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Article

Effects of agricultural gypsum with micronutrients on the yield and quality of bread wheat

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Abstract

Wheat is a crop that requires large amounts of fertilizer; nevertheless, its availability limits productivity. In alkaline soils, nutrients such as iron (Fe), copper (Cu), zinc (Zn) and manganese (Mn) are less available, which causes deficiencies that are reflected in the yield and quality of the grain. Faced with this problem, a study was conducted during the 2023-2024 autumn-winter agricultural cycle at the Norman E. Borlaug Experimental Field, located in the Yaqui Valley. Five treatments with different doses of agricultural gypsum (25 and 50 kg ha-1) enriched with micronutrients (Fe, Cu, Zn, and Mn), with and without humic and fulvic acids, were evaluated to determine the effect of the optimal dose that contributes to improving the yield and quality of Borlaug 100 bread wheat. The experimental design consisted of randomized complete blocks with four replications. The variables evaluated included: soil pH at different depths, nutrient analysis of the flag leaf, yield components, and quality parameters (protein, sedimentation index, incidence of white belly, and partial bunt). The results showed that the treatments with the high dose of agricultural gypsum and micronutrients led to a temporary acidification of the soil until the stem elongation stage, no longer than 30 days, due to a cation exchange, generating an acid hydrolysis that releases hydrogen ions, which indirectly contributed to acidification, which suggests a greater availability of nutrients for the development of the crop. This resulted in a 17% increase in yield in treatments 1 and 3 compared to the control, with a 14% increase in the number of grains per spike. In addition, values of 11.6% of protein were obtained, with less than 0.5% incidence of white belly.

Keywords:

fulvic acids, humic acids, micronutrients

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Introduction

Wheat (*Triticum aestivum* L.) is the second most important staple food in the world (Riaz *et al*., 2021). During the 2023-2024 agricultural cycle, 248 122 ha were established in southern Sonora (SIAP, 2024), which represented 51% of the national area. However, productivity has been compromised by several factors, among which water and soil quality, as well as the availability of essential nutrients, stands out (Martínez-Cruz *et al*., 2020).

The essential elements for plant metabolism are classified according to their concentration and the requirements necessary for growth and reproduction. In this way, they are divided into macro- and micronutrients (Marschner, 2012). The deficiency of any of them in the soil is a key factor that negatively impacts plant growth and development. Essential micronutrients include iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn), all of which are involved in vital metabolic processes. Nonetheless, the availability of these elements in the soil and their correct assimilation by plants can be limited by various reasons, affecting agricultural productivity (Días dos Santos *et al*., 2021).

The use of specific amendments and fertilizers can be a viable strategy to improve soil fertility and, consequently, improve parameters such as biomass (Osorio-Vera *et al*., 2021). Agricultural gypsum, chemically known as calcium sulfate dihydrate ($CaSO_4$ $2H_2O$), has established itself as an amendment that improves soil conditions and contributes to root development (Bartzen *et al*., 2020). On the other hand, soils with moderately acidic pH allow the development of plant growth-promoting microorganisms (PGPMs) (Shah *et al*., 2021). Agricultural gypsum also contributes to the supply of calcium (Ca) and sulfur (S) in the form of essential sulfates for plants (Rojas-Padilla *et al*., 2022).

Abbas *et al*. (2023) note that agricultural gypsum increases nutrient adsorption by improving the soil's texture and structure. De Cori *et al*. (2010) point out that S is a 'structural element' in plant nutrition, as it is part of compounds such as amino acids and phospholipids. For their part, Nardi *et al*. (2021) highlight that humic acids contribute to normalizing metabolism and the processes involved in photosynthesis and respiration, favoring plant development and growth. The work aimed to determine the effect of the optimal dose that contributes to improving the yield and quality of Borlaug 100 bread wheat.

Materials and methods

The study was conducted throughout the 2023-2024 agricultural cycle within the facilities of the Norman E. Borlaug Experimental Field (CENEB), for its Spanish acronym, belonging to the National Institute of Forestry, Agricultural and Livestock Research (INIFAP), for its Spanish acronym. CENEB is located in block 910 of the Yaqui Valley, Sonora, Mexico, at coordinates 27° 22' 14.40" north latitude and 109° 55' 18.14" west longitude, at 40 masl.

Sowing was carried out on December 6, 2023, using the Borlaug 100 variety, with a density of 90 kg ha^{-1}. It was performed dry, at a depth of three centimeters, in double rows spaced 85 cm apart. A soil analysis was conducted prior to the experiment, and it was determined that the soil has a clayey texture, a pH of 7.72, an electrical conductivity of 2.6 dS m^{-1}, and a contribution of 50 kg ha^{-1} of N-NO_3 and 84.99 kg ha^{-1} of P-PO_4. Fertilization was performed using 180 kg of nitrogen, sourced from urea, which was divided in half and applied in bands during the first two supplemental irrigations.

Irrigation was carried out during the stem elongation stage (z3.1), after the booting stage (z3.9), and in the heading stage (z5.5), using the Zadoks scale (Zadoks *et al.*, 1974). Broadleaf weeds were controlled with metsulfuron-methyl + iodosulfuron-methyl-sodium, whereas narrow-leaved weeds were controlled with tritosulfuron + dicamba. For the control of wheat aphid (*Schizaphis graminum*), sulfoximines and pyrethroids were applied.

The experimental design used randomized blocks with four replications per treatment. The size of each experimental unit was four 10 m long rows, using 10 plants marked in the central part of the plot. Each block was separated by a one-meter row alley and a free furrow to delimit the treatments. An analysis of variance was performed to evaluate the effect of the treatments. The comparison

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of means was carried out using the Tukey HSD test at a 95% confidence level. The analysis was performed using RStudio (Team, 2023). The treatments (Table 1) were applied only once at the time of sowing, in bands on the slope of the furrow, prior to the emergence irrigation. In addition, two applications of microorganisms (*Trichoderma harzianum*, *Pseudomonas fluorescens*, *Bacillus subtilis*, and *Bacillus cereus*) were made at a concentration of $1x10^8$ CFU ml^{-1}, at the beginning of tillering and at the beginning of the stem elongation stage.

Table 1. Treatments applied to the *Borlaug 100 wheat variety during the 2023-2024 autumn-winter agricultural cycle.

Treatments	Description
1	50 kg ha^{-1} of agricultural gypsum with micronutrients (Fe, Cu, Zn, Mn)
2	25 kg ha^{-1} of agricultural gypsum with micronutrients (Fe, Cu, Zn, Mn)
3	50 kg ha^{-1} of agricultural gypsum with micronutrients (Fe, Cu, Zn, Mn) + humic and fulvic acids
4	25 kg ha^{-1} of agricultural gypsum with micronutrients (Fe, Cu, Zn, Mn) + humic and fulvic acids
5	Control without application

*= Norman E. Borlaug Experimental Field, located in the Yaqui Valley.

The variables evaluated were: soil pH at 15 and 30 cm every seven days until pH stability with a Hanna Hi981030 soil pH meter; nutritional analysis in flag leaf (Alcantar and Sandoval, 1999) at the start stage of grain filling, yield components [number of spikes m^{-2} (NGS), spike length (SL), spike weight (SW), grains/spike, grain length (GL), weight of one thousand grains, hectoliter weight (HW), total yield (Y)], protein with the Perten Instruments analyzer, DA 7250 NIR, sedimentation index using the SDS technique (Peña *et al.*, 1990), (%) of white belly and partial bunt by visual analysis.

Results and discussion

In the soil pH variable, significant differences were found between treatments ($p < 0.01$ and 0.001) in the 0-15 and 15-30 cm depth profiles across the three samplings (Figure 1). This is because cations (Fe^{2+}, Cu^{2+}, Zn^{2+}, Mn^{2+}) react with water in a process called acid hydrolysis, releasing hydrogen ions that acidify the soil. The lowest values, on average, were identified with doses of 25 kg ha^{-1} of agricultural gypsum with micronutrients, which registered pH values of 6.7, which facilitated nutrient absorption.

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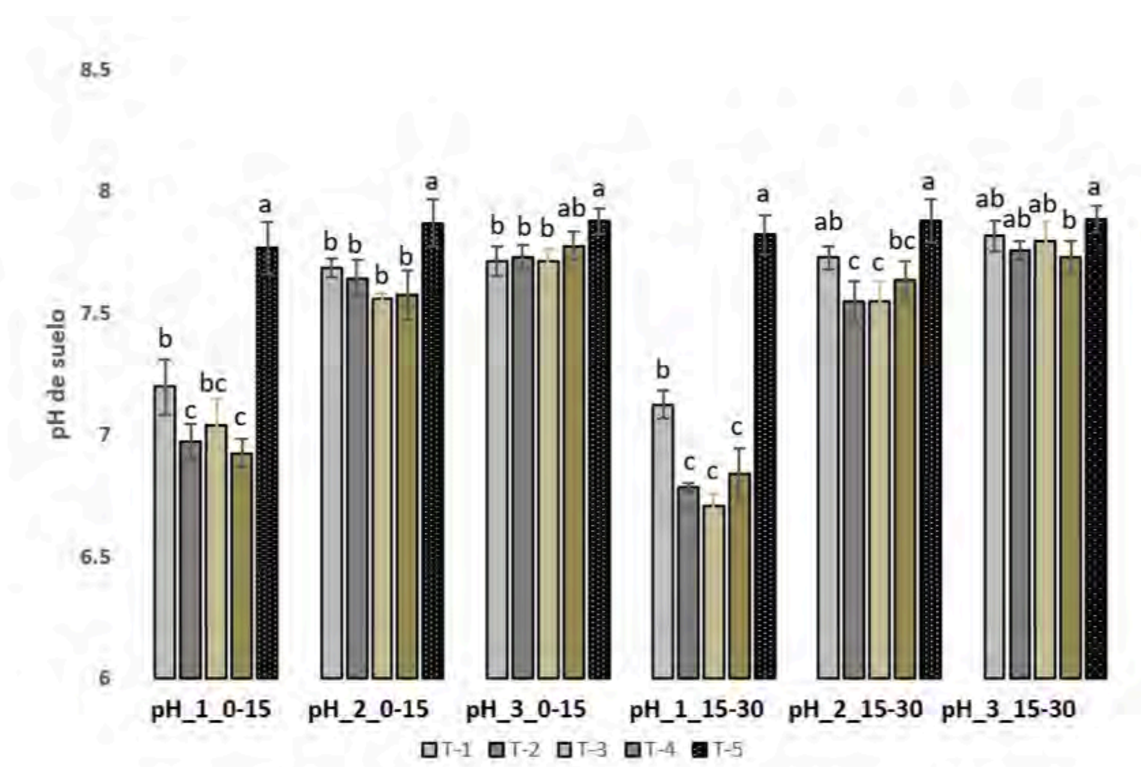
Figure 1. Effect of the application of agricultural gypsum with micronutrients (Fe, Cu, Zn and Mn) and humic and fulvic acids on soil pH, during the 2023-2024 agricultural cycle. 0-15: depth profile from 0 to 15 cm; 15-30: depth profile from 15 to 30 cm. Means with different letters indicate significant differences between treatments.



The initial pH of the soil was accompanied by an electrical conductivity of 2.6 dS m^{-1}, which classifies it as slightly saline. Based on the above, this level of salinity can hinder nutrient absorption, as confirmed by the nutritional analysis of the flag leaf. The control was the treatment that presented the lowest levels of micronutrients, according to the tables of sufficiency ranges for agronomic crops by Bryson and Mills (2014).

This is similar to what was pointed out by Ramírez *et al.* (2022), who highlighted the importance of electrical conductivity as an indicator that can provide basic information on nutrient assimilation in crops. This approach aligns with what was observed in treatment 5, where pH values remained constant from the beginning to the end of the evaluation, affecting nutrient availability.

For their part, Arroyo *et al.* (2022) mention that, when soil pH levels are elevated, the accessibility of most nutrients is compromised. In addition, Tóth *et al.* (2020) revealed that the acidic pH of the soil significantly impacts the antioxidant activity in wheat, which adversely affects the grain filling stage, leading to a decrease in the final yield. Therefore, it is essential to maintain a balance in the pH of the soil that allows adequate nutrient intake.

Agricultural gypsum with micronutrients temporarily lowers the soil's pH for a short period of time. In this work, this effect was observed up to the beginning of the stem elongation stage, which may allow the wheat crop to absorb nutrients from the soil. The ideal pH for most crops ranges from 6 to 7, as within this range, most essential nutrients are available in adequate amounts. However, some have specific availability ranges.

In the results of the nutritional analysis, Fe, Cu and Zn were increased by up to 24%, 35%, and 44%, respectively, in the treatments with a higher dose of agricultural gypsum, with or without humic and fulvic acids, compared to the control. Zn was one of the elements that presented the highest percentage in plant tissue. This coincides with Osorio-Vera et al. (2021), who note that wheat crops have a high demand for this element to achieve high yields.

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Treatments of agricultural gypsum with humic and fulvic acids increased Mn levels by 45% to 50% compared to the control. Once this element is in the plant, it can persist for long periods, carrying out various metabolic functions, which is attributed to its low mobility, as pointed out by Riesen and Feller (2005).

The foliar analysis (Table 2), agrees with Bryson and Mills (2014), who indicate that soils with a pH between 5 and 7 have higher levels of soluble Fe. They also indicate that the availability of P decreases as the pH exceeds 7; this reduction is associated with the interaction of P with higher levels of Ca and Mg available in high-pH soils. For their part, De Oliveira *et al.* (2020) note that most crops inefficiently utilize nitrogen fertilizer and that excessive fertilizer use is often employed as a preventive measure against potential deficiencies.

Table 2.Foliar nutrient analysis in the grain filling stage of the Borlaug 100 bread wheat variety, during the 2023-2024 agricultural cycle.

Treatments	N	P	K	Ca	Mn	Mg	Fe	Cu	Zn
	(%)						(ppm)		
1*	3.82	0.2	1.7	0.77	0.22	248.2	6.5	22.8	243.2
2*	3.36	0.2	1.58	0.75	0.19	225.7	6.1	22.4	275.2
3*	3.41	0.21	1.6	0.89	0.22	260.3	6.9	22.6	311.1
4*	3.38	0.22	1.57	0.77	0.2	231	6.3	21	324.1
5*	3.18	0.18	1.18	0.65	0.16	209.9	5.1	15.7	214

1*= 50 kg ha^{-1} of agricultural gypsum with micronutrients (Fe, Cu, Zn, Mn); 2*= 25 kg ha^{-1} of agricultural gypsum with micronutrients (Fe, Cu, Zn, Mn); 3*= 50 kg ha^{-1} of agricultural gypsum with micronutrients (Fe, Cu, Zn, Mn) + humic and fulvic acids; 4*= 25 kg ha^{-1} of agricultural gypsum with micronutrients (Fe, Cu, Zn, Mn) + humic and fulvic acids; 5*= control without application.

In this work, nitrogen fertilization was carried out based on a soil analysis, with the treatment of 50 kg ha^{-1} of agricultural gypsum without humic and fulvic acids being the one that increased the N content in the plant tissue by up to 22%. Nevertheless, these N levels are above what Bryson and Mills (2014) establish as the sufficiency range for wheat crops.

Table 3 presents the results of the yield component variables evaluated in this work. The mean SL ($p <$ 0.01) of T-3 exceeded the control by 3.5% and increased the NGS by up to 14%, with a significant difference ($p < 0.001$). This variable is the main component of yield variations, which agrees with Philipp *et al.* (2018), who reported high and positive correlations between these variables.

Table 3. Yield components of the Borlaug 100 bread wheat variety established in the Yaqui Valley during the 2023-2024 crop cycle.

Treatments	SL	SW	NGS	WGS	GL	HW	WTG	Y
1	10.79a	5.01a	63.82a	3.59a	0.69a	80.5a	56.5a	8a
2	10.07b	4.5c	58.65b	3.47a	0.69a	80.5a	56.7a	7.4ab
3	10.88a	4.89ab	65.25a	3.53a	0.7a	80.4a	56a	7.9a
4	10.56ab	4.52bc	57.12b	3.59a	0.7a	80.4a	57.2a	7.8ab
5	10.51ab	4.23c	57.17b	3.25a	0.7a	80.4a	56a	6.5b

SL= spike length (cm) $p < 0.01$; SW= spike weight (g) $p < 0.001$; NGS= number of grains/spike $p < 0.001$; WGS= weight of grains/spike (g); GL= grain length (cm), HW= hectoliter weight (kg hl^{-1}), WTG= weight of one thousand grains (g); Y= yield (t ha^{-1}) $p < 0.05$. Means with the same letter in the columns are not statistically different according to Tukey's test.

On the other hand, Feng *et al.* (2018) highlights that WTG has the highest effect on yield, only after NGS. Nonetheless, in WTG, we did not obtain significant differences between the different treatments. Villaseñor-Mir *et al*. (2021) used Borlaug 100 and Kronstad F2004 as controls when

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releasing the Bacorehuis F2015 variety, obtaining values of 75 kg hl^{-1} in all three varieties, 7% less than the results achieved with the application of agricultural gypsum. In the WTG variable, Chávez-Villalba *et al.* (2021) reported values 4 g lower than those of the control in the same locality, which presented the lowest values in most yield component variables.

The density of spikes and grains per m^2 was the most reliable parameter for evaluating the agronomic performance of materials (Espitia-Rangel *et al*., 2021). In the present research, these components demonstrated high sensitivity to management practices, which translated directly into the final yield. Statistical analyses revealed significant variations between treatments, with a 23%increase with the maximum application of agricultural gypsum with micronutrients. These same fertilization schemes recorded the highest concentrations of macro- and micronutrients in leaf tissue.

Likewise, Singh *et al.* (2021) demonstrated that an adequate nutritional balance enhances both the absorption and utilization efficiency of essential elements. In addition, Buenrostro-Rodríguez *et al.* (2024) identified that 240 kg of N ha^{-1} represents the optimal threshold for maximizing productivity, according to their response curves. Tsvey *et al.* (2021) emphasize that, despite being one of the most demanded nutrients, the low availability of nitrogen in the soil frequently limits its use by crops.

The publication by Yuan *et al.* (2021) added that moderate potassium (K)-based fertilization can be an effective practice for improving wheat crop productivity. Accordingly, Mazur *et al.* (2022) indicated that K and magnesium (Mg) contents have a strong positive effect on yield, which coincides with the results obtained in treatments three and four.

In the protein variable, significant differences were obtained (*p* # 0.05), with averages ranging from 11.65% to 11.2%, with treatments 1 and 2 presenting the best quality. There was a positive relationship between protein content and yield, which was influenced by the availability of nutrients in the soil. Nigro *et al.* (2019) point out that there is a negative correlation between grain yield and protein; that is, the most productive wheat expresses a lower protein content in the grain. In this sense, the results of Giancaspro *et al.* (2019) suggest that protein content is a trait of low gene expression, which is influenced by environmental conditions. This has been observed more frequently in early- and late-cycle wheat (Trivisiol *et al*., 2024).

The development of wheat grain depends mainly on the process of starch synthesis and accumulation (Liu *et al*., 2019; Xiao *et al*., 2022). The latter has the most significant effect on grain weight and yield. On some occasions, the grain lacks the right quality due to a high percentage of 'white belly' (starchy-looking spots). In this variable, the values were between 0.36% and 0.56%, which is due to the fact that the plant did not have greater N absorption needs, which generated a balance between protein and yield, which was reflected in the foliar analyses.

In the variable of partial bunt incidence, no significant difference was found between treatments despite the susceptibility of the variety. On the other hand, for the sedimentation index, values of 22.62 to 23.37 ml were obtained; however, no significant differences were found. Moreno-Araiza *et al*. (2020) note that this index is associated with the quality of the protein and, consequently, with a higher volume of bread. In addition, they indicate that when the definitive baking test is not carried out, it is necessary to evaluate both indicators.

In this study, the sedimentation/protein ratio of the different treatments ranged from 1.97 to 2.06, indicating excellent baking quality and an ideal balance between the concentration and functionality of gluten proteins (Peña *et al.*, 1990).

Conclusions

The use of agricultural gypsum with micronutrients can become an option for alkaline soils, since it caused a temporary acidity for a period of no more than thirty days following application, due to the presence of sulfates. These generate acid hydrolysis, which releases hydrogen ions and lowers the soil's pH. A slightly acidic pH makes it easier for the plant to absorb nutrients, so proper nutrition in wheat crops can lead to an increase in yield and grain quality.

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The treatment that best responded to nutrient absorption, observed during the grain filling stage, was the one containing a dose of 50 kg ha^{-1} of agricultural gypsum with Fe, Cu, Zn, and Mn. This increased yield, mainly in length, weight, and number of grains per spike. Nevertheless, the best grain quality was obtained in those treatments that do not include humic and fulvic acids.

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