interrupted by boron stress are still unclear. Similarly, the mechanisms of boron

toxicity or the adaptation mechanisms of plants to B excess is poorly understood, especially in cereal crops.

Boron is also very important for the optimum growth of legume crops; its required level in cowpea is higher than in sorghum [51]. The differences in the growth of crop plants under various application levels of boron were also previously reported [52]. With the addition of B, SDW first increased, and then decreased significantly—in both crops. These results are very similar to the findings of Turhan (2020) [49] and Metwally et al. (2018) [53], who observed significant yield reduction with increasing B levels in many crops. According to Marcar et al. (1999) [54] and Grieve and Poss (2000) [55], the dry matter production of sorghum remained constant up to 5 mM B and then decreased continuously with increasing B concentration.

It was noted, if the applied B concentration was increased, the boron content in sorghum increased. However, in salinized sorghum, B concentration decreased [56]. In different plants, B concentration increased with increasing concentrations of applied B in normal soils [56]. The combined effects of B concentration in shoot and salinity levels significantly reduced the dry matter production compared to the B toxicity alone. On the other hand, plant availability of B is limited on calcareous soils and is pH-dependent [57]. That is why sorghum B concentration in the shoot was lowest in the Khurianwala (Halic Camborthid) soil (Figure 2b). Contrarily, in sorghum, the concentration of B was decreased in saline soil conditions [58,59]. Sorghum is resistant to soil salinity, compared to other sensitive crops and legumes [60].

As the application of B increased, uptake in different parts of plants was promoted, causing B toxicity. Previous studies showed that the concentration of B in shoots was significantly higher than that in roots [46]. This might be due to the fact that dry biomass accumulation of roots was much lower than that of plant shoots, causing reduced accumulation of B in the roots as compared to shoots. All treatments receiving high B yielded a decrease in biomass, indicating that high levels of B led to a discrepancy in cell wall composition, which might have resulted in the inhibition of the rapid growth of pea plants [61,62]. Our results were in agreement with the findings of Chen et al. [63], i.e., that high B levels had a substantial harmful effect on cotton plants. It was also reported by Shah et al. [64] that high B levels caused accumulation of oxidative stress in citrus plants and ultimately resulted in reduced plant development. The fact that a higher B concentration leads to more B accumulation could explain the difference in B concentration between treatments and cultivars. Cowpea has a higher B requirement than sorghum. Our results showed that the application of B had no positive effect on grain yield. These results confirmed our finding that a high B level reduced the yield in cowpea (Figure 2b). Cowpea B requirement is unknown, but $2 \mu\text{g g}^{-1}$ B level seemed to be optimized to get the best yield. At $2 \mu\text{g g}^{-1}$ B level, shoot dry matter increased in cowpea [65]. Similarly, the toxicity symptoms of B produced on the leaves of various crops were also previously observed [66,67]. Moreover, the results of Agbenin et al. [24] proved that cowpea had a low B requirement compared to most legume crops (e.g., soybean).

Salt tolerance varies from crop to crop [68–71]. Based on published information about the combined effects of salinity and B concentration [72,73], the current study used relatively higher salinity and B levels in order to test extreme conditions. Some early investigators reported that shoot dry weight responded independently to boron and salinity with no interactive effect [74,75]. Membrane permeability was reported to be the main cause of the difference in B concentration of the crops [56,76]. Therefore, it can be concluded that membrane permeability for B is higher in sorghum in normal soil conditions, and that in saline soils, cowpea is more susceptible to B uptake. Plant availability of B is limited on calcareous soils and is pH-dependent [57]. Camacho-Cristóbal and his colleagues [10] and Gupta et al. [77] reported that soil B concentrations above $1.5\text{--}2 \mu\text{g g}^{-1}$ or below $0.5 \mu\text{g g}^{-1}$ resulted in decreased root and shoot yield. Yield and yield components of crops were affected positively and negatively by B, depending upon soil status and doses. A large increase in the yield was reported in response to B application on soils low in B [78,79].

Boron toxicity is more severe in normal soil as compared to saline soils [80]. The maximum yield of many crops was obtained by applying $3 \mu\text{g g}^{-1}$, while significant yield reduction was observed at higher levels [30]. Our findings concerning optimum B levels ($2 \mu\text{g g}^{-1}$) were very similar to [30,81]. The optimum B level observed by our experiment was within accepted critical health limits [82].

5. Conclusions

The yields of both sorghum and cowpea were optimum at $2 \mu\text{g g}^{-1}$ B application, but at a higher rate ($>2 \mu\text{g g}^{-1}$ B) a sharp decrease was observed. Boron application increased sorghum and cowpea yields, indicating a B deficiency in the studied soils. Using data on both crops, the maximum yield was obtained at $2 \mu\text{g g}^{-1}$ B application on pindorian soil (Udic Haplustalf). More studies are needed, using different soils and initial B application rates, to determine if these critical soil-test values can be applied across the region. This study showed that the addition of B with traditional macronutrient fertilizer enhanced grain and straw of sorghum and cowpea crops grown in semi-arid tropical regions.

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