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SOIL CHARACTERISTICS INFLUENCE THE DISTRIBUTION OF BORON FRACTIONS IN SOILS OF OIL PALM PLANTATIONS

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ABSTRACT

In oil palm growing countries like India, nutrient constraints were found to be the major factor limiting oil palm productivity. Despite the regular application of recommended Borax at 100 g palm^{-1} yr^{-1}, boron (B) was reported to be among the deficient nutrients observed in the oil palm plantations. There is a need to study the B fractions and their correlation with the soil characteristics to understand the fate and transformation of the applied fertiliser and their efficient management. The four types of soils (alfisol, entisol, inceptisol, and vertisol) at 0-60 cm depth were collected and analysed for textural class, pH, conductivity, organic carbon, calcium carbonate ($CaCO_3$), sesquioxides, nutrient content and B fractions. The predominant B fraction was residual B accounting for approximately 71.4%-99.3% of total B, whereas only less than 2.0% of total content accounted for plant available B fractions which included fractions that were soluble readily and adsorbed specifically in the soil surfaces. The oxide bound and organic bound fraction varied between 0.97 and 9.12 mg kg^{-1}, and 2.92 and 9.47 mg kg^{-1}, respectively. Soil characteristics like organic carbon content and soil reaction influenced the plant available B fractions positively. Readily soluble B exhibited a positive association with specifically adsorbed and organic bound, suggesting the role of both in replenishing the accessible soil B. The study shows that rather than B application, management strategies should be formulated to improve its availability from the total content.

Keywords: boron fractions, distribution, oil palm plantations, soil characteristics.

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INTRODUCTION

Oil palm is a highly nutrient demanding crop which requires adequate and balanced fertilisation for its growth and bunch yield. However, in oil palm growing countries like India, nutrient constraints were found to be the major factor limiting oil palm productivity. The micronutrient that is very much essential for the metabolic activities of plants is boron (B) (Aftab *et al*., 2022). The plants absorb 96% of B as boric acid molecules and the rest 4% as borate anions (Brdar-Jokanovic, 2020). Having greater mobility in the soil, this nutrient could be available to the plants easily but it shows widespread deficiencies in the soils next to zinc (Zn). About 132 crops from more than 80 countries were reported to be B deficient (Das *et al*., 2019), representing a significant impediment to crop production. The analytical results of 242,827 soils taken from agricultural regions of 615 districts across 28 Indian states showed B deficiency of 44.7% (Shukla *et al.,* 2021). Rather than B as a neglected micronutrient, it has been overlooked in recent times, especially in oil palm growing countries like India. Despite the regular application of recommended Borax at 100 g palm^{-1} yr^{-1}, it was reported to be among the deficient nutrients found in the oil palm plantations. Studies (Behera *et al*., 2016a; 2016b; 2016c; 2017; 2019) on Diagnosis and Recommendation Integrated System (DRIS) indices found that soils of oil palm plantations in states like Goa, Gujarat, Andhra Pradesh, Karnataka and Mizoram of India had B as limiting nutrient. In Malaysia, under severe B deficient conditions, a yield loss of 83% was

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recorded in oil palm (Rajaratnam, 1973). Thus, B supply in sufficient levels is essential for obtaining higher yields in oil palm. It is very much essential to understand the fate and transformation of the applied borax for efficient B management.

The presence of B in the solid or solution phase depends on adsorption and desorption reactions in the soil (Premalatha *et al.,* 2024). It has been reported that B gets adsorbed to clay minerals, organic matter, and iron (Fe) and aluminium (Al) oxides (Eynde *et al.,* 2020). Most soil research solely concentrated on the B form that is dissolved in hot water, with sporadic attempts on B fractions. The experiments on B fractions were also carried out in soils lacking micronutrient management. This study on B fractions in different soil types of oil palm plantations managed with recommended B applications will provide basic information on B availability, and the factors affecting it. Knowledge on total B of soils is not adequate to know the chemical behaviour and its availability. The total B present in soils was quantified through various fractions like readily soluble fraction, specifically adsorbed fraction, organically bound fraction, oxide-bound fraction, and residual fraction (Datta *et al*., 2002; Kasture *et al*., 2019). Readily soluble B is the B which remains in the solution phase or is adsorbed to the soil particles by weak force (Padbhushan & Kumar, 2017). Specifically adsorbed B includes the B which is specifically adsorbed to the organic matter or clay (Padbhushan & Kumar, 2015a). The readily soluble and specifically adsorbed B forms are available to the plants. B adsorbed to the oxides and hydroxides of Al and Fe forms oxide bound B, whereas B bound to different forms of organic matter are organically bound B (Kasture *et al.,* 2020). Residual B depends on the primary and secondary minerals that make up the crystal structure (Datta *et al*., 2002).

Although these B forms coexist in soils in a state of dynamic equilibrium (Das *et al.,* 2019), they differ in mobility and chemical behaviour (Javed *et al*., 2021). Depending on the soil type, the quantity of each B fraction differs significantly (Raza *et al*., 2002). The total B concentration in soils under Indian conditions varied from 7.0 to 630.0 mg kg^{-1} (Prasad *et al*., 2014), but only a small proportion (less than 12.2 mg kg^{-1}) of that is in a form that plants may use. The presence of B in the soil's liquid phase is greatly impacted by the adsorption reactions, which greatly impacts the fertilisation efficiency in the soil-plant system. The B in the liquid phase is available to the plants, whereas the B adsorbed onto the soil surfaces remains unavailable (Communar & Keren, 2006). Various factors like the amount of sesquioxides (R_2O_3), clay content, clay mineralogy, Calcium carbonate content ($CaCO_3$), moisture, organic matter content and solution pH decide the degree of B availability and its adsorption in soils (Sidhu & Kumar, 2018; Padbhushan & Kumar, 2017). Soils with low organic matter, light texture, salinity and high content $CaCO_3$ express a high degree of B deficiency (Boparai & Machanda, 2017). This study aimed to understand the B fractions in the soils of different types (entisol, alfisol, inceptisol and vertisol) in oil palm plantations of India and to determine their association with the soil properties. We hypothesised that soil properties significantly influence the distribution of B fractions in soils of oil palm plantations. Therefore, data obtained on B distribution in varied soil types is crucial for efficient B management.

MATERIALS AND METHODS

Soil Sampling

In this study, soil samples were collected from oil palm plantations of the two Indian states: Andhra Pradesh and Gujarat. The location, geo coordinates, climate, average annual precipitation, age, soil texture and soil types of the abstracted samples are presented in *Table 1*. The soil samples were collected between November and December 2020. Oil palm is grown as an irrigated crop in these states in equilateral triangular planting with a spacing of 9 x 9 x 9 m. The recommended dose of fertilisers (1200:600:1200:500:100 g of $N:P_2O_5:K_2O:MgSO_4$: borax $palm^{-1}$) was applied in four equal splits annually and they were applied in the weeded palm basins of 3.0 m radius. Immediately after fertiliser application, the palm basins were irrigated. Since it is a shallow rooted crop and most roots are present within 60 cm soil depth, the soils were collected from 0-20, 20-40, and 40-60 cm depths. The samples were collected 1.0 m away from the palm trunk and within the weeded palm basins. From each sampling point, three sub samples were collected and mixed to get a representative soil sample. A total of 90 soil samples (30 each from 0-20, 20-40 and 40-60 cm) were collected from 30 sampling points in each soil type. Altogether 360 soil samples were collected from four soil types. The debris and roots present in the soil were removed, and the soils were processed as per the standard procedure given by the Food and Agriculture Organization of United Nations (2019). The samples, after processing, were kept in clean airtight containers for further analysis.

Soil Analysis

The method given by Piper (1966) was followed to determine the soil textural class. Soil pH and soluble salt content were measured using a buffer calibrated pH electrode (Systronics, Model-361)

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and conductivity bridge (Systronics, Model-306) in soil suspension (2.5:1.0 water to soil ratios) following 30 min equilibrium (Jackson, 1973). The organic carbon content of the soil was assessed through the chromic acid wet oxidation technique (Walkley & Black, 1934). Soil available nitrogen (N) was estimated in Pelican's Kelplus ultima duo distillation system by following the alkaline $KMnO_4$ method given by Subbiah and Asija (1956). The available phosphorus (P) was estimated by spectrophotometry at 660 nm (Shimadzu, UV 1900i) following extraction with Olsen's reagent (0.5 M $NaHCO_3$, pH at 8.5 and soil:extractant ratio of 1:10) (Olsen, 1954). Ammonium acetate (1.0 N, pH 7.0) extraction given by Hanway and Heidal (1952) was done for available potassium (K), exchangeable form of calcium (Ca) and magnesium (Mg) estimation with the soil to extractant ratio of 1:5. Available K was analysed through flame photometer (Systronics, Model-128), whereas the exchangeable Ca and Mg were estimated by Versenate titration method (Jackson, 1973). The micronutrients like copper (Cu), Fe, manganese (Mn) and Zn were extracted by extractant consisting of 0.005 M Diethylene Triamine Penta Acetic Acid (DTPA), 0.01M $CaCl_2$. $2H_2O$ and 0.1 M Triethanolamine as outlined by Lindsay and Norvell (1978). The pH of the extractant was adjusted to 7.3 and added to the soils in the ratio of 1:2 for micronutrient extraction. Following that, the extracted micronutrients were estimated by Atomic Absorption Spectrophotometer (Shimadzu, Model - AA7000) with the analytical wavelengths of 324.8, 248.3, 279.5 and 213.9 nm for Cu, Fe, Mn and Zn, respectively. Iron (Fe_2O_3) and aluminium (Al_2O_3) oxides were estimated by the process outlined by Piper (1966). The $CaCO_3$ content was assessed by the titrimetric procedure given by Rowell (1994). The B fractions were extracted sequentially and determined by the colorimetric method (Shimadzu, UV 1900i) described by Datta *et al.* (2002). The readily soluble B and specifically adsorbed B were extracted by 0.01 M $CaCl_2$ and 0.05 M KH_2PO_4, respectively and estimated by the Azomethine-H method at 420 nm wavelength (Gupta, 1967). The oxide bound B [(0.175 M $(NH_4)_2C_2O_4$ (pH 3.25) extractable)], organically bound B (0.5 M NaOH extractable) and residual B (extracted by a mixture of H_2SO_4, HF, $HClO_4$) were estimated by carmine method at the wavelength of 585 nm outlined by Bingham (1982). The summation of these five B fractions contributes to the soil's total B content.

Statistical Analysis

Descriptive analysis like minimum, maximum, standard deviation, and mean were computed for all soil characteristics (*Table 2*). Version 16 of the SPSS programme was utilised to perform all

TABLE 1. DETAILS OF EXPERIMENTAL SOIL SAMPLES

Location	Latitude	Longitude	Climate	Average annual rainfall (mm)	Plantation age (yr)	Soil texture	Taxonomical class
Polavaram mandal, Andhra Pradesh	17°11'18" to 17°14'27" N	*81°31'1" to 81°37'18" E	Hot and humid tropical climate	1,687	5-15	Sandy clay loam to sandy loam	Alfisol
IIOPR research farm, Andhra Pradesh	16°48'29" to 16°48'57" N	*81°7'37" to 81°8'20" E		1,698	7-11	Sandy loam	Entisol
Pedapadu mandal, Andhra Pradesh	16°40'9" to 16°43'43" N	*80°59'21" to 81°2'33" E		1,597	5-15	Sandy clay loam to sandy loam	Inceptisol
Surat, Gujarat	20°51'81" to 21°22'54" N	*72°48'72" to 73°34'48" E	Tropical	1,846	2-7	Clayey to clay loam	Vertisol

Note: [a] - Soil taxonomy (Soil survey staff, 2014).

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statistical computations. The significance of the data was examined by one way ANOVA method. To document the differences in B fractions among soil types, the Duncan test with a 5.0% probability was employed (Duncan, 1955). The association among B fractions and soil characteristics was computed using Pearson's correlation analysis.

RESULTS AND DISCUSSION

The soils showed considerable variability, as seen by the wide range of values for pH, EC, organic carbon, $CaCO_3$, Al_2O_3, Fe_2O_3, clay, silt, sand, major and micronutrients (*Table 2*). The variations in the contents of different B fractions were observed in different soil types considered in the study (*Figure 1*). The readily soluble B is the B available in the soil's liquid phase and it accounts for 0.08%-1.86% of total B (*Table 3*). Similar findings were observed by Padbhushan and Kumar (2015a; 2015b) who studied the B fractions in Ca rich soils of Punjab. In all soil types, increasing soil depth resulted in a drop in readily soluble B concentration, which may be possible because of changes in organic carbon contents and pH. Higher soil organic matter in 0-20 cm soil depths of all experimental soils resulted in the accumulation of B rather than leaching (Chaudhary & Shukla, 2004). The average pH of the soils decreased with higher soil depths. The readily soluble B exhibited a strong positive association with the soil pH (alfisol, entisol, inceptisol) and organic carbon (entisol, inceptisol) (*Table 4* and *Figure 2*). An increase in soil pH increases the surface negative charges and thereby increases the availability of soluble B (Datta *et al.*, 2002). A comparatively higher proportion of readily soluble B in entisol might be ascribed to greater organic carbon. In soil depths of 0-20 and 20-40 cm, lower contents of readily soluble B in alfisol were due to higher Al_2O_3 and Fe_2O_3 content which exhibited a negative relationship. Though the average organic carbon was higher in vertisol, the lower readily soluble B in soil layers of 20-40 and 40-60 cm was due to the presence of clay fractions in large quantities (52.3%-58.4%) (*Table 2*). This fraction had a significant negative relationship with clay content in vertisol. A positive correlation between readily soluble B and major nutrients like available N (entisol, inceptisol), P (entisol, vertisol), K (entisol) and micronutrients like Cu and Zn (entisol, inceptisol, vertisol) was also observed. Considering the relationship between B fractions, readily soluble B was positively correlated with specifically adsorbed B (entisol and inceptisol) and organically bound B (alfisol, inceptisol and vertisol) (*Table 5*). This supports the conclusions of Gurel *et al.* (2019), who studied soil B fractions and their accessibility to olive trees.

TABLE 2. SOIL PROPERTIES IN EXPERIMENTAL SOIL

Parameters	Alfisol											
	Minimum			Maximum			Mean			Standard deviation		
	I	II	III	I	II	III	I	II	III	I	II	III
pH	6.28	6.15	6.13	7.92	7.70	7.52	7.43	7.34	7.19	0.46	0.45	0.39
EC (dS m^{-1})	0.14	0.13	0.18	0.60	0.65	0.62	0.32	0.37	0.36	0.15	0.17	0.13
Organic carbon (%)	0.33	0.19	0.12	0.82	0.62	0.51	0.55	0.37	0.29	0.12	0.15	0.12
$CaCO_3$ (%)	0.00	0.00	0.00	0.00	0.25	1.48	0.00	0.05	0.15	0.00	0.11	0.47
Sesquioxides (%)	8.65	10.80	11.40	15.20	20.80	23.70	11.80	14.10	17.30	2.31	2.94	3.68
Al_2O_3 (%)	5.55	3.36	7.56	8.90	17.60	14.40	7.42	8.44	10.60	1.23	4.10	2.10
Fe_2O_3 (%)	3.00	3.10	3.24	6.30	9.80	11.10	4.41	5.64	6.63	1.12	2.22	2.56

Parameters	Entisol											
	Minimum			Maximum			Mean			Standard deviation		
	I	II	III	I	II	III	I	II	III	I	II	III
pH	6.62	6.56	5.96	7.89	7.57	7.24	7.39	7.19	6.91	0.35	0.28	0.37
EC (dS m^{-1})	0.15	0.08	0.09	0.41	0.43	0.48	0.21	0.18	0.19	0.08	0.10	0.11
Organic carbon (%)	0.47	0.31	0.20	0.98	0.82	0.52	0.68	0.53	0.36	0.15	0.17	0.10
$CaCO_3$ (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sesquioxides (%)	9.60	4.00	4.11	16.50	6.70	8.26	11.96	5.47	6.12	1.89	0.90	1.28
Al_2O_3 (%)	4.29	1.52	1.73	10.60	3.84	5.54	6.18	3.01	3.40	1.83	0.80	1.14
Fe_2O_3 (%)	5.22	1.92	2.10	8.43	2.86	3.20	5.89	2.46	2.72	1.03	0.33	0.34

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TABLE 2. SOIL PROPERTIES IN EXPERIMENTAL SOIL (continued)

Parameters	Alfisol												Entisol											
	Minimum			Maximum			Mean			Standard deviation			Minimum			Maximum			Mean			Standard deviation		
	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
Clay (%)	21.80	20.00	17.00	31.60	28.00	24.00	28.10	25.10	19.50	2.90	2.79	2.62	11.30	11.80	10.20	16.30	18.00	13.50	13.60	14.60	12.20	1.54	1.73	1.00
Silt (%)	13.00	11.00	14.00	16.00	15.00	16.20	14.40	12.40	15.30	0.99	1.15	0.71	17.50	19.00	17.00	25.00	28.00	21.00	20.90	23.40	18.20	2.33	2.91	1.41
Sand (%)	60.40	58.00	54.10	69.50	68.20	62.80	66.00	62.20	56.50	2.87	3.43	2.82	59.10	55.80	66.50	69.20	66.90	71.70	65.50	62.00	69.60	2.87	3.50	1.68
N (mg kg^{-1})	140.00	112.00	112.00	260.00	182.00	154.00	172.00	147.00	128.00	39.80	24.10	16.80	98.10	84.10	56.00	252.00	182.00	168.00	159.00	130.00	109.00	44.50	31.00	31.50
P (mg kg^{-1})	11.40	10.00	10.00	57.10	25.70	18.10	21.40	15.50	12.40	13.00	4.28	2.43	9.15	7.59	7.59	50.00	34.50	29.10	23.10	18.30	16.00	11.40	8.67	7.10
K (mg kg^{-1})	77.70	76.30	74.50	238.00	210.00	164.00	150.00	131.00	114.00	62.30	49.50	39.20	84.40	80.80	48.20	224.00	143.00	104.00	117.00	102.00	89.20	35.80	17.40	16.20
Ca (meq 100 g^{-1})	2.50	2.40	2.40	6.10	6.50	6.50	4.14	4.26	4.40	1.29	1.43	1.42	2.00	2.00	2.40	4.00	3.56	4.00	3.23	2.92	3.20	0.63	0.59	0.55
Mg (meq 100 g^{-1})	1.40	1.10	1.40	4.10	4.20	4.30	2.50	2.53	2.60	1.00	1.06	0.97	1.20	1.20	0.30	2.17	2.27	2.40	1.74	1.77	1.58	0.39	0.43	0.68
Fe (mg kg^{-1})	5.44	4.84	4.05	13.44	8.85	6.70	9.42	7.00	5.17	2.10	1.34	0.92	3.62	3.46	3.48	6.69	5.69	5.71	4.91	4.23	4.45	0.93	0.71	0.76
Mn (mg kg^{-1})	3.10	2.04	2.05	4.26	3.16	3.06	3.67	2.81	2.17	0.58	0.51	0.31	2.77	2.59	2.46	7.79	6.62	6.61	5.78	4.84	4.17	1.80	1.36	1.31
Zn (mg kg^{-1})	0.93	0.64	0.63	1.45	1.05	0.88	1.11	0.80	0.72	0.16	0.12	0.07	0.80	0.83	0.80	1.30	1.00	0.94	1.06	0.91	0.87	0.15	0.06	0.05
Cu (mg kg^{-1})	0.40	0.45	0.31	0.61	0.63	0.70	0.49	0.54	0.47	0.08	0.06	0.11	0.09	0.06	0.06	0.18	0.10	0.09	0.12	0.08	0.08	0.03	0.01	0.01
	Vertisol												Inceptisol											
pH	7.31	7.26	7.20	8.28	8.04	7.84	7.66	7.50	7.39	0.34	0.26	0.21	7.40	7.33	7.22	8.24	8.17	7.98	7.90	7.78	7.63	0.28	0.27	0.22
EC (dS m^{-1})	0.45	0.21	0.32	1.16	1.02	1.11	0.73	0.60	0.55	0.28	0.26	0.23	0.24	0.19	0.30	0.70	0.71	0.70	0.44	0.45	0.47	0.16	0.18	0.16
Organic carbon (%)	0.45	0.31	0.27	1.01	0.82	0.51	0.59	0.46	0.36	0.17	0.14	0.08	0.27	0.16	0.12	0.70	0.47	0.31	0.49	0.32	0.23	0.13	0.10	0.06
$CaCO_3$ (%)	0.13	0.32	0.25	3.00	4.10	4.88	1.71	1.89	1.97	1.01	1.11	1.30	0.00	0.00	0.00	0.00	0.50	1.30	0.00	0.10	0.30	0.00	0.17	0.50
Sesquioxides (%)	5.35	5.10	5.20	8.60	8.93	8.76	6.47	7.17	7.48	0.88	1.16	1.03	2.58	2.50	2.72	9.30	7.94	7.10	6.32	5.74	5.05	2.38	1.97	1.51
Al_2O_3 (%)	2.24	2.20	1.30	4.45	4.40	5.00	3.21	3.53	3.76	0.79	0.83	1.09	0.71	0.33	0.21	6.38	3.72	3.67	2.64	2.16	1.73	1.80	1.25	1.15
Fe_2O_3 (%)	2.40	2.10	2.30	4.15	4.69	4.92	3.25	3.64	3.72	0.61	0.80	0.76	3.43	3.00	2.86	5.92	4.83	4.37	4.45	3.94	3.53	0.82	0.63	0.56

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TABLE 2. SOIL PROPERTIES IN EXPERIMENTAL SOIL (continued)

Parameters	Alfisol												Entisol											
	Minimum			Maximum			Mean			Standard deviation			Minimum			Maximum			Mean			Standard deviation		
	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
Clay (%)	32.00	48.50	54.70	44.50	57.00	62.50	37.90	52.30	58.40	3.64	2.79	2.94	14.50	20.50	12.00	19.00	29.00	15.00	16.80	24.40	13.30	1.62	2.97	1.00
Silt (%)	27.00	20.00	15.00	38.50	27.00	25.00	34.40	23.20	19.90	3.35	2.14	3.24	24.50	20.00	30.50	31.00	24.00	35.00	28.40	21.80	32.60	2.20	1.58	1.95
Sand (%)	25.40	20.30	17.50	29.50	30.30	27.40	27.70	24.50	21.80	1.62	3.70	2.96	50.20	48.00	52.30	59.50	59.50	56.70	54.80	53.80	54.10	3.14	3.66	1.55
N (mg kg^{-1})	84.00	84.00	58.90	180.80	168.00	140.10	130.10	116.20	96.70	28.60	26.50	22.90	84.00	70.00	56.00	196.10	154.10	126.10	138.70	112.00	88.20	37.10	32.4	22.00
P (mg kg^{-1})	9.11	5.98	7.72	30.60	25.00	19.80	20.80	15.50	13.40	8.53	5.70	3.80	14.00	12.80	11.00	31.30	26.50	26.70	22.20	18.10	14.80	5.83	4.53	4.90
K (mg kg^{-1})	65.90	60.60	61.80	304.80	185.70	152.20	169.40	129.80	101.90	80.90	44.00	28.00	74.10	77.00	48.20	204.30	184.80	182.10	137.50	120.00	111.30	47.60	35.90	39.90
Ca (meq 100 g^{-1})	8.30	6.50	6.50	12.50	12.20	11.00	10.40	8.80	8.40	1.30	2.19	1.53	2.10	2.00	2.20	6.50	6.30	6.60	4.32	4.12	4.33	1.70	1.65	1.68
Mg (meq 100 g^{-1})	6.00	4.70	5.20	10.40	9.30	8.8.	7.60	6.30	6.40	1.35	1.83	1.09	1.00	1.00	1.10	4.00	4.30	4.10	2.45	2.43	2.52	1.15	1.22	1.17
Fe (mg kg^{-1})	4.17	3.46	3.51	7.74	6.41	5.52	5.33	4.88	4.58	1.10	0.85	0.56	3.14	2.54	2.53	5.06	4.50	4.46	4.08	3.69	3.63	0.72	0.76	0.74
Mn (mg kg^{-1})	3.10	2.07	2.05	6.11	4.08	5.06	3.87	3.28	3.12	1.09	0.65	0.89	2.08	2.19	2.05	5.10	4.13	4.04	3.36	3.02	2.87	0.93	0.53	0.52
Zn (mg kg^{-1})	0.94	0.85	0.81	1.14	1.00	0.91	1.04	0.93	0.87	0.06	0.04	0.03	0.90	0.61	0.59	1.06	0.82	0.77	0.99	0.73	0.68	0.06	0.06	0.05
Cu (mg kg^{-1})	0.74	0.58	0.41	0.91	0.83	0.61	0.83	0.66	0.49	0.06	0.08	0.06	0.14	0.17	0.16	0.40	0.30	0.24	0.30	0.24	0.20	0.09	0.04	0.03

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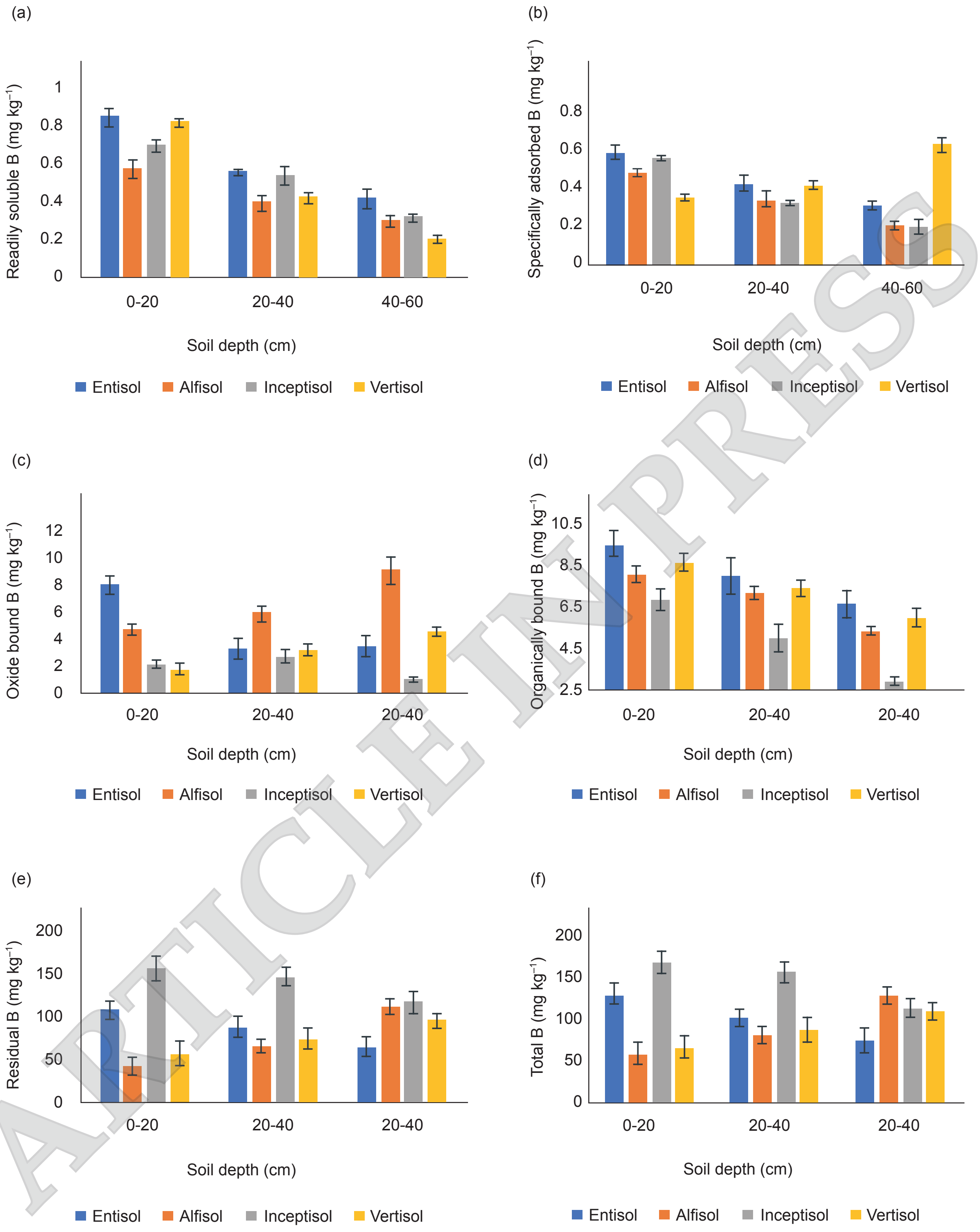

Figure 1. Depth wise distribution of (a) readily soluble B, (b) specifically adsorbed B, (c) oxide bound B, (d) organically bound B, (e) residual B and (f) total B in different soil types.

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TABLE 3. RELATIVE DISTRIBUTION OF B FRACTIONS IN DIFFERENT SOIL TYPES

Soil type	B fractions as a percentage of total B (%)										Average total B (mg kg^{-1})
	Readily soluble B		Specifically adsorbed B		Oxide bound B		Organically bound B		Residual B		
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	
0-20 cm											
Alfisol	0.49	1.76	0.62	1.94	5.13	13.09	8.05	17.00	71.40	85.66	57.5 ± 13.7
Entisol	0.23	0.66	0.17	0.51	4.22	8.79	3.40	8.55	82.19	91.38	127.9 ± 12.6
Inceptisol	0.20	0.97	0.19	0.75	0.43	2.15	3.01	7.55	89.04	96.15	173.9 ± 13.6
Vertisol	0.28	1.86	0.24	0.83	2.08	3.60	7.16	18.16	77.12	89.20	65.8 ± 13.5
20-40 cm											
Alfisol	0.18	1.28	0.22	0.65	3.35	12.15	3.91	18.01	77.64	88.43	80.2 ± 10.1
Entisol	0.47	1.33	0.22	0.97	3.56	5.83	7.35	12.75	80.25	88.11	101.6 ± 10.5
Inceptisol	0.14	0.69	0.09	0.44	1.01	4.34	0.83	7.18	89.34	96.89	156.3 ± 12.9
Vertisol	0.10	0.98	0.13	0.96	2.62	5.10	3.09	15.77	80.14	93.66	86.6 ± 15.1
40-60 cm											
Alfisol	0.08	0.40	0.41	1.20	4.67	10.57	2.20	6.66	82.09	91.94	128.3 ± 10.1
Entisol	0.30	0.80	0.14	0.82	2.19	6.48	3.94	13.63	80.16	91.32	75.0 ± 15.2
Inceptisol	0.11	0.65	0.07	0.43	0.13	2.68	0.31	6.77	90.93	99.30	113.1 ± 10.6
Vertisol	0.08	0.33	0.22	1.23	2.02	6.69	3.30	12.45	83.98	91.16	109.8 ± 10.4

Note: Min - minimum; Max - maximum.

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TABLE 4. CORRELATION AMONG SOIL CHARACTERISTICS AND B FRACTIONS

	pH	EC	Organic carbon	$CaCO_3$	R_2O_3	Al_2O_3	Fe_2O_3	Clay	Silt	Sand	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
Alfisol																			
Readily soluble B	0.385*	-0.033	0.180	-0.205	-0.470**	-0.353	-0.312	0.353	0.152	-0.436*	0.197	0.037	0.188	-0.318	-0.340	-0.073	0.131	0.027	0.035
Specifically adsorbed B	0.038	0.131	0.478**	-0.153	-0.246	-0.337	-0.201	0.584**	0.111	-0.504*	-0.309	0.437**	0.250	0.008	0.044	-0.009	-0.059	-0.256	0.155
Oxide bound B	-0.238	0.320	-0.324	0.015	0.407*	0.129	0.510**	0.219	0.287	-0.318	-0.372*	-0.258	-0.432*	-0.064	-0.222	0.100	0.414*	-0.307	-0.365*
Organically bound B	0.273	-0.139	0.253	-0.038	-0.461*	-0.264	-0.418*	0.342	0.219	0.399**	0.406*	0.160	0.279	0.084	0.031	0.290	0.315	0.186	0.090
Residual B	-0.263	0.200	-0.491**	-0.083	0.367*	0.265	0.258	0.250	0.303	-0.267	0.376*	-0.190	-0.275	0.075	-0.077	-0.356	-0.047	-0.170	-0.039
Total B	-0.254	0.208	-0.481*	-0.078	0.358	0.251	0.261	0.243	0.305	0.317	-0.366*	-0.194	-0.279	0.071	-0.089	-0.170	-0.235	-0.057	-0.067
Entisol																			
Readily soluble B	0.411*	-0.110	0.542**	-	-0.142	-0.090	-0.159	0.379*	0.342	-0.413*	0.407*	0.617**	0.616**	-0.154	-0.006	0.132	0.257	0.739**	0.542**
Specifically adsorbed B	0.663**	-0.142	0.303	-	0.008	-0.001	0.012	0.323	0.298	-0.357	0.516**	0.448**	0.462**	0.129	0.174	0.138	0.298	0.601**	0.387*
Oxide bound B	0.105	0.039	0.194	-	0.842**	0.646**	0.849**	0.443*	0.601**	-0.633**	-0.021	0.035	0.144	-0.290	-0.047	-0.125	0.123	0.033	-0.011
Organically bound B	0.103	0.190	0.675**	-	0.042	0.099	-0.017	0.038	0.112	-0.100	0.159	-0.091	0.284	0.025	-0.034	0.079	0.202	0.338	0.500**
Residual B	0.114	-0.168	0.196	-	0.588**	0.451**	0.594**	0.248	0.580**	-0.537**	-0.003	0.223	0.092	-0.482**	-0.014	0.103	0.189	0.293	0.136
Total B	0.128	0.142	0.245	-	0.612**	0.474**	0.614**	0.273	0.596**	-0.559**	0.013	0.211	0.123	-0.469**	-0.018	0.092	0.203	0.304	0.163
Vertisol																			
Readily soluble B	0.147	0.187	0.161	-0.074	-0.579**	-0.331	-0.445*	-0.612**	0.612**	0.380*	0.294	0.701**	0.183	0.218	-0.050	0.005	0.190	0.505**	0.683**
Specifically adsorbed B	-0.111	-0.232	-0.168	-0.097	-0.140	0.039	-0.254	0.488**	-0.481**	-0.315	-0.435*	0.185	-0.330	0.285	0.127	-0.239	-0.071	-0.186	-0.235
Oxide bound B	0.088	0.176	-0.299	0.709**	-0.018	0.073	-0.116	0.721**	-0.610**	-0.654**	0.040	-0.228	-0.007	-0.065	-0.194	-0.265	-0.232	-0.032	-0.314
Organically bound B	0.211	0.137	0.513**	-0.196	-0.217	-0.251	-0.009	-0.708**	0.637**	0.571**	0.350	0.044	0.265	0.294	0.161	0.245	0.192	0.598**	0.656**
Residual B	0.151	0.160	-0.217	0.807**	0.126	0.204	-0.067	0.651**	-0.535**	-0.620**	0.128	-0.276	0.161	0.072	-0.002	-0.329	-0.202	-0.459*	-0.198
Total B	0.160	0.172	-0.209	0.816**	0.104	0.188	-0.079	0.642**	-0.526**	-0.615**	0.141	-0.270	0.166	0.077	-0.011	-0.330	-0.199	-0.449*	-0.184
Inceptisol																			
Readily soluble B	0.606**	-0.382*	0.738**	-0.321	0.248	0.216	0.203	0.280	-0.253	-0.069	0.469**	0.168	0.070	-0.299	-0.292	0.261	-0.145	0.494**	0.475**
Specifically adsorbed B	0.459*	0.108	0.429*	-0.228	0.281	0.149	0.347	0.095	-0.227	0.217	0.084	0.316	0.362*	0.334	0.230	0.208	0.199	0.607**	0.450*
Oxide bound B	0.212	-0.087	0.201	-0.027	-0.003	0.043	0.068	0.797**	-0.716**	-0.202	0.190	0.394*	0.075	-0.239	-0.193	-0.008	-0.014	0.051	-0.069
Organically bound B	0.066	-0.247	0.493**	-0.228	0.347	0.302	0.238	0.214	-0.179	-0.078	0.652**	0.208	0.198	-0.329	-0.264	0.212	0.276	0.507**	0.249
Residual B	-0.196	0.168	-0.068	-0.302	0.207	-0.049	0.330	0.160	-0.246	0.135	0.066	0.031	-0.033	0.306	0.270	0.165	0.341	0.309	0.168
Total B	-0.180	0.150	-0.034	-0.311	0.223	-0.027	0.340	0.189	-0.271	0.125	0.103	0.053	-0.020	0.277	0.144	0.174	0.344	0.334	0.180

Note: *- p<0.05; **- p<0.01; R_2O_3 - sesquioxides content

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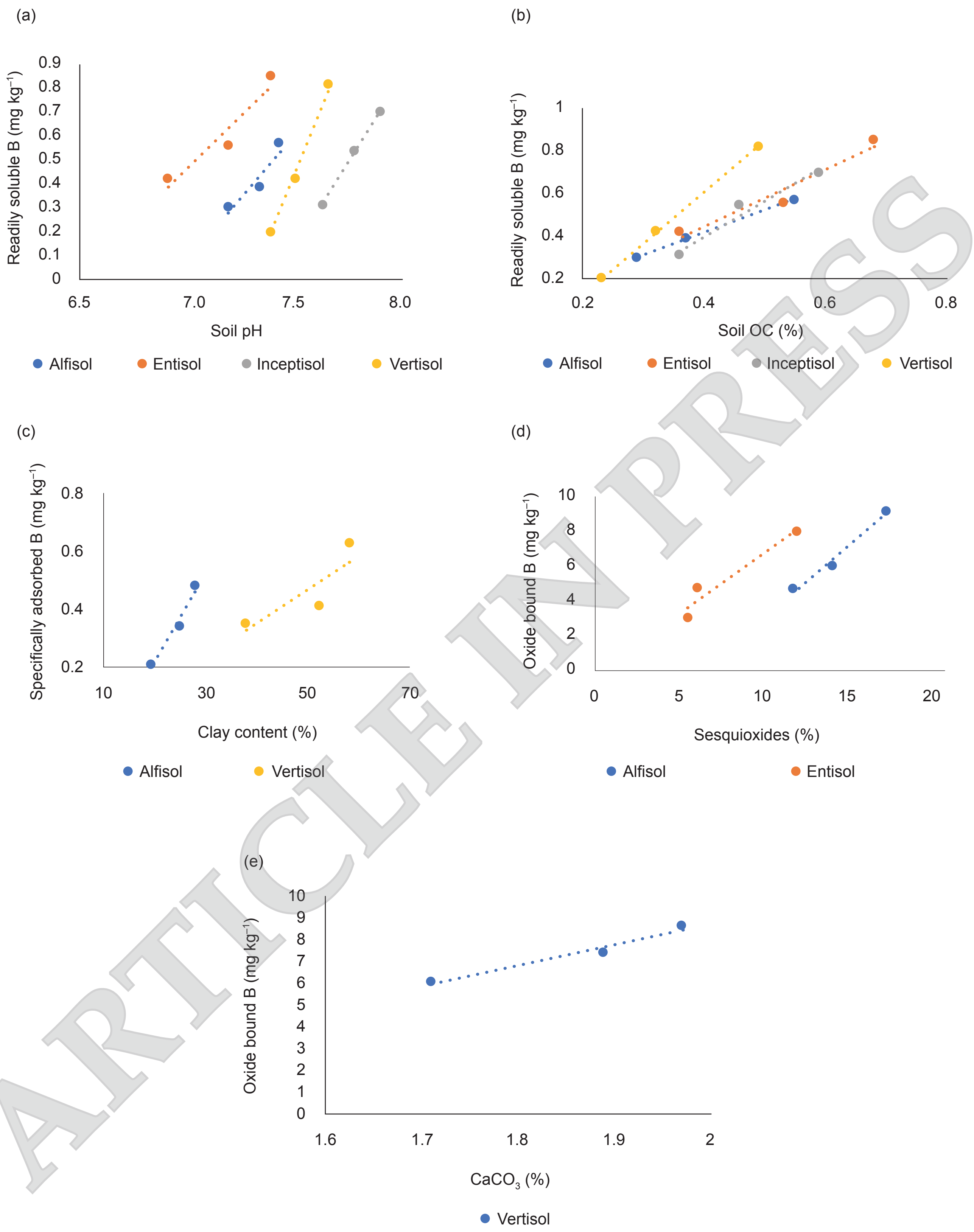

Figure 2. Effect of (a) soil pH, (b) soil organic carbon (oc), (c) clay content, (d) sesquioxides, and (e) $CaCO_3$ on various B fractions.

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TABLE 5. CORRELATION AMONG THE B FRACTIONS STUDIED IN SOILS

Item	RDS B	SAD B	OXD B	ORG B	RSL B	TOT B
Alfisol						
Readily soluble B	1					
Specifically adsorbed B	0.340	1				
Oxide bound B	-0.223	0.306	1			
Organically bound B	0.440*	0.407*	-0.349	1		
Residual B	-0.210	0.340	0.781**	-0.352	1	
Total B	-0.189	0.337	0.802**	-0.307	0.998**	1
Entisol						
Readily soluble B	1					
Specifically adsorbed B	0.718**	1				
Oxide bound B	-0.047	0.136	1			
Organically bound B	0.303	0.156	-0.301	1		
Residual B	-0.229	0.198	0.696*	0.207	1	
Total B	-0.247	0.216	0.744**	0.282	0.995*	1
Vertisol						
Readily soluble B	1					
Specifically adsorbed B	0.358	1				
Oxide bound B	-0.153	0.242	1			
Organically bound B	0.454*	0.299	-0.504**	1		
Residual B	-0.013	0.220	0.872**	-0.448*	1	
Total B	0.029	0.210	0.882**	-0.428*	0.999**	1
Inceptisol						
Readily soluble B	1					
Specifically adsorbed B	0.418*	1				
Oxide bound B	0.267	0.068	1			
Organically bound B	0.461*	0.177	0.251	1		
Residual B	-0.057	0.280	0.048	0.245	1	
Total B	-0.022	0.292	0.086	0.297	0.998**	1

Note: RDS B - readily soluble B; SAD B - specifically adsorbed B; OXD B - oxide bound B; ORG B - organically bound B; RSL B - residual B; TOT B - total B.

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The specifically adsorbed B constitutes 0.07%-1.94% of total B (*Table 3*). Comparable amounts of these pool were reported by Padbhushan and Kumar (2015a). Like readily soluble B, the specifically adsorbed B content also dropped as soil depth increased in all soil types except vertisol. Decline in absorbing surfaces with soil depth could be the cause for such a reduction. The presence of organic matter in higher quantities accounts for relatively higher quantities of specifically adsorbed B in entisol. The role of organic matter as B adsorbing surface was reported by Padbhushan and Kumar (2017). Higher clay content in vertisol is attributed to the higher contents of specifically adsorbed B at 40-60 cm (*Table 2*). Diana and Beni (2006) reported the dominating role of clay on specifically adsorbed B. The specifically adsorbed B had a positive relation with clay content (in alfisol, and vertisol), pH (in entisol, and inceptisol), organic carbon (in alfisol, and inceptisol), available N (in entisol), P (in alfisol, and entisol), and K and micronutrients like Cu and Zn (in entisol, and inceptisol) (*Table 4* and *Figure 2*). Supporting this, Gurel *et al.* (2019) established a significant positive association between specifically adsorbed B and soil parameters (pH, EC, $CaCO_3$, organic matter, clay, exchangeable K and Mg). Lower contents of specifically adsorbed B in inceptisol may be because of lower adsorbing surfaces (*Table 2*) especially organic carbon (0.23%-0.49%), sesquioxides (5.05%-6.32%) and Fe_2O_3 (3.53%-4.45%). Dey *et al.* (2017) reported lower contents of specifically adsorbed B in soils with low organic carbon. A strong positive association was found between specifically adsorbed B and organically bound B in alfisol (*Table 5*).

Of the total B content, the oxide bound B accounted for 0.13%-13.09% (*Table 3*). Comparable outcome was stated by Bhupenchandra *et al.* (2024) in acidic inceptisol of Eastern Himalaya. Pachauri *et al.* (2024) reported that yearly application of B resulted in a significant increase in oxide bound B fraction in *Typic hapludolls.* In comparison to the readily soluble B and specifically adsorbed B, the oxide bound B was larger suggesting that oxides and oxyhydroxides contribute significantly to fixation of B by isomorphous exchange and complex formation (Bhupenchandra *et al*., 2020). These contents were notably higher in entisol at 0-20 cm and in alfisol at 20-40 cm and 40-60 cm soil depths (*Figure 1*). This is linked to the higher content of oxides and hydroxides of iron and aluminium (*Table 2*), which may have offered plenty of sites for the B [$B(OH)_4^-$, $B(OH)_3$] adsorption through ligand exchange (Datta *et al.*, 2002; Kaundal *et al.*, 2014). Lower oxide bound B content was found in vertisol at 0-20 cm, whereas at soil depths of 20-40 cm and 40-60 cm inceptisol recorded significantly lower oxide bound B (*Figure 2*). This was the result of lower mean contents of Fe_2O_3 (3.25%-4.45%) and Al_2O_3 (2.03%-3.76%) in specified soil types (vertisol and inceptisol) than others (*Table 2*). The oxide bound B exhibited a strong positive association with the amount of clay and Al_2O_3, Fe_2O_3 in entisol, whereas this fraction was positively associated with the clay content and $CaCO_3$ in vertisol (*Table 4* and *Figure 2*). Diana *et al.* (2008) reported a positive correlation between oxide bound B and Fe oxides in alluvial soils of Italy. Similarly, Barman *et al.* (2014) reported that $CaCO_3$ makes B unavailable by adsorption, co-precipitation, or occlusion. Also, this fraction had a negative association with available N, K, DTPA extractable Cu and a positive association with DTPA extractable Mn in alfisol (*Table 4*). In light of its association with other B fractions, a positive relationship was found with residual B and total B in alfisol, entisol and vertisol (*Table 5*). Supporting this, Kaundal *et al.* (2014) observed a positive association among oxide bound B and total B in the acid alfisol of Northwestern Himalayas.

About 0.31%-18.16% of total B was made up of organically bound B (*Table 3*) and were unavailable for uptake by plants (Bhupenchandra *et al*., 2024). This fraction's presence in the soil could be related to the organic matter, which adsorbed the B through ligand exchange (Bolan *et al.,* 2023). Depending on the soil's level of organic carbon content, the organically bound B varied under different soil types. Here, the entisol showed higher organically bound B content followed by vertisol (*Figure 1*), which is a result of higher organic carbon status of the soils (*Table 2*). Chaudhary and Shukla (2004) stated organic carbon as the major contributor of organically bound B. The organically bound B had significant positive association with organic carbon content in entisol, vertisol and inceptisol (*Table 4*). Supporting this, Datta and co-workers found a significant positive relationship among organically bound B and soil parameters like clay, ammonium oxalate extractable Al, Fe and organic carbon (Datta *et al*., 2002). Also, the organically bound B was positively correlated with DTPA extractable Zn (in inceptisol, and vertisol) and Cu (in entisol, and vertisol). This fraction had a positive and significant correlation with readily soluble B in alfisol, inceptisol, and vertisol (*Table 5*). To meet the plant's B demand, organically bound B may have transformed into a readily soluble B. This fraction is viewed as primary sink of plant available B (Bhupenchandra *et al.,* 2020), released on decomposition of organic matter (Kumar *et al.,* 2023). In vertisol, organically bound B was negatively correlated with oxide bound B, residual B and total B (*Table 5*).

The residual B constituted the most prominent B pool, accounting for approximately 71.4%-99.3% of the total B (*Table 3*). They were present within the atomic structure of the minerals, and were improbable to be liberated in the medium and long terms (Padbhushan & Kumar, 2017; Rahman & Schoenau, 2020). Regardless of the soil, crops, fertilisation practice, and climate, a higher percentage of residual B fraction (even above 80%) has been observed by numerous workers (Das *et al.*, 2023; Datta *et al*., 2002; Gurel *et al.*, 2019; Kaundal *et al.*, 2014; Kumari *et al*., 2017; Xu *et al*., 2001). The soils of inceptisol had relatively higher residual B, since B fertilisers were continuously added (100 g palm^{-1} yr^{-1}) for 5-15 years over the oil palm plantation's age. The findings of Jegadeeswari and Muthumanickam (2017) reported significant variations in residual B under varying dose and frequencies of B application in Maize-Sunflower cropping system. Datta *et al.* (2002) reported that residual B is the structural component of sesquioxides (R_2O_3) and clay minerals. The residual B had a notable positive association with R_2O_3, Al_2O_3 and Fe_2O_3 content in entisol, whereas it was positively associated with clay and $CaCO_3$ content in vertisol (*Table 4*). This is consistent with the observations of Kaundal *et al.* (2014). Residual B was positively correlated with oxide bound B and total B, whereas it had strong negative relationship with organically bound B in vertisol (*Table 4*).

The total of all the extracted soil B fractions was added up to determine total B and it is not a trustworthy measure of B that is accessible for plant absorption (Kasture *et al*., 2020). Their concentration varied between 65.8 and 173.9 mg kg^{-1} (*Table 3*). This was consistent with the results of Diana and Beni (2006). Significant differences in concentration of total B in different soils might be due to parent material, their level of weathering, and soil management (Das &

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Purkait, 2020). The inceptisol recorded high total B at 0-20 and 20-40 cm, whereas alfisol recorded higher contents at 40-60 cm soil depth (*Figure 2*). A marked trend in total B at different soil depths was not noticed. The total B showed a positive association with Al_2O_3, and Fe_2O_3 content in entisol, whereas it was positively associated with clay and $CaCO_3$ content in vertisol (*Table 4*). Irrespective of soil types, total B had strong positive association with oxide bound B and residual B (*Table 5*).

CONCLUSION

The qualitative and quantitative relevance of soil B is better defined by their fractionation in the soils. This study offers better insights of different B fractions and their association with soil characteristics under different soil types. The residual B accounted for 71.4%-99.3% of total B, and it was the predominant fraction. The plant available B fractions (readily soluble B and specifically adsorbed B) accounted for less than 2% of total B. Soil properties like pH and organic carbon had positive relationship with readily soluble B and specifically adsorbed B, while Fe_2O_3 and Al_2O_3, clay content had positive association with oxide bound B. The association among different fractions of B indicated their interdependence. Readily soluble B showed a positive correlation with specifically adsorbed B and organically bound B, suggesting their role in replenishing the accessible soil B. This study suggests that rather than B application, management strategies should be formulated to improve its availability from the total content.

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REFERENCES

Aftab, T., Landi, M., Papadakis, I. E., Araniti, F., & Brown, P. H. (Eds.). (2022). *Boron in Plants and Agriculture: Exploring the physiology of boron and its impact on plant growth* (1st ed.). Academic Press. https://doi.org/10.1016/C2020-0-02952-X

Barman, M., Shukla, L. M., Datta, S. P., & Rattan, R. K. (2014). Effect of applied lime and boron on the availability of nutrients in an acid soil. *Journal of Plant Nutrition*, *37*(3), 357–373. https://doi.org/10.1080/01904167.2013.859698

Behera, S. K., Rao, B. N., Suresh, K., & Manoja, K. (2016a). Soil nutrient status and leaf nutrient norms in oil palm (*Elaeis guineensis* Jacq.) plantations grown on southern plateau of India. *Proceedings of the National Academy of Sciences India Section B: Biological Sciences*, *86*(3), 691–697. https://doi.org/10.1007/s40011-015-0508-y

Behera, S. K., Rao, B. N., Suresh, K., Ramachandrudu, K., & Manorama, K. (2016b). Soil fertility, leaf nutrient concentration and yield limiting nutrients in oil palm (*Elaeis guineensis*) plantations of Surat District of Gujarat. *The Indian Journal of Agricultural Sciences*, *86*(3), 409-413. https://doi.org/10.56093/ijas.v86i3.57036

Behera, S. K., Shukla, A. K., Suresh, K., & Mathur, R. K. (2019). Estimation of soil properties and leaf nutrients status of oil palm plantations in an intensively cultivated region of India. *Current Science*, *117*(3), 498. https://doi.org/10.18520/cs/v117/i3/498-502

Behera, S. K., Suresh, K., Rao, B. N., Manoja, K., & Manorama, K. (2016c). Soil nutrient status and leaf nutrient norms in oil palm (*Elaeis guineensis* Jacq.) plantations grown in the west coastal area of India. *Communications in Soil Science and Plant Analysis*, *47*(2), 255–262. https://doi.org/10.1080/00103624.2015.1118120

Behera, S. K., Suresh, K., Rao, B. N., Ramachandrudu, K., Manorama, K., & Harinarayana, P. (2017). Soil fertility and yield-limiting nutrients in oil palm plantations of north-eastern state Mizoram of India. *Journal of Plant Nutrition*, *40*(8), 1165–1171. https://doi.org/10.1080/01904167.2016.1264592

Bhupenchandra, I., Basumatary, A., Dutta, S., Das, A., Choudhary, A. K., Lal, R., Sharma, A. D., Sen, A., Prabhabati, Y., & Sahoo, M. R. (2024). Repercussions of fertilization with boron and enriched organic manure on soil chemical characteristics, boron and phosphorus fractions, and French bean productivity in an acidic Inceptisol of Eastern Himalaya. *Scientia Horticulturae*, *324*, 112589. https://doi.org/10.1016/j.scienta.2023.112589

Bhupenchandra, I., Basumatary, A., Dutta, S., Singh, L. K., & Datta, N. (2020). Impact of boron fertilization on boron fractions at different crop growth stages in cauliflower_cowpea_okra sequence in an inceptisols of North East India.

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Journal of Plant Nutrition, *43*(8), 1175–1188. https://doi.org/10.1080/01904167.2020.1724300

Bingham, F T (1982). Boron. (pp. 431-442) *Methods of Soil Analysis Part 2 - Chemical and Microbiological Properties*, In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.). American Society of Agronomy & Soil Science Society of America.

Bolan, S., Wijesekara, H., Amarasiri, D., Zhang, T., Ragályi, P., Brdar-Jokanović, M., Rékási, M., Lin, J., Padhye, L. P., Zhao, H., Wang, L., Rinklebe, J., Wang, H., Siddique, K. H., Kirkham, M., & Bolan, N. (2023). Boron contamination and its risk management in terrestrial and aquatic environmental settings. *The Science of the Total Environment*, *894*, 164744. https://doi.org/10.1016/j.scitotenv.2023.164744

Boparai, A. K., & Manchanda, J. S. (2017). Depth-wise distribution of boron in relation to soil properties in South-west Punjab. *Agropedology*, *27*(2), 177–180. https://doi.org/10.47114/j.agroped.2017.dec9

Brdar-Jokanović, M. (2020). Boron toxicity and deficiency in agricultural plants. *International Journal of Molecular Sciences*, *21*(4), 1424. https://doi.org/10.3390/ijms21041424

Chaudhary, D., & Shukla, L. M. (2004). Boron status of arid soils of Western Rajasthan in relation to their characteristics. *Journal of the Indian Society of Soil Science*, *52*(2), 194–196.

Communar, G., & Keren, R. (2006). Rate-Limited Boron transport in Soils: The effect of soil texture and solution pH. *Soil Science Society of America Journal*, *70*(3), 882–892. https://doi.org/10.2136/sssaj2005.0259

Das, A. K., & Purkait, A. (2020). Boron dynamics in soil: Classification, sources, factors, fractions, and kinetics. *Communications in Soil Science and Plant Analysis*, *51*(22), 2778–2790. https://doi.org/10.1080/00103624.2020.1849261

Das, R., Kumar, R., Sarkar, D., Das, S., Pradhan, A. K., Das, D., Srivastava, M., Sinha, A. K., Sahoo, S., Datta, S. P., & Mandal, B. (2023). Boron fractions and its availability in soils of the Indo-Gangetic plains. *CATENA*, *222*, 106877. https://doi.org/10.1016/j.catena.2022.106877

Das, R., Mandal, B., Sarkar, D., Pradhan, A. K., Datta, A., Padhan, D., Seth, A., Kumar, R., De, N., Mishra, V. N., Polara, K. B., Sharma, S., Thakur, N., Kachroo, D., Ray, M., Sharma, A., Patel, K., Garnayak, L. M., & Narkhede, W. (2019). Boron availability in soils and its nutrition of crops under long-term fertility experiments in India. *Geoderma*, *351*, 116–129. https://doi.org/10.1016/j.geoderma.2019.05.022

Datta, S. P., Rattan, R. K., Suribabu, K., & Datta, S. C. (2002). Fractionation and colorimetric determination of boron in soils. *Journal of Plant Nutrition and Soil Science*, *165*(2), 179–184. https://doi.org/10.1002/1522-2624(200204)165:2

Dey, A., Dwivedi, B. S., Meena, M. C., Datta, S. P., Polara, K. B., Sobhana, H. K., & Singh, M. (2017). Boron fractions in a vertic ustochrept as influenced by thirteen years of fertilization and manuring. *Journal of the Indian Society of Soil Science*, *65*(3), 326–333. https://doi.org/10.5958/0974-0228.2017.00038.x

Diana, G. & Beni, C. (2006). Effect of organic and mineral fertilisation on soil boron fractions. *Agricoltura Mediterranea.*, *136*, 70–78.

Diana, G., Beni, C., & Marconi, S. (2008). Organic and mineral fertilization: effects on physical characteristics and boron dynamic in an agricultural soil. *Communications in Soil Science and Plant Analysis*, *39*(9–10), 1332–1351. https://doi.org/10.1080/00103620802004037

Duncan, D. B. (1955). Multiple range and multiple F tests. *Biometrics*, *11*, 1–42. https://doi.org/10.2307/3001478

Eynde, E. V., Weng, L., & Comans, R. N. J. (2020). Boron speciation and extractability in temperate and tropical soils: A multi-surface modeling approach. *Applied Geochemistry*, *123*, 104797. https://doi.org/10.1016/j.apgeochem.2020.104797

Food and Agriculture Organization of the United Nations (2019). *Standard operating procedure for handling and preparation of soil samples for chemical and physical analysis*.

Gupta, U. C. (1967). A simplified method for determining hot-watersoluble boron in podzol soils. *Soil Science*, *103*(6), 424–428. https://doi.org/10.1097/00010694-196706000-00009

Gürel, S., Başar, H., Keskin, E., & Dirim, M. S. (2019). The determination of soil boron fractions, their relationships to soil properties and the availability to olive (*Olea europea* L.) trees. *Communications in Soil Science and Plant Analysis*, *50*(8), 1044–1062. https://doi.org/10.1080/00103624.2019.1603307

ARTICLE IN PRESS

Hanway, J. J., & Heidel, H. (1952). Soil analysis methods as used in Iowa State College soil testing laboratory. *Iowa State College of Agriculture Bulletin*, *57*, 1-31.

Jackson, M. L. (1973). *Soil Chemical Analysis*. Prentice Hall of India Private Limited.

Javed, M. B., Malik, Z., Kamran, M., Abbasi, G. H., Majeed, A., Riaz, M., Bukhari, M. A., Mustafa, A., Ahmar, S., Mora-Poblete, F., Rafay, M., & Bukhari, S. A. H. (2021). Assessing yield response and relationship of soil boron fractions with its accumulation in sorghum and cowpea under boron fertilization in different soil series. *Sustainability*, *13*, 4192. https://doi.org/10.3390/su13084192

Jegadeeswari, D., & Muthumanickam, D. (2017). Boron fertilization and its fate: Maize - Sunflower cropping system. *Madras Agricultural Journal*, *104*(4–6). https://doi.org/10.29321/maj.04.000413

Kasture, M. C., Kalokhe, D. P., & Salvi, V. G. (2019). Effect of submergence on boron fractions in soils of Konkan region of Maharashtra. *Journal of the Indian Society of Soil Science*, *67*(2), 204. https://doi.org/10.5958/0974-0228.2019.00022.7

Kasture, M. C., More, S. S., Kapse, V. D., & Jadhav, S. C. (2020). Distribution of different fractions of boron in soils of Konkan region of India. *Journal of the Indian Society of Coastal Agricultural Research*, *38*(1), 36–42.

Kaundal, A., Sharma, S. K., Kumar, P., Sankhyan, N., & Dutta, J. (2014). Distribution of boron forms in relation to soil characteristics, chemical fertilizers, and amendments in an acid alfisol of northwestern Himalayas. *Communications in Soil Science and Plant Analysis*, *45*(13), 1772–1783. https://doi.org/10.1080/00103624.2014.912286

Kumar, D., Patel, K. C., Shukla, A. K., Behera, S. K., Ramani, V. P., Suthar, B., & Patel, R. A. (2023). Long-term impact of boron addition at various dosages to a Groundnut-Cabbage system on crop yield and boron dynamics in typic haplustepts. *Agriculture*, *13*(2), 248. https://doi.org/10.3390/agriculture13020248

Kumari, K., Nazir, G., Singh, A., & Kumar, P. (2017). Studies on boron fractions with different physico-chemical properties of cultivated soils of Himachal Pradesh, India. *International Journal of Current Microbiology and Applied Sciences*, *6*(6), 1547–1555. https://doi.org/10.20546/ijcmas.2017.606.182

Lindsay, W. L., & Norvell, W. A. (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal*, *42*(3), 421–428. https://doi.org/10.2136/sssaj1978.03615995004200030009x

Olsen, S. R. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*. United States Department of Agriculture.

Pachauri, S. P., Srivastava, P. C., Pathak, A., Behera, S. K., & Shukla, A. K. (2024). Effect of different boron application schedules on yields, boron concentration and uptake of Rice-wheat rotation and changes in chemical fractions of soil boron. *Communications in Soil Science and Plant Analysis*, *55*(14), 2169–2180. https://doi.org/10.1080/00103624.2024.2346224

Padbhushan, R., & Kumar, D. (2015a). Distribution of boron in different fractions in some alkaline calcareous soils. *Communications in Soil Science and Plant Analysis*, *46*(8), 939–953. https://doi.org/10.1080/00103624.2015.1018521

Padbhushan, R., & Kumar, D. (2015b). Soil boron fractions and response of green gram in calcareous soils. *Journal of Plant Nutrition*, *38*(8), 1143–1157. https://doi.org/10.1080/01904167.2015.1009106

Padbhushan, R., & Kumar, D. (2017). Fractions of soil boron: A review. *The Journal of Agricultural Science*, *155*(7), 1023–1032. https://doi.org/10.1017/s0021859617000181

Piper, C S (1966). *Soil and plant analysis*: Hans Publishers.

Prasad, N. R., Kumar, N. D., Shivay, N. Y., & Rana, N. D. (2014). Boron in Indian agriculture-A review. *Indian Journal of Agronomy*, *59*(4), 511–517. https://doi.org/10.59797/ija.v59i4.4583

Premalatha, R. P., Manorama, K., Suresh, K., & Ramachandrudu, K. (2024). Evaluation of kinetic and isotherm models for adsorption of boron under different soil orders in oil palm plantations of India. *Communications in Soil Science and Plant Analysis*, *55*(15), 2295–2311. https://doi.org/10.1080/00103624.2024.2353770

Rahman, N., & Schoenau, J. (2020). Response of wheat, pea, and canola to micronutrient fertilization on five contrasting prairie soils. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-75911-y

ARTICLE IN PRESS

Rajaratnam, J. A. (1973). The effect of boron deficiency on oil palm fruit yield in Malaysia. *Proceeding of International Oil Palm Conference on Advances in Oil Palm Cultivation*. *The Incorporated Society of Planters* (pp. 280-288).

Raza, M., Mermut, A. R., Schoenau, J. J., & Malhi, S. S. (2002). Boron fractionation in some Saskatchewan soils. *Canadian Journal of Soil Science*, *82*(2), 173–179. https://doi.org/10.4141/s01-027

Rowell, D. L. (1994). *Soil Science: Methods and Applications*. Prentice Hall, Harlow, Longman Scientific and Technical.

Shukla, A. K., Behera, S. K., Prakash, C., Patra, A. K., Rao, C. S., Chaudhari, S. K., Das, S., Singh, A. K., & Green, A. (2021). Assessing multi-micronutrients deficiency in agricultural soils of India. *Sustainability*, *13*(16), 9136. https://doi.org/10.3390/su13169136

Sidhu, G. S., & Kumar, D. (2018). Influence of soil applied boron on yield of berseem (*Trifolium alexandrium* L.) and soil boron fractions in calcareous soils. *Journal of Plant Nutrition*, *41*(8), 980–995. https://doi.org/10.1080/01904167.2018.1431667

Soil Survey Staff (2014). '*Keys to soil taxonomy*.' *12th ed.* Natural Resources Conservation Service (USDA).

Subbiah, B., & Asija, G. (1956). Alkaline permanganate method of available nitrogen determination. *Current Science*, *25*, 259.

Walkley, A., & Black, I. A. (1934). An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, *37*(1), 29–38.

Xu, J. M., Wang, K., Bell, R. W., Yang, Y. A., & Huang, L. B. (2001). Soil boron fractions and their relationship to soil properties. *Soil Science Society of America Journal*, *65*(1), 133–138. https://doi.org/10.2136/sssaj2001.651133x

ARTICLE IN PRESS