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Original Research Article

Magnesium Fertilization Improves Grain Yield of Wheat (Triticum Aestivum L.) Across Fourteen Agro-Climatic Zones of Punjab, Pakistan

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Abstract: *Wheat (Triticum aestivum L.) is the major Rabi cereal crop of Pakistan, but farm-level yields remain below the potential of improved cultivars. Although nitrogen, phosphorus, and potassium responses are well documented, the role of magnesium in wheat productivity across Punjab's agro-climatic zones remains insufficiently explored.* ***Objective:*** *To evaluate the grain yield response of spring wheat cultivar Dilkash-2021 to graded levels of soil-applied magnesium across fourteen agro-climatic zones of Punjab, Pakistan.* ***Methods:*** *A multi-location field experiment was conducted under the Soil Fertility Punjab research project SF-76 during the Rabi 2024–25 season across fourteen agro-climatic zones of Punjab, Pakistan. Spring wheat cultivar Dilkash-2021 was grown using a randomized complete block design with three replications at each site. Five magnesium treatments, comprising 0, 15, 30, 45, and 60 kg Mg ha^{-1}, were applied as magnesium sulphate heptahydrate ($MgSO_4 \cdot 7H_2O$) through basal broadcast application. All plots received a uniform basal NPK dose of 160–114–60 kg ha^{-1}. Grain yield was recorded at maturity, and data were analyzed using two-factor combined analysis of variance to determine the effects of magnesium treatment, location, and location × treatment interaction.* ***Results:*** *Magnesium fertilization significantly improved wheat grain yield across the study locations. The treatment effect was highly significant ($F = 23.60, p < 0.01$), and the location effect was also highly significant ($F = 277.74, p < 0.01$). The location × treatment interaction was non-significant ($F = 1.34, p = 0.099$), indicating a broadly consistent response pattern across the fourteen agro-climatic zones. Pooled grain yield increased from 5037.2 kg ha^{-1} in the magnesium control to 5483.6 kg ha^{-1} at 60 kg Mg ha^{-1}, showing a mean yield gain of 446.4 kg ha^{-1}, equivalent to an 8.9% increase over the NPK-fertilized control. The highest pooled yield was recorded at 60 kg Mg ha^{-1}, while site-wise yield differences at this rate ranged from −145 kg ha^{-1} at Sahiwal to +1105 kg ha^{-1} at Sheikhupura.* ***Conclusion:*** *Soil-applied magnesium significantly enhanced wheat grain yield under Punjab's diverse agro-climatic conditions, with 60 kg Mg ha^{-1} producing the highest pooled yield response. These findings support the inclusion of magnesium fertilization as a complementary component of the existing NPK schedule for spring wheat production in Punjab.*

Keywords: Wheat, Magnesium Fertilization, Dilkash-2021, Multi-Zone Trial, Punjab

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Introduction

Wheat (Triticum aestivum L.) is the staple cereal of Pakistan and the cornerstone of the national food system, occupying approximately 9.0 million hectares, roughly 40% of the country's total cropped area, and providing nearly two-thirds of average daily caloric intake (1). Punjab alone accounts for around 75–80% of national wheat production, with the bulk of the crop grown under canal-irrigated, alkaline-calcareous soils during the Rabi season from November to May (2,3). Despite the strategic importance of wheat for national food security, the realized on-farm yield in Pakistan averages around 3.0–3.2 t ha-1, well below the 5.5–6.0 t ha-1 potential of recently released cultivars, and the yield gap has shown only modest narrowing over the past two decades (4). Among the agronomic drivers of this gap, imbalanced fertilization is consistently identified as a leading cause, with macronutrient applications skewed heavily towards nitrogen and phosphorus, comparatively neglected potassium application, and almost no attention paid to magnesium or other secondary nutrients in routine fertilizer recommendations (5).The soils of Punjab are predominantly alkaline (pH 7.5–8.5), calcareous, and low in organic matter, with substantial free CaCO3 contents that fix and immobilize several essential cations through carbonate complexation and competition with Ca2+ on exchange sites (5,6). Under these conditions, the plant availability of magnesium is constrained by three interacting mechanisms: Ca2+ dominance of cation-exchange sites under high CaCO3 loading; precipitation of Mg into carbonate complexes at alkaline pH; and Na+/K+ competition with Mg2+ for root uptake, particularly on saline-sodic patches (7). The Rabi wheat crop adds a specific physiological constraint: with sowing in November and harvest in April–May, the critical grain-filling phase falls during the late-March to mid-April window when temperatures rise rapidly and evaporative demand peaks, and any nutritional constraint on canopy photosynthesis during this phase translates directly into a penalty on grain weight and final yield (8). Despite this combination of pedological and climatological factors that would predict a substantial Mg-limitation across Punjab, calibrated soil-applied Mg dose–response data for wheat on Pakistani alkaline-calcareous soils remain sparse, and provincial fertilizer recommendations for wheat make no allowance for Mg as a routine maintenance input. Magnesium occupies a uniquely central position in plant metabolism. It is the central atom of the chlorophyll molecule, a structural and functional cofactor of more than three hundred enzymes, including Rubisco, the rate-limiting carboxylase of C3 photosynthesis to which wheat belongs, an essential activator of ATP-dependent reactions, and the principal counter-cation for phloem loading of sucrose and amino acids from source leaves to developing reproductive sinks (7,9–12). In wheat specifically, adequate Mg supply has been shown to increase leaf chlorophyll concentration, stabilize photosynthetic performance under late-season heat stress, improve phloem loading of sucrose during grain filling, and consequently raise both individual grain weight and final grain yield (10,13). Mg deficiency, by contrast, first manifests as interveinal chlorosis on older leaves, depresses photosynthetic rate even before visible symptoms develop, and shortens the effective duration of grain filling, a particularly damaging combination for wheat maturing under the late-March heat conditions that characterize the Rabi cropping window in Punjab. Where regional studies on Mg fertilization in wheat have been reported, they have typically been confined to single sites or used a single Mg rate, making it difficult to identify an agronomically optimal dose or to test whether the response is consistent across the agro-climatic diversity of the wheat belt. A multi-location, multi-zone, dose–response evaluation of Mg fertilization in wheat under the alkaline-calcareous, canal-irrigated conditions of Punjab is therefore warranted. The present study, conducted under the Soil Fertility Punjab research.

Methodology

Experimental sites

The field experiment was conducted during the Rabi 2024–25 cropping season at fourteen agro-climatic locations spanning the wheat-producing zones of Punjab, Pakistan, under the framework of the Soil Fertility Punjab research project SF-76 (“Response of wheat to different levels of magnesium fertilizer”). The fourteen sites represented the principal wheat-growing zones of the province: the central rice–wheat zone (Lahore, Hafizabad, Sheikhupura); the central cotton–wheat zone (Sahiwal, Pakpattan, Faisalabad, Khanewal); the mixed cropping and Thal margin zones (Jhang, Sargodha, Mianwali, Khushab); the southern cotton–wheat zone (Bahawalnagar, Bahawalpur); and the rainfed Pothwar zone (Attock). All thirteen of the canal-irrigated sites operated under managed surface irrigation; the Attock site lies in the Pothwar Plateau and operates predominantly under rainfed conditions with supplemental irrigation where available.

Prior to land preparation at each site, composite soil samples were collected from the 0–15 cm surface layer following standard auger sampling procedures (13). Samples were air-dried, ground, sieved through a 2 mm screen, and analyzed for electrical conductivity of the saturation extract (EC_e) by conductivity meter, pH (1:1 soil-to-water suspension) by glass electrode, organic matter by the Walkley–Black wet oxidation method, available phosphorus by the AB-DTPA extraction procedure, and exchangeable potassium by ammonium acetate extraction followed by flame photometry (13,14). The soil analytical data for the fourteen experimental sites are presented in Table 1.

Table 1: Surface (0–15 cm) soil physico-chemical properties of the fourteen experimental sites across Punjab.

Location	EC (dS m^{-1})	pH	OM (%)	Available P (ppm)	Available K (ppm)
Lahore	2.05	8.0	0.27	15.5	138
Hafizabad	3.18	8.1	1.39	2.2	258
Sheikhupura	2.20	8.4	0.63	4.7	78
Sahiwal	1.80	8.3	0.70	8.7	218
Pakpattan	1.20	8.1	0.77	10.3	198
Faisalabad	1.94	8.4	0.85	8.3	260
Jhang	0.82	8.1	0.83	9.57	116
Sargodha	0.95	7.7	0.91	7.3	187
Bahawalnagar	0.90	8.4	0.68	6.5	64
Bahawalpur	1.23	7.9	0.18	6.2	164
Khanewal	2.15	8.2	0.57	8.2	120
Mianwali	1.70	8.2	0.70	5.0	140
Khushab	1.35	8.2	0.78	5.46	109
Attock	0.83	7.7	0.89	4.3	88

Plant material

A commercially released spring wheat variety, Dilkash-2021, was used at all fourteen locations. Dilkash-2021 is a medium-maturing, high-yielding bread-wheat variety released by the Ayub Agricultural Research Institute (AARI), Faisalabad, and recommended for general cultivation across the irrigated and rainfed wheat tracts of Punjab. The variety is among the leading wheat cultivars currently sown in Punjab alongside Akbar and Urooj (USDA, 2025). Disease-free, certified seed of uniform germination was procured from authorized seed sources and used for sowing at all sites.

Treatments and experimental design

The experiment evaluated five treatments comprising a graded series of magnesium fertilization rates applied over a uniform NPK basal dose. The Mg treatments, expressed on an elemental Mg basis, were: T1 = Control (NPK only, 0 kg Mg ha^{-1}); T2 = NPK + 15 kg Mg ha^{-1}; T3 = NPK + 30 kg Mg ha^{-1}; T4 = NPK + 45 kg Mg ha^{-1}; and T5 = NPK + 60 kg Mg ha^{-1}. Magnesium was supplied as commercial magnesium sulphate heptahydrate ($MgSO_4 \cdot 7H_2O$; approximately 9.86% Mg by mass); the corresponding actual fertilizer rates applied in the field were approximately 0, 152, 304, 456, and 608 kg $MgSO_4 \cdot 7H_2O$ ha^{-1} for T1 through T5, respectively. The uniform basal NPK dose, applied to all plots including the unfertilized Mg control, comprised 160 kg N ha^{-1}, 114 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1}, supplied as urea, di-ammonium phosphate (DAP), and sulphate of potash (SOP), respectively. Treatment compositions are summarized in Table 2.

The experiment was laid out as a randomized complete block design (RCBD) at each site, with three replications, and the data from the fourteen sites were subsequently combined and analyzed as a two-factor combined ANOVA with locations and Mg fertilization levels as the two factors. The same randomization protocol was followed at all sites. Individual plot size was 250 m^2, equivalent to one-fortieth of a hectare, which accommodated a representative net plot area after exclusion of border rows.

Table 2: Treatment compositions used to study the response of spring wheat to graded levels of magnesium fertilization. Magnesium was supplied as commercial magnesium sulphate heptahydrate ($MgSO_4 \cdot 7H_2O$).

Treatment	Code	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	Mg (kg ha^{-1})
Control (NPK only)	T1	160	114	60	0
NPK + 15 kg Mg	T2	160	114	60	15
NPK + 30 kg Mg	T3	160	114	60	30
NPK + 45 kg Mg	T4	160	114	60	45
NPK + 60 kg Mg	T5	160	114	60	60

Wheat was sown during the recommended Rabi sowing window (mid-November to early December 2024) at all fourteen locations using standard line-sowing equipment with row-to-row spacing of approximately 22.5 cm and a seed rate of 125 kg ha^{-1}, the standard rate for Dilkash-2021 under irrigated Punjab conditions. At sowing, the full doses of P_2O_5, K_2O, and $MgSO_4{\cdot}7H_2O$, together with one-half of the total nitrogen, were broadcast uniformly over the prepared seedbed and incorporated into the surface soil through a final shallow tillage operation immediately before sowing, in accordance with the SF-76 standard application protocol. The remaining one-half of the nitrogen dose was applied as a top-dressing immediately before the first irrigation, which was timed at the crown-root initiation stage approximately three weeks after sowing. Subsequent irrigations were applied through the canal supply system at the standard wheat-growth-stage milestones, tillering, jointing, booting, anthesis, and grain filling, with frequency adjusted to crop demand, evaporative demand, and rainfall, except at the Attock site where rainfed conditions prevailed and irrigation was applied only when soil moisture deficits required supplemental watering. Weeds were controlled by a combination of pre-emergence and post-emergence herbicide applications consistent with the Punjab Agriculture Department's standard recommendations for wheat. Plant protection measures against aphids and rust diseases were applied uniformly across all plots whenever scouting indicated treatment thresholds had been reached. All other agronomic operations were carried out according to the standard production recommendations for irrigated and rainfed spring wheat in Punjab.

Data recording

Grain yield was the principal response variable recorded in the present study. At physiological maturity, the wheat crop was harvested manually from the net plot area, leaving border rows excluded to minimize edge effects. Harvested produce was sun-dried, threshed, and the grain was cleaned, weighed, and adjusted to a standard moisture basis of 12% using a calibrated digital grain moisture meter. Plot-level grain yield was then extrapolated to a per-hectare basis (kg ha^{-1}) at 12% moisture content.

Statistical analysis

The data for grain yield were subjected to a two-factor combined analysis of variance (ANOVA) appropriate for a multi-location randomized complete block design, with locations and treatments treated as fixed effects and replications nested within locations. Where the location × treatment interaction was non-significant, treatment means were pooled across locations and separated using Fisher's protected least significant difference (LSD) test at the 5% probability level (16). The significance of location, treatment, and location × treatment interaction effects was tested at $p \leq 0.05$ and $p \leq 0.01$ levels. The grain yield response of each Mg treatment over the unfertilized control was computed for each location as the absolute and percentage difference from T1. Statistical analyses were performed using Statistix 8.1, and graphical presentations were prepared using R/RStudio and Microsoft Excel.

Results and Discussion

Soil status of the experimental sites

Soil analytical data (Table 1) confirmed that the fourteen experimental sites represented the substantial agro-pedological diversity of the Punjab wheat belt while sharing a common alkaline-calcareous baseline. Surface soil pH ranged narrowly from 7.7 at Sargodha and Attock to 8.4 at Sheikhupura, Bahawalnagar, and Faisalabad, a range characteristic of the irrigated Indus Basin and consistently constraining the plant availability of soil-bound Mg through carbonate fixation and exchange-site competition with Ca2+ (5,7). Electrical conductivity differentiated the sites more sharply, from 0.82 dS m-1 at Jhang to 3.18 dS m-1 at Hafizabad, capturing the full range from non-saline rainfed Pothwar soils to moderately saline central canal-command soils. Organic matter content varied from 0.18% at Bahawalpur to 1.39% at Hafizabad, with the majority of sites in the 0.5–0.9% band typical of intensively cropped Punjab soils. Available phosphorus ranged from 2.2 ppm at Hafizabad (deficient) to 15.5 ppm at Lahore (medium-to-high), and available potassium varied from 64 ppm at Bahawalnagar (low) through the 78–198 ppm band (low-to-medium across most sites) to 258–260 ppm at Hafizabad and Faisalabad (high).

This combination of consistently alkaline reaction, free CaCO3, low organic matter, and broadly low-to-medium macronutrient pools provided the agro-pedological context against which the Mg response was tested. The substantial site-to-site variation in EC, OM, and available macronutrients further supplied a natural fertility gradient against which the consistency of the Mg response could be evaluated.

Analysis of variance

The combined analysis of variance for grain yield across the fourteen locations revealed highly significant main effects of both location and treatment, and a non-significant location × treatment interaction (Table 3). The location main effect (mean square 6,618,582; F = 277.74; p < 0.01) was extremely highly significant, reflecting the substantial baseline yield differences between sites that arise from soil texture, salinity, water availability, and zonal climatic conditions across Punjab. The treatment main effect (mean square 1,061,428; F = 23.60; p < 0.01) was also highly significant, confirming that the graded Mg fertilization rates produced statistically discernible grain yield differences over and above the uniform NPK basal dose. Importantly, the location × treatment interaction was non-significant at the 5% probability level (mean square 60,377; F = 1.34; p = 0.099), indicating that the magnitude and broad shape of the Mg response were consistent across the fourteen contrasting agro-climatic zones

Table 3: Combined analysis of variance for grain yield of spring wheat across fourteen locations and five magnesium fertilization levels.

Source of variation	DF	Sum of squares	Mean square	F-value	p-value
Replications (A)	2	49,341	24,671	—	—
Locations (B)	13	8.60×10^7	6,618,582 **	277.74	0.0000
Error A × B	26	619,592	23,830	—	—
Treatments (C)	4	4,245,713	1,061,428 **	23.60	0.0000
B × C interaction	52	3,139,623	60,377 ^{ns}	1.34	0.0992
Error (A × B × C)	112	5,037,844	44,981	—	—
Total	209	9.91×10^7			

Note: ** = significant at 1% probability level; ^{ns} = non-significant. Grain yield in kg ha^{-1}

Pooled grain yield response to magnesium fertilization

Pooled across the fourteen locations, soil-applied magnesium sulphate produced a progressive improvement in grain yield as the Mg rate increased from 0 to 60 kg Mg ha^{-1} (Figure 1, Table 4). The unfertilized Mg control (T1; NPK only) produced a pooled mean grain yield of 5037.2 kg ha^{-1}, while application of 15, 30, 45, and 60 kg Mg ha^{-1} produced pooled mean yields of 5190.1, 5221.0, 5381.2, and 5483.6 kg ha^{-1}, respectively. The yield response over the unfertilized control therefore rose progressively from +152.9 kg ha^{-1} (+3.0%) at T2 to +446.4 kg ha^{-1} (+8.9%) at T5, with the largest absolute yield gain recorded at the highest tested Mg rate.

The progressive and monotonic shape of the pooled-mean response curve, with the peak at the highest tested rate and no evidence of a plateau within the rates tested, is physiologically coherent and aligns with established understanding of Mg nutrition in wheat. The +8.9% pooled grain yield gain at T5 is agronomically substantial, particularly because it was obtained on top of a uniform NPK basal that already supplied N, P, and K at recommended rates for irrigated Punjab wheat. The magnitude of the response therefore reflects a relief of a latent Mg constraint that NPK-only fertilization schedules currently in widespread use across the province are unable to address.

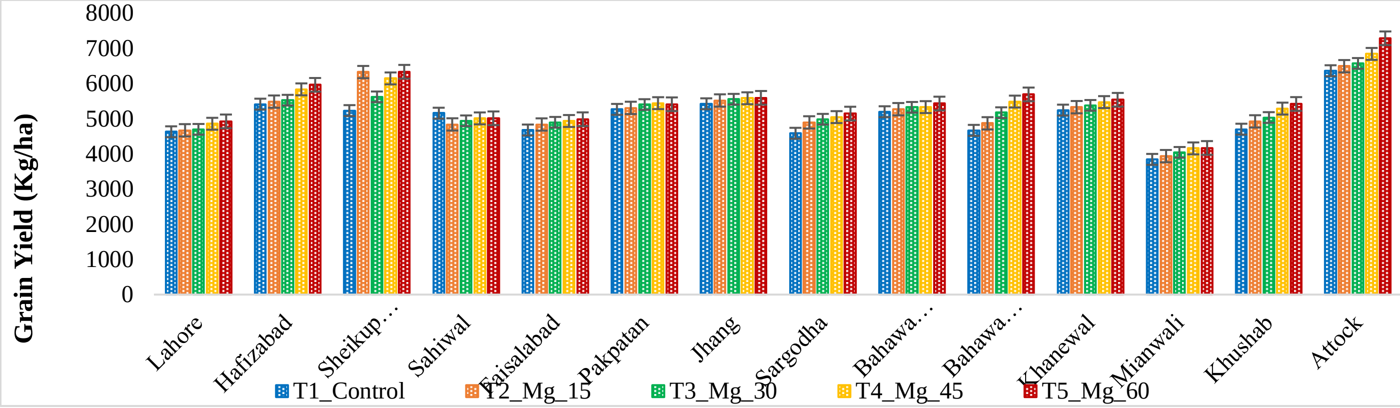

Figure 1: Performance of wheat crop at five different magnesium fertilization levels at the fourteen experimental locations across Punjab, Pakistan.

Table 4: Site-wise and pooled mean grain yield (kg ha^{-1}) of spring wheat (cv. Dilkash-2021) under five graded levels of magnesium fertilization across fourteen locations of Punjab.

Location	T1 (Mg-0)	T2 (Mg-15)	T3 (Mg-30)	T4 (Mg-45)	T5 (Mg-60)	Gain (T5−T1)	Gain (%)
Lahore	4630	4672	4700	4857	4926	+296	+6.4
Hafizabad	5416	5488	5529	5837	5965	+549	+10.1
Sheikhupura	5232	6328	5624	6148	6337	+1105	+21.1
Sahiwal	5159	4839	4943	5011	5014	−145	−2.8
Faisalabad	4680	4837	4900	4936	4987	+307	+6.6
Pakpattan	5267	5309	5405	5444	5413	+146	+2.8
Jhang	5426	5520	5556	5583	5595	+169	+3.1
Sargodha	4680	4837	4900	4936	4987	+307	+6.6
Bahawalnagar	5200	5272	5326	5331	5433	+233	+4.5
Bahawalpur	4670	4870	5174	5489	5693	+1023	+21.9
Khanewal	5246	5330	5381	5474	5540	+294	+5.6
Mianwali	3845	3938	4045	4158	4170	+325	+8.5
Khushab	4703	4926	5036	5289	5421	+718	+15.3
Attock	6367	6495	6575	6844	7289	+922	+14.5
Pooled mean	5037.2	5190.1	5221.0	5381.2	5483.6	+446.4	+8.9

Zone-by-zone response patterns

The site-wise yield responses, presented in Figures 2–15 and summarized in Table 4, can be usefully grouped by the agro-climatic zones of Punjab established in the Introduction.

Central rice–wheat zone (Lahore, Hafizabad, Sheikhupura). Baseline T1 yields ranged from 4,630 kg ha^{-1} (Lahore) to 5,416 kg ha^{-1} (Hafizabad), and yield gains at T5 ranged from +296 kg ha^{-1} at Lahore to +1,105 kg ha^{-1} at Sheikhupura, the largest single-site gain recorded in the entire study. Lahore and Hafizabad showed clean monotonic responses across the dose series. Sheikhupura, by contrast, showed a non-monotonic pattern with T2 (6,328 kg ha^{-1}) producing the second-highest yield in the series and T3 (5,624 kg ha^{-1}) dropping below T2 before T4 and T5 again climbed to the top, a pattern most plausibly attributed to replication variability at the lowest-and-second-lowest Mg doses on this particular site rather than to a genuine reversal of the dose-response relationship.

Central cotton–wheat zone (Sahiwal, Pakpattan, Faisalabad, Khanewal). Baseline T1 yields ranged from 4,680 kg ha^{-1} at Faisalabad to 5,267 kg ha^{-1} at Pakpattan, and yield responses at T5 ranged from −145 kg ha^{-1} at Sahiwal (a net yield depression relative to control) to +307 kg ha^{-1} at Sargodha-equivalent Faisalabad. The Sahiwal site showed a distinctive response curve in which T2 (4,839 kg ha^{-1}) produced a yield depression of 320 kg ha^{-1} below the control (5,159 kg ha^{-1}), followed by gradual recovery through T3 to T5 without fully returning to the T1 level. This pattern is most plausibly attributable to early-season ionic effects of the $MgSO_4 \cdot 7H_2O$ dose at low fertilizer rates on a moderately saline site (EC_e 1.80 dS m^{-1}), where the modest Mg dose at T2 (152 kg $MgSO_4 \cdot 7H_2O$ ha^{-1}) may have transiently elevated rhizosphere ionic strength without delivering sufficient elemental Mg to overcome the osmotic effect on early-season root activity. Pakpattan, Faisalabad, and Khanewal all showed monotonic responses with the peak at T5.

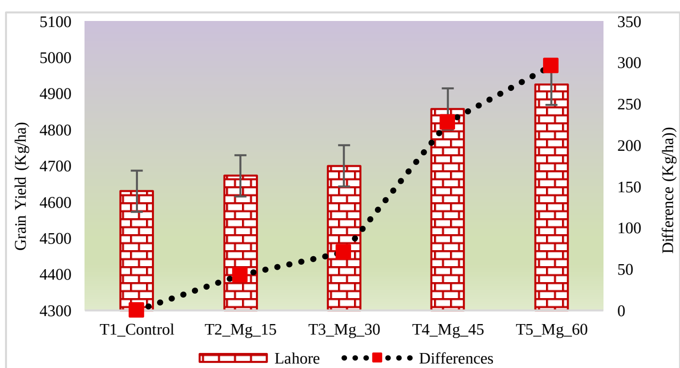

Figure 2 | Grain yield and yield difference over the unfertilized control at Lahore location and yield difference from control

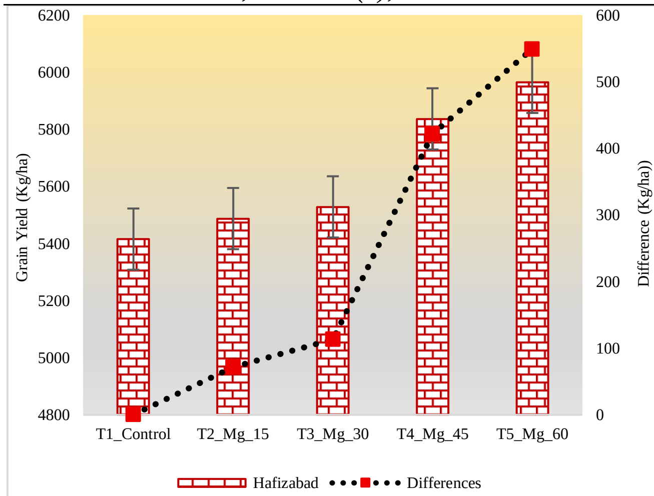

Figure 3 | Grain yield and yield difference over the unfertilized control at Hafizabad location and yield difference from control

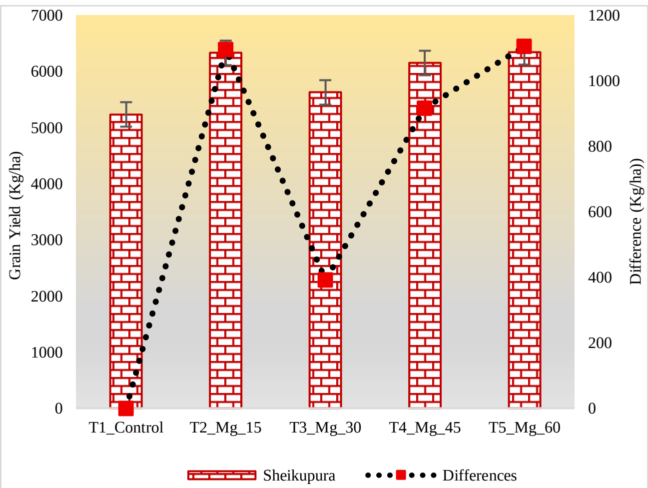

Figure 4 | Grain yield and yield difference over the unfertilized control at Sheikupura location and yield difference from control

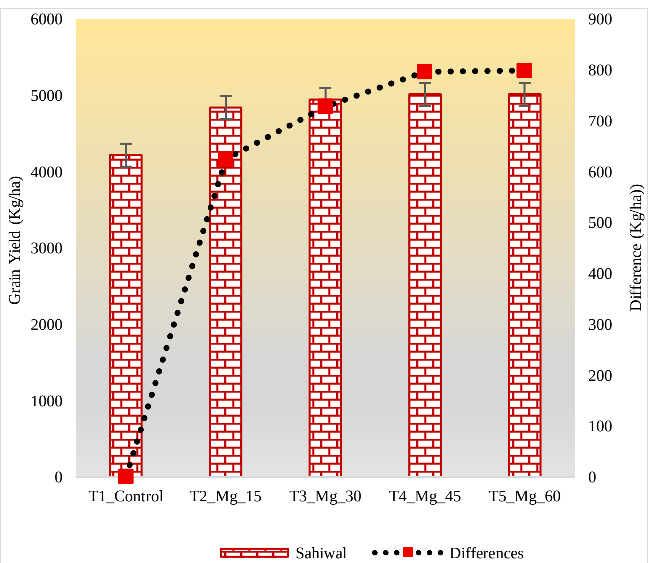

Figure 5 | Grain yield and yield difference over the unfertilized control at Sahiwal location and yield difference from control

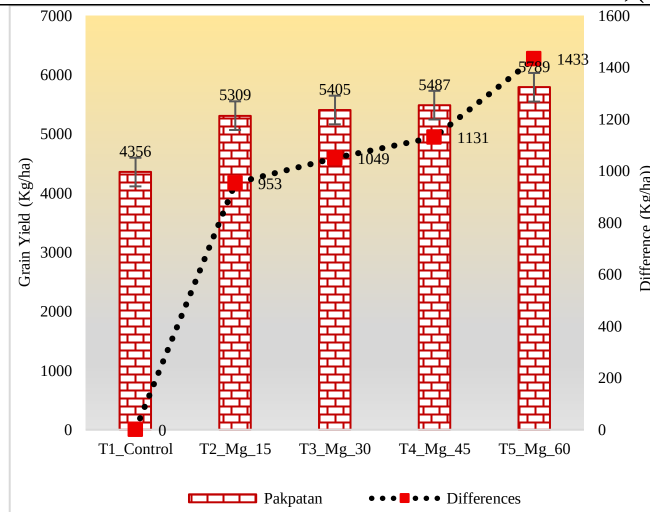

Figure 6 | Grain yield and yield difference over the unfertilized control at Pakpattan location and yield difference from control

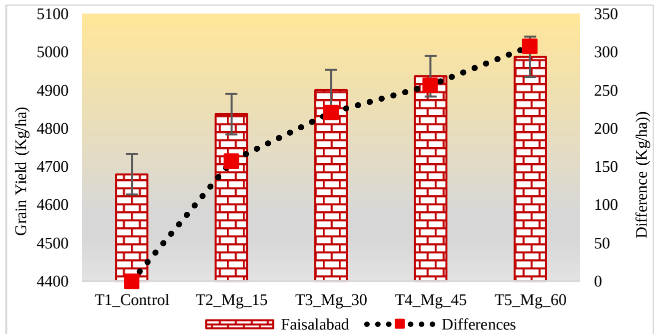

Figure 7 | Grain yield and yield difference over the unfertilized control at Faisalabad location and yield difference from control

Mixed cropping and Thal margin zone (Jhang, Sargodha, Mianwali, Khushab). Baseline T1 yields varied from 3,845 kg ha^{-1} at Mianwali (the lowest of any site in the trial) to 5,426 kg ha^{-1} at Jhang. Yield gains at T5 ranged from +169 kg ha^{-1} at Jhang (the smallest positive gain in the study) to +718 kg ha^{-1} at Khushab. All four sites in this zone showed clean monotonic responses, with the largest absolute gain at Khushab (T1 = 4,703; T5 = 5,421 kg ha^{-1}) indicating that the Mg constraint operates strongly even at the agro-ecological margin of the wheat tract. Mianwali, despite the lowest absolute yields in the trial, showed a positive and consistent dose response (+325 kg ha^{-1} at T5; +8.5% over control), demonstrating that the response is not confined to high-yielding situations.

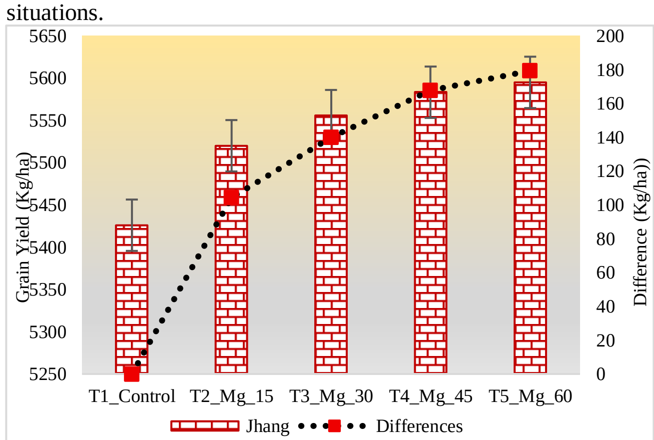

Figure 8 | Grain yield and yield difference over the unfertilized control at Jhang location and yield difference from control

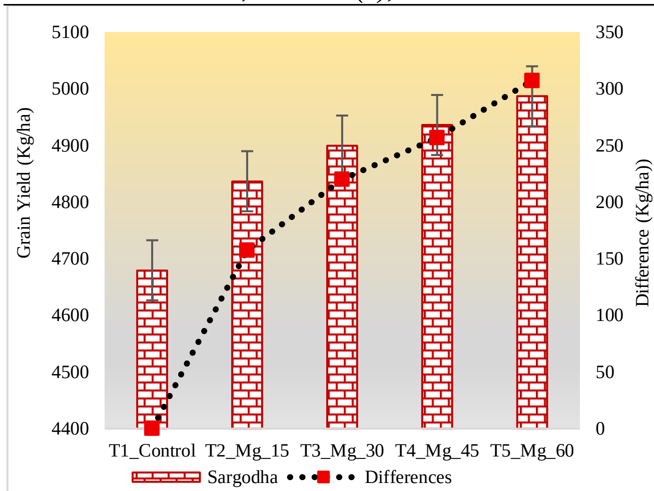

Figure 9 | Grain yield and yield difference over the unfertilized control at Sargodha location and yield difference from control

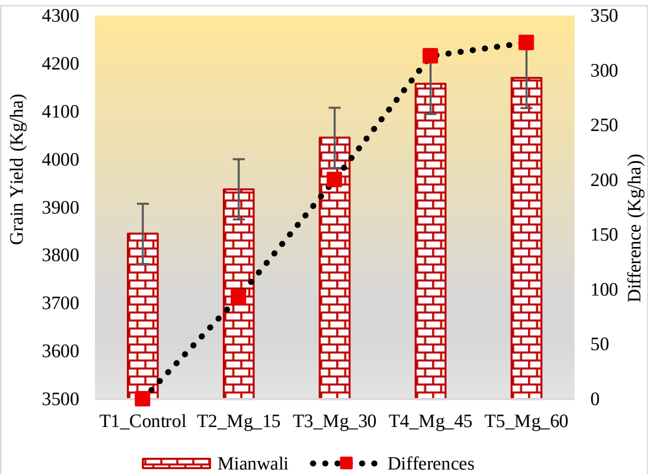

Figure 10 | Grain yield and yield difference over the unfertilized control at Mianwali location and yield difference from control

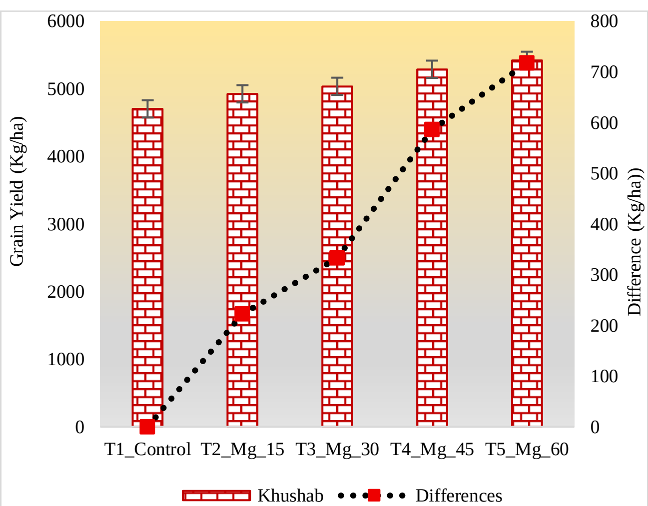

Figure 11 | Grain yield and yield difference over the unfertilized control at Khushab location and yield difference from control

Southern cotton–wheat zone (Bahawalnagar, Bahawalpur). Baseline T1 yields were 5,200 and 4,670 kg ha^{-1} at Bahawalnagar and Bahawalpur, respectively, with T5 gains of +233 and +1,023 kg ha^{-1}. The much larger response at Bahawalpur most plausibly reflects the lower baseline organic matter (0.18%) and more constrained baseline conditions at that site, which would have amplified the marginal value of every additional input.

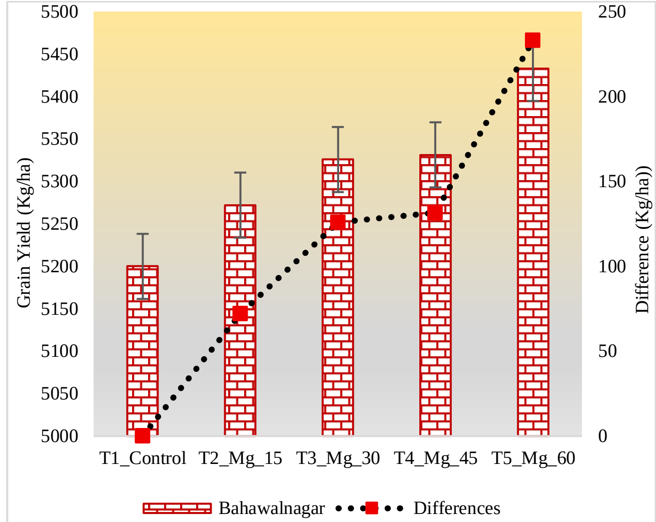

Figure 12 | Grain yield and yield difference over the unfertilized control at Bahawalnagar location and yield difference from control

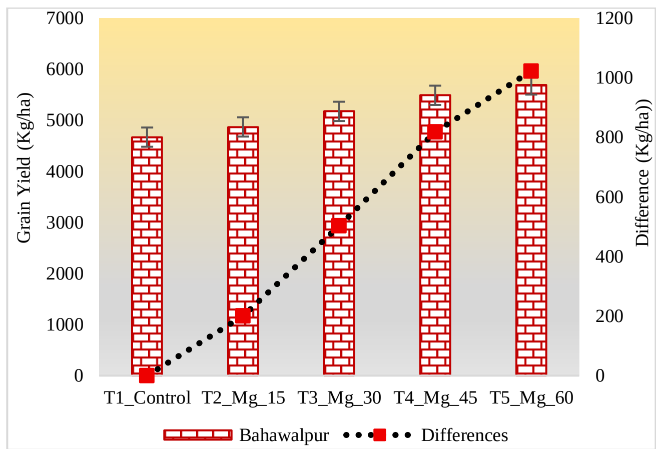

Figure 13 | Grain yield and yield difference over the unfertilized control at Bahawalpur location and yield difference from control

Rainfed Pothwar zone (Attock). The Pothwar Plateau site at Attock recorded the highest baseline T1 yield (6,367 kg ha^{-1}) and the highest T5 yield (7,289 kg ha^{-1}) of any site in the trial, with an absolute gain of +922 kg ha^{-1} (+14.5%) at the highest Mg rate. The strong positive Mg response at Attock is a particularly important finding because it demonstrates that the Mg constraint operates not only on the alkaline-calcareous canal-irrigated soils of the central and southern Punjab plain but also on the rainfed Pothwar soils, where soil chemistry, climate, and water regime are all materially different. This generalization of the Mg response across the canal-irrigated–rainfed boundary is the strongest single argument for a province-wide Mg recommendation.

Across all five zones, the highest yielding treatment at every one of the fourteen sites was T5 (60 kg Mg ha^{-1}), and the dose-response curve was monotonically positive at twelve of the fourteen sites. The two exceptions, Sheikhupura, where T3 dropped below T2 before recovering to peak at T5; and Sahiwal, where T2 produced an early-season yield depression and the curve recovered but did not exceed the control by T5, were addressed individually above; in neither case did the irregularity alter the position of T5 as the highest-yielding treatment at the site.

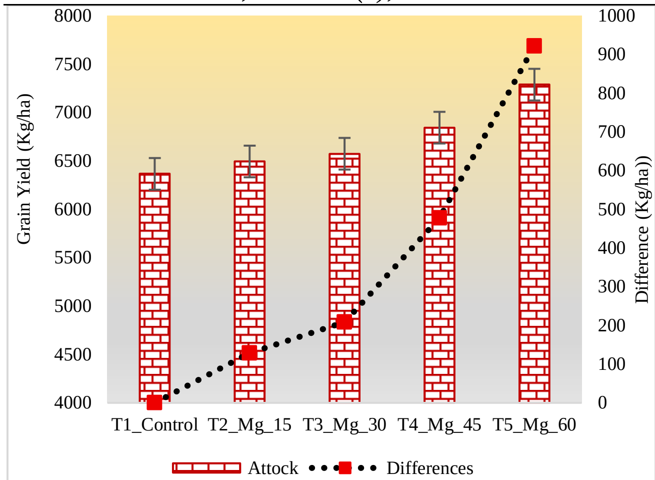

Figure 14 | Grain yield and yield difference over the unfertilized control at Attock location and yield difference from control

Physiological basis of the magnesium response

The progressive grain yield improvement observed under graded Mg fertilization is consistent with established understanding of magnesium nutrition in C3 cereals. Magnesium is the central atom of the chlorophyll molecule, a structural and functional cofactor of more than three hundred plant enzymes (including Rubisco, the rate-limiting carboxylase of C3 photosynthesis), an obligatory activator of ATP-dependent reactions across the Calvin–Benson cycle, and the principal counter-cation for phloem loading of sucrose from source leaves to developing reproductive sinks (7,9–11). Adequate Mg supply has been shown to increase leaf chlorophyll concentration, stabilize photosystem II efficiency under high-irradiance and heat stress, raise the maximum rate of carboxylation, and enhance the rate and effective duration of sucrose translocation to developing grains (12). In wheat specifically, these processes are particularly important during the late grain-filling window, the late-March to mid-April period under Punjab conditions, when temperatures rise rapidly, evaporative demand peaks, and canopy photosynthesis becomes the rate-limiting step for individual grain weight accumulation (8).

Location × treatment consistency and the case for a province-wide recommendation

The non-significant location × treatment interaction (Table 3, F = 1.34, p = 0.099) is the single most important statistical outcome of the present study from an extension standpoint. It establishes that, despite the substantial site-to-site variation in baseline soil fertility, salinity, organic matter, and macronutrient status documented in Table 1 and the substantial variation in baseline yield (T1 control yields ranged from 3,845 kg ha^{-1} at Mianwali to 6,367 kg ha^{-1} at Attock), the direction and broad shape of the Mg response was statistically conserved across the fourteen sites. The agronomic implication is direct: a single Mg fertilizer recommendation, calibrated to the optimum dose identified in the trial, can be issued as province-wide guidance for spring wheat in Punjab, without requiring site-specific calibration based on soil-test data.

Identifying the recommended Mg rate

Taking the pooled and zone-wise yield responses together, the T5 treatment (60 kg Mg ha^{-1}, applied as approximately 608 kg $MgSO_4 \cdot 7H_2O$ ha^{-1}) produced the highest grain yield at every one of the fourteen individual sites and the largest absolute grain yield response over the unfertilized control in the pooled-mean analysis, and is therefore identified as the recommended Mg rate for spring wheat (cv. Dilkash-2021) on the alkaline-calcareous soils of Punjab. At this rate, the pooled mean grain yield reached 5483.6 kg ha^{-1}, representing an absolute gain of +446.4 kg ha^{-1} (+8.9%) over the uniformly NPK-fertilized control

Conclusion

The present fourteen-location field investigation, conducted under the Soil Fertility Punjab research project SF-76 during the Rabi 2024–25 season, demonstrated that soil-applied magnesium fertilization produced a statistically significant, agronomically meaningful, and geographically reproducible improvement in the grain yield of spring wheat (cv. Dilkash-2021) across the diverse agro-climatic zones of Punjab, over and above the substantial yield baseline already established by uniform NPK fertilization. Pooled across the fourteen sites, grain yield rose progressively from 5037.2 kg ha^{-1} at the unfertilized magnesium control to 5483.6 kg ha^{-1} at the highest tested Mg rate, representing an absolute yield gain of +446.4 kg ha^{-1} (+8.9%) at 60 kg Mg ha^{-1}. The peak yield at every one of the fourteen sites was recorded at 60 kg Mg ha^{-1}, with site-wise yield gains over the control ranging from −145 kg ha^{-1} at Sahiwal to +1,105 kg ha^{-1} at Sheikhupura. The non-significant location × treatment interaction (p = 0.099) establishes that the direction and broad shape of the Mg response were statistically conserved across the substantial soil fertility, salinity, organic matter, and macronutrient gradient sampled in the trial. On this evidence, the inclusion of 60 kg Mg ha^{-1}, supplied as approximately 608 kg magnesium sulphate heptahydrate per hectare, broadcast at sowing alongside the standard 160 kg N + 114 kg P_2O_5 + 60 kg K_2O ha^{-1} schedule, is recommended as a single province-wide fertilization practice for spring wheat across Punjab, complementing rather than replacing the existing NPK schedule.

Declarations

Data Availability statement

All data generated or analysed during the study are included in the manuscript.

Ethics approval and consent to participate

Approved by the department concerned.

Consent for publication

Approved

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Conflict of interest

The authors declared the absence of a conflict of interest.

Author Contribution

AGK
Conceptualization and execution, supervision, planning, writing – original draft.
ZA
Project oversight, statistical analysis, writing – review and editing.
ZC
Experimental layout and field execution at the central Punjab trial nodes.
MRF, IH
Field execution and trial coordination at the Faisalabad-zone sites.
NM, MK
Field execution and crop management at the Bahawalpur and southern Punjab trial nodes.
MJQ
Field execution at the Sahiwal trial node.
HMR
Field execution and soil sampling at the Thal-margin sites.
FH
Field execution at the Dera Ghazi Khan trial node, soil chemical analysis.
SH
Field execution at the Rawalpindi/Pothwar trial node, data compilation.
AR
Statistical analysis support, data visualization.

All authors reviewed the results and approved the final version of the manuscript. They are also accountable for the integrity of the study.

References

1. Government of Pakistan, Finance Division, Economic Adviser's Wing. Pakistan Economic Survey 2023-24: Chapter 2 Agriculture. Islamabad: Finance Division; 2024.
2. Agriculture Department, Government of the Punjab. Agriculture Department overview. Lahore: Government of the Punjab; 2024
3. USDA Foreign Agricultural Service. Pakistan: grain and feed annual 2025. Report No.: PK2025-0003. Islamabad: United States Department of Agriculture; 2025.
4. Shahzad AN, Qureshi MK, Wakeel A, Misselbrook T. Crop production in Pakistan and low nitrogen use efficiencies. Nat Sustain. 2019;2(12):1106-14. https://doi.org/10.1038/s41893-019-0429-5
5. Rashid A, Ryan J. Micronutrient constraints to crop production in soils with Mediterranean-type characteristics: a review. J Plant Nutr. 2004;27(6):959-75. https://doi.org/10.1081/PLN-120037530
6. Imran M, Rehim A, Sarwar N, Hussain S. Zinc bioavailability in maize grains in response to phosphorus-zinc interaction. J Plant Nutr Soil Sci. 2016;179(1):60-6. https://doi.org/10.1002/jpln.201500441
7. Gransee A, Führs H. Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. Plant Soil. 2013;368(1-2):5-21. https://doi.org/10.1007/s11104-012-1567-y
8. Lobell DB, Sibley A, Ortiz-Monasterio JI. Extreme heat effects on wheat senescence in India. Nat Clim Chang. 2012;2(3):186-9. https://doi.org/10.1038/nclimate1356
9. Cakmak I, Yazici AM. Magnesium: a forgotten element in crop production. Better Crops Plant Food. 2010;94(2):23-5. DOI not available.
10. Cakmak I, Kirkby EA. Role of magnesium in carbon partitioning and alleviating photooxidative damage. Physiol Plant. 2008;133(4):692-704. https://doi.org/10.1111/j.1399-3054.2007.01042.x
11. Tränkner M, Tavakol E, Jákli B. Functioning of potassium and magnesium in photosynthesis, photosynthate translocation and photoprotection. Physiol Plant. 2018;163(3):414-31. https://doi.org/10.1111/ppl.12747
12. Hauer-Jákli M, Tränkner M. Critical leaf magnesium thresholds and the impact of magnesium on plant growth and photo-oxidative defense: a systematic review and meta-analysis from 70 years of research. Front Plant Sci. 2019;10:766. https://doi.org/10.3389/fpls.2019.00766
13. Hawkesford, M., Horst, W., Kichey, T., Lambers, H., Schjoerring, J., Møller, I. S., and White, P. (2012). Functions of macronutrients. In: P. Marschner (ed.), Marschner's Mineral Nutrition of Higher Plants, 3rd ed. Academic Press, London, pp. 135–189.
14. Estefan, G., Sommer, R., and Ryan, J. (2013). Methods of Soil, Plant, and Water Analysis: A Manual for the West Asia and North Africa Region, 3rd ed. International Center for Agricultural Research in the Dry Areas (ICARDA), Beirut, Lebanon.
15. Ryan, J., Estefan, G., and Rashid, A. (2001). Soil and Plant Analysis Laboratory Manual, 2nd ed. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.
16. Steel, R. G. D., Torrie, J. H., and Dickey, D. A. (1997). Principles and Procedures of Statistics: A Biometrical Approach, 3rd ed. McGraw-Hill Book Co., New York