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ASSESSMENT OF SOIL MICRONUTRIENT VARIABILITY AND ITS IMPACT ON CROP PRODUCTIVITY IN DISTRICT JHELUM, PAKISTAN

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Abstract

Micronutrient deficiencies are a major constraint to sustainable crop production inarid and semi-arid regions of Pakistan. This study aimed to assess thespatial variability and deficiency status of key soil micronutrients in District Jhelum. To test the hypothesis, a total of 823 soil samples were collected from different locations of District Jhelum. Soil samples were collected from two depths (0-15 & 15-30 cm) from different locations. These collected soil samples were analyzed for micronutrients including Zn, Cu, Fe, Mn & B following the standard analytical procedures at Soil and Water Testing Laboratory, Jhelum & Rawalpindi. The results of the study revealed that mainly soils of Jhelum were categorized as deficient predominately in Fe and B. We observed that Zn was ranged from 0.2 mg kg⁻¹ in Tehsils Sohawa and P.D. Khan to 1.92 mg kg⁻¹ in Tehsil Dina. Cu was found adequate in more than 50% of samples. Among analyzed samples 74% of soil samples were classified as deficient in Fe. Similarly, 90% of soil samples were categorized as having low Mn level. The frequency distribution of boron (B) in soils of District Jhelum indicated that approximately 83% of the samples contained less than 0.5 mg kg⁻¹ B, thereby classifying these soils as boron-deficient, with concentrations ranging from 0.1 to 0.99 mg kg⁻¹. Most agricultural soils in Pakistan are naturally alkaline limiting the micronutrients bioavailability. The results provide baseline data for site-specific nutrient management and fertilizer recommendations to improve soil health, enhance nutrient uptake, and support sustainable agricultural productivity.

Keywords: *Agriculture, Crop production, Jhelum Micronutrients, Soils*

INTRODUCTION

Plants require 17 essential nutrient elements to complete their life cycle, including both vegetative and reproductive phases. Of these, carbon (C), hydrogen (H), and oxygen (O) are predominantly acquired from atmospheric carbon dioxide (CO_2) and water (H_2O). As their availability is largely beyond agronomic control, these elements are considered non-mineral nutrients and collectively account for over 94% of the plant's dry biomass. The remaining 14 elements, which contribute less than 6% of the plant's dry matter, are classified as mineral nutrients. These are primarily absorbed from the soil solution or provided through fertilization. Based on the relative quantities required by plants, mineral nutrients are categorized into macronutrients and micronutrients. Macronutrients, required in larger amounts, include nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). Micronutrients, required in trace amounts, include iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), chlorine (Cl), and nickel (Ni) (1) & (2). Calcium (Ca), magnesium (Mg), and sulfur (S) are classified as secondary macronutrients. Although required in smaller quantities than the primary macronutrients i.e., nitrogen (N), phosphorus (P), and potassium (K), they are indispensable for the normal growth, development, and physiological functioning of most plant species. In addition, plants require eight micronutrients: zinc (Zn), iron (Fe), copper (Cu), manganese (Mn), molybdenum (Mo), boron (B), nickel (Ni), and chlorine (Cl). These elements are required in trace amounts, but their roles are critical in numerous biochemical and physiological processes. The classification as "micronutrients" reflects only their quantitative requirement and not their significance, as they are equally essential as macro- and secondary nutrients. Micronutrients often occur at low concentrations in soils and are consequently deficient in plant tissues. They serve as vital cofactors in enzymatic systems and play key roles in processes such as photosynthesis, nitrogen fixation, respiration, and hormone synthesis. Deficiencies in one or more of these elements can lead to marked impairments in plant growth, reduced crop yields, and compromised quality. To address such deficiencies, agronomic interventions such as the application of micronutrient enriched fertilizers, foliar nutrient sprays, and the incorporation of beneficial microbial inoculants into the soil are necessary. These practices help reestablish nutrient equilibrium, thereby enhancing plant health, productivity, and resilience (3).

Micronutrients in soil occur in a variety of chemical forms, each differing in their bioavailability to plants. These include water-soluble ions, exchangeable forms adsorbed onto cation exchange sites, chelated species bound to organic ligands, and organically complex forms associated with soil organic matter. Conversely, micronutrients bound to metal oxides or structurally integrated into the crystal lattices of secondary clay minerals are typically insoluble and thus largely unavailable for plant uptake. Generally, inorganic metallic forms of micronutrients are more plant-available than those sequestered in stable organic complexes. The bioavailability of micronutrients is significantly influenced by soil physicochemical properties, particularly soil organic matter (SOM) and soil pH. For example, acidic soil conditions enhance the solubility of many micronutrients, thereby increasing their availability, whereas alkaline conditions often lead to the precipitation or fixation of micronutrients, limiting their accessibility to plants (4). Soil organic matter (SOM) forms metal-organic complexes that can either enhance or reduce the availability of metals to plants, depending on the stability constant of each specific complex. Metals differ in their affinity for SOM, leading to variation in the stability constants of their complexes. For instance, cadmium (Cd) forms complexes with relatively low stability constants, facilitating easier extraction and higher bioavailability. Conversely, copper (Cu) forms highly stable complexes with SOM, which limits its extractability and availability. Similarly, nickel (Ni) and zinc (Zn) exhibit relatively low affinity for SOM, allowing these metals to be more readily mobilized from their organic complexes (5).

Soils in Pakistan are predominantly alkaline and calcareous, with pH values typically ranging between 7.5 and 8.5. Such alkaline conditions reduce the solubility of micronutrients in the soil solution, leading to their precipitation and subsequent decreased availability for plant uptake (6, 7). Micronutrients play a critical role in crop growth and development by regulating essential physiological and biochemical processes. Numerous studies have shown that plants maintain balanced physiological functions through the optimal uptake and utilization of micronutrients. Deficiencies in these elements can cause significant physiological disorders and growth impairment. Key processes regulated by micronutrients include cell development, protein synthesis, carbohydrate metabolism, chlorophyll biosynthesis, growth hormone synthesis, respiration, and redox reactions (8). Micronutrients deficiencies are widespread in plants and, by extension, in human populations, especially in developing countries such as Pakistan. Research on micronutrients in Pakistan commenced in the 1970s. Despite global recognition of micronutrients deficiencies, comprehensive assessments of soil micronutrient status in Pakistan’s agricultural lands remain limited (3, 9).

District Jhelum has been reported to exhibit zinc (Zn) deficiency, which significantly limits wheat yield in its rainfed areas. Extensive surveys indicate widespread Zn deficiency in both soils and wheat foliage throughout the district. The availability of bio-available Zn displays moderate to strong spatial variability. Zinc deficiency is, in fact, the most prevalent micronutrient disorder affecting crops in the rainfed Pothwar Plateau region of Pakistan (10). Similarly, in other parts of semi arid regions, deficiency of soil micro nutrients has been reported by several researchers. For example, soil samples of Chitral area were deficient in Zn (11). Surface soils of District Charsadda, Khyber Pakhtunkhwa (KPK), were found to be consistently deficient in nitrogen (N). Additionally, widespread deficiencies of phosphorus (P), zinc (Zn), and boron (B) were observed, while potassium (K), copper (Cu), and manganese (Mn) deficiencies occurred sporadically in the soils (12). The intensification of cultivation, widespread adoption of high yielding crop varieties, and increased reliance on inorganic fertilizers combined with the inherent characteristics of Pakistan's soils have contributed to the emergence of micronutrients deficiencies. Numerous studies have documented macro and micronutrients deficiencies in the soils of Khyber Pakhtunkhwa (KPK). Specifically, deficiencies of nitrogen (N), phosphorus (P), zinc (Zn), copper (Cu), and boron (B) have been reported in the districts of Bannu and Kohat (6).

There are many reasons for micronutrients deficiency in soil including calcareousness, alkaline pH, low organic matter, and improper fertilizer usage. Micronutrients deficiency in plants results in symptoms like leaf chlorosis, de shaped leaves and stunted growth which ultimately deteriorates the fruit quality. Evaluation of micronutrients status of the soil can help in promoting balanced use of inputs and 4R nutrient stewardship i.e. Right nutrient, Right rate, Right time, Right place (13, 14). This research was conducted in District Jhelum to evaluate the status of micronutrients in the soil. Located in northern Punjab along the bank of the River Jhelum, the district falls within the arid climatic zone. The agricultural landscape is characterized by small and fragmented landholdings, where farmers operate with limited resources and follow a constrained cropping pattern.

The objective of this study was to evaluate the spatial distribution and deficiency levels of essential soil micronutrients across the Jhelum District. Understanding this variability is crucial for improving site-specific nutrient management and enhancing crop productivity in the region. The outcomes of this research are intended to support the development of site-specific fertilizer recommendations suited to the district’s cropping systems. Furthermore, the study aims to inform effective strategies for micronutrient deficiency management, estimate fertilizer input requirements, and identify priorities for future research and development (R & D). Considerable progress has since been made in the R & D domain related to various aspects of micronutrient management.

MATERIALS AND METHODS

SAMPLING AREA

Soil samples were collected from multiple locations across District Jhelum as part of a farmer advisory service initiative aimed at assessing soil fertility. Jhelum lies within a semi-arid to sub-humid climatic zone and is administratively divided into four Tehsils: Jhelum, P. D. Khan, Dina and Sohawa. The district spans a total geographical area of approximately 883,310 acres, of which 320,663 acres are classified as cultivated land. The dominant soil textures in the region range from sandy loam to loam. Irrigation is primarily supported through wells and tube wells, which collectively serve approximately 28,000 acres. Additionally, the presence of hilly terrain, particularly in the northern and northwestern parts of the district, contributes to variations in topography and localized microclimatic conditions. The precise population of Jhelum is as per the latest census of 2023 is about 1382308.

According to the Department of Agriculture (Extension), District Jhelum receives an average annual rainfall of approximately 628 mm, with the highest precipitation typically occurring during the monsoon season. The major crops cultivated in the region include wheat, maize, sorghum, and rice. In recent years, farmers have begun to diversify their cropping patterns by introducing high-value crops such as garlic, grapes, and strawberries. However, a significant proportion of farmers remain unaware of the importance of soil analysis in enhancing crop productivity and maximizing profitability (13). This study aims to address this knowledge gap by providing critical insights into the soil characteristics of the district, thereby supporting farmers in making informed decisions for more efficient and sustainable agricultural practices.

SOIL SAMPLING

Geo tagged soil samples were systematically collected from multiple locations across District Jhelum at two depths: 0–15 cm and 15–30 cm. Samples were initially placed in polyethylene bags and then transferred into cloth bags labeled with waterproof lead ink. To ensure traceability, a matching internal label bearing the same identification number was included inside each bag.

The samples were transported to the laboratory and air-dried in plastic trays under shade, avoiding direct sunlight and fumes to prevent any heat-induced alterations in soil properties. Each tray was clearly numbered to maintain sample identification. Once dried soil aggregates were gently crushed using a wooden pestle and mortar and subsequently passed through a 2 mm sieve to achieve uniform particle size. The sieved samples were then stored in wide-mouthed, screw-cap plastic jars, each labeled accordingly for analysis. Physicochemical analyses were performed on the processed samples to determine electrical conductivity (EC), soil pH, soil organic matter (SOM), and soil texture. Additionally, extractable potassium (K) and available phosphorus (P) were measured following the standardized protocols prescribed by the Soil Fertility Research Institute, Punjab, Lahore (15). The DTPA extraction solution has been calibrated for soils having neutral to alkaline Ph, as described by Tarar *et al.*, 2020 (4). The soils of Pakistan are mostly alkaline in nature (16). The DTPA extraction method was selected as suitable for quantifying plant-available micronutrients in the alkaline soils of Pakistan. Diethylene triamine penta acetic acid (DTPA) functions as a chelating agent, effectively binding with water-soluble and weakly adsorbed exchangeable metal ions in the soil matrix. Given that chelation reactions proceed slowly, often requiring weeks to months to reach equilibrium, the quantity of DTPA in the solution-to-soil ratio (2:1) was calibrated to chelate metal ions at levels equivalent to ten times their atomic weight. This adjustment helps minimize competition among metal ions for binding sites on the chelating agent. Calcium chloride ($CaCl_2$) was incorporated into the extraction solution to maintain elevated CO_2 levels within the soil suspension, thereby inhibiting the dissolution of calcium carbonate ($CaCO_3$) and preventing the release of metals bound to $CaCO_3$ in calcareous soils. The extractant's pH was buffered to approximately 7.3, a condition favorable for the formation of stable metal-DTPA complexes. Tri ethanol amine (TEA) was used as the buffering agent, maintaining pH stability without interfering with flame atomic absorption spectrometry (AAS) measurements (17). The extracting solution was prepared by combining 0.005 M DTPA, 0.01 M $CaCl_2$, and 0.10 M TEA, with the pH carefully adjusted to 7.3. Soil samples were shaken with the extractant at a 1:2 soil-to-solution ratio for two hours at 25°C, followed by filtration through Whatman® Grade 42 filter paper. The filtrate was subsequently analyzed for micronutrient concentrations (Zn, Cu, Fe, Mn) using Atomic Absorption Spectroscopy (AAS). Standard solutions for these micronutrients were prepared in the DTPA extractant using Certified Reference Materials (CRMs) traceable to the National Institute of Standards and Technology (NIST). he Atomic Absorption Spectrophotometer (AAS) was calibrated using standard solutions in accordance with the instrument's operating manual to ensure precise quantification of micronutrients. Boron (B) was extracted from soil samples via the hot water extraction method and analyzed calorimetrically using Azomethine-H reagent. Micronutrients concentrations determined through DTPA extraction were utilized to evaluate soil micronutrients fertility. Based on these results, soils were categorized as having low, marginal, or adequate levels of plant-available micronutrients by comparing the data with critical thresholds established by the National Agricultural Research Center (NARC), Islamabad, Pakistan (18).

The DTPA extraction methodology is widely recognized as a reliable and effective technique for estimating plant-available micronutrients in soils, particularly those with alkaline and calcareous properties commonly found in Pakistan. According to Tarar et al. 2020(4), this method provides accurate quantification of micronutrients such as zinc, copper, iron, and manganese by selectively extracting the bio available fractions of these metals from the soil matrix. Given its suitability for soils with high pH and calcium carbonate content, the DTPA extraction procedure was adopted in the present study to ensure precise assessment of micronutrients status in the soils of District Jhelum. Utilizing this established method facilitates comparability with previous research findings and supports the development of targeted nutrient management strategies tailored to the specific soil conditions in the region (19).

RESULTS & DISCUSSION

ZINC (Zn)

The National Agricultural Research Center (NARC) classifies soil zinc (Zn) concentrations between 0.5 and 1.0 mg Zn kg^{-1} as marginally sufficient (Table I). Analysis of soil samples from District Jhelum revealed that over 50% of the samples across all surveyed locations fall within this marginal Zn range. This trend is consistent across the district's tehsils. Notably, P.D. Khan tehsil exhibits a more pronounced Zn deficiency, with 32.55% of soil samples presenting Zn concentrations below the marginal threshold (Table II, Fig. 1). The minimum Zn concentration detected was 0.2 mg kg^{-1} in Sohawa and P.D. Khan, whereas the maximum concentration of 1.92 mg kg^{-1} was observed in samples from Dina tehsil (19). In case of soils of Attock district. Different factors play a vital role in low Zinc content in soils e.g., High pH of soil, Calcareousness of soil, Low total zinc concentration in sandy and calcareous soils and soil erosion as well as runoff etc. (20, 21).

Table I. Critical limits of soil micronutrients and their relative frequency distribution in agricultural land of Jhelum district

Nutrient	Class	Range (mgKg^{-1})	% age
Zn	Low	<0.5	82.82
	Marginal	0.5-1.0	17.18
	Adequate	>1.0	0
Cu	Low	<0.2	11.29
	Marginal	0.2-0.5	39.24
	Adequate	>0.5	49.47
Fe	Low	<4.5	74.36
	Marginal	-	0
	Adequate	>4.5	25.64
Mn	Low	<1.0	90.43
	Marginal	1.0-2.0	9.57
	Adequate	>2.0	0
B	Low	<1.0	24.56
	Marginal	>1.0	51.23
	Adequate	-	24.21

Table II. Critical limits of soil micronutrients and their relative frequency distribution in agricultural land of Jhelum district (Tehsil wise break up)

Nutrient	Class	Range (mgKg^{-1})	Jhelum	Dina	P. D. Khan	Sohawa	% age
Zn	Low	<0.5	24.35	25.7	32.55	15.62	82.82
	Marginal	0.5-1.0	59.93	46	48.18	52.71	17.18
	Adequate	>1.0	19.74	28.2	19.27	31.67	0
Cu	Low	<0.2	2.64	5.46	20.93	16.13	11.29
	Marginal	0.2-0.5	38.16	41.5	39.87	37.4	39.24
	Adequate	>0.5	59.2	53	39.2	46.47	49.47
Fe	Low	<4.5	73.03	65.1	78.74	80.54	74.36
	Marginal	-	0	0	0	0	0
	Adequate	>4.5	26.97	34.9	21.26	19.46	25.64
Mn	Low	<1.0	88.82	90.8	98.34	83.79	90.43
	Marginal	1.0-2.0	11.18	9.22	1.67	16.21	9.57
	Adequate	>2.0	0	0	0	0	0
B	Low	<1.0	86.85	81.7	81.07	81.63	24.56
	Marginal	>1.0	13.15	18.3	18.93	18.37	51.23
	Adequate	0	0	0	0	0	24.21

COPPER (Cu)

The extractable copper (Cu) concentrations in soils from District Jhelum ranged from 0.1 to 1.1 mg kg^{-1}, with a mean value of 0.5 mg kg^{-1} (Table I). According to the National Agricultural Research Center (NARC), the permissible Cu concentration in soil is between 0.2 and 0.5 mg kg^{-1}.Notably, 39% of the analyzed soil samples fell within this permissible range, while approximately 50% of samples exhibited Cu concentrations above 0.5 mg kg⁻¹, indicating adequate levels. When evaluated by tehsil (Table II, Fig. 1), the percentage of samples with adequate Cu levels was 59.2% in Jhelum, 53% in Dina, 39.2% in P.D. Khan, and 46.47% in Sohawa. These findings suggest that copper deficiency is not widespread in the soils of District Jhelum (19). Similarly, Shafique *et al.*, 2021 commented that almost 57% soil samples of Sargodha districr contain adequate level of Cu (22).

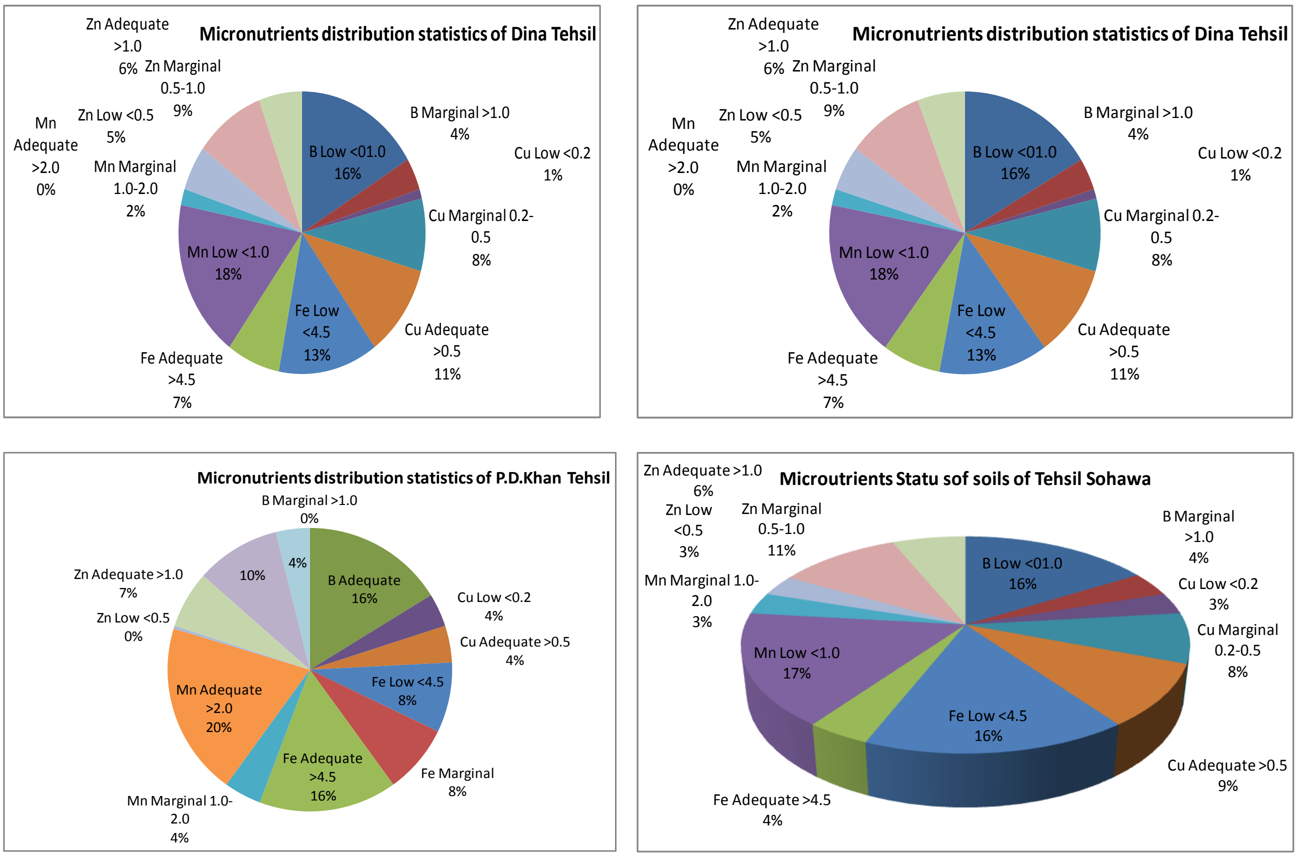

Fig. 1. Micronutrients distribution statistics of Tehsils Jhelum, Dina, P. D. Khan and Sohawa

IRON (Fe)

Iron (Fe) is essential micronutrient that often limits crop productivity. Plant Fe deficiency has been widely reported in alluvial soils across the globe. After oxygen, silicon, and aluminum, Fe is the fourth most abundant element in the Earth's crust, comprising approximately 3–5% of soil composition. In District Jhelum, the concentration of plant-available Fe ranged from 1.1 to 9.23 mg kg⁻¹ soil, with an average value of 3.9 mg kg⁻¹ (Table I). Analysis indicated that over 74% of soil samples were classified as deficient in Fe, while the remaining samples were deemed adequate (Table II, Fig. 1). No samples fell into the marginal category. The highest Fe concentrations were observed in soils from tehsil P.D. Khan, whereas lower Fe levels predominated in soils from the Jhelum and Sohawa tehsils. If we summarize it, then we will come to the point that the interplay of high soil pH, calcareous conditions, and low organic matter content in Pakistani agricultural soils significantly reduces the bioavailability of iron, despite its overall abundance. This results in widespread iron deficiency in crops, posing a critical challenge to agricultural productivity in the region. If we consider national standards for threshold values of DTPA extractable Fe (2.5 mg/kg considered deficient) then it will be revealed that almost 100 % soils of the area would be declared to be Fe deficient.

Shafique *et al.*, 2021 emphasized that intensive cultivation, especially involving horticultural crops, potatoes, and maize, may induce iron deficiency in soils unless proper maintenance fertilization practices are implemented (22). Their findings indicate that approximately 57% of soils in the Sargodha district contain sufficient iron levels to sustain intensive agricultural production, contingent upon adequate soil moisture availability throughout the cropping cycle. Similarly it was investigated that available Fe content in soil is directly related with decrease in soil pH (23).

MANGANESE (Mn)

The concentration of plant-available manganese (Mn) in the soils ranged from 0.1 to 1.87 mg kg^{-1}, with a mean value of 0.8 mg kg^{-1} (Table II, Fig. 1). Analytical results indicated that over 90% of soil samples were categorized as having "low" Mn levels, while approximately 9.57% fell into the "poor" manganese category (Table I). Such widespread Mn deficiency may lead to symptoms in crops, including chlorosis manifested as interveinal yellowing of young leaves which closely resembles iron deficiency symptoms (24).

Generally, the availability of micronutrients such as boron (B), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) decreases as soil pH increases, whereas molybdenum (Mo) availability tends to rise under more alkaline conditions. Manganese, in particular, is commonly applied alongside zinc during foliar sprays in citrus cultivation to prevent deficiencies. While some other tree crops may also show symptoms of manganese deficiency, their specific Mn requirements are not as well established. Imbalances in soil micronutrients levels can significantly impact plant health and growth. For example, manganese deficiency typically manifests as interveinal chlorosis on young, expanded leaves, whereas manganese toxicity results in brown spotting on mature leaves. Therefore, precise management of micronutrients is crucial for ensuring optimal plant development and maximizing crop productivity (25).

BORON (B)

The frequency distribution of boron (B) in soils of District Jhelum indicated that approximately 83% of the samples contained less than 0.5 mg kg^{-1} B, thereby classifying these soils as boron deficient, with concentrations ranging from 0.1 to 0.99 mg kg^{-1}. Additionally, about 17.18% of the total samples fell into the marginal deficiency category. This deficiency pattern was consistently observed across all tehsils of the district (Table II, Fig. 1). The widespread boron deficiency underscores an urgent need for coordinated action from policymakers, agricultural stakeholders, including farmers and fertilizer suppliers, to develop and implement effective soil fertility management strategies. Boron is an essential non-metallic micronutrient vital for plant growth and development. Due to its high mobility in soil, especially under conditions of excess moisture, boron is readily leached beyond the root zone, resulting in nutrient depletion. Given the narrow threshold between boron deficiency and toxicity, precise management practices are crucial to maintaining optimal soil boron levels and ensuring sustainable crop productivity (26).

Boron concentrations and bioavailability in soils are influenced by a variety of factors, including the nature of the parent material, soil texture, clay mineralogy, pH, organic matter content, irrigation sources, interactions with other soil constituents, and prevailing environmental conditions such as moderate to heavy rainfall, dry spells, and high light intensity. For instance, soils derived from boron-rich parent materials tend to have higher boron availability, while sandy soils with low clay and organic matter content typically exhibit lower boron retention and higher leaching potential. Soil pH can also affect boron solubility, with availability generally decreasing in alkaline conditions. Additionally, irrigation water quality and frequency influence boron levels, as does the competition or synergy between boron and other nutrients or minerals in the soil matrix. Environmental factors like rainfall can lead to boron leaching, whereas dry conditions may reduce its mobility. High light intensity may increase plant boron demand due to accelerated physiological processes. Understanding these complex interactions is essential for accurately diagnosing boron deficiency or toxicity and implementing appropriate management strategies across diverse agro-ecological zones (27, 28).

CONCLUSION

This study investigated the properties of soil with respect to the availability of micronutrients Zn, Cu, Fe, Mn, and B. The concentrations of these nutrients ranged as follows: Zn (0.2–1.92 mg/kg), Cu (0.12–1.1 mg/kg), Fe (1.13–9.23 mg/kg), Mn (0.1–1.87 mg/kg), and B (0.1–0.99 mg/kg), with mean values of 0.69, 0.5, 3.9, 0.8, and0.39 mg/kg respectively. Out of 823 samples analyzed, the proportion of samples classified as "Poor" in nutrient availability were: Zn (24.56%), Cu (11.29%), Fe (74.36%), Mn (90.43%), and B (82.82%). For the "Marginal" category, Zn accounted for 51.23%, Cu 39.24%, Fe 0%, Mn 9.25%, and B 17.18%. The

"Adequate" category included 24.21% of samples for Zn, 49.47% for Cu, 25.64% for Fe, with 0% for B. The availability of these micronutrients decreases significantly in soils with higher pH (alkaline soils). Since most agricultural land in Pakistan is naturally alkaline and calcareous, this contributes heavily to widespread micronutrient deficiencies if not managed properly. The study highlights a particularly alarming deficiency of Fe and B, necessitating immediate corrective measures. Soils deficient in Band Fe should be targeted with micronutrient-enriched fertilizers, particularly in P.D. Khan and Sohawa. This baseline data supports evidence-based nutrient stewardship under Pakistan's 4R framework.

Authors' contribution:

AW, SA Conceptualization;. Methodology SK, MA; Field and outdoor sample collection and analysis MSA, HII, NG; SA, SA, BA Review the manuscript; .Writing original draft SA; AH, HRA Supervision. All authors read and approved the final manuscript.

Conflict of Interest:

The authors declare no conflict of interest.

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