Article

Not peer-reviewed version

Effect of Phosphorus and Zinc Fertilization on Yield and Nutrient Use Efficiency of Wheat (*Triticum aestivum* L.) in Tigray Highlands of NORTHERN ETHIOPIA

Mulugeta Sebhatleab *, Girmay Gebresamuel, Gebreyohannes Girmay, Yemane Tsehaye, Mitiku Haile

Posted Date: 8 February 2025

doi: 10.20944/preprints202502.0605.v1

Keywords: phosphorus & zinc; balanced application; wheat nutrtional quality; food security; Tigray

Article

Effect of Phosphorus and Zinc Fertilization on Yield and Nutrient Use Efficiency of Wheat (*Triticum aestivum* L.) in Tigray Highlands of NORTHERN ETHIOPIA

Mulugeta Sebhatleab [1,*], Girmay Gebresamual [1], Gebreyohannes Girmay [1], Yemane Tsehaye [2] and Mitiku Haile [1]

[1] Land Resources Management and Environmental Protection, Mekelle University

[2] Dry Land Crop and Horticulture Sciences, Mekelle University

* Correspondence: mulusk96@gmail.com; Tel.: +251-914726755

Abstract: Wheat is a vital staple crop addressing significant nutritional needs. However, it faces micronutrient deficiencies in Ethiopia, prompting use of balanced nutrient fertilizers to obtain better yields, nutrient concentration, and nutritional quality. This study investigated the effect of different P and Zn fertilizer combinations on wheat yield and nutrient efficiency across three locations (i.e., Adigolo, Seret, and Mekelle sites) in Tigray, Ethiopia. A randomized complete block design (RCBD) was used with four P levels (0, 10, 20, 30 kg P ha^{-1}), three Zn levels (0, 5, 10 kg Zn ha^{-1}) in three replications. Results varied across locations due to differences in climate and topography. Balanced application of P and Zn fertilizers significantly increased wheat grain and biomass yields while applying higher rates of both nutrients (i.e., 30 kg P ha^{-1} and 10 kg Zn ha^{-1}) reduced yields. The combined application of 20 kg P ha^{-1} and 5 kg Zn ha^{-1} achieved the best yield which also improved Zn and P use efficiency. This combination maximized yield and zinc bioavailability for supporting food security in diverse agro-climatic conditions.

Keywords: phosphorus & zinc; balanced application; wheat nutrtional quality; food security; Tigray

---

1. Introduction

Wheat is one of the dominant staple food crops in the world. It is the leading among grain crops in coverage and production [1] and provides a major share of nutritional requirements for the world population [2]. Ethiopia has largest area (1.87 million ha^{-1}) of wheat production in Africa but its yield (3.1 t ha^{-1}) is low compared for example to that of 4.4 t ha^{-1} in South Africa [3]. Most cereal crop production especially wheat and barley are grown on soils often deficient in nitrogen, phosphorus and micronutrients [4].

Phosphorus (P) and nitrogen (N) deficiencies are widespread in the global cereal production systems [5]. Similarly, P and N deficiencies are common [6] in Ethiopia, with 80-90% of soil samples from the highlands contain P levels below 10 mg kg^{-1} [7,8] and N levels below 0.1% [7,8]. The application of P fertilizers has shown increase in wheat grain yield by up to 30% [7], and of N by up to 96%[9]

While optimal use of N and P fertilizers significantly boost wheat yield, continuous application can however lead to deficiencies in other essential nutrients such as zinc (Zn), iron (Fe), and sulfur (S) [10,11]. Phosphorus deficiency often occurs alongside deficiencies in nitrogen, sulfur, zinc, boron, and molybdenum [8,12] further indicating to a need to refine P application rates based on crop type, nutrient interactions, soil conditions, and agro-ecological zones [13]. High phosphorus application can induce zinc deficiency in soils [14]. In soils with low available zinc, the phosphorus content in leaf dry matter can exceed 0.24%, reaching toxic levels [15]. Zinc and Fe deficiencies are widespread in the sub-Saharan Africa [16]. The deficiency of these nutrients has resulted in "hidden hunger"

 doi:10.20944/preprints202502.0605.v1

where the soil lacks micronutrients sufficient for optimal plant health. In Ethiopia, with 98% of soil samples in the highlands being Zn deficient [17], Zn deficiency poses significant challenges to crop productivity and human health [18]. A study [19] also found that 72% of the population was zinc deficient.

Zinc is an essential trace element in the nutritional requirements of crop plants, animals, and humans [20,21]. The prevalence of zinc deficiency varies spatially, suggesting the need for targeted interventions [19]. Reports showed that above 30% of global soils on average were deficient in Zinc [22]. Several studies verified that the fertilization of Zn to deficient soils has significantly increased the yield of crops [23–27]. Wheat (*Triticum aestivum L.*), grain Zn content commonly ranges between 20–35 mg kg^{-1} [28]. Enhancement of Zn concentrations beyond 40 mg kg^{-1} in wheat [29] is an important global challenge. However, researchers stated that Zn uptake by plants is adversely affected by factors like soil pH, organic matter content and amount of phosphorus applied to the soil [14,30].

Ethiopia has been promoting blended multi-nutrient fertilizers since 2015 [31] to address micronutrient depletion caused by continuous use of only N and P fertilizers [32,33]. By incorporating a mix of micronutrients tailored to different regions' specific soil needs; Ethiopia's multi-nutrient fertilizer strategy supports a more holistic approach to soil management. The promotion of blended fertilizers has been supported by research and pilot projects aiming to determine the specific nutrient profiles required for various crops and soils across Ethiopia's diverse agro-ecologies. The country aims to increase crop productivity, enhance resilience to environmental stresses and nutritional value of food, contributing to better food security and health outcomes.

Zinc content in the NPSZn blended fertilizer, at around 2.5 to 3.3 kg Zn ha^{-1}, is notably lower than the average application rate ranging 5 to 15 kg ha^{-1} to effectively address soil deficiencies and improve both yield and protein content of wheat [34]. And the current application rates do not sufficiently meet the micronutrient needs of Ethiopia's soils, especially in areas with significant Zn deficiencies, such as the Tigray region [35]. The phosphorus application and utilization hinders uptake of Zinc by a plant [36]. The effective way to reduce the problem could be by application of Zn containing fertilizer to soil considering P fertilizer rates [37].

A study on faba-bean revealed that the combined application of inoculants, P, and Zn fertilizers significantly increased grain yield, nutrient uptake, and nodulation [38,39]. These findings highlight the importance of considering P and Zn interactions in crop nutrition management, especially in calcareous soils. However, there is a lack of information on effects of P and Zn interaction on yield and nutrient use efficiency of wheat in Ethiopia.

Thus, this study aims at establishing optimum rates of Zn and P fertilizers for better yield and nutrient use efficiency of wheat grown in selected locations of Tigray, Northern Ethiopia. Obtaining full understanding on combined rates of P and Zn fertilizer application, and their interactions on yield and nutrient uptake of staple cereals in specific geographical contexts will enhance bioavailability of Zn for improved food and nutritional security in the highlands of Ethiopia.

2. Materials and Methods

2.1. Description of Experimental Sites

This study was conducted on farmers' plots in Seret (Degua Temben Woreda), Adigolo (Ofla Woreda) and Mekelle (Mekelle University research field) in Tigray, northern Ethiopia (Figure 1). Seret and Adigolo are situated in Tepid to Cool Sub-Moist Mountains and Plateau (SM2-5), and Meklle site is in Tepid to Cool Sub-Moist Mid Highland (SM2-8) sub-agro ecological zones. These sites have mixed farming systems. Cereal crops like wheat, barley, teff and maize and pulses like faba bean, peas and lentiles are dominant grown.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2025 doi:10.20944/preprints202502.0605.v1

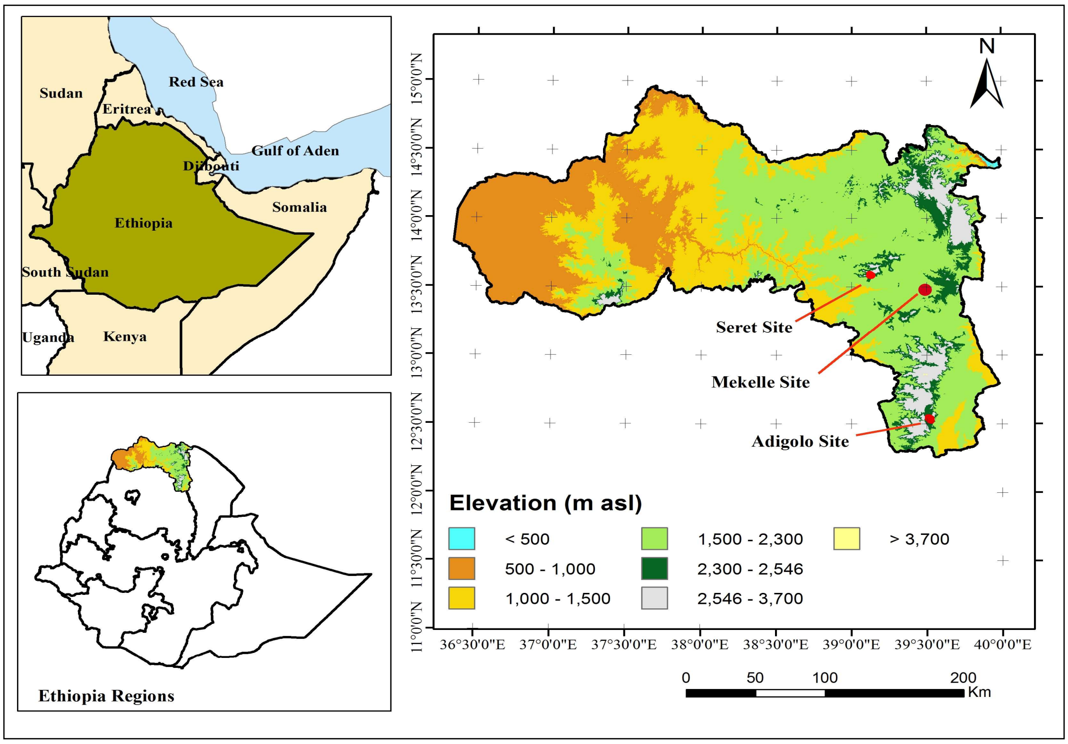
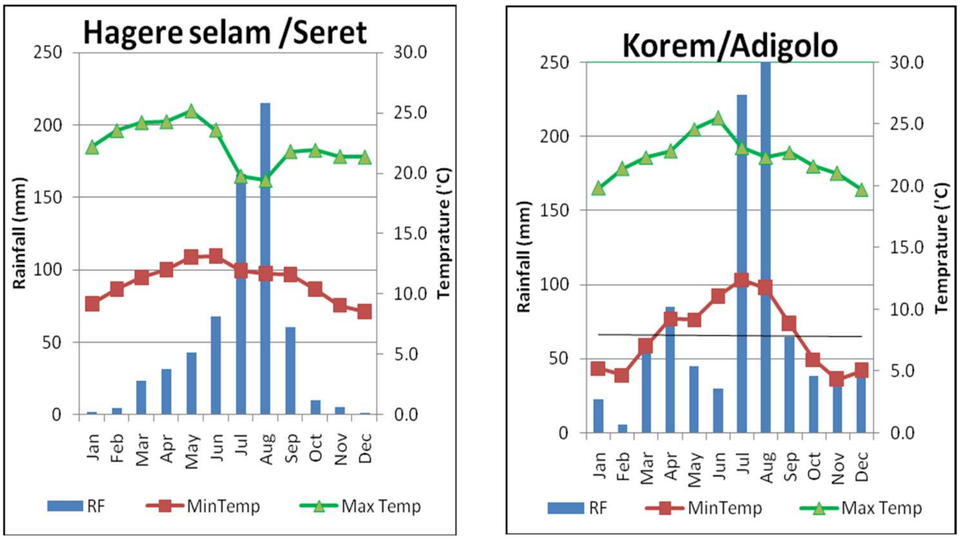


Figure 1. Location map of the study areas.

Mekelle and Seret are characterized with dry climate during September to May and rainfall season during July to August. Adigolo has a bimodal rainfall with main rain season from July to September and short rains during February to April. The mean annual rainfall at the Mekelle site was about 618 mm, 760 mm at Seret, and 901.88 mm at Adigolo (Figure 2). The maximum and minimum temperatures range from 26 to 11°C at MU, 23 to 10°C at Seret, and from 18 to 8°C at Adigolo.



Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2025 doi:10.20944/preprints202502.0605.v1

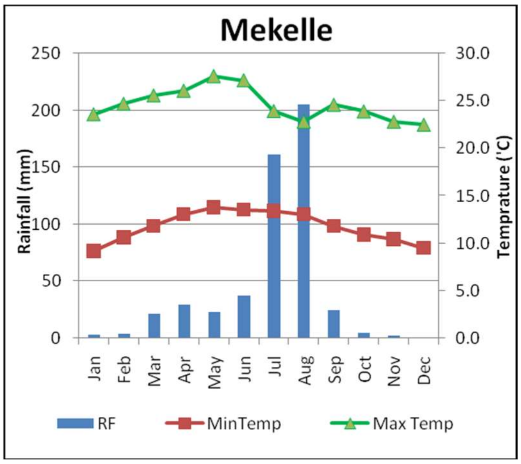


Figure 2. Average monthly rainfall and daily temperatures (Data Source: EMA 2000 to 2019). RF stands for rainfall, Min Temp for minimum temperature and Max Temp for maximum temperature.

Adigolo is found in Jurassic sedimentary rocks topped by Trap volcanic of the Ashangi Group [40]. Seret is found in Amba-Aradam formation consisting of coarse-grained, compact, and altered fluviatile sandstone and shale [41], overlain by a fine-grained basalt layer. The Mekelle site is characterized by a widespread presence of dolerite dykes and sills at 2000 m asl [42]. The dominant soil type in Adigolo include Leptosols, Fluvisols, and Vertisols [43]. Cambisols, Fluvisols and Vertisols dominate in Seret, [44], and Cambisols are quite common at the Mekelle site.

2.2. Treatments and Experimental Design

A randomized complete block design in factorial arrangements was used with four P levels (0, 10, 20, and 30 kg P ha^{-1}), and Zn levels (0, 5, and 10 kg Zn ha^{-1}) with three replications. The Zn level for treatments were used by many researchers [45,46]. The experiment was conducted during 2019 and 2020 rainy seasons. The treatment plot area was set at 3×4 m^2, each received split of 23 kg N ha^{-1} as starter-N, and a month after sowing while P and Zn were applied during sowing. Triple superphosphate (46% P), Urea (46% N), and zinc oxide (80% Zn) were used as sources of fertilizers. The ET-13-A2 (ENKOY/UQ105) wheat variety was used in the experiment at a sowing rate of 150 kg ha^{-1}.

2.3. Data Collection and Measurements

Soil Sampling and Analysis

Composite soil samples were collected at a depth of 0-30cm, prepared and analyzed following standard laboratory procedures in Mekelle Soil Research Center and Mekelle University laboratories. The soil particle size was analyzed using Bouyoucous hydrometer method [47]. Soil pH and EC were measured from a solution of 1:2.5 soils to water ratio. Soil organic carbon (OC) was determined following the Walkley and Black procedure [48]. Total nitrogen (TN) was determined using the modified micro-Kjeldahl method [49]. Available Phosphorus was determined using Olsen method [50]. Cation exchange capacity (CEC) and exchangeable bases (Ca, Mg, and K) were measured by the 1N NH4OAc at pH 7 method [51]and read from a flame photometer for exchangeable potassium (Exchangeable. K) and Atomic Absorption Spectrophotometer (AAS) for exchangeable Ca and Mg [52]. The micronutrient content of soil extractable Zn was also determined using DTPA extractable micronutrients solution measured in ASS [53]. Based on physiographical and soil data, a cluster analysis for all sites data were analyzed using the Minitab Software Application [54]. Plant samples were collected from each treatment plot in all sites at physiological maturity, at 65°C for 72 hours. Whole plant and grain samples were ground separately using a mill for digestion with nitric and

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2025 doi:10.20944/preprints202502.0605.v1

perchloric acids. Phosphorus was analyzed using the Molybdenum Blue method [55], while zinc (Zn) was determined through atomic absorption spectroscopy [56].

Yield Data and Nutrient Uptake Efficiency

Dry biomass and grain yield were measured after harvesting. The harvest index was also calculated using:

$$HI = \frac{GY}{BY} \times 100\% \quad (1)$$

where: HI= Harvest Index $GY = Grain\ Yield$, $BY = Biomass\ Yield$

The Nutrient uptake for P and Zn was calculated by multiplying the grain yield (kg ha^{-1}) with the per cent nutrient concentration) of each treatment, and was further used to calculate the nutrient use efficiency [51] as follows:

$$NUEZn = PA \times ARE = \left(\frac{Yzn - Yc}{Uzn - Uzn\ co}\right) \times \left(\frac{Uzn - Uzn\ co}{Nutrient\ Applied}\right) \quad (2)$$

where

NUEZn= Nutrient use efficiency of Zinc ARE= Apparent recovery efficiency
PA= Physiological Agronomyeld with Zinc , Yzn= Total Yield with Zinc fertilizer ,
Yc= Total yield of control , Uzn= Zinc Uptake with Zinc fertilized ,
UZn co= Zinc Uptake for control

2.4. Data Analysis

After checking the normality of all the quantitative data gathered from all sites, analysis of variance were conducted using the general linear models (GLM) procedure of Minitab Software Application [54]. Significant means were separated using the Fisher's protected least significance difference (LSD) at 5% level of probability using Genstat 17 software [57].

3. Results

3.1. Soil Characteristics

The soil analyses results indicate that the soils of both Adigolo and Seret have clay texture, Mekelle site being clay loam (Table 1). Adigolo soil has neutral pH, and the soil of Seret and Mekelle were slightly alkaline. The OC and TN content of soils of all locations were low. The available P of all three sites is below the critical soil available P value (10 mg P kg^{-1}) established for Ethiopian soils [58]. The Zn content of all soils were found below the critical value (1 mg Zn kg^{-1}) required for optimum production of wheat [59]. The Cation exchange capacity was high [60]. The sites showed 95% similarity in their top soil properties. Their variation was in rainfall, temperature, agro-ecology and topography.

Table 1. Soil physical and chemical properties and cluster analysis.

Parameters*	**Research sites**		
	Seret	**Adigolo**	**Mekelle**
Sand (%)	25.4	22.21	34.50
Silt (%)	30.2	32.29	27.15
Clay (%)	44.4	45.50	38.35
Textural class	C	C	CL

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2025 doi:10.20944/preprints202502.0605.v1

pH	7.84	7.25	7.92
SOC (%)	0.95	1.032	0.71
TN (%)	0.18	0.192	0.17
Av P (mg kg^{-1})	6.55	6.91	5.46
Zn (mg kg^{-1})	0.73	0.98	0.65
CEC (cmol(+) kg^{-1})	45.5	42.25	38.56
Exch K (cmol(+) kg^{-1})	0.22	0.2	0.20
Exch Ca (cmol(+) kg^{-1})	28.3	25.16	33.25
Exch Mg (cmol(+) kg^{-1})	10.1	8.72	12.42

** C- Clay; CL- Clay Loam; SOC- soil organic carbon; SOM- soil organic matter; Av P- available phosphorus; TN- total nitrogen; CEC- Cation Exchange Capacity; Exch K, Ca, Mg-Exchangeable Potassium, Calcium, Magnesium*

3.2. Effect of Zn and P on Yield and Yield Components of Wheat

Wheat grain and dry biomass yield were significantly ($p<0.001$) affected by the application rates of P and Zn (Table 2) across all three locations. Application of 10, 20 and 30 kg P ha-1 increased wheat grain yield increased by 24%, 70% and 44%; and biomass yield by 20%, 56% and 39%, respectively. Increasing application of phosphorus to 20 kg P ha^{-1} resulted in increase by about 37% grain and 31% biomass yield. Zinc application increased wheat grain yield by 25% and 24%; and biomass yield by 23% and 18%.

Table 2. Main plot effects of P and Zn application on grain and dry biomass yield of wheat.

Site/treatments	Grain yield (t ha^{-1})	Biomass yield (t ha^{-1})
Due to location		
Adigolo	4.46^a	12.95^a
Mekelle	3.81^c	9.54^c
Seret	4.32^b	11.36^b
$LSD_{(0.05)}$	*0.03*	*0.101*
Due to P levels		
P 0	3.11^d	8.76^d
P 10 kg ha^{-1}	3.87^c	10.47^c
P 20 kg ha^{-1}	5.30^a	13.68^a
P30 kg ha^{-1}	4.50^b	12.22^b
$LSD_{(0.05)}$	*0.034*	*0.117*
Due to Zn levels		
Znc0	3.67^c	9.95^c
Zn 5 kg ha^{-1}	4.53^a	12.19^a
Zn 10 kg ha^{-1}	4.38^b	11.71^b
$LSD_{(0.05)}$	*0.03*	*0.101*

Means within column followed by the same letter are not significantly different from each other at < 0.05.

Maximum yield were recorded when 20 kg P ha^{-1} and 5 kg Zn ha^{-1} were applied. Further increase in application rates (e.g. 10 kg Zn ha^{-1} and 30 kg P ha^{-1}) decreased yield. Yield was reduced by 18% when P application increased to 30 kg P ha^{-1}. As a result of the interaction of 5 kg Zn and 20 kg P ha^{-1}, maximum wheat grain and biomass yield were achieved (Table 3). Maximum wheat grain yield increased by 125, 140 and 145% over control in Seret, Adigolo and Mekelle sites, respectively.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2025 doi:10.20944/preprints202502.0605.v1

Table 3. Interaction effects of P and Zn application on wheat grain and dry biomass yield.

Treatment		Grain Yield ($t.ha^{-1}$)			Biomass ($t.ha^{-1}$)		
Zn (Kg ha^{-1})	P (Kg ha^{-1})	Seret	Adigolo	Mekelle	Seret	Adigolo	Mekelle
0	0	2.57^{j}	2.83^{k}	2.18^{k}	6.72^{k}	8.47^{k}	5.83^{k}
0	10	3.37^{i}	3.67^{i}	3.05^{i}	8.59^{j}	10.90^{i}	7.82^{i}
0	20	4.88^{d}	4.99^{d}	4.35^{d}	13.39^{c}	15.04^{c}	10.13^{e}
0	30	4.16^{g}	4.36^{f}	3.61^{g}	10.64^{g}	12.71^{f}	9.15^{g}
5	0	3.39^{i}	3.29^{j}	2.66^{j}	9.11^{i}	9.93^{j}	6.90^{j}
5	10	4.43^{f}	4.61^{e}	3.85^{f}	9.76^{h}	12.15^{g}	10.76^{d}
5	20	5.81^{a}	6.05^{a}	5.36^{a}	15.38^{a}	17.10^{a}	12.69^{a}
5	30	5.17^{c}	5.19^{c}	4.59^{c}	14.45^{b}	16.54^{b}	11.47^{c}
10	0	3.84^{h}	3.91^{h}	3.32^{h}	11.95^{e}	11.52^{h}	8.43^{h}
10	10	4.05^{g}	4.11^{g}	3.67^{g}	11.46^{f}	13.15^{e}	9.61^{f}
10	20	5.37^{b}	5.79^{b}	5.06^{b}	12.55^{d}	14.38^{d}	12.45^{b}
10	30	4.73^{e}	4.69^{e}	4.01^{e}	12.35^{d}	13.47^{e}	9.19^{g}
LSD(0.05)		*0.115*	*0.121*	*0.071*	*0.46*	*0.335*	*0.239*

Means within column followed by the same letter are not significantly different from each other at < 0.05.

The dry biomass yields were also increased by 129, 102 and 118% in Seret, Adigolo and Mekelle sites respectively when combined 5 kg Zn ha^{-1} and 20 kg P ha^{-1} was applied (Table 3). Wheat production is greatly impacted by increasing Zn treatment with an optimal P fertilizer rate in the different sites. Further increase in P and Zn rates resulted in declining grain and biomass yield in all sites.

3.3. Effect of Zn and P Application on Grain Nutrient Concentration

Interaction effect of P with Zn significantly increased grain Zn content, at lower P rate. The highest Zn concentration (55.5 mg kg^{-1}) is recorded at 10 kg Zn ha^{-1} and 10 kg P ha^{-1} (Table 4). When P application increased the availability of Zn in grain reduced. A 5.7 g kg^{-1} grain P was obtained with combined application of 30 kg P ha^{-1} and 5 kg Zn ha^{-1}.

Table 4. Interaction effects of P and Zn application on wheat grain and dry biomass yield.

Treatment		Grain Zn mg/kg			Grain P g/kg		
Zn (Kg ha^{-1})	P (Kg ha^{-1})	Adigolo	Seret	Mekelle	Adigolo	Seret	Mekelle
0	0	19.57^{k}	17.55^{l}	16.77^{k}	2.95^{k}	2.23^{k}	2.18^{l}
5	0	40.75^{e}	35.68^{f}	33.93^{e}	3.20^{j}	3.24^{i}	2.94^{j}
10	0	49.91^{b}	43.78^{b}	43.45^{b}	3.64^{i}	3.06^{j}	2.54^{k}
0	10	28.43^{i}	26.58^{j}	25.39^{i}	4.13^{g}	3.24^{i}	3.51^{g}
5	10	43.85^{d}	38.83^{d}	35.81^{d}	3.98^{h}	3.56^{g}	3.47^{h}
10	10	55.48^{a}	48.14^{a}	47.13^{a}	3.72^{i}	3.4^{h}	3.2^{i}
0	20	31.17^{h}	29.26^{i}	27.69^{h}	4.65^{d}	3.95^{f}	4.35^{c}
5	20	37.88^{f}	33.51^{g}	32.41^{f}	4.5^{e}	4.65^{c}	3.86^{e}
10	20	47.85^{c}	41.61^{c}	40.28^{c}	4.3^{f}	4.11^{e}	3.69^{f}
0	30	26.42^{j}	24.27^{k}	23.02^{j}	5.18^{b}	4.27^{d}	5.05^{a}
5	30	34.99^{g}	31.20^{h}	30.94^{g}	5.70^{a}	5.35^{a}	4.81^{b}
10	30	41.56^{e}	37.16^{e}	34.3^{e}	5.09^{c}	4.95^{b}	4.17^{d}

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2025 doi:10.20944/preprints202502.0605.v1

LSD(0.05)	*1.865*	*0.928*	*1.339*	*0.102*	*0.198*	*0.046*

Means within column followed by the same letter are not significantly different from each other at < 0.05.

3.4. Nutrient Use Efficiency of Wheat

At Seret and Adigolo, the highest P utilization efficiency was achieved when 10 kg P ha^{-1} with 10 kg Zn ha^{-1} and 20 kg P ha^{-1} with 5 kg Zn ha^{-1} were applied (Table 5). MU site exhibited highest nutrient use efficiency when 10 kg P ha^{-1} with 5 or 10 kg Zn ha^{-1} was applied. Lowest P use efficiency recorded when applying 30 kg P ha^{-1} and 10 kg Zn ha^{-1}. When P is applied with zinc at a low rate, its use efficiency rises.

Zinc use efficiency was highest when 5 kg Zn ha^{-1} combined with 20 kg P ha^{-1} (Table 5). A combined 10 kg Zn ha^{-1} and 10 kg P ha^{-1} application provided the lowest Zn uptake across all locations. Increasing P application rate to 20 kg P ha^{-1} increased Zn use efficiency, further increasing P and Zn significantly reduced Zn use efficiency.

Table 5. Phosphorus and Zinc use efficiency of wheat.

Treatment		**P use efficiency**			**Treatment**		**Zn use efficiency**		
P ($kgha^{-1}$)	**Zn ($kgha^{-1}$)**	**Seret**	**Adigolo**	**Mekelle**	**Zn ($kgha^{-1}$)**	**P ($kgha^{-1}$)**	**Seret**	**Adigolo**	**Mekelle**
10	0	187.6^{f}	243.8^{g}	198.9^{e}	5	0	478.4^{e}	292.2^{f}	213.3^{f}
10	5	303.7^{cd}	375.7^{c}	492.6^{a}	5	10	607.4^{c}	737.9^{c}	985.1^{c}
10	10	474.1^{a}	458.2^{a}	377.3^{b}	5	20	1731.7^{a}	1727.6^{a}	1370.7^{a}
20	0	334.1^{c}	328.9^{d}	214.6^{d}	5	30	1546.3^{b}	1614.5^{b}	1126.9^{b}
20	5	432.9^{b}	431.9^{b}	342.7c	10	0	$523.5d^{e}$	305.5^{f}	259.4^{f}
20	10	291.6^{d}	295.7^{e}	330.6c	10	10	474.1^{e}	468.0^{e}	377.3^{e}
30	0	130.8^{g}	141.5^{i}	110.4^{f}	10	20	583.2^{cd}	591.4^{d}	661.1^{d}
30	5	257.7^{e}	273.7^{f}	187.8^{e}	10	30	563.6^{cd}	500.0^{e}	336.4^{e}
30	10	187.9^{f}	166.7^{h}	112.1^{f}					
LSD(0.05)		*30.05*	*26.12*	*19.56*	*LSD(0.05)*		*127.16*	*68.54*	*58.17*

Means within column followed by the same letter are not significantly different from each other at < 0.05.

4. Discussion

With the clay and clay loam textures, soils could exhibit similar properties. Variations in site characteristics such as climate, landscape positions, and topography and soil depth determined wheat yield responses to applications of phosphorus (P) and zinc (Zn). Climate influences soil moisture levels and temperature regimes, both of which affect nutrient cycling, microbial activity, and plant growth. Landscape positions influence water drainage and nutrient movement within the soil profile. Effective soil depth determines the rooting depth of wheat plants and the volume of soil available for nutrient uptake [61].

This study showed increasing application of phosphorus to 20 kg P ha^{-1} increased grain yield by about 37% and biomass yield 31% over control. Many researches revealed that P application increased wheat grain and biomass yield [62–64]. However, application of excess P in soil reduce grain yield due to reduced uptake of micronutrients, particularly Zn [65] and excess P may even have adverse effects on yield [66]. The critical P requirements and optimum levels needs to be specified [67].

It is also showed that Zn application led to notable increases in grain yield (ranging from 21% to 25%) across locations, showing its consistent positive effect on grain yield. These results are strongly supported by many researchers [24,68] indicating that application of Zn fertilizer significantly affects grain and biomass yields. Zinc plays a crucial role in enzyme activation, hormone regulation, and protein synthesis [69]. Ensuring optimal zinc availability through appropriate fertilization practices is essential for maximizing grain yield.

The accessibility of nutrients to crops is significantly impacted by interactions as an excess of one nutrient might lead to a deficiency of another [70]. The interactions of nutrients within the soil influence the yields of annual crops [71–73]. Application of both P and Zn fertilizers play crucial roles in various physiological processes affecting crop growth, development, and ultimately yield formation [26,36]. However, soils with higher phosphate levels, from the application of P fertilizers, can cause Zn deficiency in crops [36]. Combinations of P and Zn with 20 kg P ha^{-1} and 5 kg Zn ha^{-1} have shown a synergistic effect in increasing wheat grain and biomass yields. Similar studies [26,73] have reported that combined application of P and Zn below the optimum level either nutrients increased wheat yield.

This study showed antagonistic relationship at higher rates of P and Zn fertilizer beyond 20 kg P ha^{-1} and 5 kg Zn ha^{-1} that result in reduced wheat yield. A report [46] indicates higher rates of combined P and Zn fertilizer showed reduction in wheat yield. Applying higher rate of P fertilizer dose to the soil hinders the Zn mobilization and nutrient uptake [74].

The combined application of P and Zn has influence on grain nutrient content, particularly grain Zn and P concentrations. Grain Zn concentration increased with the increasing Zn application but reduced with the increasing P application beyond 10 kg P ha^{-1}. Combined application of P and Zn increased the grain Zn as well as grain P content, particularly at lower rates [24]. Higher P rate beyond a threshold for wheat reduces grain Zn concentration [65,75,76].

Phosphorus also tends to form complexes with soil minerals by reducing the availability of free Zn ions for uptake by roots [11,36], the induction of Zn deficiency by formation of insoluble complexes between P and Zn in the soil. The reduction in Zn utilization efficiency as Zn application rates increased also resulted in a gradual decline in grain yield and dry matter production [77].

Furthermore, the use efficiency of phosphorus and zinc was significantly influenced by the combined applications of various levels of P and Zn fertilization, in line with the study conducted by Sánchez-Rodríguez [26]. Increasing P concentrations can lead to an increase in P use efficiency [78,79] which is lowered again by increasing P application as it reduces the yield [63,80]. Similarly, Zn use efficiency significantly reduced with higher rate of P application [81,82]. Overall, combined application of P and Zinc fertilizers improve the bioavailability and uptake of zinc [83]. The nutrient use efficiency varies across locations and this could be due to the variability in soil conditions, and uptake levels of nutrients by plants [84]. In our study, the maximum profit was obtained from the combined application of 5 kg Zn ha^{-1} and 20 kg P ha^{-1}, followed by the application of 10 kg Zn ha^{-1} and 20 kg P ha^{-1} (data not shown). Thus, ensuring optimal zinc utilization is crucial for achieving high crop yields and quality [36,85].

5. Conclusions

Understanding the interactions among site characteristics and nutrient management practices are important in optimizing wheat production. Emphasizing the significance of phosphorus (P) and zinc (Zn) fertilization, this research offers valuable insights for enhancing crop yields, sustainability and food security in diverse agro climatic conditions. While Zn application can increase yield, there is a critical threshold beyond which further application may lead to diminishing yields. Combination of 20 kg P ha^{-1} and 5 kg Zn ha^{-1} has been identified best to achieving maximum wheat grain yield. This combination is found to be optimum for obtaining maximum profits, improved yield and nutrient use of wheat for producers in northern highlands of Ethiopian. Therefore, to achieve sustainable wheat production and maximize yield, it is essential for farmers to carefully manage P and Zn application rates to avoid both deficiency and excess.

Author Contributions: Mulugeta Sebhatleab: conceptualization, carry out the experiments; Analyzed and interpret the data; wrote the paper. Yemane Tsehaye: statistical analysis. And interpretation Gebreyohannes Girmay and Girmay Gebresamual: Data analysis and interpretation, Review & Editing and supervision. Mitiku Haile: Editing and supervision.

Funding: This research work was supported by MU-HU-NMBU project (phase IV), a cooperation between Mekelle University (Ethiopia) and Norwegian University of Life Science (Norway).

Data Availability Statement: The data presented in this study are available on request from the corresponding author. Reviewers or interested parties who require access to the data can contact the corresponding author.

Acknowledgments: The authors have special thanks to farmers and agricultural experts of the districts who patrticipate during the experent and data collection. Authors highly appreciate to technicians of soil and plant laboratories in Mekelle University and Tigray Agricultural Research Centre who helped us in analyzing the samples collected.

Conflicts of Interest: The authors declare that there is no conflict of interest.

References

1. Giraldo, P.; Benavente, E.; Manzano-Agugliaro, F.; Gimenez, E. Worldwide Research Trends on Wheat and Barley: A Bibliometric Comparative Analysis. *Agronomy* **2019**, *9*, 352, doi:10.3390/agronomy9070352.
2. Erenstein, O.; Jaleta, M.; Mottaleb, K.A.; Sonder, K.; Donovan, J.; Braun, H.-J. Global Trends in Wheat Production, Consumption and Trade. In *Wheat Improvement*; Reynolds, M.P., Braun, H.-J., Eds.; Springer International Publishing: Cham, 2022; pp. 47–66 ISBN 978-3-030-90672-6.
3. FAOSTAT Data: Production Available online: https://www.fao.org/faostat/en/#data/QCL.
4. Aleminew, A.; Legas, A. Grain Quality and Yield Response of Malt Barley Varieties to Nitrogen Fertilizer on Brown Soils of Amhara Region, Ethiopia. *Journal of Agricultural Sciences* **2015**, *11*, 135–143, doi:org/10.5829/idosi.wjas.2015.11.3.94283.
5. Victor Roch, G.; Maharajan, T.; Ceasar, S.A.; Ignacimuthu, S. The Role of PHT1 Family Transporters in the Acquisition and Redistribution of Phosphorus in Plants. *Critical Reviews in Plant Sciences* **2019**, *38*, 171–198, doi:10.1080/07352689.2019.1645402.
6. Gadisa, N. Soil Nutrient Status and Farmers' Perception on Soil Fertility in Ethiopia: Review. *Journal of Biology, Agriculture and Healthcare* **2021**, *11*, 8.
7. Agegnehu, G.; Nelson, P.N.; Bird, M.I.; Van Beek, C. Phosphorus Response and Fertilizer Recommendations for Wheat Grown on Nitisols in the Central Ethiopian Highlands. *Communications in Soil Science and Plant Analysis* **2015**, *46*, 2411–2424, doi:10.1080/00103624.2015.1081922.
8. Hailu, H.; Mamo, T.; Keskinen, R.; Karltun, E.; Gebrekidan, H.; Bekele, T. Soil Fertility Status and Wheat Nutrient Content in Vertisol Cropping Systems of Central Highlands of Ethiopia. *Agric & Food Secur* **2015**, *4*, 19, doi:10.1186/s40066-015-0038-0.
9. Solomon, N.; Birhane, E.; Tilahun, M.; Schauer, M.; Gebremedhin, M.A.; Gebremariam, F.T.; Gidey, T.; Newete, S.W. Revitalizing Ethiopia's Highland Soil Degradation: A Comprehensive Review on Land Degradation and Effective Management Interventions. *Discov Sustain* **2024**, *5*, 106, doi:10.1007/s43621-024-00282-7.
10. Habtegebrial, K. Nitrogen and Sulphur Fertilizers Effects on Yield, Nitrogen Uptake and Nitrogen Use Efficiency of Upland Rice Variety on Irrigated Fulvisols of the Afar Region, Ethiopia. *J. Soil Sci. Environ. Manage.* **2013**, *4*, 62–70, doi:10.5897/JSSEM13.0389.
11. Hui, X.; Wang, X.; Luo, L.; Wang, S.; Guo, Z.; Shi, M.; Wang, R.; Lyons, G.; Chen, Y.; Cakmak, I.; et al. Wheat Grain Zinc Concentration as Affected by Soil Nitrogen and Phosphorus Availability and Root Mycorrhizal Colonization. *European Journal of Agronomy* **2022**, *134*, 126469, doi:10.1016/j.eja.2022.126469.
12. Duga, R. Effect of Nitrogen, Phosphorus and Sulfur Nutrients on Growth and Yield Attributes of Bread Wheat. *JENR* **2021**, *5*, doi:10.23880/jenr-16000230.
13. Gebreslassie, H.B.; Demoz, H.A. A Review on: Effect of Phosphorus Fertilizer on Crop Production in Ethiopia. *Journal of Biology* **2016**.
14. Moreno-Lora, A.; Delgado, A. Factors Determining Zn Availability and Uptake by Plants in Soils Developed under Mediterranean Climate. *Geoderma* **2020**, *376*, 114509, doi:10.1016/j.geoderma.2020.114509.
15. Tsadilas, C.; Evangelou, E.; Nikoli, T.; Tzioyvalekas, M. Determination of Critical Value of Available Soil Phosphorus for Wheat (Triticum Aestivum L.) in Calcareous Soils from Greece. *JALSE* **2022**, *54*, 322–332, doi:10.46909/journalalse-2021-028.

16. Wessells, K.R.; Brown, K.H. Estimating the Global Prevalence of Zinc Deficiency: Results Based on Zinc Availability in National Food Supplies and the Prevalence of Stunting. *PLoS ONE* **2012**, *7*, e50568, doi:10.1371/journal.pone.0050568.
17. Abera, Y.; Kebede, M. Assessment on the Status of Some Micronutrients in Vertisols of the Central Highlands of Ethiopia. *nternational Research Journal of Agricultural Science and Soil Science* **2013**, *3*, 169–173.
18. Abera, Y.; Kassa, S. Status of Soil Micronutrients in Ethiopian Soils: A Review. *ournal of Environment and Earth Science* **2017**, *7*, 6.
19. Belay, A.; Gashu, D.; Joy, E.J.M.; Lark, R.M.; Chagumaira, C.; Likoswe, B.H.; Zerfu, D.; Ander, E.L.; Young, S.D.; Bailey, E.H.; et al. Zinc Deficiency Is Highly Prevalent and Spatially Dependent over Short Distances in Ethiopia. *Sci Rep* **2021**, *11*, 6510, doi:10.1038/s41598-021-85977-x.
20. Ozturk, H.; Niazi, P.; Mansoor, M.; Monib, A.W.; Alikhail, M.; Azizi, A. The Function of Zinc in Animal, Plant, and Human Nutrition. *J. Res. Appl. Sci. Biotechnol.* **2023**, *2*, 35–43, doi:10.55544/jrasb.2.2.6.
21. Patil, R.; Sontakke, T.; Biradar, A.; Nalage, D. Zinc: An Essential Trace Element for Human Health and Beyond. *Food Health* **2023**, *5*, 13, doi:10.53388/FH2023013.
22. Alloway, B.J. *Zinc in SoilS and Crop Nutrition*; 2nd ed.; International Zinc Association and International Fertilizer Industry Association: Brussels, Belgium and Paris, France, 2008;
23. Haileselassie, B.; Bedadi, B.; Kidanu, S.; Mamo, T. Effect of Zinc Containing Fertilizers on Yield and Grain Quality of Tef [(Eragrostis Tef (Zucc.) Trotter] in Some Soils of Tigray Region, Ethiopia.
24. Khan, F.U.; Khan, A.A.; Qu, Y.; Zhang, Q.; Adnan, M.; Fahad, S.; Gul, F.; Ismail, M.; Saud, S.; Hassan, S.; et al. Enhancing Wheat Production and Quality in Alkaline Soil: A Study on the Effectiveness of Foliar and Soil Applied Zinc. *PeerJ* **2023**, *11*, e16179, doi:10.7717/peerj.16179.
25. Firdous, S.; Agarwal, B.; Chhabra, V. Zinc-Fertilization Effects on Wheat Yield and Yield Components. *Journal of Pharmacognosy and Phytochemistry* **2018**, *7*, 3497–3499.
26. Sánchez-Rodríguez, A.R.; Rey, M.-D.; Nechate-Drif, H.; Castillejo, M.Á.; Jorrín-Novo, J.V.; Torrent, J.; Del Campillo, M.C.; Sacristán, D. Combining P and Zn Fertilization to Enhance Yield and Grain Quality in Maize Grown on Mediterranean Soils. *Sci Rep* **2021**, *11*, 14, doi:10.1038/s41598-021-86766-2.
27. Yadav, A.; Singh, D.; Kumar, R.; Sachan, R.; Kumar, K.; Singh, A.; Tiwari, A.; Singh, K.K. Response of Different Level of Phosphorus, Zinc and Rhizobium Inoculation on Growth Yield Attributes and Yield of Chickpea (Cicer Aretinum L.). *IJECC* **2022**, *12*, 1954–1964, doi:10.9734/ijecc/2022/v12i1131184.
28. Cakmak, I.; Kutman, U.B. Agronomic Biofortification of Cereals with Zinc: A Review. *European J Soil Science* **2018**, *69*, 172–180, doi:10.1111/ejss.12437.
29. Cakmak, I.; Kalayci, M.; Kaya, Y.; Torun, A.A.; Aydin, N.; Wang, Y.; Arisoy, Z.; Erdem, H.; Yazici, A.; Gokmen, O.; et al. Biofortification and Localization of Zinc in Wheat Grain. *J. Agric. Food Chem.* **2010**, *58*, 9092–9102, doi:10.1021/jf101197h.
30. Recena, R.; García-López, A.M.; Delgado, A. Zinc Uptake by Plants as Affected by Fertilization with Zn Sulfate, Phosphorus Availability, and Soil Properties. *Agronomy* **2021**, *11*, 390, doi:10.3390/agronomy11020390.
31. Simtow, F. An Assessment of National Fertiliser Policies, Regulations and Standards for Ethiopia. In Proceedings of the An Assessment of National Fertilizer Policies, Regulations and Standards for Ethiopia; African Fertilizer and Agribusiness Partnership: 50 Park Place, Suite 1003 Newark, NJ 07102, 2015; p. 35.
32. Elias, E.; Okoth, P.F.; Smaling, E.M.A. Explaining Bread Wheat (Triticum Aestivum) Yield Differences by Soil Properties and Fertilizer Rates in the Highlands of Ethiopia. *Geoderma* **2019**, *339*, 126–133, doi:10.1016/j.geoderma.2018.12.020.
33. Terfa, A.E.; Mellisse, B.T.; Kebede, M.M.; Elias, E.; Yadessa, G.B. Effect of Blended Fertilizer Application on Bread Wheat Yield and Profitability on Andosols of Southwestern Highlands of Ethiopian. *Communications in Soil Science and Plant Analysis* **2023**, *54*, 73–82, doi:10.1080/00103624.2022.2109664.
34. Khattak, S.G.; Dominy, P.J.; Ahmad, W. Effect of Zn as Soil Addition and Foliar Application on Yield and Protein Content of Wheat in Alkaline Soil. *J. Natn. Sci. Foundation Sri Lanka* **2015**, *43*, 303, doi:10.4038/jnsfsr.v43i4.7965.

 doi:10.20944/preprints202502.0605.v1

35. Abay, K.A.; Abay, M.H.; Amare, M.; Berhane, G.; Aynekulu, E. Mismatch between Soil Nutrient Deficiencies and Fertilizer Applications: Implications for Yield Responses in Ethiopia. *Agricultural Economics* **2022**, *53*, 215–230, doi:10.1111/agec.12689.
36. Mousavi, S.R. Zinc in Crop Production and Interaction with Phosphorus. *Australian Journal of Basic and Applied Sciences*, **2011**, *5*, 1503–1509.
37. Singh, K.; Verma, G.; Manchanda, J.S. Soil and Foliar Zinc Application for Enhancing Grain Zinc Content of Aromatic Rice Genotypes Grown on Zinc Deficient and Sufficient Soil. *Jour. of Soi. and Wat. Conser.* **2020**, *19*, 223, doi:10.5958/2455-7145.2020.00030.2.
38. Weldua, Y.; Haileb, M.; Habtegebrielb, K. Effect of Zinc and Phosphorus Fertilizers Application on Yield and Yield Components of Faba Bean (Vicia Faba L.) Grown in Calcaric Cambisol of Semi-Arid Northern Ethiopia.
39. Yohannes, D.; Kiros, H.; Yirga, W. Inoculation, Phosphorous and Zinc Fertilization Effects on Nodulation, Yield and Nutrient Uptake of Faba Bean (Vicia Faba L.) Grown on Calcaric Cambisol of Semiarid Ethiopia. *J. Soil Sci. Environ. Manage.* **2015**, *6*, 9–15, doi:10.5897/JSSEM2013.0406.
40. Tarekegn, T.; Shiferaw, L.; Sirak, T.; Shimelis, F.; Maarten, W.; Vince, U. *Hydrogeological Mapping for Climate Resilient WASH in Ethiopia – LOT 1*; Target sites Ofla woreda, Tigray; ACACIAWATER: Van Hogendorpplein 4 2805 BM Gouda, 2022; p. 95;.
41. Gebreyohannes, T.; Smedt, F.D.; Hagos, M.; Gebresilassie, S.; Amare, K.; Kabeto, K.; Hussein, A.; Nyssen, J.; Bauer, H.; Moeyersons, J.; et al. Large-Scale Geological Mapping of the Geba Basin, Northern Ethiopia. In Proceedings of the Tigray Livelihood Paper No 9; VLIR – Mekelle University IUC Program: Mekelle, Ethiopia, 2010; p. 46.
42. Andrea, S.; Paola, M.; Francesco, D.; Claudio, F.; Bekele, A. Erosion-Tectonics Feedbacks in Shaping the Landscape: An Example from the Mekele Outlier (Tigray, Ethiopia). *Journal of African Earth Sciences* **2017**, *129*, 870–886, doi:org/10.1016/j.jafrearsci.2017.02.028.
43. Yemane Gebremeskel; Weldemariam Gebrehiwot; Girmay Gebresamuel *CASCAPE Experiences in Integrated Soil Fertility and Nutrient Management in Southern*; Mekelle University: Mekelle, Ethiopia, 2020;
44. Nyssen, J.; Naudts, J.; De Geyndt, K.; Haile, M.; Poesen, J.; Moeyersons, J.; Deckers, J. Soils and Land Use in the Tigray Highlands (Northern Ethiopia). *Land Degrad Dev* **2008**, *19*, 257–274, doi:10.1002/ldr.840.
45. Keram, K.S.; Sharma, B.L.; Kewat, M.L.; Sharma, G.D. Effect of Zinc Fertilization on Growth, Yield and Quality of Wheat Grown Under Agro-Climatic Condition of Kymore Plateau of Madhya Pradesh, India. *The Bioscan* **2014**, *9*, 1479–1483.
46. Arshad, M.; Adnan, M.; Ahmed, S.; Khan, A.K.; Ali, I.; Ali, M.; Ali, A.; Khan, A.; Kamal, M.A.; Gul, F.; et al. Integrated Effect of Phosphorus and Zinc on Wheat Crop. *American-Eurasian J. Agric. & Environ. Sci.* **2016**, *16*, 455–459, doi:10.5829/idosi.aejaes.2016.16.3.12887.
47. Bouyoucos, G.J. Hydrometer Method Improved for Making Particle Size Analyses of Soils[1]. *Agronomy Journal* **1962**, *54*, 464–465, doi:10.2134/agronj1962.00021962005400050028x.
48. Walkley, A.; Black, I.A. An Examination of the Degtjareff Method for Determining Soil Organic Matter and a Proposed Modification of Thechromic Acid Titration Method 1934.
49. Bremner, J.M.; Mulvaney, C.S. Nitrogen Total. In *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties*; Madison,: Wisconsin USA, 1982; pp. 595–625.
50. Olsen, S.R. Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate.
51. Chapman, H.D. Cation-Exchange Capacity! In *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties*, *9.2*; 1965; pp. 891–901.
52. Jones, J. *Laboratory Guide for Conducting Soil Tests and Plant Analysis*; 1st ed.; Taylor & Francis Group: Milton, 2001; ISBN 978-0-8493-0206-0.
53. Lindsay, W.L.; Norvell, W.A. Development of a DTPA Soil Test for Zinc, Iron, Manganese, and Copper. *Soil Science Soc of Amer J* **1978**, *42*, 421–428, doi:10.2136/sssaj1978.03615995004200030009x.
54. Minitab, L. Getting Started with Minitab Statistical Software 2021.
55. Wieczorek, D.; Żyszka-Haberecht, B.; Kafka, A.; Lipok, J. Determination of Phosphorus Compounds in Plant Tissues: From Colourimetry to Advanced Instrumental Analytical Chemistry. *Plant Methods* **2022**, *18*, 22, doi:10.1186/s13007-022-00854-6.

56. Elango, D.; Kanatti, A.; Wang, W.; Devi, A.R.; Ramachandran, M.; Jabeen, A. Analytical Methods for Iron and Zinc Quantification in Plant Samples. *Communications in Soil Science and Plant Analysis* **2021**, *52*, 1069–1075, doi:10.1080/00103624.2021.1872608.
57. Goedhart, P.W.; Thissen, T.N.M. *Biometris GenStat Procedure Library Manual 17th Edition*; 2014; pp. 1–190;.
58. Tadesse, K.; Abdulkadir, B.; Admasu, W.; Habte, D.; Admasu, A.; Tadesse, A.; Debebe, A. Soil Test-Based Phosphorus Fertilizer Recommendation for Malting Barley Production on Nitisols. *Open Agriculture* **2022**, *7*, 171–180, doi:10.1515/opag-2022-0078.
59. Gurjer, K.; Sharma, S.; Yadav, K. Establishment of Critical Limit of Zinc for Wheat Crop. *The Pharma Innovation Journal* **2022**, *11*, 1457–1461.
60. *Booker Tropical Soil Manual*; Landon, Rj.R.K.M., Ed.; Paperback Edition.; Longman Scientific & Technical ; J. Wiley: Harlow, Essex, England : New York, NY, 1991; ISBN 13: 978-0-582-00557-0 (pbk).
61. Hirzel, J.; Matus, I. Effect of Soil Depth and Increasing Fertilization Rate on Yield and Its Components of Two Durum Wheat Varieties. *Chilean J. Agric. Res.* **2013**, *73*, 55–59, doi:10.4067/S0718-58392013000100008.
62. Noonari, S.; Kalhoro, S.A.; Ali, A.; Mahar, A.; Raza, S.; Ahmed, M.; Shah, S.F.A.; Baloch, S.U. Effect of Different Levels of Phosphorus and Method of Application on the Growth and Yield of Wheat. *NS* **2016**, *08*, 305–314, doi:10.4236/ns.2016.87035.
63. Ghafoor, A.M.R. Effect of Phosphorus Fertilizer Application on Some Yield Components of Wheat and Phosphorus Use Efficiency in Calcareous Soil. *Journal of Dynamics in Agricultural Research* **2016**, *3*, 46-52,.
64. Liu, L.; Miao, Q.; Wang, H.; Xue, Y.; Qi, S.; Zhang, J.; Li, J.; Meng, Q.; Cui, Z. Optimizing Phosphorus Application for Winter Wheat Production in the Coastal Saline Area. *Agronomy* **2022**, *12*, 2966, doi:10.3390/agronomy12122966.
65. Zhang, W.; Liu, D.; Liu, Y.; Chen, X.; Zou, C. Overuse of Phosphorus Fertilizer Reduces the Grain and Flour Protein Contents and Zinc Bioavailability of Winter Wheat (*Triticum Aestivum* L.). *J. Agric. Food Chem.* **2017**, *65*, 1473–1482, doi:10.1021/acs.jafc.6b04778.
66. Garcia-Oliveira, A.L.; Chander, S.; Ortiz, R.; Menkir, A.; Gedil, M. Genetic Basis and Breeding Perspectives of Grain Iron and Zinc Enrichment in Cereals. *Front. Plant Sci.* **2018**, *9*, 937, doi:10.3389/fpls.2018.00937.
67. Menna, A.; Semoka, J.; Amuri, N.; Mamo, T. Wheat Response to Applied Nitrogen, Sulfur, and Phosphorous in Three Representative Areas of the Central Highlands of Ethiopia -I. *IJPSS* **2015**, *8*, 1–11, doi:10.9734/IJPSS/2015/20055.
68. Keram, K.S.; Sharma, B.L.; Sharma, G.D.; Thakur, R.K. Impact of Zinc Application on Its Translocation into Various Plant Parts of Wheat and Its Effect on Chemical Composition and Quality of Grain. *Academic Journals* **2013**, *8*, 2218–2226, doi:10.5897/SRE2013.5583.
69. A., S.; A., S.; N, M. Role of Zinc Nutrition for Increasing Zinc Availability, Uptake, Yield, and Quality of Maize (*Zea Mays* L.) Grains: An Overview. *Communications in Soil Science and Plant Analysis* **2020**, *51*, 2001–2021, doi:10.1080/00103624.2020.1820030.
70. Aboyeji, C.M.; Dunsin, O.; Adekiya, A.O.; Suleiman, K.O.; Chinedum, C.; Okunlola, F.O.; Joseph, A.; Ejue, S.W.; Adesola, O.O.; Olofintoye, T.A.J.; et al. Synergistic and Antagonistic Effects of Soil Applied P and Zn Fertilizers on the Performance, Minerals and Heavy Metal Composition of Groundnut. *Open Agriculture* **2020**, *5*, 1–9, doi:10.1515/opag-2020-0002.
71. Fageria, V.D. Nutrient Interactions in Crop Plants. *Journal of Plant Nutrition* **2001**, *24*, 1269–1290, doi:10.1081/PLN-100106981.
72. Rietra, R.P.J.J.; Heinen, M.; Dimkpa, C.O.; Bindraban, P.S. Effects of Nutrient Antagonism and Synergism on Yield and Fertilizer Use Efficiency. *Communications in Soil Science and Plant Analysis* **2017**, *48*, 1895–1920, doi:10.1080/00103624.2017.1407429.
73. Dargie, S.; Girma, T.; Chibsa, T.; Kassa, S.; Boke, S.; Abera, A.; Haileselassie, B.; Addisie, S.; Amsalu, S.; Haileselassie, M.; et al. Balanced Fertilization Increases Wheat Yield Response on Different Soils and Agroecological Zones in Ethiopia. *Ex. Agric.* **2022**, *58*, e23, doi:10.1017/S0014479722000151.
74. Soumya, S.; B C, V.; Debarati, B.; Somnath, R. Management of Phosphorus Zinc Antagonism to Improve Nutrient Use Efficiency Compressed. *Food and Scientific Reports* **2022**, *03*, 40–43.

75. Ova, E.A.; Kutman, U.B.; Ozturk, L.; Cakmak, I. High Phosphorus Supply Reduced Zinc Concentration of Wheat in Native Soil but Not in Autoclaved Soil or Nutrient Solution. *Plant Soil* **2015**, *393*, 147–162, doi:10.1007/s11104-015-2483-8.
76. Mohammed, S.B.; Dzidzienyo, D.K.; Yahaya, A.; L. Umar, M.; Ishiyaku, M.F.; Tongoona, P.B.; Gracen, V. High Soil Phosphorus Application Significantly Increased Grain Yield, Phosphorus Content but Not Zinc Content of Cowpea Grains. *Agronomy* **2021**, *11*, 802, doi:10.3390/agronomy11040802.
77. Kumar, D.; Patel, K.C.; Ramani, V.P.; Shukla, A.K.; Behera, S.K.; Patel, R.A. Influence of Different Rates and Frequencies of Zn Application to Maize–Wheat Cropping on Crop Productivity and Zn Use Efficiency. *Sustainability* **2022**, *14*, 15091, doi:10.3390/su142215091.
78. Luo, L.; Zhang, X.; Zhang, M.; Wei, P.; Chai, R.; Wang, Y.; Zhang, C.; Siddique, K.H.M. Improving Wheat Yield and Phosphorus Use Efficiency through the Optimization of Phosphorus Fertilizer Types Based on Soil P Pool Characteristics in Calcareous and Non-Calcareous Soil. *Agronomy* **2023**, *13*, 928, doi:10.3390/agronomy13030928.
79. Zhu, Y.; Smith, S.E.; Smith, F.A. Zinc (Zn)-Phosphorus (P) Interactions in Two Cultivars of Spring Wheat (Triticum Aestivum L.) Differing in P Uptake Efficiency. *Annals of Botany* **2001**, *88*, 941–945, doi:10.1006/anbo.2001.1522.
80. Shabnam, R.; Iqbal, Md.T. Phosphorus Use Efficiency by Wheat Plants That Grown in an Acidic Soil. *Braz J Sci Technol* **2016**, *3*, 18, doi:10.1186/s40552-016-0030-7.
81. Zhang, W.; Zhang, W.; Wang, X.; Liu, D.; Zou, C.; Chen, X. Quantitative Evaluation of the Grain Zinc in Cereal Crops Caused by Phosphorus Fertilization. A Meta-Analysis. *Agron. Sustain. Dev.* **2021**, *41*, 6, doi:10.1007/s13593-020-00661-0.
82. Yu, B.-G.; Chen, X.-X.; Cao, W.-Q.; Liu, Y.-M.; Zou, C.-Q. Responses in Zinc Uptake of Different Mycorrhizal and Non-Mycorrhizal Crops to Varied Levels of Phosphorus and Zinc Applications. *Front. Plant Sci.* **2020**, *11*, 10, doi:10.3389/fpls.2020.606472.
83. Amanullah; Inamullah; Alwahibi, M.S.; Elshikh, M.S.; Alkahtani, J.; Muhammad, A.; Khalid, S.; Imran; Ahmad, M.; Khan, N.; et al. Phosphorus and Zinc Fertilization Improve Zinc Biofortification in Grains and Straw of Coarse vs. Fine Rice Genotypes. *Agronomy* **2020**, *10*, 1155, doi:10.3390/agronomy10081155.
84. Jayara, A.S.; Kumar, R.; Pandey, P.; Singh, S.; Shukla, A.; Singh, A.P.; Pandey, S.; Meena, R.L.; Reddy, K.I. Boosting Nutrient Use Efficiency Through Fertilizer Use Management. *Appl. Ecol. Env. Res.* **2023**, *21*, 2931–2952, doi:10.15666/aeer/2104_29312952.
85. Hamzah Saleem, M.; Usman, K.; Rizwan, M.; Al Jabri, H.; Alsafran, M. Functions and Strategies for Enhancing Zinc Availability in Plants for Sustainable Agriculture. *Front. Plant Sci.* **2022**, *13*, 1033092, doi:10.3389/fpls.2022.1033092.