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Boron Deficiency in Pakistani Soils and Its Impact on Cotton Physiology

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Abstract

Boron (B) is an essential micronutrient critical for plant growth and development, playing a vital role in cell wall synthesis, membrane integrity, and reproductive processes. Despite its importance, boron deficiency is a prevalent issue in Pakistan, significantly affecting soil fertility and crop productivity. This review consolidates findings from various studies, highlighting the alarming extent of boron deficiency across different regions of Pakistan. Results from several studies reveal that boron deficiency varies widely, ranging from 5% to over 92% in soil samples, depending on the region, soil type, and cropping systems. Critical deficiencies have been reported in major agricultural areas such as Punjab, Sindh, Kashmir, and the Pothohar plateau, with implications for key crops including wheat, cotton, rice, and orchards. These deficiencies often result from calcareous soil conditions, high soil pH, and improper nutrient management practices. Addressing boron deficiency through balanced fertilization strategies, precision agriculture, and region-specific interventions is crucial to improving crop yields and ensuring sustainable agricultural production in Pakistan. This review provides an insightful synthesis of the spatial extent, causes, and impacts of boron deficiency, emphasizing the need for targeted soil and crop management strategies to mitigate this critical issue.

1. Introduction

Cotton serves as a fundamental pillar of Pakistan's economy, functioning as both a critical agricultural commodity and the backbone of the nation's largest manufacturing sector. The cotton-textile complex represents one of Pakistan's most significant economic sectors, contributing substantially to gross domestic product, export earnings, and employment generation across rural and urban areas. Pakistan's position as the fifth largest cotton producer globally, combined with its status as a major consumer and exporter of cotton-derived products, underscores the crop's central importance in the country's economic structure (Radhakrishnan, 2017).

Micronutrients such as boron, zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) act as catalysts in enzymatic processes and structural components of cotton plants. While required in smaller quantities compared to macronutrients, their absence critically impairs metabolic functions, including photosynthesis, cell wall formation, and hormone regulation. Zinc, for instance, facilitates auxin synthesis and carbohydrate metabolism, particularly in root development. Manganese contributes to chlorophyll production and nitrogen assimilation, while copper enhances lignin formation and disease resistance (Oosterhuis & Weir, 2010). Boron's unique role lies in its involvement in the cell wall pectin synthesis, pollen tube growth, and carbohydrate translocation. These functions are vital during flowering and

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boll development, where boron deficiency disrupts seed formation and fiber elongation. Studies indicate that 70% of boron uptake occurs post-flowering, aligning with peak demand during boll maturation. This temporal specificity underscores the need for targeted boron supplementation during reproductive phases (Rochester *et al.*, 2012).

A well-known dietary condition in many nations worldwide, including Pakistan, is a shortage in boron (B) (Day & Aasim, 2020; Patil, Jaleel, & Qadri, 2023). Inceptisol, Aridisol, Vertisol, Entisol, Alfisol, and Mollisol are the six soil orders of the US Soil Taxonomy that correspond to the approximately 22 million hectares of agricultural soils that make up the majority of Pakistan's cultivated areas (Rashid, Zia, & Ahmad, 2022). The primary components of the soils were loess and calcareous alluvium. Pakistan has an arid to semi-arid climate, except a few high mountains in the north. These soils are therefore calcareous ($CaCO_3$, 1.5-13.5%), alkaline (pH, 7.5-8.8), and deficient in organic matter. These soil characteristics, along with enhanced B requirements for crops, especially cotton, yield a lot of crops and less use of B. The combination of soil conditions, the high boron (B) requirements of high-yielding crop varieties, and the limited use of B fertilizers often results in B deficiency in crops. Intense monsoon rains during July and August, along with waterlogged conditions in flooded rice fields, can cause B to leach beyond the root zone. Conversely, dry surface soils during drought periods in the growing season can restrict B uptake by plant roots. This deficiency may lead to flower bud abortion, though it can be mitigated by applying B fertilizers. However, managing B levels is challenging due to the narrow threshold between deficiency and toxicity (Yau & Ryan, 2008).

2. Functions of boron in cotton crop

Boron (B) serves as a critical micronutrient in cotton physiology, influencing processes ranging from cellular architecture to reproductive success and fiber biosynthesis (Table 1). Its primary physiological function lies in cross-linking rhamnogalacturonan-II (RG-II) pectin polymers within plant cell walls, where this borate-diol ester bonding creates a three-dimensional pectic network that regulates wall porosity and mechanical strength (Azeem *et al.*, 2021). In cotton, this structural reinforcement prevents cell wall rupture during rapid fiber elongation, maintaining turgor pressure critical for cell expansion, reduces wall pore size from 7.5 nm in deficient cells to 4.2 nm under adequate boron, thereby restricting pathogen entry while allowing nutrient diffusion and stabilizes plasma membranes by binding to phospholipid head groups, reducing oxidative damage during boll maturation Bolaños *et al.*, 2023. Field studies demonstrate that boron-sufficient cotton plants exhibit 23% thicker secondary cell walls in fiber cells compared to deficient counterparts, directly enhancing fiber tensile strength. The RG-II dimerization process consumes 95% of cellular boron, underscoring its structural priority over metabolic functions Zhang *et al.*, 2022. Boron's impact on cotton reproduction manifests through key mechanisms including pollen tube guidance and fertilization, where boron facilitates the formation of arabinogalactan proteins (AGPs) in stigma exudates, creating a chemotropic gradient for pollen tube growth; at 0.3 ppm boron concentration, pollen germination rates increase from 42% to 78%, pollen tube growth velocity accelerates by 1.2 μm/min, and fertilization success improves by 35% compared to deficient conditions Abbas *et al.*, 2023. Additionally, boron-mediated auxin transport ensures proper ovule differentiation, with boron-deficient flowers exhibiting 59% smaller embryo sacs and seed abortion rates escalating from 12% to 41% under boron scarcity, while boll retention improves by 28% with foliar boron sprays (0.2% Solubor®) at flowering. Boron also forms complexes with mannitol and sucrose, enabling phloem mobility of these carbohydrates into developing bolls; isotopic tracing shows 10B-labeled mannitol-borate complexes move 3.8 times faster than free boron, with 68% of boll carbohydrates originating from remobilized leaf reserves, and boron-sufficient plants allocating 22% more photosynthates to bolls versus vegetative growth (Radhakrishnan, 2017; Oosterhuis & Weir, 2010; Rochester *et al.*, 2012).

3. Boron deficiency in Pakistani soils

Boron deficiency in Pakistani soils is primarily driven by three interconnected factors: high soil pH, elevated calcium carbonate ($CaCO_3$) content, and low organic matter. These conditions dominate Pakistan's agricultural landscapes, particularly in cotton-growing regions, creating widespread boron unavailability (Yadav *et al.*, 2023 Nadian *et al.*, 2010, Niaz *et al.*, 2007).

High soil pH significantly reduces boron availability by decreasing its solubility in the soil solution. In alkaline conditions, which are common in many Pakistani agricultural areas, boron ions tend to adsorb onto clay particles and

Table 1. Boron Function in Cotton Crop

Sr. No.	Boron Function	Reference
1	Alleviating salt stress, maintaining cell wall structure, and regulating ion homeostasis.	(Lu *et al.*, 2023)
2	Cotton plants include improving yield, cycling in soil, and enhancing soil fertility when combined with cover crops and appropriate fertilization rates.	(dos Santos Cordeiro, dos Santos Cordeiro, & Ferrari, 2022)
4	Cotton plants include promoting dry matter production, regulating oxidative stress, and inducing the production of proline and glycinebetaine as nonenzymatic antioxidants.	Lu *et al.*, 2023)
5	Photosynthesis and Nutrient Utilization Enhances photosynthesis, supports nutrient uptake, and mitigates environmental stresses.	(Wu *et al.*, 2024)
6	Improved Fiber Quality Promotes better fiber strength, length, and micronaire through boronfertilized foliar sprays.	(Lu *et al.*, 2023)
7	Stress Tolerance through Enzymatic Activity Enhances enzymatic antioxidant activity under abiotic stresses.	(Song *et al.*, 2019)
8	Reproductive Development Boron aids pollen viability and ovule fertilization, improving boll formation.	(Belsky, 2012)
9	Yield Stability in Variable Climates Enhances yield stability under diverse climate conditions through better soil-plant boron dynamics.	(Niaz, 2010)
10	Boron stimulates root elongation and branching, improving water and nutrient uptake.	(Turan *et al.*, 2021)
11	Enhances water retention and root hydraulics.	(Kour & Yadav, 2022)
12	Boron increases chlorophyll concentration, improving photosynthetic capacity.	(Jain *et al.*, 2009)
13	Protects membrane lipids under oxidative stress conditions.	(de Souza Júnior *et al.*, 2022)
14	Regulates auxin and cytokinin levels for improved growth.	(Peleg & Blumwald, 2011)
15	Seed Germination Improvement Enhances germination rates under stress.	(Azeem *et al.*, 2021)

oxides, or precipitate in less soluble forms. As a result, even if total boron content in the soil is adequate, the fraction accessible to plant roots becomes limited. This is why crops grown on high-pH soils frequently exhibit boron deficiency symptoms despite fertilizer applications Yadav *et al.*, 2023.

Elevated calcium carbonate ($CaCO_3$) content further compounds boron unavailability. Calcium carbonate not only maintains high soil pH but also provides surfaces that adsorb boron, effectively immobilizing it. In calcareous soils, which cover large parts of Pakistan's irrigated zones, boron tends to bind tightly to carbonate minerals, reducing its movement into the root zone. Over time, this process leads to a persistent deficit that is difficult to correct without targeted soil amendments or foliar applications Nadian *et al.*, 2010.

Low organic matter levels also play a critical role in limiting boron availability. Organic matter acts as a reservoir that retains boron in soluble complexes, preventing it from leaching or becoming fixed in unavailable forms. When soils are depleted of organic matter due to continuous cropping and limited residue returns, their capacity to hold boron diminishes. Consequently, boron becomes less available to crops, and deficiency symptoms are more likely to appear, especially in coarse-textured soils with poor nutrient retention Niaz *et al.*, 2007. The extent of Boron deficiency has been given in Table 2 Boron Deficiency in Pakistani Soils.

4. Approaches to Diagnose Boron Deficiency

Soil and plant analysis are reliable tools for diagnosing B deficiency. Among these, soil testing is more practical and widely adopted to predict the B fertilizer needs of crops. Most common method for B is the hot water extraction (HWE) method, originally introduced by Berger and Truog (1944), is the easiest approach for assessing B fertility in alkaline soils, such as those in Pakistan. However, the HWE method is labor-intensive and susceptible to errors. To address these limitations, research in Pakistan has validated an alternative soil testing procedure-0.05 M HCl extraction-developed by (Ponnamperuma, Cayton, & Lantin, 1981) for acid soils. This simpler and more economical method is more effective for testing B deficiency in calcareous soils (Rafique, Rashid, Bhatti, Rasool, & Bughio, 2002). Although, the dilute HCl method extracts B compared to HWE, slightly less, there is a strong correlation between these two methods, as indicated by the regression equation (Rafique *et al.*, 2002). The critical soil B levels for diagnosing deficiency are 0.5 mg kg^{-1} for the dilute HCl method0.45 & for HWE method 0.50 mg kg-1. These thresholds may vary slightly depending on soil type and crop species (Rashid, 2006).

Plant analysis is a reliable method for identifying boron (B) deficiency in crops. This involves assessing B concentrations in entire plants, such as young cereal shoots, or specific parts, like the youngest fully expanded leaves during the bloom stage. Such analysis helps determine if B levels are within the critical range for a particular plant species. Variations in B requirements among crop genotypes necessitate species-specific evaluations to ensure accurate diagnosis. For locally cultivated genotypes in Pakistan, critical boron (B) levels have been identified. These levels differ across species, among varieties within a species, and even between various plant parts of the same variety (Reuter & Robinson, 1997).

A systematic B indexing study conducted across Pakistan's 3 million ha cotton belt revealed B concentration (mean 53.1 mg kg^{-1}) ranges of 27.0-71.0 mg kg^{-1} in cotton leaves. This analysis, supported by extensive field experiments, showed that 50% of the cotton fields were deficient in B (Rafique *et al.*, 2002).

5. Boron Deficiency in Pakistani Soils

Boron deficiency is a widespread problem affecting many cropping systems across Pakistan. Numerous studies have documented that substantial proportions of soils, ranging from about 5% in some localized surveys to over 90% in others, contain boron concentrations below critical thresholds required for optimal plant growth. The prevalence of deficiency varies by region, soil type, and cropping pattern, but is consistently reported as a significant constraint to productivity in cereals, cotton, rice, and orchards. Soils with high pH and elevated calcium carbonate are particularly prone to boron fixation, further reducing its availability to plants. Boron deficiency impairs reproductive development, reduces grain and fruit set, and ultimately lowers crop yields and quality. These findings underscore the importance of routine soil testing and site-specific boron management strategies to sustain crop production and soil health in Pakistan's diverse agro-ecological zones.

The table provides an overview of boron (B) deficiency in Pakistani soils, summarizing findings from various studies (Table 2). It highlights the widespread occurrence of B deficiency across different regions, its impact on crop productivity, and the critical soil B levels associated with deficiency symptoms.

6. Implications for Sustainable Cotton Farming

Effective boron management is essential because the margin between deficiency and toxicity is very narrow. The first step is to conduct regular soil testing to determine the boron status and identify areas that require corrective measures. Where deficiency is confirmed, soil application of boron fertilizers, such as borax or boric acid, can be applied at recommended rates, usually ranging from 0.5 to 2 kg boron per hectare. Care must be taken to avoid over-application, as excess boron can quickly become toxic to plants Qazi *et al.*, 2021.

Foliar sprays of soluble boron products (e.g., boron 5% liquid formulations) are particularly effective for quick correction during critical growth stages like flowering and fruit set. In addition, maintaining or increasing organic matter content in soil helps to improve boron availability by forming

Table 2. Boron Deficiency in Pakistani Soils

Sr. No.	Boron Deficiency	Summarized Abstract	Reference
1	92% soil samples were found deficient in B	Total 1194 georeferenced soil samples were collected at a depth of 0-15cm	(Tarar et al., 2020)
2	90% samples were deficient in Boron	Out of 13 soils, 12 were found boron deficient (less than 0.5 µg g-1).	(Niaz et al., 2002)
3	41% of the soil samples analyzed in Sargodha district, Punjab, Pakistan is deficient in boron.	Survey of soil micronutrient status in Sargodha district, Punjab, Pakistan - Deficiency of boron in soils requires immediate action	(Shafique, 2021)
4	The 34.7% soil samples showed low concentration of B	Micronutrients have a key role in plant growth -their deficiency negatively affects growth, yield, reproduction	(Sheikh et al., 2023)
5	Boron deficiency is prevalent in 35-56% of the soils under field crops in Pakistan.	Boron deficiency prevalent in 35-56% of field crops in Pakistan - Boron fertilization increases crop yields and quality	(Rashid & Rafique, 2017)
6	Approximately 50% of the soils studied in Kashmir were found to be deficient in boron.	Critical limit of boron in soils and plants determined - 50% of soils studied found to be deficient in boron	(Nazir & Wani, 2017)
7	Approximately 81% of the soil samples in Punjab, Pakistan were found to be deficient in available boron.	Study on soil extractable and fertilizer boron - Relationship to soil properties, crop yields, and plant boron levels	(Niaz et al., 2013)
8	Approximately 64% of the sampled fields in the Pothohar plateau in Pakistan were found to be deficient in boron.	Boron deficiency in rainfed wheat in Pakistan - B use increased wheat yields up to 11%	(Rashid et al., 2011)
9	Approximately 5% of the soil samples collected from Punjab, Pakistan were deficient in boron.	Boron deficiency in soil, cotton, and wheat samples - Boron application increased seed cotton and grain yield	(Boparai, 2017)
10	The study conducted in Pakistan found that the soils in the major rice-growing areas of Punjab and Sindh were deficient in boron.	Boron deficiency affects rice productivity and grain quality.	(Rashid et al., 2009)
11	Approximately 50% of the sampled fields in Jehlum district and 115 fields in Chakwal district of Pakistan were found to be deficient in boron.	Boron deficiency in rainfed sorghum in Pakistan. - Boron fertilization increased grain yield in sorghum.	(Rashid et al., 1997)
12	Some areas of Northwest Frontier Province (NWFP) of Pakistan have been reported to be deficient in one or more micronutrients, including boron.	Field experiment conducted to study micronutrient deficiency in wheat - Micronutrient treatments increased wheat yield and dry matter	(Asad & Rafique, 2002)
13	Micronutrient deficiency in soils and plants reported.	The study was initiated to determine the response of cotton and wheat crops to boron on high-pH-calcareous soils in Pakistan	(Ibrahim et al., 2007)
14	The study found a widespread deficiency of boron in Pakistani orchard soils.	Orchards in Pakistan have low yields due to imbalance fertilization. Micronutrient deficiencies, especially zinc and boron, are widespread	(Zia et al., 2006)
15	The study found that boron deficiency and toxicity are widespread in arid and semi-arid soils in Punjab, Pakistan.	Study assessed yield response and soil boron fractions.	(Javed et al., 2021)
16	Boron deficiency impairs plant growth and reduces yield.	Boron is an essential plant nutrient with a crucial role in agriculture. - Boron deficiency impairs plant growth and reduces yield.	(Nazir et al., 2016)

stable complexes that reduce leaching losses and enhance nutrient retention.

In calcareous or high pH soils, where boron becomes less available, the use of organic amendments or acidifying fertilizers can slightly increase boron solubility. Balanced fertilization practices that avoid excessive lime or calcium applications are also important for sustaining boron supply. Finally, regular monitoring of both soil and plant tissue boron levels, combined with farmer training and site-specific recommendations, ensures crops receive adequate boron without the risk of toxicity Niaz *et al.*, 2007. The list of products commercially available in the market of boron fertilizers is given in Table 3.

resulting in premature abscission of flowers and bolls, compromised fiber development, and substantial yield penalties. To mitigate boron deficiency in cotton, a range of agronomic interventions can be employed;

Soil-Based Applications: The incorporation of boron into soil through amendments such as borax or boronated fertilizers is an effective strategy for correcting chronic deficiencies. These treatments enhance the residual boron pool in the soil, improving long-term micronutrient availability.

Foliar Application: Targeted foliar sprays of boron during critical phenological stages-particularly flowering and boll formation-offer a rapid corrective measure. This approach is especially valuable in addressing transient or in-season boron deficiencies that are difficult to manage through soil amendments alone.

Integrated Nutrient Management (INM): INM offers a comprehensive framework that synchronizes nutrient supply with crop demand, while considering soil health and environmental sustainability. By aligning boron applications with the physiological requirements of the crop and prevailing soil conditions, INM minimizes the risk of deficiency and enhances nutrient use efficiency.

Table 3. List of products commercially available in market of boron fertilizers

Sr. No.	Brand Name	Composition
1	Borolix	Boron Inorganic Liquid (5%)
2	Sada Bahar	Boron Inorganic Liquid (5%)
3	Imperial Fix	Boron Inorganic Liquid (5%)
4	Royal Boron	Boron Inorganic Liquid (5%)
5	Nissan-5	Boron Inorganic Liquid (5%)
6	Pollinator	Multi Micronutrient Inorganic Solid (Zn=7%, B=3%)
7	Zeneca Extra	Multi Micronutrient Inorganic Solid (Zn=6%, Fe=2%, Mn=1%, B=1%)
8	Lajawab	Multi Micronutrient Inorganic Solid (Zn=4%, Fe=2%, Mn=3%, B=1%)

7. Conclusion

To Boron deficiency is a major problem in cotton production worldwide. It is estimated to affect over 40% of cotton fields globally, resulting in yield losses of up to 50%. Boron deficiency is particularly severe in sandy soils with low pH, as well as in soils with high levels of calcium or magnesium.

There are a number of factors that can contribute to boron deficiency in cotton, including; Intensive cropping practices: Intensive cropping practices, such as monocropping and high-yielding varieties, can deplete soil boron levels over time. Irrigation practices: Irrigation with poor-quality water can leach boron out of the soil. Fertilizer practices: Improper fertilizer management practices can also contribute to boron deficiency, The exclusive application of nitrogen or potassium without concurrent boron supplementation can inadvertently exacerbate micronutrient imbalances, leading to boron deficiency in cotton (Gossypium hirsutum L.). The phenotypic manifestation of boron deficiency varies with the intensity of nutrient stress but commonly includes interveinal chlorosis, marginal necrosis, and increased stem brittleness. Under acute deficiency, reproductive structures are significantly affected,

Boron deficiency poses a significant constraint to optimal cotton productivity and fiber quality. A nuanced understanding of its physiological implications, coupled with proactive nutrient management, is imperative for sustaining yield potential and ensuring superior lint characteristics in cotton production systems.

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10. Conflict of Interest

The authors declare no conflict of interest.

11. Authors' Contribution

Hafiz Tanvir Ahmad conceived the idea, Hanzla Mansha, Adnan Sabir collected the review of literature Aqsa Rehman, Asba Fatima, Muhammad Saad Ikram, Arisha and Ijaz Mehboob wrote the manuscript and Noor ul Ain critically reviewed the manuscript.

12. SDGs Addressed

This research aligns with SDG 2 (Zero Hunger) by improving cotton yield through better nutrient management, and SDG 12 (Responsible Consumption and Production) by encouraging efficient fertilizer use. It also supports SDG 15 (Life on Land) by promoting sustainable soil and crop health.

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