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Combined Effects of N, P, and Fe, Zn Fertilization on Barley (Hordeum vulgare L.) Yield and Grain Quality in Southeastern Tigray, Ethiopia

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Abstract

Barley is a vital crop for smallholder farmers in Ethiopia's highlands, but productivity is constrained by poor soil fertility and inadequate fertilizer management. A field experiment was conducted in Southeastern Tigray during the 2017/18 Ethiopian cropping rainy season to evaluate the effects of macronutrients (N and P) and micronutrients (Fe and Zn) on barley yield, yield components, and grain quality. A split-plot design with three replications was used, with three N and P treatments (MA1 = control, MA2 = 100 kg Urea ha^{-1} + 100 kg DAP ha^{-1}, MA3 = 50 kg DAP ha^{-1} + 50 kg Urea ha^{-1}) as main plots and four Zn and Fe foliar treatments (P1 = control, P2 = 25 kg Zn ha^{-1}, P3 = 25 kg Fe ha^{-1}, P4 = 12.5 kg Zn ha^{-1} + 12.5 kg Fe ha^{-1}) as subplots. Results showed that combining macronutrients and micronutrients produced better responses than either alone. The combination of 100 kg Urea ha^{-1} + 100 kg DAP ha^{-1} with 12.5 kg Zn ha^{-1} + 12.5 kg Fe ha^{-1} gave the highest grain yield (2.62 t/ha and 2.17 t/ha), Fe content (374.8 mg kg^{-1} and 155.3 mg kg^{-1}), and protein content (15.6% and 12.4%) at Dejen and Kedamay-weyane, respectively. This nutrient combination is recommended to improve barley yield, grain Fe, and protein content in the study area.

Keywords: *Barley, interaction effect, macronutrient, micronutrient*

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1. Introduction

Barley (*Hordeum vulgare L.*) is a globally significant cereal, ranking fourth in production after maize, wheat, and rice (FAO, 2021). Major global producers include the European Union, Russia, Ukraine, Canada, and Turkey, with the EU producing approximately 52 million metric tons in 2021. In Africa, Ethiopia is the second-largest barley producer after Morocco. In Ethiopia, barley is a staple crop in highland regions, used for both food and malt production. Its adaptability to challenging environments makes it critical for food security and economic sustainability (FAO, 2021).

Barley ranks fifth in area coverage among Ethiopian crops, cultivated on about 1 million hectares with an annual production of 2.21 million tons and an average yield of 2.22 t/ha (CSA, 2022). It is mostly grown by smallholder farmers under low-input, low-rainfall systems, with food barley representing 85–90% of production and malt barley the remaining 10–15% (Alemu *et al*., 2015). However, yields remain below the global average of 3.2–3.5 t/ha (FAO, 2021). In Tigray, barley ranks fourth in area but yields average only 1.8 t/ha, reflecting constraints such as nutrient deficiencies, soil degradation, and limited adoption of improved practices.

Nutrient deficiencies, particularly nitrogen (N), phosphorus (P), iron (Fe), and zinc (Zn), are widespread and severely limit barley growth (Abera *et al*., 2011; Agegnehu *et al*., 2011). Nitrogen and phosphorus are essential macronutrients for plant growth, while Fe and Zn are critical micronutrients for metabolic processes including enzyme activation and chlorophyll synthesis (Zhang et al., 2017). Addressing these deficiencies is vital not only for productivity but also for grain quality, which affects food and nutritional security. Biofortified barley enriched with Fe and Zn can mitigate human micronutrient deficiencies, offering both economic and public health benefits.Targeted fertilization combining macro- and micronutrients has shown potential to enhance crop productivity and soil health (Abera *et al*., 2011; Agegnehu *et al.*, 2011). However, limited research exists on the interaction effects of N, P, Fe, and Zn under Southeastern Tigray's specific agro-ecological conditions. Optimizing nutrient combinations and application timing can address site-specific deficiencies and guide evidence-based fertilizer recommendations. This study aimed to evaluate the effects of N, P, Fe, and Zn fertilization on barley yield, yield components, and grain quality in Southeastern Tigray.

2. Materials And Methods

The study was conducted at two sites in Southeastern Tigray, Ethiopia, during the 2016/17 main season under rain-fed conditions. A split-plot design was used, with macronutrient treatments as main plots and micronutrient treatments as subplots. Macronutrient treatments included: - MA1: Control, MA2: Full dose (100 kg urea ha^{-1} + 100

kg DAP ha^{-1}), and MA3: Half dose (50 kg urea ha^{-1} + 50 kg DAP ha^{-1}). Micronutrient treatments included: P1: Control, P2: 25 kg Zn ha^{-1}, P3: 25 kg Fe ha^{-1}, and P4: 12.5 kg Zn ha^{-1} + 12.5 kg Fe ha^{-1}.

kg DAP ha^{-1}), and MA3: Half dose (50 kg urea ha^{-1} + 50 kg DAP ha^{-1}). Micronutrient treatments included: P1: Control, P2: 25 kg Zn ha^{-1}, P3: 25 kg Fe ha^{-1}, and P4: 12.5 kg Zn ha^{-1} + 12.5 kg Fe ha^{-1}.

Main plots were replicated three times. Macronutrients were applied at planting and with split N application, while micronutrients (Zinc and iron) were applied as foliar sprays in the form of zinc sulfate heptahydrate ($ZnSO_4 \cdot 7H_2O$) and ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$), respectively, each prepared as a 0.5% (w/v) solution at vegetative or early reproductive stages. Seeds of the "*Fetina*" which is a food or malt barley variety, were sown at 125 kg ha^{-1} with 20 cm row spacing (July 10, 2017, at Dejen; July 18, 2017, at Kedamay-weyane). Composite soil samples (0–30 cm) were collected before planting and after harvest to assess fertility changes. Soil analyses included texture, organic carbon, total nitrogen, cation exchange capacity (CEC), pH, available phosphorus, and total Zn and Fe. Standard laboratory methods were followed: organic matter by Walkley and Black (Jackson, 1958), total N by Micro-Kjeldahl (Bremner *et al*., 1982), pH in 1:2.5 soil-water suspension (Jackson, 1958), CEC by ammonium acetate method (Chapman, 1965), available P by Olsen method (Olsen *et al*., 1954), and Zn and Fe by DTPA extraction (Lindsay and Norvell, 1978).

Agronomic data collected included plant height, spike length, number of kernels per spike, tiller number, thousand seed weight, grain yield, and above-ground biomass. Grain protein was estimated from nitrogen content using the factor 6.25 (ESA, 2001), while grain Zn and Fe were determined using atomic absorption spectroscopy (Jones, 2001). Analysis of variance (ANOVA) was performed using GenStat 14th edition. Treatment means were separated using Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$. LSD values were presented only where required to indicate the minimum significant difference among treatments. (Gomez and Gomez, 1984).

3. Results And Discussion

3.1. Soil physical and chemical properties of the experimental site

The laboratory analysis of selected physicochemical soil properties for the experimental sites is presented in Table 1. The soils at both Dejen and Kedamay-weyane were predominantly clay loam with neutral pH. Soil organic matter and organic carbon contents were very low at both sites. The cation exchange capacity (CEC) was also low, measuring 10.56 cmol(+)/kg at Kedamay-weyane and 11.63 cmol(+)/kg at Dejen, indicating low soil fertility mainly due to continuous cultivation and limited incorporation of organic materials. Soil organic carbon (0.4%) and total nitrogen (0.18%) were rated as very low to low according to Tadesse *et al*. (1991). Available phosphorus was high at Dejen and medium at Kedamay-weyane (Olsen *et al*., 1954). According to Benton (2003), the total Fe and Zn contents were low at both sites.

Table 1

Some physicochemical properties of the study sites

Soil parameters		Before harvesting		After harvesting	
		Dejen site	***Kedamay-weyane site***	***Dejen site***	***Kedamay-weyane site***
pH		7.11	7	6.94	6.8
EC (dS/m)		0.71	0.62	0.78	0.67
OC (%)		0.84	0.35	0.99	0.4
CEC (cmol(+)/kg)		10.25	10.16	11.63	10.56
Total N (%)		0.17	0.14	0.182	0.154
Available P (mg kg^{-1})		21.56	19.66	24.6	20.75
Total Fe (mg kg^{-1})		4.85	2.40	8.5	3.13
Total Zn (mg kg^{-1})		0.0036	0.00087	0.0144	0.005
Soil texture	Sand (%)	58	30	46	35
	Silt (%)	20	18	25	22
	Clay (%)	22	52	29	43
Textural class		Sandy clay loam	Clay	Sandy clay loam	Clay

pH= Soil pH; OC= Organic Carbon; CEC= Cation Exchange Capacity; TN= Total Nitrogen; AP= Available Phosphorus; Fe= Iron; Zn= Zinc

3.2. Effects of macro- (N and P) and micro-nutrients (Zn and Fe) on plant height, spike length, and tiller number

Application of macronutrients (N and P) significantly affected plant height, spike length, and tiller number at both Dejen and Kedamay-weyane sites. Micronutrients (Zn and Fe) significantly influenced plant height only at Dejen and spike length at both sites, while their interaction with macronutrients was generally not significant except for spike length at Dejen. The tallest plants were recorded from MA2 (100 kg Urea ha^{-1} + 100 kg DAP ha^{-1}), reaching about 84 cm at Dejen and 86 cm at Kedamay-weyane, while the control treatment produced the shortest plants. The increase in plant height with N and P application is attributed to improved vegetative growth and root development.

Micronutrient treatments also increased plant height at Dejen, where the combined application of Zn and Fe (P4: 12.5 kg Zn ha^{-1} + 12.5 kg Fe ha^{-1}) resulted in the highest increase (about 6%)

compared with the control. However, the effect was not significant at Kedamay-weyane, possibly due to differences in soil conditions and micronutrient availability. Spike length was significantly affected by both macronutrient and micronutrient applications. The longest spike length was recorded from MA2 (8.48 cm) among macronutrient treatments, while P4 produced the longest spikes among micronutrient treatments.

Macronutrient application significantly increased tiller number per plant, with the highest values recorded from MA2 (5.6 and 5.3 tillers per plant at Dejen and Kedamay-weyane, respectively). In contrast, micronutrient application and its interaction with macronutrients had no significant effect on tiller number, although the combined Zn and Fe treatment slightly increased tiller numbers compared with the control.

Overall, the results indicate that macronutrient application played a major role in improving plant growth traits of barley, while micronutrients had moderate effects, particularly on plant height and spike length.

Table 2

Mean comparisons of main effects on plant height, spike length and tiller number

Treatments	*Dejen site*			*Kedamay-weyane site*		
	PH(cm)	SL(cm)	TN	PH(cm)	SL(cm)	TN
Macronutrient						
MA1	68.2^{c1}	6.88^{c}	3.50^{b}	62.9^{c}	6.12^{c}	2.58^{c}
MA2	83.9^{a}	8.48^{a}	5.58^{a}	86.1^{a}	7.66^{a}	5.25^{a}
MA3	74.9^{b}	7.48^{b}	4.5^{ab}	75.7^{b}	7.10^{b}	3.92^{b}
LSD (0.05)	2.73	0.099	1.493	3.55	0.41	0.52
P-Value	<.001	<.001	.044	<.001	<0.001	<.001
CV (%)	1.6	0.6	14.6	2.1	1.6	5.8
Micronutrients						
P1	73.6^{c}	7.38^{d}	4.11^{a}	74.2^{a}	6.842^{b}	3.78^{a}
P2	75.7^{b}	7.67^{b}	4.67^{a}	74.8^{a}	7.03^{a}	3.89^{a}
P3	75.2^{b}	7.57^{c}	4.68^{a}	75.1^{a}	6.97^{a}	4.00^{a}
P4	78.4^{a}	7.83^{a}	4.67^{a}	75.5^{a}	6.99^{a}	4.00^{a}
LSD[3] (0.05)	1.06	0.08	0.60	1.87	0.116	0.47
P-Value	<.001	<.001	0.17	0.49	0.018	0.72
CV (%)	1.4	1.0	13.4	2.5	2.7	12.0

Different letters according to Duncan's multiple range tests indicate significant differences (P<0.05).
MA1= control, MA2= full dose (100 kg Urea ha^{-1} +100 kg DAP ha^{-1}), MA3= half dose (50 kg Urea ha^{-1} + 50 kg DAP ha^{-1}). P1= control, P2= 25 kg Zn ha^{-1}, P3= 25 kg Fe ha^{-1} and P4= (12.5 kg Zn ha^{-1}+12.5 kg Fe ha^{-1}). LSD=Least Significance Difference; CV=Coefficient of Variation. [4]PH=Plant height, SL=Spike length, TN=Tiller number.

3.3. Effects on number of kernels per spike

Application of macronutrients (N and P) and micronutrients (Zn and Fe) significantly affected the number of kernels per spike at both Dejen and Kedamay-weyane, while their interaction was not significant. The highest kernel number was obtained from MA2 (100 kg Urea ha^{-1} + 100 kg DAP ha^{-1}) with 20.3 and 22.4 kernels per spike at Dejen and Kedamay-weyane, respectively, followed by MA3. The lowest values were recorded in the control treatment. Micronutrient application also increased kernel number, where the combined application of Zn and Fe (P4) produced the highest increase, followed by Fe alone (P3) and Zn alone (P2). The improvement is attributed to the roles of N and P in promoting vegetative growth and reproductive development, and the roles of Zn and Fe in enhancing photosynthesis, protein synthesis, and grain formation.

3.4. Effects on biomass yield

Both macronutrient and micronutrient applications had highly significant effects on barley biomass yield at both sites, although their interaction was not significant. The highest biomass yield was obtained from MA2 with 8.28 t/ha at Dejen and 8.32 t/ha at Kedamay-weyane, while the control produced the lowest yield. The half dose treatment (MA3) also increased biomass yield by about 19–22% compared with the control. Among micronutrient treatments, P4 (combined Zn and Fe) produced the highest biomass yield, followed by P3 and P2. The increase in biomass yield is related to the roles of N and P in enhancing vegetative growth, chlorophyll formation, and energy transfer, while Zn and Fe improve photosynthesis, enzyme activity, and overall plant metabolism.

3.5. Effects on grain yield

Macronutrients, micronutrients, and their interaction significantly affected barley grain yield at both sites. The highest grain yield was recorded from MA2 with 2.26 t/ha at Dejen and 2.02 t/ha at Kedamay-weyane, followed by MA3. Micronutrient treatments also increased grain yield, with the combined application of Zn and Fe (P4) producing the greatest improvement, followed by Fe (P3) and Zn (P2). The interaction of MA2 and P4 produced the highest grain yield (2.62 t/ha) at Dejen and 2.17 t/ha at Kedamay-weyane, while the control gave the lowest yields. These results confirm that balanced application of macro- and micronutrients enhances barley productivity.

3.6. Effects on thousand seed weight

Application of N and P and micronutrients significantly affected thousand seed weight at both sites, although their interaction was significant only at Dejen. The highest thousand seed weight was obtained from MA2 with 59 g at Dejen and 61.5 g at Kedamay-weyane, followed by MA3. The increase in seed weight is attributed to the role of N in promoting photosynthesis and prolonged leaf activity, and P in energy transfer and grain filling. Their combined application improves assimilate production and grain development, resulting in heavier seeds.

Table 3

Mean comparison of main effects on number of kernels per spike, biomass yield and grain yield

Treatments	*Dejen site*				*Kedamay-weyane site*			
	NKPS	BY(t/ha)	GY(t/ha)	TSW	NKPS	BY(t/ha)	GY(t/ha)	TSW
Macro-nutrients								
MA1	15.58^{c}	5.10^{c}	1.35^{c}	52.4^{c}	15.42^{c}	5.04^{c}	1.23^{c}	51.4^{c}
MA2	20.33^{a}	8.28^{a}	2.26^{a}	59.1^{a}	22.42^{a}	8.32^{a}	2.02^{a}	61.5^{a}
MA3	17.75^{b}	6.30^{b}	1.74^{b}	54.9^{c}	20.50^{b}	6.48^{b}	1.92^{b}	53.8^{b}
LSD (0.05)	0.641	1.91	2.38	0.38	1.102	2.50	0.67	0.98
P-Value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CV (%)	1.6	1.3	5.9	0.3	2.5	1.7	1.7	0.8
Micro-nutrients								
P1	16.67^{d}	6.15^{c}	1.56^{c}	54.3^{c}	18.44^{c}	6.13^{c}	1.58^{c}	54.4^{d}
P2	17.56^{c}	6.48^{b}	1.77^{b}	55.5^{b}	19.33^{b}	6.55^{b}	1.71^{b}	55.2^{c}
P3	18.22^{b}	6.62^{b}	1.78^{b}	55.8^{b}	19.56^{b}	6.67^{b}	1.74^{b}	56.0^{b}
P4	19.11^{a}	7.01^{a}	2.02^{a}	56.2^{a}	20.44^{a}	7.12^{a}	1.87^{a}	56.8^{a}
LSD[4](0.05)	0.330	2.24	1.361	0.39	0.415	1.88	0.45	0.66
P-Value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CV (%)	1.9	3.5	7.7	0.7	2.2	2.9	2.6	1.2

NKPS= number of kernels per spike, GY=grain yield, BY= biomass yield

3.7. Effect of N, P, Fe, and Zn on barley grain quality

Application of macronutrients (N and P) and micronutrients (Zn and Fe) significantly affected barley grain Zn concentration at both sites, while their interaction was not significant. The highest grain Zn concentrations were recorded in the control plots (19.3 mg kg^{-1} at Dejen and 38.8 mg kg^{-1} at Kedamay-weyane), indicating a negative relationship between P application and Zn uptake. High phosphorus levels reduce Zn availability through the formation of insoluble Zn–phosphate compounds and by limiting mycorrhizal activity. Application of Zn fertilizer (25 kg Zn ha^{-1}) significantly increased grain Zn concentration at both sites, confirming the importance of Zn fertilization in improving grain Zn content.

3.8. Effects on grain Fe concentration

Both macronutrient and micronutrient applications significantly affected barley grain Fe concentration at the two sites. The highest grain Fe contents were obtained from the full macronutrient treatment (MA2: 100 kg Urea ha^{-1} + 100 kg DAP ha^{-1}), reaching 333.7 mg kg^{-1} at Dejen and 127 mg kg^{-1} at Kedamay-weyane. Micronutrient application also increased grain Fe concentration, with the highest values recorded from the combined Zn and Fe treatment (P4). Compared with the control, grain Fe content increased by 29.3% at Dejen and 46.2% at Kedamay-weyane. The interaction of MA2 and P4 produced the highest Fe concentrations (374.9 mg kg^{-1} at Dejen and 155.3 mg kg^{-1} at Kedamay-weyane). These results indicate that balanced application of macro- and micronutrients enhances micronutrient accumulation in barley grain.

Table 4

Main effects of N and P, and Fe and Zn on grain quality parameters

Treatments[2]	***Dejen site***			***Kedamay-weyane site***		
	Zn (mg kg^{-1})	**Fe (mg kg^{-1})**	**Protein (%)**	**Zn (mg kg^{-1})**	**Fe (mg kg^{-1})**	**Protein (%)**
Macronutrients						
MA1	19.26^{a1}	126.1^{c}	6.88^{c}	38.77^{a}	85.10^{c}	5.18^{c}
MA2	15.77^{b}	333.7^{a}	13.94^{a}	29.63^{c}	127.0^{a}	11.37^{a}
MA3	15.20^{b}	210.2^{b}	10.54^{b}	35.62^{b}	99.30^{b}	8.23^{b}
LSD (0.05)	2.869	30.85	0.495	1.988	10.42	0.706
P-Value	0.033	<0.001	<0.001	<0.001	<0.001	<0.001
CV (%)	7.6	6.1	2.1	2.5	4.4	3.8
Micronutrients						
P1	15.38^{b}	195.0^{d}	9.01^{c}	33.25^{b}	84.10^{d}	7.15^{d}
P2	18.00^{a}	213.8^{c}	10.35^{b}	36.41^{a}	98.30^{c}	8.04^{c}
P3	17.38^{a}	232.3^{b}	10.46^{b}	34.9^{ab}	109.8^{b}	8.44^{b}
P4	16.21^{ab}	252.2^{a}	11.97^{a}	34.8^{ab}	123.0^{a}	9.42^{a}
LSD[3] (0.05)	1.784	4.319	0.468	1.797	3.896	0.109
P-Value	0.028	<0.001	<0.001	0.009	<0.001	<0.001
CV (%)	10.8	2.0	4.5	2.5	3.8	1.3

3.9. Effects on grain protein content

Application of macronutrients N and P significantly increased barley grain protein at both Dejen and Kedamay-weyane. The full-dose treatment (100 kg urea + 100 kg DAP/ha, MA2) produced the highest protein contents of 13.94% at Dejen and 11.37% at Kedamay-weyane, representing increases of 32–38% over the half-dose and over 100% relative to the unfertilized control. Nitrogen drives this effect as a key component of amino acids and proteins, while phosphorus supports energy transfer, root development, and nitrogen assimilation, enhancing protein biosynthesis during grain filling.

Micronutrient application (Zn and Fe) also improved protein content, with P4 (12.5 kg Zn + 12.5 kg Fe/ha) achieving 12% at Dejen and

9.4% at Kedamay-weyane. The combination of full macronutrients and micronutrients (MA2 + P4) produced the highest protein levels (15.62% at Dejen, 12.45% at Kedamay-weyane), while the lowest values occurred in the control. Protein content was generally higher at Dejen, reflecting the site's higher grain Fe concentration, and aligns with studies showing N, P, Zn, and Fe enhance both yield and grain protein in cereals (Fageria and Baligar, 2005; Alloway, 2008; Agegnehu *et al.*, 2014).

Table 5

Interaction effect of some micro and macronutrients on yield and quality of barley

		Dejen site				*Kedamay-weyane site*			
Macro-nutrient	Micro-nutrients	Grain Concentration			Grain Yield (t/ha)	Grain Concentration			Grain Yield (t/ha)
		Zn ($mgkg^{-1}$)	Fe ($mgkg^{-1}$)	Protein (%)		Zn ($mgkg^{-1}$)	Fe ($mgkg^{-1}$)	Protein (%)	
MA1	P1	17.89	97.9	5.71	1.19	36.74	69.86	4.11	1.14
	P2	20.73	120.1	6.92	1.29	45.39	81.48	5.06	1.22
	P3	20.48	134.9	7.16	1.42	36.54	91.63	5.64	1.24
	P4	17.96	151.6	7.72	1.52	38.43	97.50	5.91	1.32
	P-Value	0.002	<0.001	0.03	0.025	0.03	0.01	0.045	0.035
MA2	P1	12.47	296.5	12.69	2.08	28.12	98.78	10.22	1.91
	P2	17.41	318.5	13.26	2.08	29.46	118.25	11.06	1.99
	P3	16.31	344.8	14.18	2.26	30.27	135.46	11.76	2.02
	P4	16.88	374.9	15.61	2.62	30.65	155.33	12.45	2.17
	P-Value	<0.001	<0.001	0.02	0.035	<0.001	<0.001	0.015	0.045
MA3	P1	15.78	190.5	8.64	1.41	34.89	83.68	7.12	1.68
	P2	15.87	202.8	10.88	1.91	34.37	95.13	7.99	1.91
	P3	15.36	217.2	10.04	1.68	37.91	102.16	7.92	1.97
	P4	13.80	230.2	12.59	1.95	35.32	116.12	9.90	2.13
	P-Value	<0.001	<0.001	<0.001	0.031	0.002	<0.001	0.023	0.023
LSD (0.05)		3.464	30.37	0.786	2.76	3.050	10.57	0.693	0.85
P-Value		0.127	<0.001	0.006	0.019	<0.001	<0.001	<0.001	0.003
Mean		16.74	223.3	10.45	17.8	34.84	103.78	8.26	17.3

N fertilizer improves grain Zn and Fe contents by affecting the levels of Zn-or Fe-chelating nitrogenous compounds required for transport of Zn and Fe within plants and/or the abundance of Zn or Fe transporters needed for root uptake and phloem loading of Zn and Fe. N applications promoted Fe concentration in grain. Similar to what was observed in Zn, there was a positive correlation between tissue contents of Fe and N.

The applications of phosphorus fertilizers to soils low in available zinc may induce zinc deficiency and increase the zinc requirement of plants. Part of the induced Zn deficiency observed in this study could be due to the inhibition of uptake by other divalent cations or a dilution of plant zinc which is because of the increased growth from the added phosphorus. Several experimental results indicate that there are additional phosphorus-zinc interactions in plants, including inhibition of zinc translocation from the roots to the shoot and physiological inactivation of zinc within the shoots

4. Conclusion and Recommendations

4.1. Conclusion

The interaction effect of macro- (N and P) and micro-nutrients (Zn and Fe) showed a greater effect than the main effects of macronutrients (N and P) or micronutrients (Zn and Fe) alone. The result showed that the application of 100 kg Urea/ha + 100 kg DAP/ha combined with 12.5 kg Zn/ha + 12.5 kg Fe/ha had the highest grain yield, Fe and grain protein contents of barley in both *Dejen* and *Kedamay-weyane* sites. Therefore, this combination of N and P and Fe and Zn treatments is recommended for a better grain yield, grain Fe concentration and protein content in the study area. For wider scale up implementation, the scientific world generally has more trust in nutrient management recommendations based on soil, climate and land use characteristics. Since the experiment was carried out in two locations but in one cropping season, it is suggested to conduct further studies in multi- seasons and locations to reach at conclusive recommendation of N, P Fe and Zn application for barley grain production and quality aspects in wider but similar environments.

4.2. Recommendations

The study demonstrated that integrated application of macronutrients (N and P) and micronutrients (Zn and Fe) significantly improved barley yield, yield components, grain Fe, and protein content. Therefore, balanced nutrient management involving both macro- and micronutrients is recommended for barley production in Southeastern Tigray and similar agro-ecological areas. The application of 100 kg urea ha^{-1} + 100 kg DAP ha^{-1} combined with 12.5 kg Zn ha^{-1} + 12.5 kg Fe ha^{-1} showed the best performance and can be considered a promising fertilizer option for improving barley productivity and nutritional quality. However, further multi-location and multi-season studies, including economic analysis, are required to validate the recommendation and ensure its feasibility for smallholder farmers. Future research should also focus on optimizing Zn and Fe application methods, evaluating nutrient use efficiency, and integrating organic and inorganic nutrient sources to improve soil fertility and sustain barley production.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the

corresponding author upon reasonable request. All relevant data supporting the findings of this study are included within the manuscript.

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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