

Research Article

Boron Characterization, Distribution in Particle-Size Fractions, and Its Adsorption-Desorption Process in a Semiarid Tunisian Soil

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Boron is essential for crop growth but needed in very small amounts. The range between boron deficiency and toxicity for plants is quite narrow. These stress conditions gravely reduce yield and quality of many crop species. Therefore, understanding the factors and the reactions affecting boron availability in soil is necessary. Against this framework, our research aims to determine the available boron status in a semiarid soil of Dour Ismail irrigated perimeter (North Tunisia). The objectives are also to investigate boron distribution in different particle-size fractions throughout the soil profile and to understand boron adsorption-desorption mechanisms according to some soil properties. For this purpose, one soil profile was dug in the field plot that had not received any previous boron fertilization. Soil samples were gathered from the different horizons of the profile and analyzed for the main physicochemical properties. Our results showed that the studied soil is Stagnic Fluvisol (clavic). The highest boron amounts were recorded in deep horizons and were greatly affected by soil salinity, organic matter, and clay contents. However, the increase in the pH level and the high percentage of total lime significantly diminished the available boron amounts in surface layers. The investigation of depth boron distribution in the different particle-size fractions indicated a considerable contribution of the silt $(2-50 \,\mu\text{m})$ fraction (52% of the soil total available boron), while the coarse (>50 μm) and clay (<2 μm) fractions seem to play a less important role. The adsorption data were fitted to Freundlich adsorption isotherm. It revealed that adsorption of boron increased with the increase of boron concentrations in soil solution. Desorption isotherm denotes that the accumulated boron in soil was not easily released. Adsorption and desorption of boron in soil were greatly affected by soil properties, such as pH, salinity, sand content, clay content, total organic carbon, total nitrogen, and cation exchange capacity.

1. Introduction

Boron (B) is a necessary micronutrient for the growth of all crops [1]. It plays a key role in a diverse range of plant functions including cell division and sugar transport. B is also required for the production of nucleic acids and the development of reproductive structures [2]. In soil, B content evolves and must be monitored frequently because of the narrow range between the levels of B deficiency and toxicity as compared to other nutrients [3]. Therefore, the management of this nutrient is critical. Indeed, appropriate B supply is necessary for obtaining better yields.

In soil, B exists in four major forms: (a) in rocks and minerals; (b) on clay surfaces and iron and aluminium oxides; (c) combined with organic matter (OM); and (d) as boric acid and B in the soil solution [4]. Nevertheless, only a few forms are available to plants and their determination is important for delineating the deficient soils. B deficiency is prevalent in coarse-textured acidic soils developed mainly in high rainfall zones. Moreover, soils with low OM content and high adsorption capacity (e.g., soils with high soil pH level and rich in clay minerals) are generally B deficient [5]. On the contrary, B toxicity symptoms are often observed in arid and semiarid regions owing to the use of irrigation waters high in B. Recently, several adverse environmental effects related to B have been traced back to poor manure management practices and inappropriate B fertilizer applications. For example, when humans and animals consume large amounts of B-containing food or drink water, the B concentrations in their bodies may rise to levels that can cause health problems. For plants, B toxicity symptoms are different and they depend on plant species. Stunted growth is common, and fruit trees may be less productive. Therefore, in order to recommend the correct rate of B application and to assess the agricultural and environmental B impacts, it is necessary to investigate B distribution in soil and to understand its adsorption-desorption behavior.

In soil, the mobility, transport, and partitioning of B depend on various soil chemical properties, namely, pH level, salinity, and the contents of clay minerals, sesquioxides, carbonates, and OM [5, 6]. B is retained by adsorption onto soil mineral and humic particles and by forming insoluble precipitates. B adsorption was found to increase gradually in the soil with increasing pH, to reach a maximum around pH 9.0 and to decrease with further increase in pH. Above pH 9, B adsorption was increased from the solution of higher electrical conductivity (EC) [7]. Mahler [8] claimed that coarse-textured soils with limited OM content are often low in B available for plants. Subsequently, soils rich in OM and clay contents adsorb a greater B amount [9]. The release of sorbed B is of immense significance, as plants respond primarily to the B activity in the soil solution. Therefore, adsorption and desorption reactions are among the major factors that regulate B concentration in soil solution and ultimately availability to plants.

Currently, the study of B occurrence and distribution in soils through a multitude of approaches (B characterization, B fractionation, extraction techniques and methodologies, etc.) has been the major focus of agronomists and soil scientists. Consequently, innumerable researchers have studied B dynamic in soil for a long time [10–12]. Most of these studies have focused on B in soil surface horizons with little attention given to B distribution according to depth. In reality, few researchers investigated this issue in Mediterranean semiarid regions like Tunisia [13, 14]. Thus, there is a pressing need for fundamental understanding of B distribution in such areas.

Against this backdrop, the present research was undertaken to better determine the available B content in the Tunisian soil of Dour Ismail irrigated perimeter (North Tunisia), as well as to investigate its depth distribution in the different particle-size fractions. The current study also aims to understand B adsorption-desorption mechanisms with different soil properties.

2. Materials and Methods

2.1. Soil Sampling and Physicochemical Analysis. To achieve the objectives of the present study, one pit was dug in Dour Ismail irrigated perimeter situated in the Northwest of Tunisia (Béja Governorate-Goubellat delegation) (Figure 1). The main geomorphological, bioclimatic, and pedological

characteristics of the studied area are detailed in [13]. Three soil samples were gathered from each horizons of the profile (the four horizons were considered, see Table 1), air-dried, sieved through a 2 mm diameter mesh, and stored in sealed containers at 5°C. Then, 12 soil samples were analyzed for the main physicochemical properties according to international standards. The soil pH level was measured with a pH meter in water (pH in H₂O) and in 0.01 M calcium chloride solution (pH in CaCl₂) (1:5 soil: reagent ratio) (ISO 10390). The salinity was measured as electrical conductivity (EC) with an EC meter in the soil aqueous extract (1:5 soil: water ratio) (ISO 11265). Soil texture was determined using the Robinson pipette method after oxidation of the OM with H_2O_2 and clay dispersion by hexametaphosphate solution (NF X31-107). Total calcium carbonate (TCaCO₃) was measured using the volumetric method (NF ISO 10693). Soil samples were also characterized for total organic carbon (TOC) by the sulfochromic oxidation method (ISO 14235) and total nitrogen (TN) by the modified Kjeldahl method (NF ISO 11261). The cation exchange capacity (CEC) was obtained with ammonium acetate following the Metson method (NF X31-130). Finally, the available B was extracted in boiling water and measured by the ICP-AES analytical method (inductively coupled plasma atomic emission spectroscopy) (NF X31-122).

Three replications were performed for each executed analysis and were expressed as an average of the three values. Moreover, we submitted each soil samples to a particle-size fractionation to isolate coarse fraction (>50 μ m), silt fraction (2–50 μ m), and clay fraction (<2 μ m). All separated soil fractions were quantified for their available B contents. B adsorption-desorption reactions were also studied in each horizon.

2.2. Particle-Size Fractionation. Forty grams of soil was dispersed in 200 mL of distilled water with 0.5 g of sodium hexametaphosphate and shaken for 16h with five agate balls. The suspension was then filtered through a $50 \,\mu m$ filter under a distilled water jet. The fraction $>50 \,\mu m$ was recovered by sieving. The suspended material passing the finer sieve (fraction $<50 \,\mu\text{m}$) was further submitted to 10 min ultrasonic treatment in the continuous mode to ensure soil particles dispersion. The used sonicator is a heat system ultrasonic model W225R (20 kHz frequency, 100 W power). The fraction $20-50 \,\mu\text{m}$ was also obtained by sieving (20 μ m filter). However, the fractions 2–20 μ m and $<2 \mu m$ were obtained by four sedimentation/decantation and centrifugation cycles. Each fraction was later dried in an oven under 40°C to reach a constant weight. The different fractions are finely weighed and crushed to be analyzed for available B. In order to simplify the comparison, our results were expressed for the total sand fraction (>50 μ m), total silt fraction (2–50 μ m), and clay fraction (<2 μ m).

2.3. B Adsorption-Desorption Studies. For B adsorption studies, 10 g of soil samples were placed in 50 mL polypropylene centrifuge tubes with 20 mL of 0.01 M CaCl₂



FIGURE 1: (a) Geographic situation of the study area. (b) Position of the studied soil profile.

TABLE 1: Selected physicochemical properties of the studied soil.

Depth (cm)	Hz	pН	EC (dS/m)	Sand (%)	Silt (%)	Clay (%)	TCaCO ₃ (%)	TOC (%)	TN (‰)	C/N	OM (%)	CEC (meq/100 g)	B (mg/kg)
0-25	A_{p}	8.30	1.36	41.46	26.48	32.06	13.16	1.23	1.12	10.98	2.12	30.67	0.64
25-50	A/C	8.23	1.89	37.39	23.78	38.83	12.75	0.81	1.40	5.79	1.39	25.33	0.63
50-75	C1	8.08	2.07	36.44	21.95	41.60	8.50	0.73	0.62	11.77	1.26	20.00	0.66
75-100	C2	8.05	2.08	37.91	19.16	42.93	6.25	0.61	0.6	10.17	1.05	17.33	0.74

Hz: horizons; EC: electrical conductivity; TCaCO₃: total lime; TOC: total organic carbon; TN: total nitrogen; OM: organic matter; CEC: cation exchange capacity.

solution and contained different quantities of B (5, 10, 20, 40, and 80 mg of B/L as H_3BO_3). The contents were shaken for 24 hours. The suspension was further centrifuged, and a 10 mL aliquot of the clear supernatant was removed and filtered. Subsequently, B was determined in the filtrate. Soil B adsorption was obtained by subtracting B in solution, after centrifugation and filtration from B added in the different concentrations. The following adsorption equation was used to define B adsorption in the soils:

Freundlich equation:
$$\log\left(\frac{x}{m}\right) = \frac{1}{n}\log(c) + \log K$$
, (1)

where x/m = the amount of adsorbed B (mg/kg), c = the equilibrium B concentration (mg/L), K = Freundlich constant, estimates the adsorption capacity (mg/kg), and 1/n = Freundlich constant, estimates the adsorption intensity.

B desorption was initiated with a removal of 10 mL of aliquot from equilibrated solution and an addition of 10 mL of B-free 0.01 M CaCl₂ solution. The mixture was resuspended by agitation and equilibrated for 24 hours. The suspensions were centrifuged, and 10 mL of the supernatant was removed for B determination. The amount of desorbed B was calculated as the difference between equilibrium B concentration at each desorption step and the equilibrium B concentration before each desorption step divided by 2

(dilution factor). This procedure was determined following a method that is described in [15].

3. Results and Discussion

3.1. Relationship between B Distribution and Soil Characteristics. Table 1 shows the main physicochemical properties of the studied soil. The pH level was basic (≈ 8) and slightly dropped with depth. Similarly, the EC values increased as we moved from the surface (1.36 dS/m) to deep lavers (2.08 dS/m). The soil texture was dominated by clavsilt fractions ($\approx 60\%$) throughout the profile. The TCaCO₃ percents decreased with the increase in depth. The A_p surface horizon of the studied soil exhibits the highest OM contents with 1.23% of TOC and 1.12% of TN. These values decreased with depth and reached 0.61% and 0.60%, respectively. The CEC has the same behavior as the TOC and TN. The values varied from 30.67 meq/100 g top to 17.33 meq/100 g bottom. The greater CEC values recorded at the surface might be due to the higher OM content. Mahajan et al. [16] and Kumari et al. [17] reported a similar relationship. The examination of B distribution in the studied soil showed an increase in the available B content as we moved from surface horizon $A_{\rm p}$ (0.64 mg/kg) to the deep horizon C2 (0.74 mg/kg). The low B values recorded in surface layers may be explained by a slight increase in the pH level (8.30) and a relatively high TCaCO₃ (13.16%) amount. Indeed, B adsorption in soil depends on the soil pH level. It rises between pH 6.0-8.5 and reaches the highest values around pH 9. B adsorption decreases with further pH increases [3]. Furthermore, soils containing important amounts of lime are usually low in available B [18]. The calcium carbonate increases B adsorption by soils since it raises the soil solution pH. Several researchers observed a similar result and failed to get a significant correlation between TCaCO₃ and the available B content of the soil [18]. The great B amounts recorded in deep layers correspond to a slight enrichment in TOC (0.61%) and mainly to a great percentage of clay-silt fractions ($\approx 62\%$). Our results are in line with some earlier studies, which have shown that OM [4] and clay contents [19] affect the B bioavailability. Indeed, Raza et al. [4] and Chaudhary et al. [20] showed a positive correlation between soil OM content and available B. Later, Turan and Horuz [21] claimed that available B is freed as a result of the mineralization of OM caused by microorganisms. Moreover, our results clearly reveal that the clay-silt content (\approx 62%) in the studied soil seems to be among the determinative factors, which influence B bioavailability. Similar results have been reported in [19, 22, 23]. The authors showed that fine-textured soils usually contain more available B than coarse-textured soils because of their greater content of clay minerals. The C₂ deep horizon of the studied soil showed high amount of available B (0.74 mg/kg) and was slightly saline (2.08 dS/m) as compared to the A_p surface horizon (1.36 dS/m)m). In fact, some investigators advocated that B adsorption was greater for the high EC solution [7, 24]. The authors pointed out that B adsorption, as a function of a B concentration solution is independent of salinity in the pH range 4 to 9 up to EC 7.9 dS/m.

A statistical analysis was performed to find out possible correlations between the available B contents and the studied soil properties (pH, EC, clay, silt, sand, TCaCO₃, TOC, TN, CEC, and C/N). Three values of each parameter were used for the correlation matrix. The results reflected a significant and positive-correlated relationship between the available B and the clay fraction ($r^2 = 0.64$ at p < 0.05). Kumari et al. [17] found a similar correlation. The authors revealed that finetextured soils usually contain more available B than coarsetextured soils. Besides, the EC showed a significant and positive correlation with the available B $(r^2 = 0.53 \text{ at})$ p < 0.05). Our result agrees with that of [25], which stated that the onset of salinization is accompanied by an increase in the available B content. However, our findings showed a negative relationship between the available B content and the pH level ($r^2 = -0.79$ at p < 0.05). This appears to correspond to the common belief that an increase in pH would increase B adsorption and consequently cause a reduction in B availability [3]. The same negative relationship was revealed between the available B and the TCaCO₃ content $(r^2 = -0.90 \text{ at } p < 0.05)$. Indeed, the calcium carbonate acts as an important B adsorbing surface in soil [18].

3.2. Depth B Distribution in Particle-Size Fractions. The investigation of depth B distribution in the different particle-size

fractions indicated a considerable contribution of the silt $(2-50 \,\mu\text{m})$ fraction to B adsorption in soil especially in depth. This fraction contains 52% of the total available B ($B_{2-50\mu m}$ / TB = 52%). However, the sandy fraction $(B_{>50\mu m}/TB = 26\%)$ and the clay fraction ($B_{<2\mu m}/TB = 15\%$) seem to play a less important role (Figure 2). Our results do not offer support for the common theory that the finer-sized material and particularly clay minerals should contain more B than the coarser fractions. Indeed, the majority of previous studies [26] attested that the clay fraction has more contribution to the B content of soils. Kumari et al. [17] and Anitha et al. [27] revealed that all B fractions showed a positive correlation with clay content, namely, the readily soluble one $(r^2 = 0.88 \text{ at}$ p < 0.01 and $r^2 = 0.474$ at p < 0.05). However, few studies are in line with what we found [17]. The authors showed that the silt fraction had a positive but nonsignificant relationship with the available B ($r^2 = 0.21$).

B partition in sand fraction decreased as we moved from the surface $(B_{>50\mu m}/TB = 32\%)$ to deep horizons $(B_{>50\mu m}/TB = 26\%)$ (Figure 2). In fact, sand content in the studied soil dropped with depth (Table 1). Then, the great sand content recorded mainly in surface layers enhanced more content of extractable B. B partition in the clay fraction ($B_{<2\mu m}/TB$) has the same behavior as the sand fraction. The B values dropped from 25% top to 15% bottom although clay content increased in depth. However, some previous studies [28] revealed that the increase in clay content reduced the extractable B content because of the intensity of the adsorption force. Moreover, the lowest B values recorded in the clay fractions especially in depth correspond to significant OM levels (1.05%). Indeed, B adsorption in clay surfaces decreases as OM content increases. Soil OM occupies the reactive adsorption sites on clay fractions [29].

3.3. Adsorption of B. The quantity of B adsorbed in each horizon was traced against the equilibrium concentrations in order to acquire the adsorption isotherm. We noticed that as the equilibrium of B concentration increased, the quantity of the adsorbed B increased in all horizons of the studied soil. However, at high B equilibrium concentration, soil samples show a remarkable difference in B adsorbed than at low B equilibrium concentration (Figure 3). Many researchers have also reported that the adsorption of B increased with the increase of B concentration in soil solution [30, 31]. The highest amount of B adsorption was recorded in the A/C horizon. Nevertheless, the lowest amount of B adsorption was recorded in A_p surface horizon. Indeed, the A/C horizon had the highest $pH_{(CaCl_2)}$ value (7.75) of soil solution, while the A_p horizon showed the lowest pH_(CaCl₂) value (7.67). In addition, our results indicated that the B adsorption amount was positively correlated with the soil pH_(CaCl,) level $(r^2 = 0.95 \text{ at } p < 0.05) \text{ and clay content } (r^2 = 0.76 \text{ at } p < 0.05).$ Based on these findings, it could be concluded that B adsorption was mainly controlled by the soil pH level. Moreover, it greatly depends on the content of clay fraction of the soil. In general, soils with low clay content will adsorb less B than those with higher clay content [11].



FIGURE 2: Depth B distribution in particle-size fractions of the studied soil.

B adsorption behavior in soil has been described using the Freundlich equation. This equation has been successfully verified in several soil types [11, 19, 23]. The adsorption parameters from the Freundlich equation are presented in Table 2. The results showed a wide dispersion of the adsorption capacity values (K) of the different horizons of the studied soil. Indeed, the A/C surface horizon showed the highest value (K = 4.75 mg/kg), while the A_p surface horizon recorded the lowest value (K = 0.88 mg/kg). This trend was expected based on the different proprieties of the horizons, in particular, the increasing in clay contents and pH values. In this context, Alleoni and Camargo [10] have found that Freundlich constant *K* follows the tendency of high values in fine-textured soils. In fact, the maximum K value of the A/C horizon could be attributed to the great clay-silt amount





40

35

30

Adsorbed B (mg/kg) 25 20 15 10

FIGURE 3: Amounts of the adsorbed B of the different horizons of the studied soil.

(>62%), the high $pH_{(CaCl_2)}$ level, and the slightly enrichment in TOC (0.81%) and TN (1.40%). However, the lowest adsorption capacity of A_p surface horizon was related to the great amount of sand content (41.46%) and the low pH_(CaCl₂) level. In addition, the result of the statistical analysis showed a positive correlation between adsorption capacity (K) values and (1) the soil $pH_{(CaCl_2)}$ level ($r^2 = 0.93$ at p < 0.05), (2) the TN content $(r^2 = 0.60^{\circ} \text{ at } p < 0.05)$, and (3) the clay-silt amount ($r^2 = 0.48$ at p < 0.05) and a negative relationship with the sand fraction ($r^2 = -0.48$ at p < 0.05). In reality, it has often been shown that fine-textured soils adsorb more B than coarse-textured soils [22]. Besides, our findings showed that the quantity of OM, particularly TN, is considered as one of the main soil components that affects B adsorption. Similar results have also been reported in [18, 32]. The authors showed a positive correlation between the content of soil OM and the amount of the adsorbed B. The strong relationship between adsorption capacities and the increase in soil pH values ($r^2 = 0.93$ at p < 0.05) proves that the pH is one of the most important factors that enhance B adsorption by soil [32]. In fact, B adsorption in soil was found to be increased from pH 3 to 8, showed a peak at pH 8 to 10, and declined with further increasing [31]. This positive relationship between soil pH level and B adsorption could possibly be elucidated as the abundance of borate ions to boric acid or by the rising number of adsorption sites at the high pH value [12]. Based on our adsorption results, we can conclude that soil pH level, OM, and clay contents are the main chemical properties of soil that affect the adsorption of B [32-34].

3.4. Desorption of B. The knowledge of desorption reaction is interesting for determining if the adsorbed B of soil can be easily released. The amount of the desorbed B was expressed as percentage of the adsorbed B (Figure 4). The A_p surface horizon had desorbed high percentage of B (62.2%), whereas the A/C horizon desorbed less B percentage (49.71%). Indeed, the $A_{\rm p}$ surface horizon, which has low affinity for B adsorption, had released a great B amount. Therefore, B adsorption and desorption process were oppositely associated.

Depth (cm)	Horizons	$pH_{(CaCl_2)}$	H	Freundlich	adsorptio	n	H	DI			
			1/n	n	Κ	R^2	1/n'	n'	K'	R^2	DI
0-25	Ap	7.67	0.70	1.42	0.88	0.82	0.61	1.62	0.84	0.73	1.13
25-50	A/C	7.75	0.43	2.31	4.79	0.79	0.70	1.42	1.09	0.92	0.61
50-75	C1	7.70	0.73	1.36	1.61	0.88	1.03	0.96	0.37	0.97	0.70
75-100	C2	7.72	0.64	1.54	2.02	0.72	0.80	1.24	0.68	0.91	0.80

TABLE 2: Freundlich adsorption and desorption coefficients and desorption index of the studied soil.

 R^2 : regression coefficient; DI: desorption index.



FIGURE 4: Amounts of desorbed B expressed as percentage of the adsorbed B.

Our results are in line with [11, 23], which have reported that soil having low B adsorption desorbs more B amounts. In addition, B desorption was higher in A_p surface horizon with a great sand content. In this context, Arora and Chahal [35] observed that coarse-textured soils aimed to desorb large B amounts in comparison with fine-textured soils.

The behavior of B desorption was described by the same Freundlich equation, as it has been reported by [15]. The comparison of adsorbed and desorbed isotherm values of each horizon indicates two reaction types of B desorption. In fact, when isotherms of B adsorption are similar to desorption isotherms, it means that B adsorption is reversible. For instance, in the case of the A_p surface horizon, isotherms of B adsorption (K = 0.88) and desorption (K' = 0.84) presented very similar results. This horizon exhibited therefore a reversible B desorption reaction. Nevertheless, the nonconformity between adsorption and desorption isotherms indicates that B adsorption is hysteric and not easily reversible. In reality, all the studied horizons, except the $A_{\rm p}$ surface horizon, exhibited a hysteric adsorption process. For the C₁ horizon, the B desorption isotherm (K' = 0.37) widely differs from the adsorption isotherm (K = 1.61). Desorption process in C₁ deep layer was not easily reversible. Thus, it contributed to a great retention of B (not released) [36].

Desorption characteristics of the soil were identified with a desorption index (DI) calculated as the ratio of Freundlich adsorption and desorption slopes. Indeed, if the n'_{des}/n_{ads} value is near one (\approx 1), it shows reversible desorption. On the contrary, if DI is lower than one (<1), the desorption process is hardly reversible. The data reported in Table 2 show the DI values of the different studied horizons. The value of DI of the A_p surface horizon (DI = 1.13), showing reversible adsorption-desorption process. The other horizons displayed DI values <1,

tending towards hysteric desorption (Figure 5). Previous studies also showed that the content of adsorbed B might not be released in a completely reversible way [15, 36]. An attempt was made to relate DI values to different soil properties. Significant correlations were observed with sand fraction $(r^2 = 0.94 \text{ at } p < 0.05)$, silt fraction $(r^2 = 0.53 \text{ at } p < 0.05)$, TOC content ($r^2 = 0.79$ at p < 0.05), and CEC values ($r^2 = 0.59$ at p < 0.05). Similarly, Arora and Chahal [11] have shown a positive correlation between the desorbed B amount and the sand content. In addition, our results revealed that OM and silt contents, unlike clays, contribute significantly to the release of B in soil and thus to its bioavailability for plants. Indeed, DI values showed a negative correlation with clay content ($r^2 = -0.76$ at p < 0.05), pH_(CaCl₂) level ($r^2 = -0.86$ at p < 0.05), and EC values ($r^2 = -0.83$ at p < 0.05). These results could be ascribed to the fact that the adsorption of B increases at high pH level, EC value, and clay content.

4. Conclusion

Based on our findings, a variety of soil properties (OM content, particle-size fractions, percentage of calcium carbonate, soil pH level, and salinity) have been identified as affecting the dynamic of B and its distribution in the soil of Dour Ismail irrigated perimeter (North Tunisia). Our results showed that the increase in the pH level and the great percentage of TCaCO₃ significantly diminished the available B contents mainly in surface horizons. However, the accumulation of B in depth corresponds to an enrichment in OM (1.05%), to a high EC solution (2.08 dS/m), and to a high percentage of clay-silt fractions (\approx 62%).

The investigation of depth B distribution in the different particle-size fractions showed a considerable contribution of the silt $(2-50 \,\mu\text{m})$ fraction (52% of the total available B) to B adsorption especially in depth, while the clay (<2 μ m) and the coarse (>50 μ m) fractions seem to play a less important role. The lowest B values recorded in the clay fractions mainly in depth correspond to significant OM levels (1.05%). Soil OM occupies the reactive adsorption sites on clay surfaces, therefore decreasing B adsorption.

Indeed, a deeper understanding of the factors affecting B bioavailability in soils is essential for the assessment of B deficiency or toxicity under different conditions. It is worth mentioning that B availability is monitored by the equilibrium B concentration in soil. It described B adsorption and desorption reactions by Freundlich adsorption isotherm.

The adsorption of B by soil increased with increasing B concentration in soil solution. The most important soil properties affecting the B adsorption capacities (*K* values) in



FIGURE 5: Comparison between adsorbed and desorbed B amounts of the different horizons of the studied soil.

the studied soil were: $pH_{(CaCl_2)}$ level ($r^2 = 0.93$), TN content ($r^2 = 0.60$), and clay-silt amount ($r^2 = 0.48$).

Desorption isotherm denotes that accumulated B in soil cannot be easily released. It exhibits a hysteretic adsorption process in all horizons, except the A_p surface horizon, which revealed a reversible adsorption process. Indeed, soils which have a higher affinity for B adsorption tended to desorb less B amounts, namely, A/C horizon. B desorption was positively correlated with sand ($r^2 = 0.94$), silt ($r^2 = 0.53$), TOC ($r^2 = 0.79$), and CEC values ($r^2 = 0.59$) and negatively with pH_(CaCl₂) ($r^2 = -0.86$), salinity ($r^2 = -0.83$), and clay ($r^2 = -0.76$).

Based on our results, it appears possible to declare that OM and silt content can play an important role in B adsorption-desorption process in soil. In reality, the study of B distribution in different particle-size fractions, as well as a thorough understanding of the factors that affect its bioavailability for plants, is essential to better manage B deficiency or toxicity in soil.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

 G. Nazir, U. Sharma, and P. Kumar, "Boron—its importance in crop production, status in Indian soils and crop responses to its application," *International Journal of Advanced Research*, vol. 4, no. 5, pp. 654–660, 2016.

- [3] S. Goldberg, D. L. Corwin, P. J. Shouse, and D. L. Suarez, "Prediction of boron adsorption by field samples of diverse textures," *Soil Science Society of America Journal*, vol. 69, no. 5, pp. 1379–1388, 2005.
- [4] M. Raza, A. R. Mermut, J. J. Schoenau, and S. S. Malhi, "Boron fractionation in some Saskatchewan soils," *Canadian Journal* of Soil Science, vol. 82, no. 2, pp. 173–179, 2002.
- [5] A. Niaz, A. Nawaz, S. Ehsan et al., "Impacts of residual boron on wheat applied to previous cotton crop under alkaline calcareous soils of Punjab," *Science Letters*, vol. 4, no. 1, pp. 33–39, 2016.
- [6] D. R. Chaudhary and L. M. Shukla, "Boron status of arid soils of Western Rajasthan in relation to their characteristics," *Journal of the Indian Society of Soil Science*, vol. 52, no. 2, pp. 194–196, 2004.
- [7] S. Goldberg, D. L. Suarez, and P. J. Shouse, "Influence of soil solution salinity on boron adsorption by soils," *Soil Science*, vol. 173, no. 6, pp. 368–374, 2008.
- [8] R. L. Mahler, "Boron in Idaho: essential plant micronutrients," in *Current Information Series 1085*, University of Idaho Extension, Idaho Commission for Libraries, Boise, ID, USA, 2007.
- [9] J. Matula, "Boron sorption in soils and its extractability by soil tests (mehlich 3, ammonium acetate and water extraction)," *Plant, Soil and Environment*, vol. 55, no. 1, pp. 42–49, 2009.
- [10] L. R. F. Alleoni and O. A. D. Camargo, "Boron adsorption in soils from the State of São Paulo, Brazil," *Pesquisa Agropecuária Brasileira*, vol. 35, no. 2, pp. 413–421, 2000.
- [11] S. Arora and D. S. Chahal, "Effect of soil properties on boron adsorption and release in arid and semi-arid benchmark soils," *Communications in Soil Science and Plant Analysis*, vol. 41, no. 21, pp. 2532–2544, 2010.
- [12] F. Steiner, M. D. C. Lana, T. Zoz, R. Fey, and J. F. Frandoloso, "Boron adsorption in lowland soils from Paraná State, Brazil," *Semina: Ciências Agrárias*, vol. 33, no. 4, pp. 1391–1402, 2012.
- [13] I. Dridi, A. Tlili, S. Fatnassi, H. Hamrouni, and M. Gueddari, "Effects of boron distribution on sugar beet crop yield in two Tunisian soils," *Arabian Journal of Geosciences*, vol. 11, no. 15, p. 400, 2018.
- [14] A. Tlili, I. Dridi, S. Fatnassi, H. Hamrouni, and M. Gueddari, "Effects of boron distribution on sugar beet crop yield in two soils of dour ismail irrigated perimeter (Béja-Goubellat-North Tunisia)," in *Recent Advances in Environmental Science from the Euro-Mediterranean and Surrounding Regions*, A. Kallel, Ed., Advances in Science, Technology & Innovation, Tunis, Tunisia, pp. 417–420, 2018.
- [15] M. A. Elrashidi and G. A. O'Connor, "Boron sorption and desorption in soils," *Soil Science Society of America Journal*, vol. 46, no. 1, pp. 27–31, 1982.
- [16] A. Mahajan, S. K. Sharma, R. D. Gupta, and R. Sharma, "Morphological, physical and chemical properties of soils from North West Himalayas," *Bulgarian Journal of Agricultural Science*, vol. 13, pp. 607–618, 2007.
- [17] K. Kumari, G. Nazir, A. Singh, and P. Kumar, "Studies on boron fractions with different physico-chemical properties of cultivated soils of Himachal Pradesh," *International Journal of Current Microbiology and Applied Sciences*, vol. 6, no. 6, pp. 1547–1555, 2017.
- [18] A. Niaz, A. M. Ranjha, Rahmatullah, A. Hannan, and M. Waqas, "Boron status of soils as affected by different soil characteristics-pH, CaCO₃, organic matter and clay contents,"

Pakistan Journal of Agricultural Sciences, vol. 44, no. 3, pp. 428-435, 2007.

- [19] M. K. Sandabe and S. Mohamed, "Boron adsorption by some semi-arid soils of North Eastern Nigeria," *International Journal of Applied Agricultural Research*, vol. 6, no. 1, pp. 71–76, 2011.
- [20] D. R. Chaudhary, L. M. Shukla, and A. Gupta, "Boron equilibria in soil—a review," ARCC Journals, Agricultural Reviews, vol. 26, no. 4, pp. 288–294, 2005.
- [21] M. Turan and A. Horuz, "Bitki beslemenin temel ilkeleri," in *Bitki Besleme*, M. R. Karaman, Ed., pp. 123–347, Gübretaş Rehber Kitaplar Dizisi, Pelin Matbaacılık, Çorum, Turkey, 2012.
- [22] S. Goldberg and C. Su, "New advances in boron soil chemistry," in *Advances in Plant Animal Boron Nutrition*, F. Xu, Ed., pp. 313–330, Springer, Dordrecht, Netherlands, 2007.
- [23] A. Dey, B. S. Dwivedi, M. C. Meena, and S. P. Datta, "Adsorption-desorption of boron in major soils of India," *Journal of the Indian Society of Soil Science*, vol. 61, no. 3, pp. 179–187, 2013.
- [24] A. Niaz, M. Ibrahim, A. Nisar, and S. A. Anwar, "Boron contents of light and medium textured soils and cotton plants," *International Journal of Agriculture and Biology*, vol. 4, pp. 534–536, 2002.
- [25] D. R. Chaudhary and L. M. Shukla, "Boron forms and their relationships with characteristics of arid soils of Western Rajasthan," *Journal of the Indian Society of Soil Science*, vol. 52, no. 2, pp. 197–199, 2004.
- [26] P. Cornillon, "La répartition du bore dans les différentes fractions granulométriques du sol," *Bulletin Association France et Sol*, vol. 5, pp. 3-9, 1970.
- [27] M. S. Anitha, K. S. Anil Kumar, K. M. Nair, C. R. Shivaprasad, L. G. K. Naidu, and D. Sarkar, "Soil boron and its fractions in agro-climatic zones of Karnataka," *Clay Research*, vol. 32, pp. 25–33, 2013.
- [28] B. Colak, A. Korkmaz, and A. Horuz, "Boron status, boron fractions and its availability in sugar beet grown soils," *Anadolu Journal of Agricultural Sciences*, vol. 28, no. 3, pp. 157–167, 2013.
- [29] C. Marzadori, L. V. Antisari, C. Ciavatta, and P. Sequi, "Soil organic matter influence on adsorption and desorption of boron," *Soil Science Society of America Journal*, vol. 55, no. 6, pp. 1582–1585, 1991.
- [30] S. Arora and D. S. Chahal, "Suitability of adsorption isotherms for behavior of boron in soils varying in clay and organic matter content," *Agrochimica*, vol. 51, no. 4-5, pp. 182–193, 2007.
- [31] M. Shafiq, A. M. Ranjha, M. Yaseen, S. M. Mehdi, and A. Hannan, "Comparison of Freundlich and Langmuir adsorption equations for boron adsorption on calcareous soils," *Journal of Agricultural Research*, vol. 46, no. 2, pp. 141–148, 2008.
- [32] K. Saltali, A. V. Bilgili, C. Tarakcioglu, and A. Durak, "Boron adsorption in soils with different characteristics," *Asian Journal of Chemistry, Ghaziabad*, vol. 17, no. 4, pp. 2487–2494, 2005.
- [33] S. Goldberg, "Reactions of boron with soils," *Plant and Soil*, vol. 193, no. 2, pp. 35–48, 1997.
- [34] A. K. Mondal, B. Mandal, and L. N. Mandal, "Boron adsorption characteristics of some acidic alluvial soils in relation to soil properties," *Communications in Soil Science and Plant Analysis*, vol. 24, no. 19-20, pp. 2553–2567, 1993.
- [35] S. Arora and D. S. Chahal, "Modelling boron adsorption kinetics in benchmark soils of Punjab, India," in *Soil Abiotic*

and Biotic Interactions and the Impact on the Ecosystem and Human Welfare, P. M. Huang, Ed., pp. 245–266, Science Publishers, New York, NY, USA, 2005.

[36] E. Okazaki and T. T. Chao, "Boron adsorption and desorption by some Hawaiian soils," *Soil Science*, vol. 105, no. 4, pp. 255–259, 1968.





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