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EFFECT OF PHOSPHORUS-ZINC (P-ZN) INTERACTION IN CALCAREOUS TORRIFLUVENT SOIL ON WHEAT (*TRITICUM ASTEVUM* L.) YIELD

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Abstract

A factorial pot experiment in split-split plot design was carried out to study the effect of phosphorus-zinc (P-Zn) interaction in calcareous Torrifluvent soil on wheat (*Triticum astevum* L.) yield, concentration and content of P and Zn in grain and straw. Phosphorus, as triple superphosphate (TSP), was added to soil at three rates (0, 30 and 60 mg P_2O_5 kg^{-1} soil, symbolized P_0, P_{30} and P_{60}, respectively). Zinc also was applied at three rates (0, 10 and 20 mg kg^{-1} soil, symbolized Zn_0, Zn_{10} and Zn_{20}, respectively). Two Types of zinc carriers were also examined, *i.e.* sulphate (Zn-Sulphate) and ethylene diamine tetra acetic acid (Zn-EDTA). Results showed a positive significant effect of P-Zn interaction on grain yield, straw yield, concentration and content of P in grain and straw, Zn content in grain. Whereas, the grain-Zn concentration decreased with increasing phosphorus level. The highest grain and straw yields were at the treatment $P_{60}\times Zn_{20}$-sulphate. The highest grain-P concentration (0.2501 mg kg^{-1}) and content (20.72 g pot^{-1}) were at the treatment $P_{60}\times Zn_{10}$-sulphate, while the lowest grain p concentration (1.973 mg kg^{-1}) and content (10.70 g pot^{-1}) were at $P_0\times Zn_0$ treatment. Interaction treatment $P_{60}\times$Zn-sulphate was the superior in grain and straw yields, grain-P concentration and grain-P content per pot. No-significant effect was recorded among Zn sources at P_{30} in all the studied traits. Whereas significant differences in grain yield, grain-P content and grain-Zn content among the two sources at P_{60} treatments were found.

Key words: Zn-sulphate, Zn-EDTA, P-Zn interaction, Calcareous soil, Wheat.

Introduction

Zinc and phosphorus are the main components of many enzymes and compounds which control plant growth and productivity. Zinc contributes to cell division, protein synthesis, transformation and consumption of carbohydrates, pollen tube formation, seed and grain formation, chlorophyll and auxin synthesis and biomembranes integrity (Pandey, *et al*., 2006; Alloway, 2008; Storey, 2015).

Phosphate play role in photosynthesis, respiration, cell division and enlargement, the transformation of sugars and starches, energy storage and transfer, nutrient movement within the plant and transfer of genetic characteristics from one generation to the next (Mengel and Kirkby, 2001). Also, organic and inorganic phosphates act as a buffer in the maintenance of plant cellular pH (Hopkins, 2015).

Iraqi soils classified within the severely zinc-deficient soils. Irrigated soils in the Mesopotamian plain (Entisol and Aridisol) and the dry farming soils, in the north part of Iraq (Mollisolls, Vertisols and Inceptisols), were the lowest in the international Zn fields (Sillanpââ, 1982). So, crops grown in such as soils, especially cereals crops, show zinc deficiency (low tissue zinc concentration), growth reduction, low yield, and low zinc concentration in grains. Wheat is the main component of food for Iraqi community. Hence, zinc and other micronutrients content in wheat grains must take high attention to Iraqi people's health, especially children. A mild to moderate zinc deficiency among 55.7% of 2090 healthy subjects (aged 1 month to 85 years) was recorded in Baghdad city by Al-Timimi *et al*., 2005. They reported that the lower mean concentration of Zn-serum was in infants, children, and older ages (50-85 years) compared to adolescents and adults (<50 years).

Retention, precipitation and dissolution are the processes which controlling P availability. In calcareous soils, these governed by soil pH, carbonate minerals,

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soluble Ca and Mg, iron oxides and hydrous oxides, soil mineralogy, clay content, organic matter content, and soil water (Menel and Kirkby, 2001; Hopkins, 2015). In addition to these factors, zinc availability is controlled also by total soil zinc, manganese and iron oxides, CEC, redox potential, phosphate ion, and zinc carrier (Al-Hadethi *et al*., 2001; Catlett *et al*., 2002; Obrador *et al*., 2003; Wang and Dustin, 2005; Al-Tamimi, 2006; Alloway, 2008).

Abroad studies showed contradictory views about the interaction among zinc and phosphate ions and their effect on plant nutrition and yield. Many workers reported a negative effect of interaction among these two ions. This may be due to their interaction in soil solution (Agbenin, 1998), or to a reduction in zinc diffusion coefficient in soil with phosphate addition in case of Zn addition or not (Melton *et al*., 1973). Also, the negative effect may be due to reduction in zinc transport coefficient from roots to upper shoots (Singh *et al*., 1988) or the irregularity of metabolism in plant cells due to nutritional disturbance among zinc and phosphate (Loneragan *et al.,* 1979). Other workers reported that high P had indirectly a negative effect on Zn content in plant tissue. This was due to the reduction in Zn activity as a result of it's interacting with the other micronutrients (Barben *et al.,* 2007, 2010). On the contrary, many other workers mentioned a positive interconnection among the two ions (Dravid and Goswami, 1986; Arshed *et al*., 2016). They mentioned that the addition of phosphate increased dry matter yield, zinc uptake, and zinc concentration in plant tissue. Other researchers believe that phosphate addition does not affect plant content of zinc, and the reduction of its concentration in plant tissue related to plant growth increase (dilution effect) (Singh *et al.*, 1988; Soltangheisi *et al.*, 2014). This contradiction of opinion may be due to neglecting plant variety and class. Recently this opinion was confirmed by the results of many workers. Bouain *et al.*, (2014) and Khan *et al.*, (2015) reported a contrast effect of P-Zn interaction on growth, grain yield, biomass, photosynthesis, and concentration of the two ions with a differing genotype of the cultivar.

Nearly 80% of Iraqi soils are calcareous, while the rest gypsiferous. These soils have alkaline pH, high soluble calcium and magnesium, low concentration of available P and Zn. Thus, addition of these two elements is essential for crops fortification, economic yield and public health. Many workers reported the response of crops cultivated in Iraqi soils to the addition of P or Zn. Whereas very few studies published dealing with the interaction of combined addition of these two elements to Iraqi soils using corn plant mainly. This work was conducted to assess the interconnection effect of combined addition of Zn and P to highly calcareous Typic Torrifluvent silty clay soil on wheat yield, P and Zn concentration on grain, and to clarify the effect of zinc carrier type.

Materials and Methods

Biological Experiment

A surface sample (0-30 cm) was collected from calcareous Typic Torrifluvent soil from Al-Raied Agricultural Project, in Abu-Ghraib, Central Iraq. Table 1 illustrates some chemical properties of the used soil and particle size distribution.

The soil was air-dried, sieved through a 4 mm sieve. A 3500 g of the soil was packed in each plastic pot over a 500 g of clean water washed fine gravel. The first dose of N (30 mg N kg^{-1} soil) and all dose of K–fertilizer (15 mg K_2O kg^{-1} soil) was incorporated with the soil before sowing, while the second dose of N (equal to the first dose) was added 3 weeks after emergence. Concentrated calcium superphosphate was incorporated with soil before sowing at three levels (0, 30 and 60 mg P_2O_5 kg^{-1} soil). All treatments of zinc (Zn-sulphate and Zn-EDTA) were added as a solution at three levels (0, 10 and 20 mg Zn kg^{-1} soil). Ten seeds of wheat (*Triticum astevum* L.), Eba-99 variety were sown in each pot, then thinned to eight one week after emergence. Irrigation was carried out using gravimetric method to compensate lost water when soil moisture reaches 75% of field capacity. Spikes and air shoots were harvested at physiological maturity, oven-dried at 65^{0}C until constant weight.

Laboratory Analyses

Plant tissue was digested using concentrated HNO_3 and perchloric acid, 72%. Available soil phosphorus was extracted using 1 M sodium bicarbonate as proposed by Olsen, and determined calorimetrically using ammonium molybdate method modified by Watanabe and Olsen. Phosphorus in plant tissue was determined calorimetrically using ammonium vanadate method. Soil available zinc

Table 1: Some chemical and physical properties of the soil used in the experiment.

EC_e dS m^{-1}	pH	ECC g kg^{-1}	OM Cm^+kg^{-1}	CEC mg kg^{-1}	DTPA Zn mg kg^{-1}	Olsen P	Clay g kg^{-1}	Silt	Sand	Texture
3.8	7.4	250	13	26	0.7	4.5	440	410	150	Silty Clay

EC_e: Electrical conductivity of the paste extract;
ECC: equivalent calcium carbonate; OM: Organic matter; CEC: Cation exchange capacity.

was extracted using DTPA method proposed by Lindsay and Norvell. Zinc in soil and plant samples were determined using Atomic Absorption Spectrophotometer. EC_e and pH were determined at soil paste extract using conductometric and potentiometric methods, respectively. Carbonate minerals equivalent was determined by gravimetric method. Cation exchange capacity was determined using power's method. Organic carbon was determined using the modified method of Walkley-Black. All previous chemical analyses were executed as described in Al-Tamimi (2016). Particle size distribution was carried out using the pipette method as was described by Bouyoucos, 1962.

Statistical Analysis

Analysis of variance (ANOV) for data was carried out using GenStat software program. Least significant differences at 5% was used to compare variance among means of the treatments.

Results and Discussion

Interaction among zinc levels and phosphorus levels

Statistical analysis results showed that grains yield was significantly ($p<0.05$) affected by the interaction of P-Zn levels added to the soil table 2. Grain yields were 7. 014, 6.711 and 7.302 g pot^{-1} at the treatments $P_{30}Zn_0$, $P_{30}Zn_{10}$ and $P_{30}Zn_{20}$, respectively. While it was 7.900, 7.820 and 8.296 g pot^{-1} at the treatments $P_{60}Zn_0$, $P_{60}Zn_{10}$ and $P_{60}Zn_{20}$, respectively. The highest grains yield (8.296 g pot^{-1}) was at the interaction treatment $P_{60}Zn_{20}$ with a relative increment over the treatments P_0Zn_0, $P_{60}Zn_0$ and $P_{30}Zn_{20}$ of 28.2 %, 5.0 % and 13.6 %, respectively. These results confirmed that grains wheat yield enhanced with the highest levels of P and Zn. This may be due to the addition of these two ions at high levels improve the nutritional balance of these two elements in the calcareous soil and provides the plant with its need of P and Zn. This is due to the many functions of P and Zn in the vital construction processes. Insufficient providing plant with P and/or Zn negatively affects its growth and production. This finding was in line with the results of Khan *et al.*, 2015 and Arshad *et al.*, 2016 who mentioned a positive relationship among these two ions added to soil and increased grains yield of wheat.

Analysis of data also revealed that interaction treatments of the second and third levels of P with Zn_{10} ($P_{30}Zn_{10}$ and $P_{60}Zn_{10}$ treatments) had a non-significant negative effect on grains yield compared to the treatments $P_{30}Zn_0$ and $P_{60}Zn_0$ table 2. Whereas increasing the levels of added Zinc ($P_{30}Zn_{20}$ and $P_{60}Zn_{20}$ treatments) increased grains yield significantly. This results cannot be well explained. It might be due to nutrient imbalance, which was overcame with increasing the added level to Zn_{20}.

Results in table 2 confirmed a significant increase ($p<0.05$) in straw yield as a result of combined addition of P and Zn in comparison to control treatment (P_0Zn_0), While the significant and non-significant decrease was noticed at the interaction treatment $P_{30}Zn_{10}$ and $P_{30}Zn_{20}$, respectively compared to $P_{30}Zn_0$. Interaction treatment $P_{60}Zn_0$ gives the highest straw yield (11.128 g pot^{-1}), exceeded non-significantly the other two treatments of Zn with the highest level of P ($P_{60}Zn_{10}$ and $P_{60}Zn_{20}$) and significantly all treatments of Zn with P_{30} ($P_{30}Zn_0$, $P_{30}Zn_{10}$ and $P_{30}Zn_{20}$). This may be due to the effect of the combined application of the two elements were more obvious in increasing grain yield compared to straw yield (Khan *et al.*, 2015). The increment in straw yield with increasing added phosphorus from P_{30} to P_{60} with the addition of Zn_0, Zn_{10} and Zn_{20} were 12.37%, 20.97% and 11.27%, respectively. This result was in line with the results of Khan *et al.,* 2015 who reported that Zn was more effective in increasing straw and grain yield at higher levels of P application.

Results in table 2 indicated also a significant ($p<0.05$) effect among P levels × Zn levels added to the soil on grain-P concentration. Means of grain-P concentration were 2.067, 2.247 and 2.097 mg kg^{-1} at the treatments $P_{30}Zn_0$, $P_{30}Zn_{10}$ and $P_{30}Zn_{20}$, respectively. Whereas the means were 0.2271, 0.2421 and 0.2270 mg g^{-1} at the treatments $P_{60}Zn_0$, $P_{60}Zn_{10}$ and $P_{60}Zn_{20}$, respectively. Interaction treatment $P_{60}Zn_{10}$ gave the highest grain-P concentration (2.421 mg g^{-1}) with an increment of 0.448 mg kg^{-1} (22.7%), followed by the treatment $P_{60}Zn_{20}$ (2.270 mg kg^{-1}) with an increment of 0.297 mg kg^{-1}

Table 2: Interaction effect of Zn-P levels on some studied properties.

Added, mg kg^{-1}		grain yield	straw yield	P mg. kg^{-1} in grain	Zn µg g^{-1} in grain	P, grain mg pot^{-1}	Zn, grain µg pot^{-1}
P	Zn	g pot^{-1}					
0	0	5.424	7.411	1.973	16.200	10.698	87.869
	10	5.552	7.786	2.067	24.950	11.350	138.522
	20	5.558	7.656	2.128	25.294	11.741	140.584
30	0	7.014	9.960	2067	14.497	14.499	101.682
	10	6.711	9.030	2.247	23.968	15.087	160.849
	20	7.302	9.687	2.097	23.018	15.312	168.077
60	0	7.900	11.192	2.271	14.324	17.939	113.160
	10	7.820	10.924	2.421	22.638	18.982	177.029
	20	8.296	10.779	2.270	22.822	18.832	189.331
$LSD_{0.05}$		0.4273	0.5131	0.069	0.7247	1.101	7.322

(15.0%) compared to control treatment (P_0Zn_0). All levels of P × Zn levels resulted in a significant increase in the grains-P compared to the control treatment. Increasing the concentration of added Zn from Zn_{10} to Zn_{20} decreased the percentage of grains-P concentration at both levels of P addition. It decreased from 2.247 and 2.421 mg g^{-1} at the treatments $P_{30}Zn_{10}$ and $P_{60}Zn_{10}$, respectively to 2.097 and 2.270 mg g^{-1} at the treatments $P_{30}Zn_{20}$ and $P_{60}Zn_{20}$, respectively. This result was in agreement with the result of Khan *et al.,* 2015 who reported that application of P increased whereas Zn application decreased the concentration of grain P. This result was related to growth increase of plant shoot and yield with increasing phosphorus and zinc levels (dilution effect). Grain P content per pot (Table 2, column 5) confirmed this conclusion. The highest grain P content (18.980 mg pot^{-1}) and the lowest (10.698 mg pot^{-1}) were in the treatments $P_{60}Zn_{10}$ and $P_{60}Zn_{20}$, respectively. This result was consistent with the results of Khan *et al*., 2015; Imran *et al*., 2015 and Arshad *et al.,* 2016 who found that the combined addition of P+Zn increased grain P content in wheat and maize more than sole addition.

Data shown in table 2 emphasized that zinc concentration in grain increased significantly ($p<0.05$) with increasing level of added zinc at all levels of P addition. The lowest concentrations were 14.497 µg g^{-1} and 14.324 µg g^{-1} at the treatments $P_{30}Zn_0$ and $P_{60}Zn_0$, respectively. Significant reduction in zinc concentration at these two treatments in comparison with the control treatment (P_0Zn_0) was related to Zn dilution due to increased grain yield due to P addition. This result was in line with the result of Sacristán *et al*., (2018) on calcareous soils. The total content of grain-Zn per pot (last column in table 2) reinforces this conclusion. Its content was 87.869 at control treatment, whereas increased significantly ($p<0.05$) to 101.682 and 113.160 µg pot^{-1} at the treatments $P_{30}Zn_0$ and $P_{60}Zn_0$, respectively. The highest zinc grain concentrations (24.950 and 25.294 µg g^{-1}) were at the treatments P_0Zn_{10} and P_0Zn_{20}, respectively. While the total grain-Zn content at these two treatments was the lowest (138.522 and 140.584 µg pot^{-1}, respectively) compared to the other interaction treatments received Zn_{10} and Zn_{20}. This finding explained that combined addition of P+Zn increased plant Zn uptake more than sole application. The treatment $P_{30}Zn_{10}$ was superior in grain Zn concentration among the other P×Zn interaction, *i.e.* $P_{30}Zn_{20}$, $P_{60}Zn_{10}$ and $P_{60}Zn_{20}$. Whereas the highest content of Zn in grain (189.331 µg pot^{-1}) was at the treatment $P_{60}Zn_{20}$. This result confirms the dilution effect factor with increasing the level of added P and Zn.

Table 3: Interaction effect of P levels and Zn source on some studied properties.

Added P, mg kg^{-1}	Zn Source	grain yield	straw yield	P mg. kg^{-1} in grain	Zn µg g^{-1} in grain	P, grain mg pot^{-1}	Zn, grain µg pot^{-1}
		g pot^{-1}					
0	Zn-Sulphate	5.636	7.693	2.039	21.664	11.396	122.098
	Zn-EDTA	5.387	7.542	2.073	22.632	11.130	121.918
30	Zn-Sulphate	7.019	9.607	2.114	20.492	14.838	143.833
	Zn-EDTA	6.999	9.511	2.160	20.497	15.123	143.458
60	Zn-Sulphate	8.303	11.128	2.328	19.699	19.332	163.560
	Zn-EDTA	7.708	10.802	2.312	20.157	17.817	155.370
$LSD_{0.05}$		0.356	0.429	0.600	0.717	0.855	6.941

Interaction among zinc source and phosphorus levels

Results in table 3 showed non-significant differences ($p<0.05$) in grain yield among the two sources of Zn at P_0 and P_{30} addition levels. Whereas significant difference in grain yield among the two sources of Zn was found with increasing phosphorus addition levels to P_{60}. We can conclude that at P_{30} level, each source of Zn was able to supply the plants with an adequate amount of Zn necessary to carry through its vital activities. Addition of phosphorus at P_{30} and P_{60} increased grain yield significantly with both two sources of Zn compared to P_0×Zn-sources. Also, significant differences was notice in grain yield among the two sources of Zn with increasing phosphorus from P_{30} to P_{60}. The lowest grain yield was at the treatment P_0×Zn-EDTA, and the highest grain yield was at the treatment P_{60}×Zn-sulphate. This confirmed the result mentioned previously that P-Zn interaction had a positive effect on grain yield and Zn are more effective at the higher P application level. This result may be due to the rule of combined addition of P and Zn at high levels in reducing P and Zn deficiency stress and best correction of nutrition balance among these two elements at higher addition levels in calcareous soil.

Interestingly, P_{60}×$ZnSO_4$ was superior in grain yield (8.303 g pot^{-1}) with a significant increase ($p<0.05$) in comparison with P_{60}×Zn-EDTA. This cannot be well explained. It may be due to the rule of sulphate as plant nutrition ion. Similarly, the differences among Zn-sulphate and Zn-EDTA effect on straw yield was at the same trend as with grain yield. The lowest straw yield was noticed at P_0×Zn-EDTA, while the highest straw yield was at P_{60}×Zn-sulphate. Non-significant differences in straw yield were noticed among the tow sources of Zn at each level of P addition table 3.

Non-significant differences in grain-P concentration were noticed among the two sources of Zn at each level of P addition. Whereas grain-P concentration significantly increased ($p<0.05$) with increasing addition levels to P_{30} and P_{60} with both sources of Zn table 3. The lowest grain-P concentration (2.039 mg kg^{-1}) was in P_0×Zn-sulphate treatment, and the highest (2.328 mg kg^{-1}) in P_{60}×Zn-sulphate treatment. This result confirmed the positive effect of combined addition of P and Zn to the soil on P percentage. Grain-P per pot reinforced this opinion. It increased with increasing P level, with significant differences ($p<0.05$) among the three levels of P. While significant difference ($p<0.05$) among Zn-sources was notice at P_{60} only. The highest P content per pot was 19.332 mg pot^{-1} at P_{60}×Zn-sulphate.

Obtained data table 3 also showed that the combined addition of P and Zn decreased grain-Zn concentration significantly. Whereas a non-significant difference was noticed among the two sources of zinc at each level of addition (P_{30} and P_{60}). The highest grain-Zn concentration was (22.632 µg g^{-1}) at P_0×Zn-EDTA followed by the treatment P_0×Zn-sulphate (21.664 µg g^{-1}), with a significant difference among them. The lowest grain-Zn concentration (19.699 µg g^{-1}) was at P_{60}×Zn-sulphate. This was related to grain yield increasing (dilution effect). Grain-Zn content support this conclusion. It was increased with increasing P level with a significant difference among the two sources of Zn at P_{60} level only. The highest Zn content (163.560 µg pot^{-1}) was at P_{60}× Zn-sulphate.

Table 4: Interaction effect of P levels, Zn levels and Zn source on some studied properties.

P	Zn source mg kg^{-1}	Zn level g pot^{-1}	grain, g pot^{-1}	straw, mg kg^{-1}	grain-P in grain	Zn µg g^{-1} mg pot^{-1}	P, grain µg pot^{-1}	Zn, grain
	$ZnSO_4$	0	5.424	7.411	0.1973	16.200	10.70	87.869
		10	5.880	8.070	0.2048	24.483	11.80	143.960
		20	5.604	7.598	0.2095	24.309	11.69	136.227
0	Zn-EDTA	0	5.424	7.411	0.1973	16.200	10.70	87.869
		10	5.224	7.502	0.2086	25.417	10.90	132.778
		20	5.512	7.715	0.2161	26.278	11.79	144.844
	$ZnSO_4$	0	7.014	9.960	0.2067	14.497	14.50	101.682
		10	6.799	9.238	0.2290	23.993	15.56	163.792
		20	7.244	9.623	0.1985	22.987	14.38	166.518
30	Zn-EDTA	0	7.014	9.960	0.2067	14.497	14.50	101.869
		10	6.623	8.822	0.2204	23.943	14.61	158.574
		20	7.361	9.752	0.2210	23.050	16.26	169.671
	$ZnSO_4$	0	7.899	11.024	0.2277	14.284	17.99	112.829
		10	8.276	10.899	0.2501	22.297	20.72	184.530
		20	8.733	11.462	0.2208	22.517	19.28	196.641
60	Zn-EDTA	0	7.902	11.360	0.2265	14.364	17.89	113.504
		10	7.364	10.949	0.2341	22.980	17.24	169.133
		20	7.858	10.097	0.2331	23.127	18.32	181.732
$LSD_{0.05}$			0.5318	0.7644	0.0020	0.8003	1.444	8.301

Interaction among zinc source, Zinc levels and phosphorus levels

Table 4 explained the interaction effect of Zn source × Zn level × P level. Results confirmed that the interaction among the three studied factors was significantly ($p<0.05$) increased grain yield, straw yield, grain-P concentration, grain-P content, and grain-Zn content. The highest grain and straw yields (8.733 and 11.462 g pot^{-1}, respectively) were at the treatment P_{60} × Zn_{20}-sulphate, whereas the treatment P_0 × Zn_0-sulphate and Zn_0-EDA had the lowest grain and straw yields (5.424 and 7.411 g pot^{-1}, respectively). The highest values of grain-P concentration (2.501 mg kg^{-1}) and grain-P content (20.72 mg pot^{-1}) were at the treatment P_{60} × Zn_{10} sulphate, whereas the lowest values of grain-P concentration (1.973 mg kg^{-1}) and grain-P content (10.70 mg pot^{-1}) were at P_0 × Zn_0-sulphate and Zn_0-EDTA treatments.

The highest (26.278 µg g^{-1}) and the lowest (14.284 µg g^{-1}) concentration of Zn in grain were at the treatments P_0 × Zn_{20}-EDTA and P_{60}×Zn_0-sulphate, respectively. Whereas the highest Zn content in grain (196.641 µg pot^{-1}) and the lowest (87.869 µg pot^{-1}) were at the treatments P_{60} × Zn_{20}-sulphate and (P_0 × Zn_0-EDTA and P_0 × Zn_0-sulphate), respectively.

This result confirmed that the interaction among the three studied factors positively affects grain and straw yields, grain-P concentration and content, grain-Zn content, and negatively grain-Zn concentration.

In conclusion, the combined addition of P+Zn to the highly calcareous Torrifluvent soil increased grain yield, straw yield, % grain-P, grain-P content, and grain-Zn content, while grain-Zn concentration decreased. High levels of P and Zn were superior for high yield and fortification with P and Zn. Sulphate carrier was better than EDTA at a high level of P addition. The best interaction treatment for yield and grain-Zn content was P_{60} × Zn_{20}-sulphate.

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