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Boron deficiency diagnosis and management in field crops in calcareous soils of Pakistan: A mini review

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ABSTRACT

The ~22 million ha soils of Pakistan (23° 53′ to 36° 49′ N, 61° 15′ to 74° 50′ E) are predominantly calcareous and low in organic matter. Boron (B) deficiency is prevalent in 40–78% areas under field crops causing yield, produce quality and economic losses. Boron deficiency is more severe in rainfed than irrigated soils. Both hot water extraction and dilute HCl method are used for evaluating B status; and locally determined internal B requirement varies from 53 mg kg^{-1} in cotton leaves to 6 mg kg^{-1} in youngest leaves of rice. Extent and severity of B deficiency in crops have been determined and spatial variability of B in soils and crops has been mapped. Boron fertilization increases crop yields appreciably (e.g., cotton and wheat, 14%; rice, 15–25%) and, thus, is highly cost-effective, more so by foliar feeding. Annually applied 0.75–1.0 kg B ha^{-1} corrects the deficiency; 2–3 foliar sprays of 0.1% B solution are also effective. Boron use improves produce quality; e.g., rice milling return, head rice recovery and cooking quality. Soil B fertilization leaves residual effect for 2–4 crops, and repeated annual applications of 1.0 kg B ha^{-1} in calcareous soils were safe. However, current B fertilizer use in Pakistan is negligible, i.e., 92 Mg B per annum compared with potential requirement of 2245 Mg B per annum. Constraints to B use include stakeholders' ignorance about benefits of B use and inadequate availability of quality B fertilizers.

1. Introduction

Boron (B) deficiency is a well-recognized nutritional disorder in many countries of the world [1–3], including Pakistan [4–6]. The ~22 million ha agricultural soils across much of the cultivated areas in Pakistan pertain to six soil orders of the *US Soil Taxonomy*, which, in order of their extent, are Aridisol, Entisol, Inceptisol, Alfisol, Vertisol and Mollisol [7].

The soils were developed of calcareous alluvium and loess parent materials. The climate in Pakistan, except for in some high mountains in the north of the country, is mostly arid to semi-arid [7]. Therefore, these soils are alkaline (pH, 7.5–8.8), calcareous ($CaCO_3$, 1.5–13.5%) and are low in organic matter (0.1–1.2%) [8]. These soil conditions, coupled with elevated B demand for high yielding crop cultivars and rare use of B fertilizer, are conducive to B deficiency in crop plants. Torrential rains during monsoon season (i.e., July–August) and abundant soil moisture (e.g., in flooded rice fields) may cause B leaching beyond the root zone while dry surface soils during dry spells during crop growing seasons may retard root absorption of B. Boron deficiency can result in abortion of flower buds/ or flowers in crops like cotton and panicle sterility in cereals, like wheat [9] and rice [10], and malformed seeds (e.g., hollow heart in peanut) [11–12]. Boron fertilizer application can alleviate the deficiency. However, managing B deficiency can become a challenge due to the narrow range between its deficiency and toxicity [6, 13].

This review addresses B deficiency diagnosis and management in field crops in calcareous soils of Pakistan.

2. Prognosis/diagnosis of boron deficiency

Soil testing as well as plant analysis are effective for prognosis/diagnosis of B deficiency. Soil testing is relatively a more practical and widely used approach for predicting B fertilizer need of field crops. Hot water extraction (HWE) is the most commonly used test for evaluating B fertility status of alkaline soils, like those of Pakistan [14]. However, this method is tedious and is prone to error. Research in Pakistan has established that a simpler, less prone to error and economical soil test procedure, i.e., 0.05 *M* HCl method of Ponnamperuma et al. [15], initially designed for acid

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soils, is equally effective for diagnosing B deficiency in calcareous soils (Table 1). Dilute HCl procedure extracts slightly less soil B than HWE; but there is a good agreement between B contents extracted by the two methods ($R^2 = 0.92$; $P \leq 0.01$; Figure 1). The relationship is: HCl B = 0.855(HWE B) - 0.023 [16–17]. The critical level of soil B for deficiency diagnosis is 0.5 mg kg^{-1} by HWE method and 0.45 mg kg^{-1} by dilute HCl procedure [4–5]. However, soil test B levels at which B deficiency in crop plants is expected may vary to some extent according to soil type and crop species [4].

Boron deficiency in crop plants can be diagnosed effectively by plant analysis. Analysis of B concentration in the whole plants (e.g., young whole shoots of cereals) or in a specific plant part (like youngest fully expanded leaves at bloom stage) can help diagnose whether B concentration is below or above an established critical B concentration/range for a particular plant species. Crop genotypes may vary in their internal B requirement; therefore, critical levels for deficiency diagnosis were determined for some locally grown crop genotypes in Pakistan. Critical B levels in diagnostic plant parts of locally grown crop genotypes varied between species, varieties of the same species, and plant parts of the same variety (Table 2). Whereas locally determined plant analysis diagnostic norms for many field crops were not very far from values in the literature, the critical B level determined in cotton leaves (without petioles), i.e., 53 mg kg^{-1} [18], was much higher than generally listed critical level of 15-20 mg kg^{-1} [1, 19]. In our systematic B indexing of farmer-grown cotton crop and extensive field experiments throughout the cotton belt in Pakistan spanning over 3 million ha, B concentration range in cotton leaves was 27.0–71.0 mg kg^{-1} (mean 53.1 mg kg^{-1}) and 50% of cotton fields were diagnosed as deficient in B [17–18].

3. Extent of boron deficiency in field crops

In Pakistan, initial crop yield increases with B fertilizer were observed in cotton [20] and rice [21]. However, B research did not receive due emphasis until mid-1980s, primarily due to lack of laboratory facilities for B analysis, like B-free glassware. Subsequent extensive nutrient indexing surveys of farmer-grown crops coupled with greenhouse and field experiments led to identification and establishment of B deficiency in many crops including cotton [17–18], wheat [22–23], rice [10, 24], maize [23], sugarcane [25–26], peanut [27–28], sorghum [29] and rapeseed-mustard [14, 30].

In nutrient indexing surveys of multiple field crops, the soil test B in irrigated alluvial calcareous soils of Pakistan was 0.07–2.19 mg kg^{-1} (mean, 0.64 mg kg^{-1}) [4, 10, 17] and was much lower in loess-derived, rainfed soils of Pothohar plateau in northern Punjab province, i.e., 0.10–1.08 mg kg^{-1} (mean, 0.47 mg kg^{-1}) [31]. Boron deficiency problem was diagnosed in 50% of irrigated cotton fields in Punjab and Sindh provinces [17] and in 55% cultivated fields of the rainfed Pothohar plateau [31]. Thus, despite greater mining of B by

Table 1. Relationships between hot water extractable boron, dilute HCl extractable boron and plant B content in calcareous soils of Pakistan.

Soil test B	Correlation Coefficient (r)			
	HCl B	Rapeseed[a]		Cotton[b]
		Leaf B	B Uptake	Leaf B
HWE B	0.96**	0.97**	0.84**	0.43**
HCl B	-	0.97**	0.86**	0.46**

[a] Greenhouse-cum-lab incubation study
[b] Soil test and leaf B in cotton fields of Multan district, Punjab province, Pakistan (n= 75)
Source: Rafique et al. [17]; Rashid et al. [30]

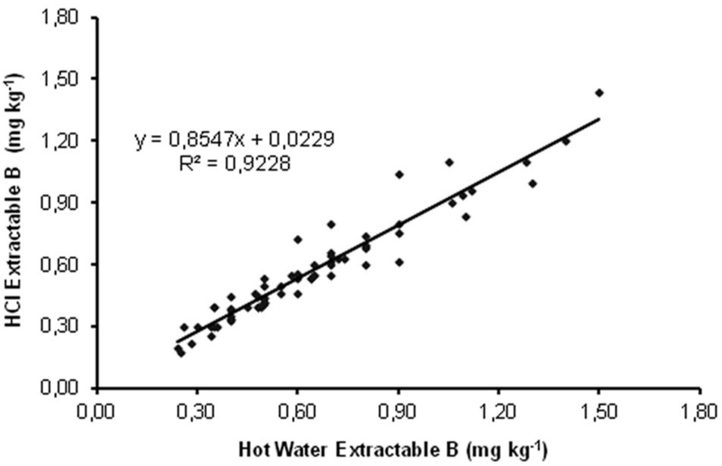

Figure 1. Relationship between HWE B and dilute HCl B in 70 cotton–wheat soils of Rahim Yar Khan district of Punjab province in Pakistan (Source: Rafique et al. [17]).

Table 2. Critical levels of boron in diagnostic plants/plant parts of some locally grown crop genotypes in Pakistan.

Species and cultivar	mg B kg^{-1} DM	
	Whole Shoots[1]	Youngest Leaf[2]
Wheat (*Triticum aestivum*, cv. Pak-81)	4–6	5–7
Rice (*Oryza sativa*)		6
Cotton (*Gossipium hirsutum*, cvs. many)		53
Sorghum (*Sorghum bicolor* Merr.)		
cv. Pothohar	18	31
cv. PAEC-SS-I	17	25
Rapeseed (*Brassica napus*, cv. Shiralee)	32	38
Mustard (*Brassica juncea*, cv. BARD-I)	41	49
Chickpea (*Cicer arietinum*, CM-72)		49[3]
Peanut (*Arachis hypogaea*, cv. BARD-699)		29[4]
Sunflower (*Helianthus annuus*)		
4-Week	46–63	
8-Week	36	

[1] Young whole shoots ($\leq$30 cm tall)
[2] Youngest fully expanded leaf blade at flowering
[3] Youngest leaf
[4] Shoot terminals
Source: Rashid and Rafique [18]; Rashid et al. [4]

more biomass producing irrigated crops, B deficiency is more severe and slightly more widespread in rainfed crops [31]. Multiple nutrient indexing investigations in the country have revealed existence of B deficiency in 40–78% crop areas under various crops, e.g., irrigated wheat, 48%; rainfed wheat, 64%; flooded rice, 40% [23]; irrigated maize, 50%; irrigated sugarcane in Punjab province, 69% [26] irrigated sugarcane in Sindh province, 45% [25]; rainfed sorghum, 67% [29]; rainfed rapeseed, 57%; rainfed mustard, 78% [30]; and rainfed peanut, 50% [27]. Relatively better soil B availability in irrigated calcareous soils is attributed to B augmentation with irrigated water (e.g., 0.20–0.26 kg B ha^{-1} in cotton-wheat system soils [32]) and more crop residue recycling in irrigated fields [33].

The 1982-published FAO global study on micronutrients had revealed that 49% of the soils sampled from Punjab province, 55% soils from Khyber Phakhtunkhawa KP province and 62% from Sindh province in Pakistan were deficient in B [37]. Soon after this revelation, existence of widespread B deficiency was verified by soil analyses studies in various parts of the country, e.g., during 1986-1988 in 55-89% soils of (KP) province [34–35]. During 1990s, a nutrient indexing investigation of soils in Mansehra and Swat districts of KP province (the only small area in the country having some mildly acid soils), the extent of soil B deficiency was 45% in alkaline soils and 0% in acid soils [36]. This clearly revealed that B deficiency problem is of its low solubility in alkaline pH environment, rather than low total B content in soils. However, soil-plant B status in the largest province of Pakistan, i.e., Balochistan, is hardly known where soils are highly calcareous and predominantly rainfed.

Up till 2000, in Pakistan B deficiency problem was recognized only in a few selected crops, like cotton gown in Punjab and Sindh province over 3 million ha [4]. Subsequent research, however, revealed that B deficiency is even a more serious micronutrient disorder in aromatic Basmati varieties of rice as well as in coarse grain IRRI type rice cultivars grown in Punjab and Sindh [10, 24]. Also, during this period B deficiency was established in many additional crops; and the risk of B deficiency for crop production is increasing over time [38]. Therefore, the need for continued diagnosis, delineation of deficient areas, and effective management of B deficiency in field crops cannot be overemphasized. As B fertilizer use enhances paddy yield to the tune of 20–30% and simultaneously improves rice grain quality, the positive effects of B fertilization in rice are phenomenal. In short, the two milestone developments, i.e., identification and establishment of B deficiency in cotton and rice crops, have played a major role in creating awareness about the importance of adequate B nutrition of crops in the country.

In summary, local experimental evidence [4, 32] has adequately established prevalence of B deficiency in many field crops. The field crops known to be suffering with B deficiency in Pakistan are listed in Table 3. In fact, the extent of B deficiency in Pakistan's field crops is not lesser than that of zinc (Zn) deficiency. Rather, B deficiency appears to be a more widespread micronutrient problem compared with Zn deficiency; the only limitation appears to be much less research information about B compared with Zn.

3.1. Soil types and boron deficiency

In a nutrient indexing investigation of rainfed peanut in Pothohar plateau of Pakistan, HWE B in topsoils varied with their parent materials, i.e., alluvium, 0.54 mg kg^{-1}; loess, 0.50 mg kg^{-1}; residuum from sandstone, 0.40 mg kg^{-1}; and redeposited loess, 0.26 mg kg^{-1}. However, the extent of B deficiency had no relationship with the parent materials, but was somewhat related to the soil types. Amongst the soils belonging to Ustochrepts, B deficiency was observed in 50% fields of Typic Ustochrepts, 50–75% fields of Aridic Ustochrepts, 33–100% fields of Calcic Ustochrepts and

83–100% fields of Fluventic Ustochrepts. Similarly, B deficiency existed in 50–100% fields belonging to Typic Haplustalfs, 33% of Typic Ustochrepts and 100% of Lithic Torripsamments [27]. According to Bell [39], risk of B deficiency can be inferred from soil parent material, soil properties (like texture, pH, calcareousness), incidence of leaching, rainfall intensity and frequency and soil drying. For example, the soils developed on B deficient-sedimentary rocks, such as sandstone and shale and on granite, are more likely to be deficient than the soils developed on basaltic or alluvial parent materials. Clayey soils contain more B than sandy soils [40].

3.2. Delineation of boron deficient areas

As soils are developed by the action of soil forming factors (like wind, water, weather) over parent materials over geological time periods, soil properties and inherent nutrient availability are not uniform even across short distances. Therefore, spatial variability of B has been mapped in irrigated cotton grown over 3 million ha areas and rainfed wheat, sorghum, peanut, and rapeseed-mustard grown in the 1.82 million ha *Pothohar* plateau. In general, soil and plant B maps were in good agreement (e.g., Figure 2). In the absence of effective soil advisory service, these maps can help

Table 3. Salient field crops requiring boron fertilizer use in Pakistan.

Alfalfa (*Medicago sativa*)	Rice (*Oryza sativa* L.)
Clovers (*Trifolium* spp.)	Sorghum (*Sorghum bicolor*)
Cotton (*Gossypium hirsutum*)	Sugarbeet (*Beta vulgaris*)
Maize (*Zea mays*)	Sugarcane (*Saccharum efficinarum*)
Mustard (*Brassica napus*)	Sunflower (*Helianthus annus*)
Peanut (*Arachis hypogaea*)	Tobacco (*Nicotiana tabaccum*)
Rapeseed (*Brassica napus*)	Wheat (*Triticum aestivum*).

Source: Adapted from Rashid et al. [4]

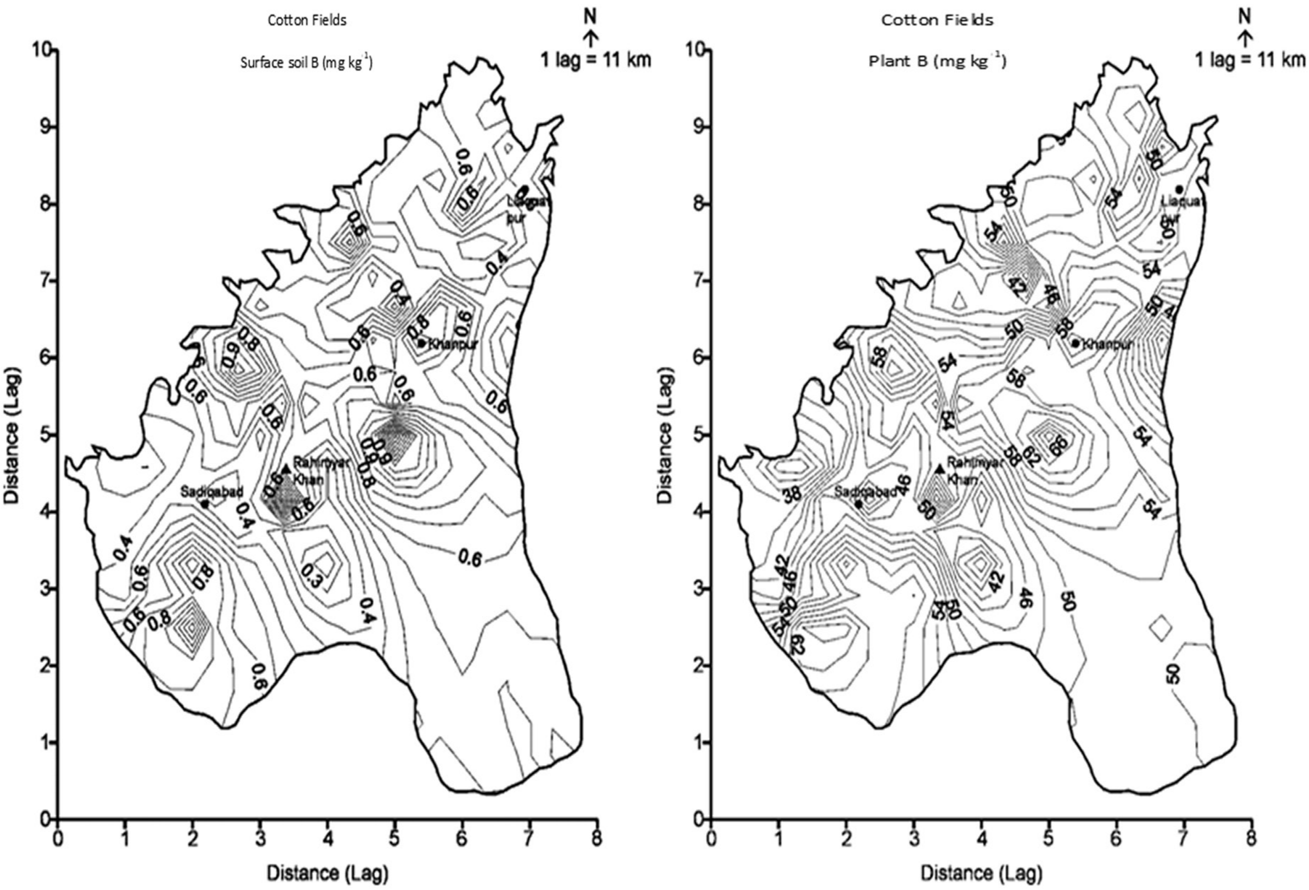

Figure 2. Spatial variability soil B in soils and associated cotton leaves within Rahim Yar Khan district, Punjab province (Source: Rafique [32]).

identify areas needing B fertilizer, and also help focus future research and development.

3.3. Boron deficiency in salt-affected soils in Pakistan

The FAO global study on micronutrients had observed high B in soils of Pakistan, especially in cotton-growing areas of the countries [37]. However, subsequent extensive research carried out throughout the country over the past three decades (comprising of nutrient indexing of farmer-grown crops and field experimentation), has rather identified and established B deficiency to be a widespread problem in many crops including cotton [5, 17, 18]. In fact, contrary to the general perception of high B content in salt-affected soils, Yasin et al. [41] observed B deficiency even in the saline and saline-sodic soils (EC up to 16.3 dS m^{-1}) of the cotton-belt in Pakistan as maximum HWE B in these soils was 2.2 mg B kg^{-1} soil. Almost, simultaneously, Aslam et al. [42] observed appreciable increases in paddy yield with B fertilizer application to salt-affected soils of the rice-belt in Punjab province. Thus, so far, B toxicity has not been observed anywhere in the country.

4. Managing boron deficiency in field crops

The prevalence of B deficiency in field crops was initially verified by crop responses to B fertilization of the B-deficient soils, collected from the respective crop growing regions, in pot culture experiments. Once reasonable yield increases were observed in greenhouse conditions, extensive farmers' field trials were conducted in the respective crop growing regions of the country.

Appreciable yield increases both with soil B fertilization and foliar sprays of B have been recorded in irrigated crops and rainfed crops. The reported yield increases in some salient field crops with B fertilizer in field conditions are presented in Table 4. With B fertilization, substantial improvement in yield of flooded rice is depicted in Figure 3 and of irrigated cotton in Figure 4. The salient improvement in yields of field crops with B

Table 4. Yield increases and profitability of B fertilization in some field crops.

Crop[1]	B applied ($kg\ ha^{-1}$)	Control yield ($t\ ha^{-1}$)	Yield increase (%)	Value: cost ratio	Reference
Cotton	1.0–1.5	2.38	14	16:1	Rashid and Rafique 18]; Rafique [32]
	Foliar B	2.38	13	25:1	
Rice					
cv. *Basmati*	0.75–1.0	3.04	18–25	38:1	Rashid et al. [10]
cv. *IR-6*	1.0	4.34	15–30	36:1	
Wheat	0.75–10	2.58	14	4:1	Rafique [32]; Rashid et al. [44]
Maize	1.0	5.20	12	7:1	Rafique [23]
Potato	Foliar B	17.10	10	9:1	Rafique [23]
Peanut	1.0	1.77	23	11:1	Rashid et al. [27]; Rafique et al. [28]

[1] All crops were irrigated, except for peanut

Figure 3. Substantial improvement in paddy (cv. Super Basmati) yield with B use in a calcareous rice soil of Pakistan (Source: Rashid et al. [10]).

fertilizer use were: flooded rice, 15-25%; irrigated cotton, 14% (Figure 5); irrigated maize, 12-20%; rainfed wheat, 14%; and rainfed peanut, 23% (Table 4). Both soil fertilization and foliar feeding of B were almost equally effective in curing B deficiency. Whereas soil application costs a little more, it leaves beneficial residual effect for subsequent crop(s). Foliar feeding of B is relatively more cost-effective but is a practical option only for high-value/special field crops, like cotton, requiring sprays of pesticide – foliar sprays of B are effective when made in combination with pesticides. In general, 0.75–1.0 kg B ha^{-1} or 2–3 foliar sprays of 0.1% B solution are adequate to cure B deficiency in field crops. Boron fertilization reduces flower shedding and/or panicle sterility, as shown for rice in Figure 6; it also improves fruit number and fruit size (e.g., in cotton, Table 5). These attribute improvements with B fertilization result in crop yield increases.

In accordance with the literature, we also experienced evident genotypic difference to B deficiency (e.g., Figure 7; Rashid et al. [30]).

Contrary to the general belief that B deficiency in field crops reduces grain-setting more than vegetative growth (e.g., Rerkasem and Jamjod [9, 43]), in our

Figure 4. Improvement in cotton productivity with B use in a calcareous soil of Pakistan (Source: Rafique [32]).

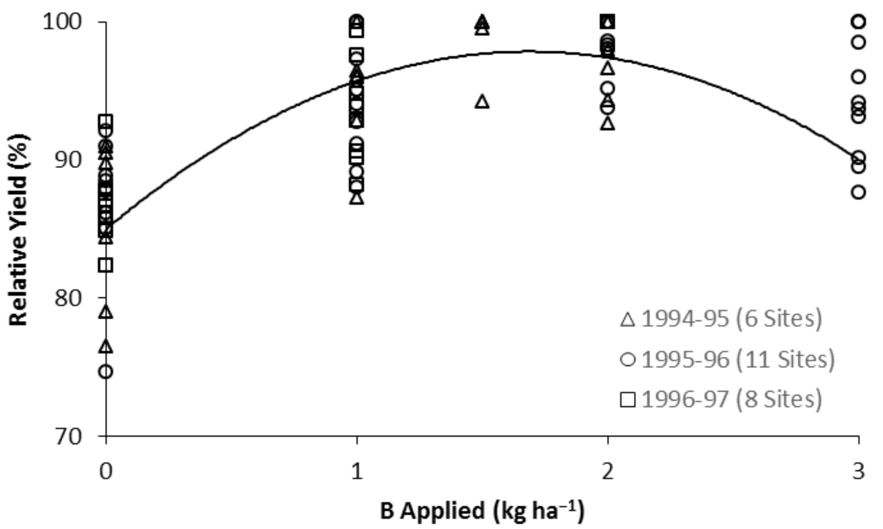

Figure 5. Relationship between B fertilizer rate and seed cotton yield (maximum yield: 1994-95, 2970 kg ha^{-1}; 1995-96, 2706 kg ha^{-1}; 1996-97, 1995 kg ha^{-1}) (Source: Rashid and Rafique [18]).

Figure 6. Alleviation of rice panicle sterility and post-harvest shedding by using B in a calcareous soil of Pakistan (Source:Rashid et al. [10]).

Table 5. Boron nutrition and cotton fruit setting.

Crop year	Boll weight (g boll^{-1})		Bolls per plant	
	Control	+B	Control	+B
1994-95	3.54	3.90	22	28
1995-96	3.46	3.66	29	32
1996-97	3.41	3.54	24	27
1997-98	3.18	3.30	20	22
Mean	**3.40**	**3.60**	**24**	**27**

Source: Rashid and Rafique [18]

Figure 7. Differential susceptibility of rapeseed genotypes to boron deficiency in a calcareous soil of Pakistan (Source: Rashid et al. [30]).

experience this was not true in case of some field crops grown in B deficient calcareous soils, like wheat [44], rapeseed [14, 29] and rice. Contrarily, because of B deficiency in rice, reduction in straw biomass production was more compared with reduction in paddy yield (Rashid et al. [10, 45]).

Appreciable yield increases with B fertilization in extensive field experiments throughout the country have adequately established that B fertilizer use is highly profitable in a variety of field crops, more so as foliar feeding. As fertilizer B dosage for correcting B deficiency is very small and crop yields with B application are appreciable, use of B fertilizer is highly cost-effective i.e., value-cost ratios are 16:1 in cotton and 30:1 in rice (Table 4).

It is worth emphasis that on soils low in B, there may be limited or no benefit of B fertilizer use if other major constraints are limiting production. For example, deficiencies of nitrogen (N), phosphorus (P) and/or potassium (K) may mask the consequences of low soil B level. Bell et al. [46] observed that, across 15 B-responsive sites in Thailand, there was only a weak yield increase with B fertilizer alone. At the same sites, with basal fertilizers applied, B response was much greater. On the other hand, fertilizer B use not only enhances crop yields but also improves/optimizes use efficiency of other farm inputs, including N, P, and K fertilizers. Thus B use brings substantial indirect economic benefits as well.

5. Produce quality improvements with boron fertilization

Boron fertilizer use not only enhances crop yield but, in many instances, quality of the crop produce also gets improved. A salient experience in Pakistan is an appreciable improvement in milling and cooking quality of rice with fertilizer B use. In extensive rice field experiments on cvs. Super Basmati, Basmati-385, KS-282, and IR-6, carried out by National Agricultural Research Center, in rice belt of the Punjab and in Sindh, B use not only enhanced paddy yields, substantially (Table 4), but also increased kernel milling recovery and head rice recovery as well as improved cooking quality traits, i.e., increased elongation upon cooking, reduced bursting upon cooking and reduced stickiness upon cooking (Table 6). Rice quality improvement with better B nutrition of plants is attributed to better grain filling and uniform crop maturity [10, 24].

6. Residual and cumulative effect of boron fertilization

Application of B fertilizer to irrigated calcareous soils left beneficial effect on one to three subsequent crops. Also, B fertilizer use in every alternate crop in various cropping systems proved safe and beneficial.

In permanent layout field experiments on cotton-wheat, maize-potato and rice-wheat cropping systems, B fertilization, @ 1.0 kg ha^{-1}, resulted in 8–10% yield increases of the first cotton and maize crops and 25% yield increase of the first rice crop. Residual fertilizer B increased yield of one subsequent crop in case of cotton-wheat and maize-potato systems (by 5–7% over control yields; Table 7) and of three subsequent crops in rice-wheat system (up to 22% of rice and by 12% of wheat). Effect of residual fertilizer B on productivity of all subsequent crops was negligible (Table 7).

In determining effect of repeated B fertilizer use, B application to every alternate crop each year also increased yield of each crop appreciably in all cropping systems, throughout the experimental periods (Table 7). Repeated B fertilization also led to mild build-up of soil B, i.e., by 0.05–0.06 mg kg^{-1} soil; thus, maximum observed soil B even after harvest of the last crops in all cropping systems was quite lower than the generally suggested critical level for deficiency, i.e., 0.5 mg kg^{-1}. As generally suggested toxicity level for most crops is 3.5 mg B kg^{-1} soil, annual repeated applications of the recommended 0.75–1.0 kg B ha^{-1} to every alternate crop for many more years is not expected to cause B toxicity.

Table 6. Rice quality improvement with boron use in calcareous soils of Pakistan.

Grain characteristic	*Basmati-385*		*Super Basmati*	
	Control	+ B	Control	+ B
Total Milled Rice (%)	71.1	73.1	70.4	72.0
Head Rice (%)	54.3	57.6	52.9	56.5
Kernel Thickness (T) (mm)	1.52	1.53	1.53	1.54
Kernel Lengh:Breadth	4.13	4.15	4.56	4.53
Quality Index (Length/BreadthxTickness)	2.70	2.69	2.97	2.94
Elongation Ratio upon Cooking	1.94	1.98	1.97	2.00
Bursting upon Cooking (%)	11	8	10	7
Alkali Spreading (Score 1–7)[a]	4.5	4.8	4.7	5.0

[a] Alkali spreading value: 4–5 score = Intermediate G.T. type rice
Source: Rashid et al. [10, 24]

Table 7. Residual and cumulative effect of soil-applied B on productivity of cotton-wheat and maize-potato systems in calcareous soils (mean data of 2 field sites).

B applied (kg ha^{-1})	Year-I		Year-II		Year-III		Year-IV	
	Seed Cotton/Grain Yield (Mg ha^{-1})							
	Cotton	Wheat	Cotton	Wheat	Cotton	Wheat	Cotton	Wheat
Control	2.02	3.31	2.15	3.18	1.90	3.02	2.30	3.34
1.0 (1st cotton crop only)	2.22	3.54	2.24	3.24	1.92	3.04	2.34	3.25
1.0 (every cotton crop)	2.22	3.54	2.41	3.43	2.15	3.32	2.56	3.54
	Grain/Tuber Yield (Mg ha^{-1})							
	Maize	Potato	Maize	Potato	Maize	Potato	Maize	Potato
Control	7.51	18.29	7.10	19.21	6.52	18.84	6.84	17.91
1.0 (1st maize crop only)	8.11	19.20	7.31	19.42	6.40	18.77	6.92	17.50
1.0 (every maize crop)	8.11	19.20	7.74	20.36	7.04	19.59	7.17	19.97

Source: Rafique [23, 32]

Boron fertilizer uptake by the first crop in all cropping systems varied from 1.7 to 4.4% of the applied B dose. As total quantity of un-utilized B fraction is not fixed irreversibly in the soil, B fertilization leaves beneficial residual effect on subsequent crop(s). Boron fertilizer is known to leave longer residual effect in silty and clay soils compared with sandy soils. Thus, B application in medium to heavy textured soils @ 1.0 kg ha^{-1} is expected to be effective for 2–4 crop seasons.

Our permanent layout field studies in Pakistan also revealed that repeated B applications to one crop every year raised soil B status mildly, presumably because of high B fixation capacity of the calcareous soils. As unwanted repeated application of B fertilizer may result in soil B buildup to toxic level, periodic soil testing is suggested to monitor soil B status as a consequence of fertilization.

As uptake of B fertilizer by the first crop is very low (~2.0–3.0%), soil B fertilization leaves appreciable residual effect for subsequent crops in the rotation. Yearly application of a safe dose of 0.75–1.0 kg B ha^{-1} in calcareous soils, over four years, did not prove toxic to cotton, rice and wheat crops. However, current B use in the country is negligible. As enhanced B fertilizer use in Pakistan will increase farmer income and national economy, B fertilizer availability (especially as B-fortified fertilizers) in time and space warrants improvement.

7. Potential and actual boron fertilizer use in Pakistan

Current use of B fertilizer in Pakistan is negligible, i.e., ~92 Mg B per annum [38]. According to a recent estimate by Rashid et al. [38], potential fertilizer B requirement in the country for all crops, i.e., field crops, vegetables and fruits is about 2245 Mg B *per annum.* Out of this, 1980 Mg B *per annum* pertains to field crops. Thus, current use of B fertilizer is negligible compared with actual requirement. As B fertilizer use is highly profitable (Table 4), a more effective technology transfer program can enhance its use. In 2017, Rashid et al. [38] have postulated that, with an enabling environment, annual fertilizer B off take for field crops is expected to escalate to 396 Mg after two year, 594 Mg after four years, 792 Mg after 6 years, 891 Mg after 8 years, and 990 Mg after 10 years. As cotton crop is more remunerative and yield increases in rice are phenomenal, faster B fertilizer adaptability is expected in these crops [38].

In Pakistan, predominant constraints to B use include farmers' ignorance about the need and benefits of B fertilizer use, difficulty in access to quality B fertilizer products, and application problems (e.g., difficulty in uniform field distribution of small quantities of B products and preparation of spray solutions). Unless genuine constraints on the part of small landholder resource-poor farmers are addressed adequately, widescale adoption of B fertilizer use is not promising.

8. Research and development needs

Though B research over the past three decades has generated quite valuable information, still a lot remains to be learnt for formulating sound strategies for attaining adequate B nutrition of crop plants. The areas requiring R&D emphasis include: monitoring B status of soils and crops in the left over geographical areas (like Balochistan and Sindh provinces) and cropping systems (like fruit orchards and vegetables); study feasibility of B fertigation in fruits, vegetables and high value crops; study residual and cumulative effects of B use in various cropping systems and fruit orchards; and investigate the role of B in plant, animals, and human health continuum.

The development activities needed to realize benefits of research information include: improving soil organic matter through integrated plant nutrient management; improving availability of B fertilizer products, preferably as B-fortified fertilizer formulations; and extensive field demonstrations of beneficial impact of B fertilizers on crop yield and profitability.

9. Conclusions

Boron deficiency in field crops grown in calcareous soils is a serious nutritional disorder causing yield, produce quality and economic losses. The 0.01 *M* HCl test can reliably predict fertilizer needs in calcareous soils; analysis of diagnostic plant part at right growth stage can also determine B status of crop plants. The deficiency is corrected by B fertilization in a highly cost-effective manner; both soil application (@ 0.75–1.0 kg B ha^{-1}) as well as 2–3 foliar sprays of 0.1% B solution is effective. Soil application leaves a beneficial residual effect on three succeeding crops in rice-wheat system and on one crop in all upland cropping systems like cotton-wheat and maize-potato rotations. However, current B fertilizer use is far less than actual requirements. Therefore, improvements in availability of B fertilizer technology transfer are warranted.

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