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Magnesium Fertilization Improves Grain Yield, Net Photosynthetic Rate, and Thousand Grain Weight of Spring Hybrid Maize (Zea mays L.) under Alkaline-Calcareous Soils of Southern Punjab

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Abstract

Maize (Zea mays L.) productivity in southern Punjab is increasingly limited by latent secondary-nutrient deficiencies on the region's alkaline-calcareous soils, where free $CaCO_3$, low organic matter, and Ca^{2+}-dominated cation exchange sites jointly constrain the plant availability of magnesium. Despite magnesium's central role as the chlorophyll metal, an essential Rubisco cofactor, and the principal cation for sucrose phloem loading, calibrated soil-applied Mg dose–response data for spring-planted hybrid maize on Pakistani alkaline soils are limited. A two-location field trial was therefore conducted during the Rabi 2024–25 season at Hasilpur and Chishtian (District Bahawalnagar) to evaluate the response of spring-planted DK6317 hybrid maize to five graded levels of magnesium sulphate heptahydrate ($MgSO_4 \cdot 7H_2O$), at 0, 20, 40, 60, and 80 kg $MgSO_4 \cdot 7H_2O$ ha^{-1} and applied as a broadcast basal alongside a uniform NPK (225–150–125 kg ha^{-1}) plus Zn–B supply. The experiment was laid out as a randomized complete block design with three replications at each site and analyzed as a two-factor combined ANOVA. Treatment effects were highly significant ($p < 0.01$) for grain yield, net photosynthetic rate (Pn), and thousand-grain weight (TGW). Pooled mean grain yield rose progressively from 7,624.1 kg ha^{-1} at the control to 7,964.8 kg ha^{-1} at the highest Mg rate (+4.5%), while Pn increased significantly from 24.67 to 29.90 mmol CO_2 m^{-2} s^{-1} (+21.2%) and TGW increased from 281.1 to 328.1 g (+16.7%) over the same Mg gradient. The disproportionately large gain in TGW, set alongside the parallel rise in Pn, established a coherent mechanistic chain in which magnesium supply enhanced photosynthetic capacity through the late grain-filling window and translated into greater photo-assimilate partitioning to the developing kernel. All three response curves were still rising at the highest tested rate. On this evidence, the inclusion of 80 kg $MgSO_4 \cdot 7H_2O$ ha^{-1} as a basal soil-broadcast input is recommended as a regional Mg fertilization practice for spring hybrid maize across the canal-irrigated districts of southern Punjab.

Keywords: *Hybrid maize, magnesium fertilization, $MgSO_4 \cdot 7H_2O$, net photosynthetic rate, thousand grain weight.*

I. Introduction

Maize (*Zea mays* L.) is the third most important cereal crop of the world after wheat and rice, providing food, feed, fodder, and industrial raw material across a wide range of agro-ecological zones (FAOSTAT, 2023). Global maize production has grown rapidly over the past two decades on the strength of hybrid technology, improved agronomy, and rising demand from the livestock and starch industries, reaching roughly 1.2 billion tonnes from about 200 million hectares (FAO, 2023). In Pakistan, maize has emerged as the third major cereal after wheat and rice and the fastest-growing cereal crop in terms of both acreage and per-hectare yield, currently cultivated on approximately 1.44 million hectares with an annual production of around 8.24 million tonnes (GoP, 2025). The expansion has been driven largely by the rapid uptake of single-cross hybrids, the growth of the poultry and dairy feed industries, and the establishment of a Rabi-season maize crop in the irrigated districts of Punjab, where spring-planted hybrids now contribute a substantial share of national output (Ali et al., 2020). Despite these gains, the realized on-farm yield remains well below the genetic potential of available hybrids, and the persistent yield gap has been attributed to imbalanced fertilization, sub-optimal plant population, and the increasing prevalence of micro- and secondary-nutrient deficiencies on the country's predominantly alkaline-calcareous soils (Gen et al., 2021; Bibi et al., 2024). The soils of southern Punjab, where much of the country's Rabi maize is now grown, are characteristically alkaline, calcareous, and low in organic matter, with pH values typically ranging from 7.8 to 8.5 and substantial free $CaCO_3$ contents (Waheed et al., 2025). Under these conditions, the plant availability of several essential cations, including magnesium, is constrained by competition with Ca^{2+} on exchange sites, by the alkaline reaction that favours Mg fixation in carbonate complexes, and by the relatively low Mg content of the alluvial parent material (Gransee and Führs, 2013). The Rabi maize crop adds physiological constraint: with sowing in early February and harvest in late May, grain filling coincides with rapidly rising temperatures and high evaporative demand during late April and May, when canopy photosynthesis becomes the rate-limiting step for kernel weight accumulation (Lobell et al., 2013).

Any nutritional constraint on photosynthetic capacity during this window, therefore, translates directly into a penalty on thousand-grain weight and grain yield. Although nitrogen, phosphorus, and potassium responses in maize have been extensively documented in Pakistan, the role of magnesium, and particularly its interaction with location-specific soil conditions and end-of-season heat stress, has received comparatively little attention.

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 C_3 and C_4 photosynthesis), an essential activator of ATP-dependent reactions, and the principal counter-cation for phloem loading of sucrose and amino acids (Cakmak and Yazici, 2010; Gransee and Führs, 2013). Under Mg-sufficient conditions, leaf chlorophyll content, photosystem II efficiency, and net photosynthetic rate are all enhanced, with downstream consequences for assimilate partitioning to reproductive sinks (Tränkner et al., 2018). In maize specifically, adequate Mg supply has been shown to increase leaf chlorophyll concentration, stabilize photosynthetic performance under high-light and heat stress, improve phloem loading of sucrose from source leaves to developing kernels, and consequently raise thousand-grain weight and grain yield (Jezek et al., 2015; Hauer-Jákli and Tränkner, 2019). Mg deficiency, by contrast, first manifests as interveinal chlorosis on older leaves, reduces photosynthetic rate even before visible symptoms develop, and reduces the duration and effective rate of grain filling, a particularly damaging combination for spring-planted maize maturing under thermally stressful conditions (Cakmak and Yazici, 2010). Despite this physiological centrality, calibrated soil-applied Mg dose–response data for hybrid maize on alkaline-calcareous soils of Pakistan are sparse, and current provincial fertilizer recommendations for maize do not routinely include magnesium as a maintenance input.

Where regional studies on Mg fertilization in maize have been reported, they have typically been confined to a single site or a single Mg rate, making it difficult to identify an agronomically optimal dose or to establish whether the response is consistent across soils with differing fertility status. A multi-location, dose–response evaluation of Mg fertilization in hybrid maize under the alkaline-calcareous, semi-arid conditions of southern Punjab is therefore warranted. The present study was designed (i) to evaluate the response of spring-planted hybrid maize (cv. DK6317) to four graded levels of soil-broadcast magnesium sulphate heptahydrate ($MgSO_4 \cdot 7H_2O$), and applied over a uniform NPK basal dose, at two contrasting sites in District Bahawalnagar during the Rabi 2024–25 crop season; (ii) to quantify the response in terms of three complementary variables, grain yield, net photosynthetic rate, and thousand grain weight, that together capture both the yield and the underlying physiological mechanism; and (iii) to test whether the Mg response interacts significantly with location, thereby clarifying whether a single regional recommendation is justified or whether site-specific calibration is required.

2. Materials and Methods

2.1 Experimental sites

The field experiment was conducted during the Rabi 2024–25 cropping season at two collaborating sites in District Bahawalnagar, southern Punjab, Pakistan, one at Hasilpur and one at Chishtian, under the framework of the Soil Fertility (Field) Bahawalpur research project SF-111 ("Evaluation of the effect of magnesium sulphate on spring hybrid maize"). Both sites lie within the canal-irrigated, semi-arid tract of the Indus Basin and are characterized by hot summers, mild winters, low to moderate annual rainfall, and alluvial, calcareous soils developed on Indus Basin sediments. Prior to land preparation, composite soil samples were collected from each site at two depths (0–15 cm and 15–30 cm) following standard auger sampling procedures (Ryan et al., 2001). 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

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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 (Ryan et al., 2001; Estefan et al., 2013). The soil analytical data for the two experimental sites are presented in Table 1.

Both sites carried alkaline (pH 8.16–8.40), moderately saline (EC_e 2.70–3.19 dS m^{-1}) soils with low organic matter content (0.55–0.79%). Available phosphorus was generally low to medium across both sites (4.38–10.9 ppm), while available potassium ranged from 96 to 130 ppm. These soil characteristics, alkaline pH, free $CaCO_3$, moderate salinity, and low organic matter, represent conditions widely recognized to limit the plant availability of soil-bound magnesium through Ca^{2+}/Mg^{2+} exchange-site competition and carbonate fixation (Gransee and Führs, 2013), and were therefore expected to amplify the agronomic value of Mg supplementation.

Table 1. Soil physico-chemical properties of the two experimental sites at two sampling depths.

Soil parameter	EC (dS m^{-1})	pH	OM (%)	Available P (ppm)	Available K (ppm)
Hasilpur					
Depth 0–15 cm	2.73	8.24	0.79	6.98	130
Depth 15–30 cm	3.19	8.16	0.55	4.38	104
Chishtian					
Depth 0–15 cm	2.90	8.40	0.71	10.90	125
Depth 15–30 cm	2.70	8.30	0.77	9.10	96

2.2 Plant material

A commercially available single-cross maize hybrid, DK6317 (Dekalb, Bayer Crop Science), was used at both locations. DK6317 is a medium-maturing single-cross hybrid widely adopted for spring planting in the canal-irrigated districts of Punjab and was selected for its consistent performance under the prevailing Rabi-season conditions of southern Punjab. Disease-free, certified seed was procured from authorized hybrid seed distributors and used for sowing at both sites.

2.3 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 a MgO-equivalent basis, were: T1 = Control (NPK only, 0 kg $MgSO_4$ ha^{-1}); T2 = NPK + 20 kg $MgSO_4$ ha^{-1}; T3 = NPK + 40 kg $MgSO_4$ ha^{-1}; T4 = NPK + 60 kg $MgSO_4$ ha^{-1}; and T5 = NPK + 80 kg $MgSO_4$ ha^{-1}. Magnesium was supplied as magnesium sulphate heptahydrate ($MgSO_4 \cdot 7H_2O$; Epsom salt), which contains approximately 16.26% $MgSO_4$ by mass; the corresponding actual fertilizer rates applied in the field were approximately 0, 123, 246, 369, and 492 kg $MgSO_4 \cdot 7H_2O$ ha^{-1} for T1 through T5, respectively. The uniform basal NPK dose comprised 225 kg N ha^{-1}, 150 kg P_2O_5 ha^{-1}, and 125 kg K_2O ha^{-1}, applied as urea, di-ammonium phosphate (DAP), and sulphate of potash (SOP), respectively. In addition, all experimental plots, including the unfertilized Mg control, received a uniform basal application of zinc at 5 kg ha^{-1} (as zinc sulphate) and boron at 1.0 kg ha^{-1} (as borax) to ensure that the response to graded Mg fertilization could be evaluated independently of any underlying micronutrient limitation other than Mg itself.

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 two 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 both sites. Individual plot size was 250 m², equivalent to one-fortieth of a hectare, which was sufficient to accommodate a representative net plot area for harvesting after exclusion of border rows.

Table 2. Treatment compositions used to study the response of spring hybrid maize to graded levels of magnesium fertilization.

Treatment	Treatments	N (kg ha⁻¹)	P_2O_5 (kg ha⁻¹)	K_2O (kg ha⁻¹)	MgO (kg ha⁻¹)
Control (NPK only)	T1_Control	225	150	125	0
NPK + 20 kg $MgSO_4$	T2_MgO_20	225	150	125	20
NPK + 40 kg $MgSO_4$	T3_MgO_40	225	150	125	40
NPK + 60 kg $MgSO_4$	T4_MgO_60	225	150	125	60
NPK + 80 kg $MgSO_4$	T5_MgO_80	225	150	125	80

2.4 Crop management

Maize was sown on 4 February 2025 at both locations and harvested on 29 May 2025, giving a crop cycle of approximately 114 days. At sowing, the full doses of P_2O_5, K_2O, $MgSO_4 \cdot 7H_2O$, $ZnSO_4$, and borax, together with one-third 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. The remaining nitrogen was applied in two further equal splits: one-third at the knee-height stage (approximately 35–45 days after sowing) and the final one-third at the three-feet-height stage, applied as a top-dressing approximately 15–20 days after the second N application. Seed was placed in opened furrows at the recommended depth, and a uniform plant population consistent with standard production recommendations for spring hybrid maize in Punjab was maintained at both sites through manual thinning at the early vegetative stage. Irrigation was applied through the canal supply system: the first irrigation was given immediately after sowing to ensure uniform germination, and subsequent irrigations were applied at critical growth stages including knee-height, tasseling, silking, and grain filling, with frequency adjusted to crop demand, evaporative demand, and rainfall. Weeds were controlled by a combination of pre-emergence herbicide application and one manual hoeing during the early vegetative phase. Plant protection measures against stem borer (*Chilo partellus*) and fall armyworm (*Spodoptera frugiperda*) 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 spring-planted hybrid maize in Punjab.

2.5 Data recording

Three response variables were recorded: grain yield, net photosynthetic rate, and thousand grain weight.

1. Grain yield (kg ha^{-1}). At physiological maturity, all cobs were harvested from the net plot area, leaving border rows excluded to minimize edge effects. Harvested cobs were sun-dried, threshed, and the grain was cleaned, weighed, and adjusted to a standard moisture basis of 14% using a calibrated digital grain moisture meter. Plot-level grain yield was extrapolated to a per-hectare basis (kg ha^{-1}) at 14% moisture content.

2. Net photosynthetic rate (Pn, mmol CO_2 m^{-2} s^{-1}). Net photosynthetic rate was measured on fully expanded ear leaves at the silking stage using a portable infrared gas analyzer-based photosynthesis system (CI-340 Handheld Photosynthesis System, CID Bio-Science, USA). Measurements were taken on randomly selected plants per plot between 09:00 and 11:00 hrs local time on cloud-free days, under ambient photosynthetic photon flux density, CO_2 concentration, and leaf temperature. The plant-level readings per plot were averaged to give a single plot-level Pn value used in subsequent analyses.

3. Thousand grain weight (TGW, g). Following threshing and moisture adjustment, three random sub-samples of 1,000 grains were drawn from the cleaned grain of each plot using a seed counter and weighed on an electronic precision balance (resolution 0.01 g). The three sub-sample weights were averaged to give a single plot-level TGW value at 14% moisture basis.

2.6 Statistical analysis

The data for grain yield, net photosynthetic rate, and thousand grain weight were each subjected to 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 significant, simple effect means were computed for each treatment within each location; where it 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 (Steel et al., 1997). The significance of location, treatment, and location × treatment interaction effects was tested at $p \leq 0.05$ and $p \leq 0.01$ levels. The yield, Pn, and TGW 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.

3. Results and Discussion

3.1 Soil status of the experimental sites

The soil analytical data presented in Table 1 confirmed that both experimental sites carried alkaline, calcareous, low-organic-matter soils typical of the southern Punjab cropping plain, with surface pH ranging from 8.16 to 8.40 across the two locations and both sampling depths. Electrical conductivity values (2.70–3.19 dS m^{-1}) indicated moderate salinity at both sites, with the Hasilpur subsoil registering the highest EC (3.19 dS m^{-1}). Organic matter content was uniformly low (0.55–0.79%), and available phosphorus was generally inadequate at the Hasilpur subsoil (4.38 ppm) while ranging from low-medium to medium at the other sampling positions (6.98–10.9 ppm). Available potassium ranged from 96 to 130 ppm across the four soil samples. Collectively, these soil conditions, alkaline pH, free $CaCO_3$, moderate salinity, and low organic matter, represent the broader fertility constraints under which the maize crop was raised and were expected to amplify the agronomic value of magnesium supplementation.

The combination of high pH, calcareous mineralogy, and moderate salinity is widely recognized as constraining Mg availability through three interacting mechanisms: Ca^{2+} dominance of cation exchange sites under high $CaCO_3$ loading; precipitation of Mg in carbonate complexes at alkaline pH; and Na^+ competition with Mg^{2+} for root uptake under elevated soil salinity (Gransee and Führs, 2013; Tränkner et al., 2018). The site-to-site contrast in EC and available P further provided a useful natural gradient against which the consistency of the Mg response across locations could be evaluated.

3.2 Analysis of variance

The combined analysis of variance across the two locations revealed significant treatment effects on all three response variables (Table 3). For grain yield, the location main effect was non-significant, while the treatment effect was highly significant ($p < 0.01$) and the location × treatment interaction was also significant ($p < 0.01$). For net photosynthetic rate, both the location main effect and the treatment effect were highly significant ($p < 0.01$), while their interaction was non-significant. For thousand grain weight, only the treatment effect was significant ($p < 0.01$), with both the location main effect and the interaction term remaining non-significant.

Table 3. Combined analysis of variance (mean squares) for grain yield and associated traits of spring hybrid maize across two locations and five magnesium fertilization levels.

Source of variation	DF	Grain yield (MS)	Pn (MS)	TGW (MS)
Replications (A)	2	22,986	4.67	734.23
Locations (B)	1	41,813 ns	43.20 **	3.33 ns
Error A × B	2	34,726	0.22	570.03
Treatments (C)	4	149,747 **	22.71 **	1,284.05 **
B × C interaction	4	23,479 **	2.92 ns	28.92 ns
Error A × B × C	16	8,990	1.92	501.01
Total	**29**			

*Note: * = significant at 5% probability level; ** = significant at 1% probability level; ns = non-significant. Grain yield in kg ha*$^{-1}$*; Pn in mmol* CO_2 m^{-2} s^{-1}*; TGW in g.*

These ANOVA patterns convey three useful pieces of information for downstream interpretation. First, the highly significant treatment effects across all three variables confirm that the graded Mg fertilization rates produced statistically discernible responses over and above the uniform NPK basal dose. Second, the contrasting pattern of the location main effect, non-significant for grain yield and TGW but highly significant for Pn, indicates that the two sites achieved broadly similar absolute yield ceilings but differed measurably in their photosynthetic machinery, with Hasilpur registering consistently higher Pn values than Chishtian across all five Mg levels. Third, the significant location × treatment interaction for grain yield, set against non-significant interactions for the two upstream physiological variables, suggests that the yield-level response of Mg differed slightly between the two sites despite a broadly consistent underlying physiological response.

3.3 Grain yield response to magnesium fertilization

Across both locations, soil-applied magnesium sulphate heptahydrate produced a progressive improvement in grain yield as the Mg rate increased from 0 to 80 kg $MgSO_4$ ha^{-1}, with the highest yield recorded at the highest tested dose (Figure 1, Table 4). The unfertilized NPK-only control (T1) produced a pooled mean grain yield of 7,624.1 kg ha^{-1}, while application of 20, 40, 60, and 80 kg $MgSO_4$ ha^{-1} produced pooled mean yields of 7,606.1, 7,757.7, 7,886.0, and 7,964.8 kg ha^{-1}, respectively. The yield response over the unfertilized control therefore rose from a marginal −0.2% at T2 to +1.8% at T3, +3.4% at T4, and +4.5% at T5, with the highest grain yield gain of +340.7 kg ha^{-1} over the NPK-only control recorded at the 80 kg $MgSO_4$ ha^{-1} rate. The small yield depression observed at T2 in the pooled mean reflects a site-specific dip at Hasilpur, where T2 produced a yield 76.8 kg ha^{-1} below the control, while at Chishtian T2 produced a small positive gain of 40.7 kg ha^{-1}; this divergence is the principal driver of the significant location × treatment interaction.

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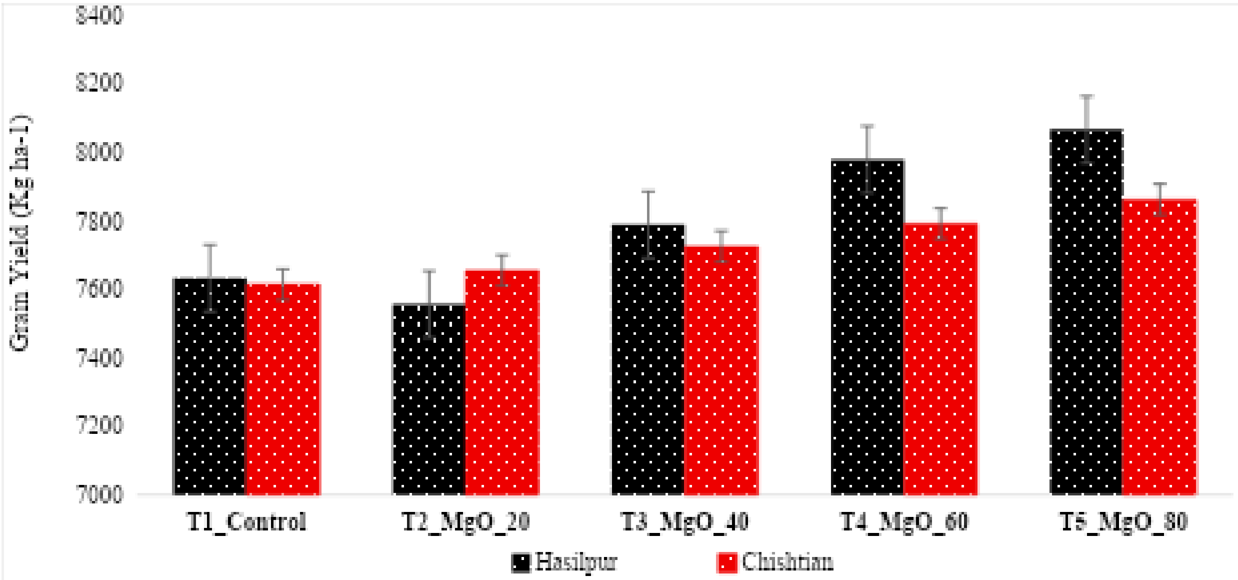

Figure 1 | Performance of maize crop at five different magnesium fertilization levels at two different locations

The progressive and monotonic shape of the yield response curve, with the peak observed at the highest tested rate and no evidence of a plateau or decline, is physiologically consistent with established understanding of Mg nutrition in maize. Hybrid maize is a high-yielding C_4 crop with intense reproductive sink strength and substantial Mg uptake during the grain-filling phase, and the demand for Mg at this stage routinely exceeds the supply that alkaline-calcareous soils can deliver from native pools (Hauer-Jákli and Tränkner, 2019). The continuing yield response at 80 kg $MgSO_4$ ha^{-1} suggests that the sufficiency threshold for Mg on these soils, under spring planting and the prevailing heat stress regime of the late grain-filling window, has not yet been reached within the rates tested. The absolute yield gain of +340.7 kg ha^{-1} from T1 to T5 represents a measurable agronomic response on top of an already optimized NPK schedule and confirms that magnesium is a latent yield-limiting factor for spring-planted hybrid maize on these soils.

Table 4. Site-wise mean grain yield, net photosynthetic rate, and thousand grain weight of spring hybrid maize under five graded levels of magnesium fertilization at Hasilpur and Chishtian.

Treatment	Grain Yield			Net Photosynthetic rate			Thousand Grain weight	
	Hasilpur	Chishtian	Pooled	Hasilpur	Chishtian	Pooled	Hasilpur	Chishtian
T1 (0)	7633.3	7614.8	7624.1	25.23	24.10	24.67	270.4	291.7
T2 (20)	7556.6	7655.6	7606.1	26.63	25.70	26.17	286.5	308.7
T3 (40)	7789.5	7725.9	7757.7	28.67	26.37	27.52	301.7	309.0
T4 (60)	7979.5	7792.6	7886.0	29.67	25.77	27.72	315.2	318.0
T5 (80)	**8066.7**	**7863.0**	**7964.8**	**31.77**	**28.03**	**29.90**	**321.5**	**334.7**

3.4 Net photosynthetic rate response to magnesium fertilization

Net photosynthetic rate showed a strong, monotonically rising response to magnesium fertilization at both locations (Figure 2). Pooled across the two sites, net photosynthetic rate increased progressively from 24.67 mmol CO_2 m^{-2} s^{-1} at the unfertilized control (T1) to 29.90 mmol CO_2 m^{-2} s^{-1} at the highest Mg rate (T5), corresponding to an absolute increase of +5.23 mmol m^{-2} s^{-1} and a relative gain of +21.2% over the control. The site-wise responses were directionally identical: at Hasilpur, Pn rose from 25.23 to 31.77 mmol m^{-2} s^{-1} (a gain of +6.53 mmol m^{-2} s^{-1} or +25.9% over control), and at Chishtian from 24.10 to 28.03 mmol m^{-2} s^{-1} (a gain of +3.93 mmol m^{-2} s^{-1} or +16.3% over control). The non-significant location × treatment interaction (Table 3) confirms that the broad shape of the Pn response was consistent across the two sites, although the absolute magnitude was greater at Hasilpur, in line with the significant location main effect.

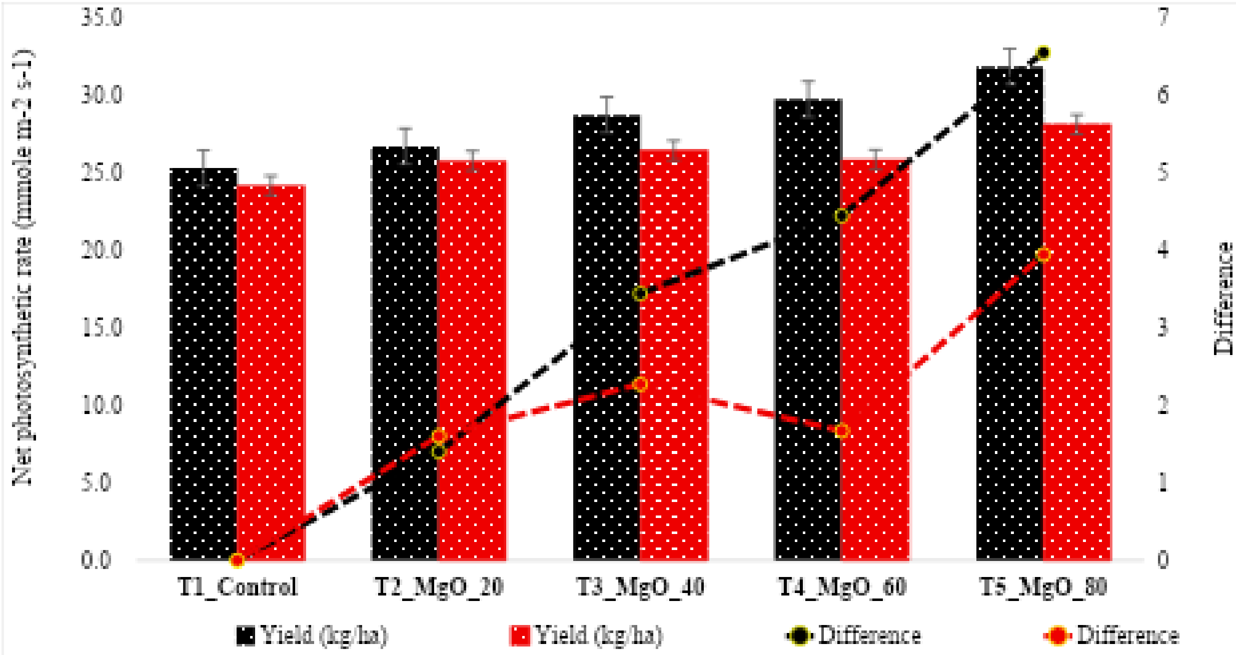

Figure 2 | Net Photosynthetic rate of maize crop at five different magnesium fertilization levels at both Hasilpur and Chistian locations and difference from control

The strong photosynthetic response to Mg fertilization is mechanistically the central finding of the present study and is fully consistent with magnesium's biochemical role in C_4 photosynthesis. Magnesium is the central atom of the chlorophyll molecule, an essential structural cofactor of Rubisco and PEP carboxylase, and an obligatory activator of more than three hundred enzymes, including those of the Calvin–Benson cycle and the C_4 shuttle (Cakmak and Yazici, 2010; Tränkner et al., 2018). Under Mg-deficient conditions, leaf chlorophyll concentration declines, photosystem II efficiency falls, and net photosynthetic rate is depressed even before visible interveinal chlorosis develops on older leaves (Jezek et al., 2015; Hauer-Jákli and Tränkner, 2019). Restoration of Mg supply through soil-applied fertilization has been shown to elevate leaf Mg concentration, restore chlorophyll content, and increase the maximum rate of carboxylation, with corresponding improvements in measured Pn in maize and other C_4 cereals (Jezek et al., 2015). The +21.2% pooled increase in Pn recorded here at the highest Mg rate falls within the upper range of values reported in the recent meta-analysis of Hauer-Jákli and Tränkner (2019), which found mean photosynthetic gains of 15–25% in Mg-supplemented field crops under conditions of moderate to severe baseline Mg limitation.

3.5 Thousand-grain weight response to magnesium fertilization

Thousand grain weight showed the strongest relative response of any variable measured in the present study, rising progressively at both locations across the full Mg dose series (Figure 3). Pooled across the two sites, TGW rose from 281.1 g at the unfertilized control to 328.1 g at the highest Mg rate, corresponding to an absolute increase of +47.0 g and a relative gain of +16.7% over the control. At Hasilpur, TGW increased from 270.4 g (T1) to 321.5 g (T5), a gain of +51.1 g (+18.9%), while at Chishtian TGW rose from 291.7 g to 334.7 g, a gain of +43.0 g (+14.7%). The TGW response was monotonically positive across the dose series at both sites, with no evidence of a plateau within the range tested, and the non-significant location × treatment interaction (Table 3) confirms that the broad TGW response was conserved across both locations.

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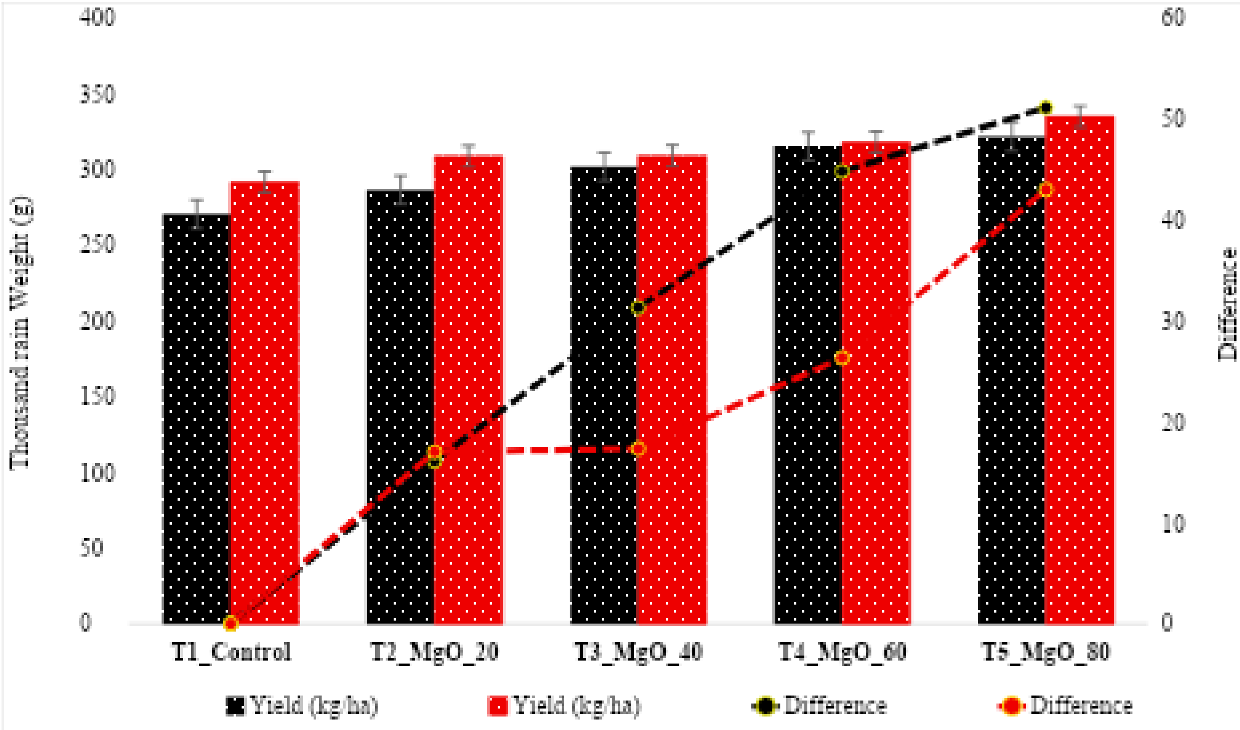

Figure 3 | Thousand Grain Weight of maize crop at five different magnesium fertilization levels at both Hasilpur and Chistian locations and difference from control

The magnitude of the TGW response, substantially larger in relative terms than the grain yield response, is mechanistically informative and represents arguably the most interpretable finding of the present study. Because grain yield in maize is the product of plant population, kernels per plant, and individual kernel weight, the disproportionately large gain in TGW indicates that magnesium fertilization improved the present crop primarily through enhanced grain filling rather than through increased kernel set or stand density (Tollenaar and Lee, 2002). This is the classical signature of improved late-season source capacity, where supply of photosynthate to the developing kernel during the grain-filling window becomes the rate-limiting step for individual kernel growth (Borrás et al., 2004). The TGW response observed here is therefore the direct, downstream agronomic expression of the upstream photosynthetic response documented in section 3.4: Mg supplementation elevated leaf Pn through the silking and early grain-filling phases, and the additional photo-assimilate produced was preferentially partitioned to the kernel, increasing individual grain weight. This source–sink chain is the established mechanism by which Mg fertilization improves cereal grain yield on Mg-limiting soils (Cakmak and Yazici, 2010; Hauer-Jákli and Tränkner, 2019).

3.6 Location × treatment interaction and the consistency of the Mg response

The significant location × treatment interaction for grain yield (Table 3, $p < 0.01$), set against non-significant interactions for Pn and TGW, requires careful interpretation. The site-wise yield responses (Figures 4 and 5) show that both Hasilpur and Chishtian responded positively to Mg fertilization across the full dose series, with the highest yield at each site recorded at T5 (8,066.7 kg ha^{-1} at Hasilpur; 7,863.0 kg ha^{-1} at Chishtian) and the absolute yield gain over the control ranging from +241.1 kg ha^{-1} at Hasilpur (+3.2%) to +248.2 kg ha^{-1} at Chishtian (+3.3%). The principal source of the interaction was the divergent response at T2 (20 kg $MgSO_4$ ha^{-1}): at Hasilpur, T2 produced a small yield depression of −76.8 kg ha^{-1} (−1.0%) relative to control, while at Chishtian T2 produced a small positive gain of +40.7 kg ha^{-1} (+0.5%). The two response curves converged at T3 onwards, with both sites showing parallel yield gains at the 40, 60, and 80 kg $MgSO_4$ ha^{-1} rates.

The small T2 dip at Hasilpur is most plausibly attributed to the higher baseline soil salinity at that site (EC_e 3.19 dS m^{-1} in the subsoil, the highest value recorded in either trial location), where the sulphate ion supplied with the modest Mg dose at T2 may have transiently elevated rhizosphere ionic strength without delivering enough Mg to offset the osmotic effect on early-season root activity. Once the Mg dose was raised to 40 kg $MgSO_4$ ha^{-1} and above, the agronomic benefit of Mg supply outweighed any transient ionic effect, and the yield response at Hasilpur converged with Chishtian. Importantly, the broad pattern of monotonic improvement up to the highest tested rate was preserved at both locations, and the formal statistical significance of the interaction notwithstanding, the practical extension message, that 80 kg $MgSO_4$ ha^{-1} produces the highest grain yield response at both sites, is unaffected.

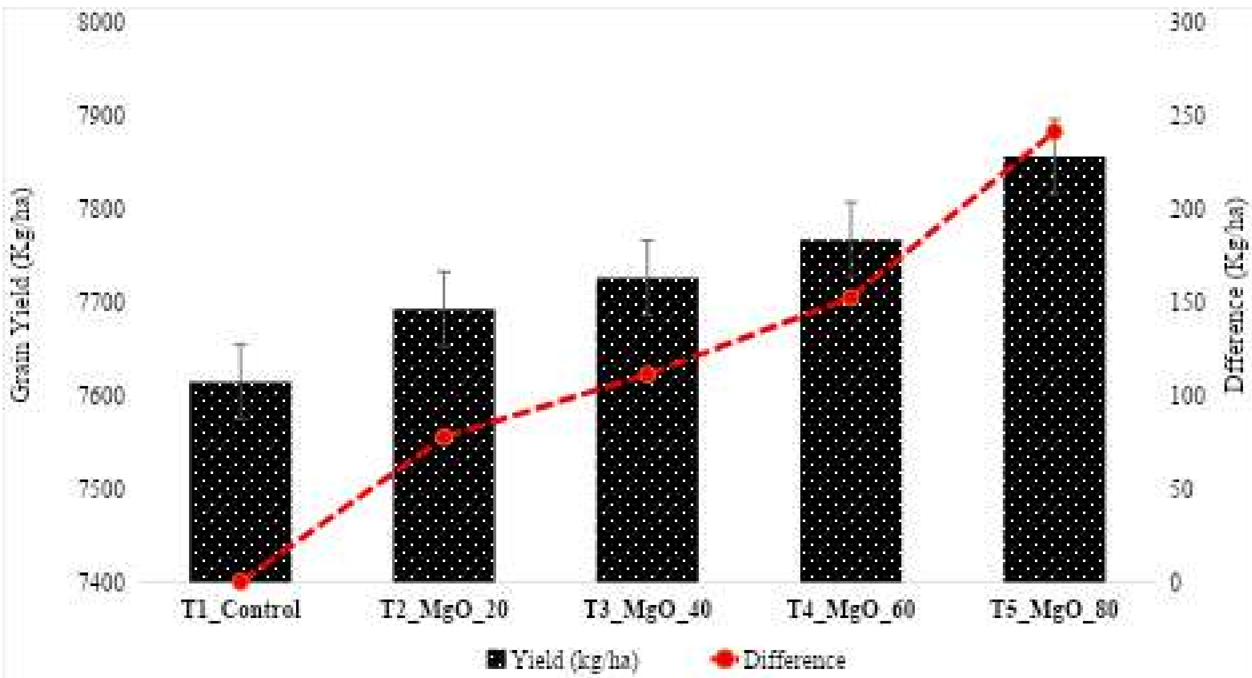

Figure 2 | Yield performance of maize crop at five different magnesium fertilization levels at Hasilpur location and yield difference from control

https://doi.org/10.53762/grjnst.04.03.19

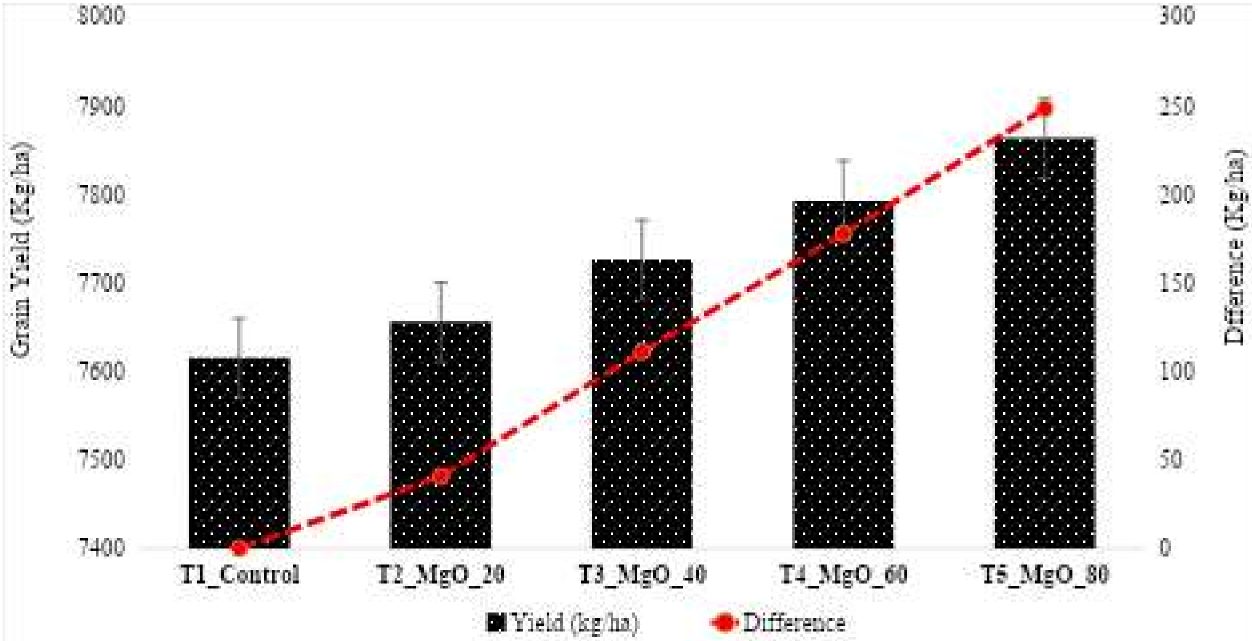

Figure 3 | Yield performance of maize crop at five different magnesium fertilization levels at Chistian location and yield difference from control

The non-significant location × treatment interactions for both Pn and TGW further reinforce that the underlying physiological response of the crop to Mg fertilization was conserved across the two sites; only the yield-level expression differed marginally at the lowest Mg rate.

3.7 Mechanistic synthesis and the recommended Mg rate

Taken together, the present results establish a coherent and physiologically interpretable mechanistic chain: soil-applied magnesium fertilization at 80 kg $MgSO_4$ ha^{-1} raised leaf magnesium status; elevated leaf chlorophyll content and Rubisco activation, as expressed in a +21.2% increase in net photosynthetic rate over the unfertilized control; enhanced the supply of photo-assimilate to developing kernels through the late grain-filling window; produced a +16.7% gain in thousand grain weight; and translated into a +4.5% gain in grain yield on a pooled-mean basis. It is worth emphasizing that the observed gains were obtained over an NPK basal already supplemented with Zn and B at agronomic rates, indicating that the response is attributable specifically to relief of the Mg constraint rather than to a generalized correction of micronutrient deficiency. This source-driven yield response is the established physiological signature of improved Mg nutrition in cereals (Cakmak and Yazici, 2010; Tränkner et al., 2018; Hauer-Jákli and Tränkner, 2019) and is particularly relevant for spring-planted Rabi maize in southern Punjab, where the grain-filling phase falls in late April and May under rising temperatures and high evaporative demand, precisely the conditions under which Mg-mediated stabilization of photosynthetic machinery is most agronomically valuable (Lobell et al., 2013; Tränkner et al., 2018).

On the strength of the largest grain yield response, the largest Pn gain, and the largest TGW gain over the unfertilized NPK-only control, the T5 treatment (80 kg $MgSO_4$ ha^{-1}, is identified as the recommended Mg rate for spring-planted hybrid maize on the alkaline-calcareous soils of District Bahawalnagar and the wider southern Punjab cropping plain. The fact that the grain yield, Pn, and TGW response curves were all still rising at the highest tested rate, with no evidence of a plateau, indicates that the true sufficiency threshold for soil-applied Mg under these conditions may lie at or beyond 80 kg $MgSO_4$ ha^{-1}, and that future work should evaluate even higher Mg rates (e.g., 100–120 kg $MgSO_4$ ha^{-1}) to determine the upper limit of the agronomic response. For current extension purposes, however, the inclusion of 80 kg $MgSO_4$ ha^{-1} as a basal soil-broadcast input alongside the standard NPK schedule emerges as both the agronomically and physiologically defensible recommendation supported by the present data.

4. Conclusion

This multi-location field study demonstrated that soil-applied magnesium sulphate heptahydrate, broadcast at sowing alongside a uniform NPK basal dose, improved the productivity of spring-planted hybrid maize (cv. DK6317) under the alkaline-calcareous, canal-irrigated conditions of southern Punjab during Rabi 2024–25. Across the 0–80 kg MgO ha^{-1} series, pooled grain yield rose from 7,624.1 to 7,964.8 kg ha^{-1} (+4.5%), net photosynthetic rate from 24.67 to 29.90 mmol CO_2 m^{-2} s^{-1} (+21.2%), and thousand grain weight from 281.1 to 328.1 g (+16.7%), with the disproportionate gain in grain weight alongside the parallel rise in photosynthesis indicating that enhanced Mg supply sustained late-season photosynthesis and improved photo-assimilate partitioning to the kernel. The response was positive at both sites, peaking at the 80 kg $MgSO_4$ ha^{-1} rate; accordingly, 80 kg $MgSO_4$ ha^{-1} as a basal soil-broadcast input, complementing existing N, P, and K recommendations, is recommended for spring-planted hybrid maize across canal-irrigated southern Punjab, while future work should test higher rates (100–120 kg $MgSO_4$ ha^{-1}), Kharif maize, wider soil gradients, and grain quality to develop a fully integrated regional Mg recommendation.

Author Contributions

MJQ; Conceptualization and Execution, Supervision, Planning, Writing – original draft; **MRF**, **SJ**; Experimental layout, Field execution and crop management at Hasilpur and Chishtian sites; **MBL, AGK**; Treatment application, Field supervision; **MK, AS**; Data analysis, Statistical computation, Data visualization; **MA, HMR**; Soil sampling, Soil chemical analysis, Soil fertility characterization; **SUR, AR, GM**; Grain yield, Pn, and TGW data recording, Data compilation; **HMR, MJQ, AGK**; Writing – review & editing.

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