Relationship between Available and Soluble Boron with Some Soil Properties

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Abstract

This study investigated 20 agricultural soils area in Duhok governorate/ Iraqi Kurdistan region to find out how much boron was soluble, exchangeable, and available, then show related it to soils' characteristics. To contribute to future agricultural planning and soil fertility management in the area by offering the first baseline data on the distribution of boron in Duhok soils. The results showed that the textures of studied soils ranged from sandy clay loam to clay, and soil slightly alkaline and non-saline, while organic matter between (1.03 – 3.79) percent. The boron forms soluble, exchangeable and available boron ranged from (0.003 to 1.63), (0.084 to 1.8) and (0.089 to 2.99) $mg.kg^{-1}$ respectively. According to soluble boron the studied soils can classified low level include Chamblk ,Tshish, Derkar, Derabun, Sharya, Zawita, Batifa, Shexka, Bardarash. Kanimasi and Deralok, but the another soils contain sufficiency boron. Soluble boron showed positive significant correlation with EC (r=0.49*), A- $CaCO_3$ (r=0.44*), CEC (r=0.52*) and clay (r=0.52*) but negative significant noted with pH (-0.48*) and $CaCO_3$ (r=¯0.125),. Exchangeable boron exposed positive significant relation with EC (r=0.45*), O.M (r=0.52*), but negative significant relationship noted with pH (-0.53*) and SO_4 (-0.57*). While available boron displayed positive significant relation with EC (r=0.54*), clay (r=0.44*) and O.M (r=0.67**) but negative significant noted with both pH and SO_4 (-0.51*). The available boron greatly significant positive correlated with soluble boron (r=0.85**) and exchangeable boron (r= 0.82**) while the soluble boron positive significantly correlated with exchangeable (r= 0.54*).

Keywords: Soluble Boron, Exchangeable Boron, Available Boron.

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Introduction

Boron (B) is a non-metal element with the atomic number 5 and an atomic mass of 10.81[1], is a crucial component for crop growth, development, productivity, and quality [2, 3, 4]. One of the most mobile and often lacking microelements in soils is boron [5, 6]. Boron is a crucial trace element and one of the key inorganic micronutrients that plants need for healthy and proper growth [7, 8] Depending on the pH of the soil, B is distributed unevenly in the soil solution and in the organic and mineral fractions as boric acid [$B(OH)_3$] and tetrahydroxy borate [$B(OH)_4$]$^-$[6]. However, fewer than 5–10% are in a form that plants can use [9]. It was suggested that the optimal range for soil boron was between 0.5 and 2.0 ppm [10]. According to [11], boron-containing minerals are either very soluble (hydrated B minerals) or extremely insoluble (tourmaline) and they usually have little influence on the solubility of B in soil solution. The following minerals include boron: Tourmaline [$Na(Mg,Fe)_3Al_6$ $(BO_3)_3$ $Si_6O_{18}.(OH)_4$],Colemanite ($Ca_2B_6O_{11}$. $5H_2O$), Borax ($Na_2B_4O_7.10H_2O$), Ulexite (NaCa $B_5O_9.8H_2O$), and Kotoite ($Mg_3(BO_3)_2$). The two most common B fertilizers are borax and solubor [12]. There was negligible link between carbonates and B pools, and low correlation coefficients existed between the B pools and particle size distribution. According to the results, relatively little of the B in Saskatchewan soils is easily soluble; the bulk of B is present in residual or occluded form. It seems that a suitable way to estimate available B is to use hot water soluble B [13].

One significant factor influencing agricultural output is the amount of B present in soil and irrigation water [14]. Numerous variables, including soil texture, pH, EC, CEC, free $CaCO_3$, organic carbon, and interactions with other elements, influence the availability of B [15]. In Indian soil, the available-B concentration varies between 0.04 and 7.40 $mg.kg^{-1}$ [16]. According to [17], fine-textured soils have more accessible B than coarse-textured soils do. In plants, boron can have a direct or indirect role in the creation of the cell wall and plasma membrane, the metabolism of proteins and carbohydrates, and the synthesis of ribonucleic acid (RNA). Furthermore, B interacts with other nutrients including zinc, phosphorus (P), calcium, nitrogen (N), and potassium [18]. According to [19], around 30% of Indian soils are now B deficient, particularly those with a coarse texture, low organic matter (OM) content, high calcium carbonate ($CaCO_3$) concentration, and alkalinity issues. Since boron is crucial for boll formation, blooming, pollination, and seed development, it also plays a direct and indirect role in the cell proliferation of new shoots and roots [20].

[21] noted that boron deficiency or toxicity doesn't just impact crop yields — it also affects the availability of other nutrients like potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) in the soil. Low organic content, sandy, much leached, calcareous (>15% calcium carbonate), high pH (>7), and newly limed

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soils are susceptible to B shortage [22]. Depending on the species, the critical deficiency level (CDL) of B in mature tissue ranges from 5 to 39 $mg.kg^{-1}$ dry matter [23]. It was determined that the optimal range for soil boron was 0.5–2.0 ppm, with lower and higher values signifying toxicity and inadequacy [10]. B is unique among the fundamental nutrients since it has the narrowest value between sufficiency and toxicity among key micronutrients [24, 25] for vegetal-soil systems. A common problem in very wet regions, particularly on sandy soils, is B deficiency [26]. Grasping the different fractions of boron in soil is key to understanding how it behaves chemically— it reveals how boron binds in the soil, how it moves, how available it is to plants, and what impact it might have on the environment [27, 28]. Boron in soil exists in five main forms: freely soluble (including both the solution and non-specifically adsorbed forms), specifically adsorbed, bound to oxides, bound to organic matter, residual, and occluded boron [28], [29]. Normally, soil's available boron status falls between 10 and 300 mg kg^{-1} [30]. Water-soluble boron levels in soil are typically grouped into five categories: very low (0.2 $\mu g.g^{-1}$), low (0.25 to 0.5 $\mu g.g^{-1}$), medium (0.51 to 1.0 $\mu g.g^{-1}$), high (1.1 to 2.0 $\mu g.g^{-1}$), and very high (greater than 2.0 $\mu g.g^{-1}$) [31].

The Aims of the Study: As the first investigation of its kind in this region, this study aims to establish baseline data on boron distribution, support the development of improved soil management strategies for sustainable agriculture, to address this gap, the research sets out to pursue the following aims:

1. Study the concentrations of available, exchangeable and soluble boron in different soil samples from the Duhok region.
2. To identify the influence of soil chemical and physical characteristics on boron availability and mobility and analyze the relationship between boron levels and some soil properties
3. To provide the first baseline data on boron distribution in Duhok soils and contributes to future agricultural planning and soil fertility management in the region.

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Materials and Methods

Twenty surface soil samples (0–30 cm depth) were collected from the Duhok Governorate in the Iraqi Kurdistan Region on August 25 and 28, 2024,, which located between (42 ^{o} 20'- 44 ^{o} 17' E Longitude, and 36^{o}18'-37^{o}20'N Latitude), as shown in (Figure, 1). The sampling locations included (Chamblk, Kanimasi, Tshish, Hizawa, Derkar, Derabun, Asihe, Balqus, Semeel, Sharya, Zawita, Mangesh, Batifa, Bamarny, Deralok, Chaman, Shexka, Qasrok, Bardarash, and Akre).

After collecting the samples, it was quickly transferred to the laboratory. The soil samples were air-dried to remove moisture, which helps prevent changes in chemical properties before analysis. Once dry, I spread the soil out and passed it through a 2 mm sieve (Figure 2). The processed soil was then stored in plastic containers and sealed

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tightly to preserve its original characteristics until testing.

Figure 1. Location of Taking Soil Sample in the Duhok Region

Figure 2. Soil Sample Air dried & sieved through a sieve (2mm),and stored in plastic container

Determination of Soil Properties

The particle size distribution was measured using the hydrometer technique, following the procedure outlined by [32].The pH in soil extracts (1:2) was measured using a portable pH meter of type WTW/Inolab 7110 [33]. Electrical conductivity (EC) in a soil extract (1:2 soil: water) was measured using an EC-meter model (Microprocessor Conductivity/TDS meter HANNA-HI-9635) and expressed as dS m^{-1} at 25°C [33]. The organic carbon content of the soil was determined using the Walkley-Black technique, which involved oxidizing O.M. with concentrated H_2SO_4 and potassium dichromate ($K_2Cr_2O_7$) according to [34], the residual ($K_2Cr_2O_7$) is back-titrated using ferrous sulfate heptahydrate

$$\text{Organic Matter \%} = \text{O.C\%} \times 1.724 \ldots. (1)$$

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Soluble cations and anions were estimated using soil extract (1:2 soil: water): soluble calcium and magnesium ($Ca^{2+}$and Mg^{2+}) EDTA-2Na (0.02 N) was utilized in the titration method to estimate the amount of soluble calcium and magnesium. Ammonium purpurate was used as an indicator, and the pH of the solution was raised to 12 using NH_4OH for calcium determination. Eriochrom Black-T was then used to adjust the pH 10 for calcium + magnesium determination [35].

Soluble sodium and potassium (Na^+ and K^+) were measured using a Flame Photometer (model JENWAY/PFP7) after calibrating the device with standard solutions, following the method of [33]. Soluble carbonate and bicarbonate (CO_3^{2-} + HCO_3^-) concentrations were determined through titration with 0.01N sulfuric acid, using phenolphthalein and methyl orange as indicators, following the method outlined by [33]. Chloride (Cl^-) Using K_2CrO_4 as an indicator, the chloride was measured by titrating with $AgNO_3$ [33].

Total carbonate was measured by treating a known weight of soil with 1N hydrochloric acid using a Calcimeter, following the method of [36]. Active carbonate was determined according to the method described by [37], using 0.2M ammonium oxalate and titrating the solution with 0.2M potassium permanganate. The flame photometer model, JENWAY, LDT, FELSTED, DUNMOW, ESSEX, CM63LB, and MODE: FFP7 are used to calculate cation exchange capacity (CEC). This technique saturates the exchange sites with Na ions by treating the soil with 1N sodium acetate (pH 8.2). According to [38], soluble sodium is then eliminated by washing with 95% ethanol, and exchangeable sodium is extracted using 1N ammonium acetate (pH 7.0).

Determination of Boron Fraction (Available, Soluble, and Exchangeable)

- Determination of Available Boron

The available boron in the soil was measured using the curcumin method, I prepared the curcumin solution fresh each day because it decomposes quickly. It must be stored in a dark container away from light, and it is only effective for about two hours after preparation. as described by [39]. To measure the available boron in soil, I first prepared a standard boron curve. I started by dissolving 0.114 grams of boric acid (H_3BO_3) in distilled water and diluting the solution to one liter. This gave me a stock solution with a concentration of 20 mg. L^{-1} (ppm) of boron. From this stock, I prepared a series of standard solutions with concentrations of 15, 12.5, 10, 7.5, 5, and 2.5 ppm. Next, I diluted 15 mL of the 20 ppm stock solution to 100 mL with distilled water. This produced another set of standard solutions with the following concentrations: 3, 2.5, 2, 1.5, 1, and 0.5 ppm. These standards were used to create the calibration curve for measuring the available boron in the soil samples. The laboratory temperature was maintained at a constant (25–28°C). I weighed 20 grams of soil and mixed it with 40 mL of hot distilled water. To heat the samples, I used a water bath and placed the mixture in an Aluminum Tea Strainer or perforated Aluminum Cup container (instead of glass) since boron was metalloid to avoid boron contamination, as boron can react with glass when heated. After heating, I

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allowed the solution to cool to room temperature and let it stand for 15 minutes. Next, I added 10 mL of Ethanol 95% to the solution and centrifuged at a constant temperature (55-58°C) for 15 minutes. The supernatant was then filtered using Whatman No. 42 filter paper. I transferred the filtrate into a clean volumetric bottle and made up the volume with Ethanol 95%. Finally, I measured the boron concentration using a spectrophotometer set to a wavelength of 540 nm. The steps were shown in (Figure 3, 4, 5, 6 and 7).

Determination of Soluble Boron

The soluble boron in the soil was measured using the curcumin method, as described by [39], I weighed 20 grams of soil and added 40 mL of distilled water, placing the mixture into a plastic bottle, then I shook the samples for two hours using a shaker and allowed them to sit at room temperature for 24 hours. After that, I filtered the samples using Whatman No. 42 filter paper. For the analysis, I used the curcumin method, I prepared the curcumin solution fresh each day because it decomposes quickly, it must be stored in a dark container away from light, and it is only effective for about two hours after preparation. To measure the soluble boron, I used a standard curve for boron. The room temperature during the experiment was stable, between 25°C and 28°C, after filtering the samples; I followed the same procedure used for available boron, including heating the samples in a water bath before continuing with the analysis (Figure 8 and 9) .

Determination of Exchangeable Boron

Exchangeable boron was calculated using the following equation:

$$\boxed{\text{Exchangeable Boron} = \text{Available Boron} - \text{Soluble Boron}}$$

Statistical Analysis

In this study, Minitab 19 software was used to perform correlation analysis to investigate the relationships between different forms of boron—namely available, soluble, and exchangeable boron—and various physical and chemical properties of the soil, including both cationic and anionic constituents. The results revealed several statistically significant correlations, indicating that the distribution and behavior of boron in the soil are influenced by its interaction with other soil components. Single asterisks (*) denote correlations that are statistically significant at the $P \leq 0.05$ level, while double asterisks (**) indicate correlations that are highly significant at the $P \leq 0.01$ level.

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Figure 3.Heating a Sample of Available Boron in Water Bath at constant Temperature

Put the sample into a centrifuge tube and place the tube in its designated position in the centrifuge

Figure 5. Cooling the sample to room temperature

Figure 6.transferred the filtrate into a clean volumetric Flask 25 ml and complete the volume with Ethanol

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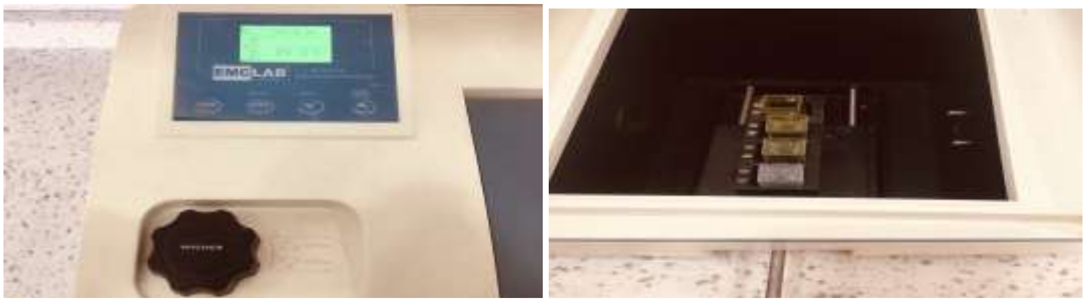

Figure 7. place the sample in the spectrophotometer to measure boron at a wavelength of 540 nm, using the transmission mode.

. Determination of Exchangeable Boron

Figure 8: The sample was placed in a mechanical shaker

Figure 9: The sample was filtered and collected in plastic bottles.

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Table 1: The chemical and physical properties of studied soil.

Na^+ mg.kg^{-1}	A-$CaCO_3$ %	$CaCO_3$ %	EC dS.m^{-1}	pH	Texture	Sand %	Silt %	Clay %	Soil Locations	No
16.02	12.0	18.00	0.261	8.00	S. C.L.	58.50	9.30	32.20	Chamblk	1
15.78	8.0	5.00	0.31	7.72	C.L	43.40	22.50	34.10	Kanimasi	2
16.20	15.0	14.31	0.35	7.80	CL	26.00	32.85	41.15	Tshish	3
12.10	7.0	4.00	0.3	7.60	Cl	27.14	21.26	51.60	Hizawa	4
14.37	9.0	16.80	0.25	7.50	Cl	25.10	23.30	51.60	Derkar	5
20.40	13.5	12.40	0.4	7.70	Cl	29.00	24.64	46.36	Derabun	6
18.30	13.5	20.36	0.47	7.50	Cl	9.40	30.90	59.70	Asihe	7
17.90	15.0	22.78	0.29	7.70	Cl	28.65	24.75	46.60	Balqus	8
27.60	11.5	18.62	0.39	7.60	Cl	25.10	21.30	53.60	Semeel	9
36.70	14.0	20.67	0.32	8.00	Cl	17.40	28.50	54.1	Sharya	10
10.93	6.0	9.00	0.28	7.60	S.Cl	11.16	35.00	53.84	Zawita	11
14.70	15.0	17.60	0.27	7.55	Cl	24.30	16.60	59.10	Mangesh	12
11.30	5.0	4.00	0.29	7.34	Cl	21.55	35.35	43.10	Batifa	13
18.50	7.5	10.30	0.299	7.50	Cl	24.90	29.75	45.35	Bamarny	14
13.80	9.5	8.00	0.27	7.54	Cl	24.9	18.5	56.6	Deralok	15
25.16	9.0	12.00	0.54	7.74	Cl	24.90	18.50	56.60	Chaman	16
23.51	11	20.7	0.34	7.53	Cl	26.1	22.3	51.6	Shexka	17
15.3	16	19.75	0.267	7.40	Cl	14.90	25.80	59.30	Qasrok	18
24.5	16	27.26	0.26	8.20	S. L	64.90	18.30	16.80	Bardarash	19
11.5	7	13.00	0.258	7.40	Cl	21.00	19.90	59.10	Akre	20

*S.Cl.L=Sandy clay loam; Cl. L = Clay loam; Cl = Clay ;S.L=Sandy loam

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Continued

CEC Cmol.kg^{-1}	O.C %	O.M %	Cl^- mg.kg^{-1}	HCO_3^- mg.kg^{-1}	SO_4^{2-} mg.kg^{-1}	CO_3^{2-} mg.kg^{-1}	Mg^{2+} mg.kg^{-1}	Ca^{2+} mg.kg^{-1}	K^+ mg.kg^{-1}	Soil Locations	No
17.70	*0.6*	*1.03*	*31.95*	*146.40*	*107.52*	*0*	*4.86*	*52.1*	*37.62*	Chamblk	1
28.64	*2.2*	*3.79*	*35.5*	*244.00*	*6.72*	*0*	*20.40*	*42*	*18.3*	Kanimasi	2
22.63	*1.8*	*3.1*	*85.2*	*206.00*	*80.26*	*0*	*18.02*	*81*	*15.3*	Tshish	3
27.87	*0.9*	*1.55*	*63.9*	*244.00*	*115.97*	*0*	*21.60*	*38*	*15.3*	Hizawa	4
18.54	*0.8*	*1.37*	*33.5*	*152.00*	*244.99*	*0*	*17.80*	*30*	*16.1*	Derkar	5
26.81	*1.2*	*2.07*	*78.1*	*250.00*	*9.02*	*0*	*21.60*	*58*	*32.56*	Derabun	6
18.63	*1.5*	*2.586*	*71.0*	*366*	*128.26*	*0*	*7.29*	*68.14*	*13.28*	Asihe	7
19.73	*0.72*	*1.24*	*47.9*	*195.00*	*40.90*	*0*	*14.58*	*36.07*	*12.34*	Balqus	8
17.84	*1.1*	*1.9*	*113.6*	*341.60*	*235.01*	*0*	*12.00*	*55.00*	*55.31*	Semeel	9
29.53	*0.9*	*1.55*	*170.4*	*174.00*	*118.66*	*0*	*7.20*	*65.00*	*38.65*	Sharya	10
35.27	*0.6*	*1.03*	*99.4*	*208.00*	*58.18*	*0*	*16.80*	*65.00*	*19.45*	Zawita	11
21.47	*1.9*	*1.9*	*85.2*	*200.00*	*57.41*	*0*	*9.60*	*61.00*	*26.98*	Mangesh	12
28.19	*1.6*	*2.76*	*71.0*	*205.00*	*38.78*	*0*	*19.00*	*45.00*	*25.6*	Batifa	13
27.49	*1.5*	*2.58*	*71.0*	*150.00*	*10.75*	*0*	*14.40*	*37.00*	*28.78*	Bamarny	14
20.30	*0.98*	*1.69*	*92.3*	*118.00*	*2.69*	*0*	*16.80*	*40.00*	*22.98*	Deralok	15
27.93	*1.55*	*2.68*	*78.1*	*286.40*	*74.3*	*0*	*14.50*	*76.15*	*26.56*	Chaman	16
20.78	*1.2*	*2.06*	*49.7*	*265.00*	*54.53*	*0*	*16.90*	*65.32*	*25.82*	Shexka	17
32.65	*1*	*1.724*	*68.0*	*124.00*	*72.38*	*0*	*19.20*	*41.00*	*16.78*	Qasrok	18
17.00	*0.8*	*1.379*	*34.2*	*122.04*	*197.57*	*0*	*14.40*	*46.00*	*18.43*	Bardarash	19
33.34	*1.9*	*3.27*	*85.2*	*110.00*	*8.64*	*0*	*4.80*	*52.00*	*24.33*	Akre	20

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Table 2: The* Available, *Exchangeable and soluble boron in studied soil

Exchangeable Boron (mg.kg^{-1})	Soluble Boron (mg.kg^{-1})	Available Boron (mg.kg^{-1})	Soil Location	No
0.080	0.010	0.090	Chamblk	1
0.960	0.500	1.460	Kanimasi	2
0.987	0.003	0.990	Tshish	3
1.300	0.700	2.000	Hizawa	4
0.150	0.040	0.190	Derkar	5
1.230	0.230	1.460	Derabun	6
0.800	0.700	1.500	Asihe	7
0.630	0.500	1.130	Balqus	8
0.760	0.700	1.460	Semeel	9
0.790	0.040	0.830	Sharya	10
0.611	0.089	0.700	Zawita	11
0.760	0.700	1.460	Mangesh	12
1.100	0.230	1.330	Batifa	13
1.700	0.990	2.690	Bamarny	14
1.600	0.330	1.930	Deralok	15
1.360	1.630	2.990	Chaman	16
1.400	0.230	1.630	Shexka	17
0.990	0.700	1.690	Qasrok	18
0.084	0.005	0.089	Bardarash	19
1.390	1.000	2.390	Akre	20

Results and Discussion

Chemical and Physical Properties soil studies:

1. Soil Texture

The soils texture across the study area exhibited a range of textures from sandy clay loam to clay (Table, 1), indicating significant variation in particle size distribution. For example, Chamblk had a sandy clay loam texture and Bardarash had Sandy loam texture, while most other locations such as Hizawa, Derkar, Derabun, Asihe, Balqus, Semeel, Sharya, Zawita, Mangesh, Deralok, Qasrok and Akre had predominantly clay textures these textural differences greatly influence other soil chemical and physical properties are expected to have higher water retention, nutrient-holding capacity, and cation exchange capacity (CEC). Another soil has clay loam texture such as Kanimasi, Tshish, Bamarny, Chaman and Shexka.

2. Soil pH and Electrical Conductivity (EC)

Soil pH ranged from 7.34 (Batifa) to 8.2 (Bardarash) showing that all soils were slightly alkaline. Alkaline conditions are common in calcareous soils and can influence nutrient availability, especially of micronutrients like iron and boron. Electrical conductivity (EC) values ranged from 0.25 to 0.47dS.m^{-1} (Table, 1) the high value noted in Asihe soil due to low precipitation but the low result demonstrate in Derkar soil owing to high precipitation which can leaching the salt to the depth of soil, suggesting the studied soil among from non-saline to slightly saline soils. Although no critical salinity problems were detected, higher EC values in area like Asihe soil may require monitoring under irrigation, especially for salt-sensitive crops.

3-Calcium Carbonate ($CaCO_3$) and Active $CaCO_3$ (A-$CaCO_3$)

Calcium carbonate content varied widely, ranging from 4% in (Hizawa, Batifa) soil to 27.26% in Bardarash soil (Table, 1) , indicating differences in parent material and degree of soil development. A-$CaCO_3$ content, which is the more reactive portion influencing soil chemistry, ranged from 5% (Batifa) to 17.5% (Tshish). High $CaCO_3$ and active $CaCO_3$ can limit buffer pH changes, while also affecting boron adsorption.

4-Catios in Soils

The sodium (Na^+) content varied from 10.93 mg.kg^{-1} (Zawita) to 36.70 mg.kg^{-1} (Sharya), which is relatively low and not indicative of sodicity problems. However, continuous accumulation in areas like Sharya may influence soil structure and permeability over time, Na has positive significant correlation with $CaCO_3$, and A-$CaCO_3$ by r=0.44* (Table, 3). Potassium (K^+) ranged from 12.34 mg.kg^{-1} in Balqus to 55.31 mg.kg^{-1} in Semeel, indicating generally adequate potassium levels across the soils, especially in fine-textured areas with higher clay content which helps retain K. Calcium (Ca^{2+}) levels showed notable variation from 30 mg.kg^{-1} in Derkar to 81 mg.kg^{-1} in Tshish and have high positive significant relation with EC (0.62**). However magnesium (Mg^{2+}) ranged from 4.86 mg.kg^{-1} in Chamblk and Kanimasi to 21.60 mg.kg^{-1} in Derkar and Asihe and relate with positive but significant with silt (r=0.35). The higher concentrations of Ca and Mg, especially in clay-rich soils, support

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stronger cation exchange capacities and better soil structure, but may also lead to cation imbalances if not monitored.

5-Anions in Soils

Bicarbonate (HCO_3^-) levels ranged from 110 mg.kg^{-1} (Akre) to 366 mg.kg^{-1} (Asihe) in Table, 1. High bicarbonate levels are common in calcareous soils and may interfere with micronutrient availability, particularly iron and zinc. Bicarbonate showed greater positive significant relationship with EC (r=0.79**). Chloride (Cl^-) ranged from 31.95 mg.kg^{-1} (Chamblk) to 170.40 mg.kg^{-1} (Sharya). While these levels are generally safe, elevated chloride in some areas suggests a need for periodic salinity monitoring, especially under irrigation. (Cl^-) demonstrated negative significant correlation with sand (r=-0.46*) and proved positive correlation but non-significant with CEC (r=0.44) and clay (r=0.40). The level of SO_4^{2-} ranged between (2.69 - 244.99) mg.kg^{-1} the high result noted in Derkar soil on the other hand low number shown in Deralok soil. SO_4^{2-} illustrate negative relation while non-significant with O.C (r=-0.43) and O.M (r=-0.42).

6- Organic Matter and Organic Carbon

Organic carbon (OC) content ranged from 0.60% to 2.2% (Table, 1), the high number shown in Kanimasi soils however the small value illustrated in Chamblk soil. while organic matter (OM) ranged between (1.03 – 3.79)%. These levels are modest but important indicators of soil fertility and biological activity. Higher OM values improve soil structure, water retention, and nutrient cycling, with locations like Kanimasi showing relatively better soil organic status. Conversely, lower values in Chamblk may indicate reduced biological activity or past land degradation.

7- Cation Exchange Capacity (CEC)

CEC values different from 17.7 cmol(+). kg^{-1} in Chamblk soil to 35.27 cmol(+).kg^{-1} in Zawita soil (Table, 1). Higher CEC is typically associated with finer soil texture and higher organic matter, as seen in Zawita soil. These soils can hold more nutrients and are more resistant to leaching. Lower CEC values found in Chamblk soils which low organic matter.

Boron Forms in Studied Soils

Boron is distributed in various soil components, including soil solution, organic matter (OM) and minerals. Boron in soil solution is readily available for plant uptake, but maintaining B in the soil solution is an important aspect for plant nutrition and it is controlled by the pools of B in other soil fractions and their equilibration with soil solution [15].

1-Soluble Boron

Retaining B in the soil solution is crucial for plant nutrition and is regulated by the pools of B in other soil fractions and their equilibration with soil solution, boron in soil solution is easily available for plant uptake [15]. The portion of soil solution that is most easily absorbed by plants is called soluble-B, and it is weakly adsorbed by soil particles. It makes up 1% to 2% of Total-B [40]. In this study the soluble Boron, the immediately plant-available form, ranged from (0.003 to 1.63) mg.kg^{-1} (Table, 2) great values found in Chaman soil where as little number noted in Tshish soil, the higher

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quantity of soluble boron suggesting potential boron toxicity, especially for sensitive plants, while very low levels like in Tshish may limit uptake.[13] reported that an average of 1% of the total soil B was present as hot water-soluble B.

According to [31] the level of soluble boron in studied soils can classified following very low level include Chamblk ,Tshish, Derkar, Derabun, Sharya, Zawita, Batifa, Shexka, Bardarash. But the following soils contain low level are: Kanimasi and Deralok. Whereas the medium levels of soluble-B include Hizawa, Asihe, Balqus, Semeel, Mangesh, Bamarny, Qasrok and Akre. Morever Chaman soil contain high level of soluble-B. The mean contents of water-soluble (WS-B) in alluvium-derived soils of Punjab were 0.24 mg kg^{-1} soil. All the forms of B were related with soil properties, especially organic carbon (C) content, clay content, texture, and cation exchange capacity; different forms were correlated significantly with each other [41]. The mean value of readily soluble boron is 0.32 mg kg^{-1} [28].

Soluble boron fractions showed significant negative correlations with Soil pH ($r=-0.48^*$, $P\leq0.05$. This indicates that as pH increases, the availability of these boron fractions tends to decrease. And showed negative correlation with sand ($r=-0.39$) but non-significant. At higher pH values, particularly in alkaline soils, boron tends to form less soluble compounds or becomes more strongly adsorbed to clay minerals and iron/aluminum oxides, thereby reducing its solubility and availability.

Soluble boron displayed significant positive correlations with electrical conductivity (EC) ($r=0.49^*$, $P\leq0.05$) in (Table, 3), This suggests that as soil salinity (indicated by EC) increases, the concentrations of these boron fractions also tend to increase. This relationship is often observed in arid and semi-arid regions where high evaporation rates lead to the accumulation of soluble salts, including boron, in the soil profile. Boron, being a mobile nutrient, can accumulate in the soil solution alongside other soluble ions, leading to higher EC values. The Pearson correlation coefficient between $CaCO_3$ and Soluble Boron is -0.125, with a p-value of 0.610.This indicates a very weak and statistically non-significant inverse relationship. Interpretation: Soluble boron, being the most mobile and transient form in soil solution, appears less affected by calcium carbonate content, likely due to its dynamic equilibrium with soil moisture and leaching processes. calcium carbonate also acts as an important B adsorbing surface in calcareous soils [42]. And positive correlation while non-significant noted between SB with active calcium carbonate ($r=0.44$). The positive correlation between $CaCO_3$ and SB might be attributed to the presence of soluble calcium salts in calcareous soils, which can contribute to the overall salinity and potentially lead to a higher concentration of soluble boron. Soluble-B demonstrated positive correlations non-significant with organic carbon (O.C) and organic matter (O.M) ($r=0.43$, and $r= 0.41$ $P>0.05$) respectively. The extractable B was found to be positively related with organic carbon 11. Soluble-B and OM did not significantly correlate [44]. Cation exchange capacity (CEC) showed a significant positive correlation with SB ($r=0.52^*$, $P\leq0.05$) in (Table, 3). The positive correlation with soluble boron might be due to the fact that higher CEC often indicates a greater capacity for retaining various ions, including those that contribute to soluble boron. These results were in line with the findings of [45, 46].

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Also Soluble-B showed a significant positive correlation with Clay (r=0.52∗, P≤0.05). This suggests that soils with higher clay content tend to have higher soluble boron concentrations. This could be attributed to the higher surface area and potential for adsorption/desorption of boron in clay-rich soils. Coarse textured (sandy) soils often restrained less available B than fine textured soils, thus B deficiency frequently arise in areas located in sandy soils [47]. Native B was significantly positively correlated with soil clay content [48]. The positive relationship between clay and soluble boron reinforces the need for texture-specific boron management strategies. In clayey soils, where boron fixation may occur, split applications or foliar sprays may be more effective. Conversely, sandy soils with low clay content often exhibit poor boron retention, increasing the risk of deficiency under leaching conditions [49].

2- Exchangeable Boron

This fraction ranged from 0.02 to 1.8 mg. kg^{-1} (Table, 2) the high value found in Asihe soil whereas the small quantity noted in Chamblk soil. This form is loosely held on soil colloids and can become plant-available over time. High exchangeable B in Asihe reflects stronger adsorption–desorption dynamics, possibly influenced by clay and organic matter content. Exchangeable-B shown positive significant correlation with soluble-B (r= 0.54* P≤0.05) and available-B (r= 0.82**, P<0.01) indicating that these fractions are closely interconnected and may represent different stages in the dynamic cycling of boron in soil [41]. These results were in line with the findings of [50]. Different forms were correlated significantly with each other. These findings carry practical implications for soil fertility management. The strong associations between available boron and both soluble and exchangeable forms suggest that comprehensive soil testing should consider multiple boron fractions to accurately assess plant availability.

Negative relation found between exchangeable boron forms with the soil pH (r=-0.53*, P≤ 0.05). Interestingly, exchangeable boron showed significant correlation with EC (r = 0.45*, P≤0.05) in (Table, 3). Organic carbon (O.C) and organic matter (O.M) demonstrated significant positive correlations with Exch-B ($r=0.45^*$, and $r=0.52^*$, P≤0.05) respectively. Soil organic matter adsorbs more B than mineral soil constituents on a weight basis [51]. Adsorbed B and adsorption maxima have been found to be significantly correlated with organic carbon content [52].This highlights the crucial role of soil organic matter in binding and retaining boron. Organic matter contains functional groups (e.g., hydroxyl, carboxyl) that can adsorb boron, thus contributing to its availability in the exchangeable and adsorbed forms. Our findings are consistent with numerous studies that emphasize the importance of organic matter as a major reservoir for boron in soils [53]. Correlation analysis exhibited that soil B is positively correlated with OM whilst it had negative correlation with pH [54]. A significant negative correlation (r = -0.522, p = 0.022) suggests that higher calcium carbonate content tends to reduce the amount of exchangeable boron in the soil. This is consistent with known soil chemistry, where $CaCO_3$-rich (calcareous) soils adsorb or

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precipitate boron, reducing its mobility and bioavailability. For anions, Bicarbonate (HCO_3) exhibited- nonsignificant positive correlation with Exch-B (r=0.31) and a positive significant correlation with SO_4 (r=0.57*, P≤0.01), indicating potential competition between borate and sulfate ions for adsorption sites, as supported by findings from [55]. This is expected as HCO_3 is a major anion contributing to alkalinity and soluble salt content. Some studies have suggested that in certain soil types, sulfate can compete with borate for adsorption sites, thereby influencing boron retention [56].

3- Available Boron

Available Boron (AB) ranged from 0.03 mg. kg^{-1} in Chamblk soil to 2.99 mg. kg^{-1} in Chaman soil (Table, 2). Values below 0.5 mg. kg^{-1} are generally considered deficient for most crops, indicating possible boron deficiency in Chamblk and Bardarash soil are deficiency. Available-B reported highly positive significant correlation with soluble-B (r=0.85**, P≤ 0.01). Hot water soluble-B appears to be a good method to estimate available-B [13]. Soil pH showed significant negative correlations with AB (r=−0.51*, P≤0.05), P≤0.05), this indicates that as pH increases, the availability of these boron fractions tends to decrease, suggesting that boron availability decreases as soils become more alkaline — a trend consistent with the behavior of boron in calcareous soils, where adsorption to oxides and carbonates becomes more pronounced at higher pH levels. Our results are in line with [57] who reported that boron availability declines in calcareous and high-pH soils due to enhanced adsorption onto clay minerals, iron/aluminum oxides, and calcium carbonate. Decreased availability at higher pH levels is associated with decreased B concentration in soil solution [55].

Parent material, texture, clay mineral composition, pH, liming, organic matter content, irrigation sources, interactions with other elements, and environmental conditions such as moderate to heavy rainfall, dry weather, and intense light all have an impact on the amount of boron that is present in soils [58,52].

And Avail-B displayed significant positive correlations with electrical conductivity (EC) (r=0.54*, P≤0.05), this suggests that as soil salinity (indicated by EC) increases; the concentrations of these boron fractions also tend to increase, implying that boron availability may increase in more saline soils due to ionic competition and reduced adsorption, this phenomenon also noted by [59]. *The significant positive correlation between available boron and clay content (r = 0.44*,* P ≤ 0.05) in this study aligns with the findings of [13], who reported that fine-textured soils, such as those with higher clay content, tend to retain more available boron compared to coarse-textured soils.

The Pearson correlation coefficient between Available Boron (AB) and calcium carbonate ($CaCO_3$) is (-0.387), with an associated *p*-value of 0.102. This indicates a moderate inverse association, wherein increasing $CaCO_3$ concentrations tend to correspond with a decline in available boron content. Positive correlation but non-significant established between AB with HCO_3 and CEC (r=0.36 and r=0.38) respectively. However, the lack of significant correlations with adsorbed and exchangeable boron suggests that while

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$CaCO_3$ might influence the readily available boron, its effect on the more strongly bound fractions might be limited. Avail-B demonstrated highly significant positive correlations with organic carbon and organic matter (r=0.62**and r=0.67**, $P\leq 0.01$) respectively. This due to role of soil organic matter in binding boron, highlighting the role of organic matter in enhancing boron retention and availability through complexation and improved moisture retention, which aligns with results reported by [60]. The strongest evidence that OM affects the availability of soil B is derived from studies that show a positive correlation between levels of SOM and the amount of hot-water-soluble B [54, 13, and 61]. The organically bound boron pool is pivotal in governing transformation and distribution of boron in different fractions, organic carbon and CEC favored by high organic matter content has positive correlation with different boron fractions [41].

These findings collectively suggest that boron availability in soil is influenced by a complex interaction of pH, organic matter, salinity, calcium compounds, and soil texture, and aligns with existing literature that emphasizes boron's sensitivity to soil chemical and physical conditions. Among the all anions, SO_4 showed a positive significant correlation with avail-B (r=0.51*, $P\leq 0.05$).

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Table 3- Correlations between boron fractions with physical and chemical properties and with them

O.M	O.C	CEC	SO_4	CL	HCO_3	K	Na	Mg	Ca	A.$CaCO_3$	$CaCO_3$	EC	pH	Exch-B	Sol- B	Avail- B	
																0.85**	Soluble-B
															0.54*	0.82**	Exch-B
														-0.53*	-0.48*	-0.51*	pH
													-0.01	0.45*	0.49*	0.54*	EC
												0.39	-0.22	-0.522*	-0.125	-0.387	$CaCO_3$
											0.69**	0.25	-0.08	0.03	0.44*	0.24	A-$CaCO_3$
										0.04	0.11	0.62**	0.38	0.19	0.06	0.11	Ca
									-0.27	-0.20	-0.29	-0.02	-0.11	0.02	-0.13	0.03	Mg
								-0.27	0.35	0.44*	0.44*	0.43	0.35	-0.10	0.00	-0.06	Na
							0.54*	-0.36	0.19	-0.05	0.27	0.17	0.05	-0.04	0.04	-0.04	K
						0.19	0.27	0.06	0.47*	0.02	0.28	0.79**	-0.10	0.31	0.27	0.36	HCO_3
					0.12	0.48*	0.46*	-0.27	0.44*	0.07	0.07	0.21	0.09	0.20	0.06	0.06	CL
				-0.04	0.19	0.20	0.35	-0.15	-0.04	0.04	0.18	0.05	0.23	-0.57*	-0.23	-0.51*	SO_4
			-0.08	0.44	0.28	0.03	-0.12	-0.08	0.06	0.17	0.28	0.23	-0.52*	0.25	0.52*	0.38	CEC

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		0.22	-0.43	0.02	0.22	-0.07	-0.16	-0.02	0.27	0.13	0.23	0.26	-0.35	0.45*	0.43	0.62*	O.C
	0.93**	0.17	-0.42	-0.02	0.24	-0.10	-0.11	0.07	0.23	0.04	0.17	0.34	-0.32	0.52*	0.41	0.67**	O.M
0.11	0.07	-0.86*	0.12	-0.46*	-0.13	0.05	0.00	0.01	-0.01	-0.21	-0.28	-0.11	0.31	-0.15	-0.39	-0.22*	Sand
-0.06	-0.16	0.30*	-0.23	0.34	0.06	-0.28	0.05	0.35	0.00	-0.11	-0.11	0.00	0.00	0.17	-0.12	0.01	Silt
-0.11	-0.01	0.90**	-0.04	0.40*	0.13	0.08	-0.02	-0.17	0.01	0.30	0.39	0.14	-0.38	0.10	0.52*	0.44*	Clay

*Correlations are significant at $P \leq 0.05$.

** Correlations are significant at $P \leq 0.01$.

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Conclusion

The following are some of the conclusions that the study reached:

1-The study revealed that soils in the area are predominantly clay-rich with alkaline pH and calcareous nature.

2-Fertility indicators such as potassium, organic matter, and CEC were generally adequate but varied depending on soil texture and organic matter inputs.

3-Boron management emerges as a key concern, with some locations showing deficiency, while others risk toxicity. Understanding these spatial variations is essential for site-specific soil fertility management and sustainable land use planning.

4-The corresponding ranges for the soluble, exchangeable, and available forms of boron were 0.003 to 1.63, 0.084 to 1.8, and 0.089 to 2.99 $mg.kg^{-1}$ respectively.

5-Soil pH, electrical conductivity, organic matter, and clay content emerge as key factors influencing boron dynamics.

6-Strong negative correlation noted between pH and boron fractions

7- Positive correlation with EC highlights potential boron toxicity risks in saline environments.

8- Organic matter and clay contribute to improved boron status in soils.

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