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Effect of Phosphorus Rates and Varieties on Grain Yield, Nutrient Uptake and Phosphorus Efficiency of Tef [*Eragrostis tef* (Zucc.) Trotter]

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ABSTRACT

Tef [*Eragrostis tef* (Zucc.) Trotter] is the major cereal crop in Ethiopia. Increasing tef yield requires improving soil phosphorus (P) supply and identifying P efficient varieties. An experiment was conducted at Wenago, Ethiopia, from May to August, 2011, during the main cropping season, to investigate the role of P supply in relation to grain yield, nutrient uptake (N, P, Ca and K) and P efficiency, and to investigate varietal differences for these parameters using four P rates (0, 3, 6 and 9 g/m^2 P_2O_5) as main plots and three tef varieties (DZ-Cr-37, DZ-Cr-82, and DZ-Cr-255) as subplots in split-plot design with three replications. For respective 0, 3, 6 and 9 g/m^2 P_2O_5, grain yield was 84, 203, 215 and 218 g/m^2, total biomass 586, 897, 971 and 1016 g/m^2, and harvest index 0.14, 0.23, 0.22 and 0.22. For respective variety DZ-Cr-37, DZ-Cr-82, and DZ-Cr-255, grain yield was 194, 182 and 163 g/m^2, total biomass 810, 922 and 871 g/m^2, and harvest index 0.24, 0.19 and 0.18. Total plant nutrients (g/m^2) for respective 0, 3, 6 and 9 g/m^2 P_2O_5 were N 3.92, 7.95, 9.49 and 10.80, P 0.57, 1.20, 1.49 and 1.66, calcium 0.16, 0.27, 0.38 and 0.45, and K 4.45, 7.96, 9.70 and 10.50. For respective 3, 6 and 9 g/m^2 P_2O_5, P physiological efficiency (PE) was 224, 153 and 127, apparent recovery (AR) 0.49, 0.36 and 0.28, and agronomic efficiency (AE) 92, 50 and 35. For respective variety DZ-Cr-37, DZ-Cr-82 and DZ-Cr-255, PE was 248, 130 and 126, AR 0.28, 0.44 and 0.41, and AE 68, 57 and 51. The present experiment suggests that excess P supply beyond 3 g/m^2 could result in low grain yield increase and low P recovery requiring soil P assessment prior to fertilizer application. Moreover, variety DZ-Cr-37 may be incorporated in the future breeding programs for P efficiency in tef.

KEYWORDS

Tef; Eragrostis Tef; Phosphorus; Grain Yield; Nutrient Uptake; P Efficiency

1. Introduction

Tef [*Eragrostis tef* (Zucc.) Trotter] is the major cereal crop in Ethiopia growing widely from sea level up to 2800 m above sea level under various rainfall, temperature and soil conditions [1]. However, the average yield of tef is low (less than 1 t/ha) [2] which is partly attributed to low soil fertility [3]. In Ethiopia, N is deficient in almost all soils [4] and P is deficient in about 70% of soils [5]. P is less available for plant uptake in most tropical soils mainly because of its fixation with Ca in alkaline soils and Fe and Al oxides in acidic soils. Moreover, the majority of applied P fertilizers in these soils are fixed and made unavailable for plant uptake [6,7].

The development of P efficient genotypes with a great ability to grow and yield in soils with limited phosphorus supply improves the sustainability of crop production [8,9]. This also reduces production costs associated with P fertilizer applications and minimizes environmental pollution resulting from run-off and leaching of excess P fertilizer [10]. Phosphorus efficiency of the genotype can be due to its ability to acquire P from limited soil P supply and/or its ability to produce high yield per unit P acquired [11].

The differences in P uptake involve the differences in changing rhizosphere pH, release of organic compounds, and root surface area [12,13] as well as production and secretion of phosphatase to the rhizosphere [14,15]. On the other hand, the differences in the use of internal phosphorus may be related to the ability of plants to translocate and use it in dry matter production [16]. Even though, genotypic variation in P efficiency has been reported in several crops such as wheat [9,17,18], maize [19] and rice [20], the information in tef is scanty. This experiment was therefore carried out to investigate the role of P supply in relation to grain yield, nutrient uptake (N, P, Ca and K) and P efficiency, and to investigate varietal differences for these parameters in tef.

2. Materials and Methods

A field experiment was conducted at Wenago, Ethiopia, during 2011 main cropping season using three commonly grown tef varieties: DZ-Cr-37, DZ-Cr-82, and DZ-Cr-255, obtained from Debre-Ziet Agricultural Research Center, Ethiopia. Wenago, 6˚19'N 38˚16'E, is located at an altitude of 1763 m above sea level. It has the average annual rainfall and temperature of 1344 mm and 20.60˚C, respectively, and for the experiment duration of May to August, the monthly average rainfall was 166 mm, and the average maximum and minimum temperature was 26.10˚C and 15.04˚C, respectively. The analysis of soil samples at 0 - 30 cm depth for the experimental field was found to be clay texture (51% clay, sand 29%, and silt 20%), pH 5.35 (in H_2O), organic matter 2.02%, total N 0.10%, available P 4.60 ppm (Olsen), exchangeable Ca and Mg 10 meq/100g each, exchangeable K 23 meq/100g, and CEC 30.40 meq/100g.

The experimental design was a split plot with three replications. The P rates (0, 3, 6 and 9 g/m^2 P_2O_5) constituted the main plots and three tef varieties were subplots. Tef varieties were planted at recommended rate of 30 kg/ha on 26 May 2011. Each plot consisted of five rows, 1 m long with spacing of 20 cm between rows. The distance between replications was 1.5 m and that of main plots was 2 m. The 40 kg/ha N in the form of urea and diammonium phosphate (DAP) and all P rates, in the form of DAP, were applied at planting. Each plot was kept free from weeds with frequent hand weeding.

Days to 50% flowering and maturity, grain yield (g/m^2), total biomass (g/m^2), harvest index (the ratio of grain yield to total biomass), and plant height (cm), panicle weight (g/plant) and seed weight (g/plant) (averages for five random plants per plot) were recorded. Samples of grain and straw were oven dried at 65˚C to constant weight before estimating grain yield and total biomass. Grain and straw N were analyzed using Kjeldahl method [21], and P, Ca and K were analyzed using methods of Association of Official Analytical Chemists [22]. The nutrient concentration data were used to calculate nutrient uptake in grain and in total plant.

Determination of Phosphorus Efficiency

Phosphorus efficiency parameters were calculated according to Mengel and Kirbky [6] as:

$$\text{Physiological efficiency } (\text{PE}) = (\text{GYf-GYc})/(\text{TPf-TPc})$$

$$\text{Apparent recovery } (\text{AR}) = (\text{TPf-TPc})/\text{Ps}$$

$$\text{Agronomic efficiency } (\text{AE}) = (\text{GYf-GYc})/\text{Ps}$$

where GYf = grain yield of fertilized plot, GYc = grain yield of control plot, TPf = total plant P of fertilized plot, TPc = total plant P of control plot, and Ps = fertilizer P supply.

The grain yield and yield related parameters as well as nutrient uptake and P efficiency data were analyzed using GLM procedure of the SAS [23].

3. Results

3.1. Grain Yield and Yield Related Parameters

Analysis of variance showed that grain yield and yield related parameters except grain filling period were significantly affected by P application. However, the effect of variety was only significant for grain yield, total biomass and harvest index, and that of P × variety interaction was only significant for total biomass and harvest index (**Table 1**).

Grain yield and yield related parameters increased with increasing P rate except for days to flowering and maturity, and grain filling period. Grain yield increased from 84 to 218, total biomass 586 to 1016, harvest 0.14 to 0.22, panicle weight 0.49 to 0.73, and seed weight 0.25 to 0.38 when P rate was increased from 0 to 9 g/m^2 P_2O_5. On the other hand, the differences between 3, 6, and 9 g/m^2 P_2O_5 rates were not significant for these parameters. In addition, increasing P rate from 0 to 9 g/m^2 P_2O_5 reduced days to flowering and maturity by 14 and 13 days, respectively. Varieties DZ-Cr-37, DZ-Cr-82 and DZ-Cr-255 had the grain yield of 194, 182 and 163, respectively. Variety DZ-Cr-37 had also significantly highest value of harvest index compared to varieties DZ-Cr-82 and DZ-Cr-255 (**Table 2**).

3.2. Nutrient Uptake

Grain and total plant nitrogen (N), phosphorus (P), calcium (Ca) and potassium (K) were significantly affected by P application. The effect of variety was significant for these parameters except total plant N and that of P × variety interaction was only significant for grain Ca (**Table 3**).

Table 1. **Significance of mean squares for grain yield and yield related parameters across four phosphorus (P) rates and three tef varieties.**

Source of variation	d.f.	GY (g/m^2)	TB (g/m^2)	HI[1] (ratio)	PHT (cm)	DTF	DTM	GFP	PW (g/plant)	SW[2] (g/plant)
Replication	2	416ns	3118ns	1.16ns	86ns	10.10ns	17.44ns	1.86ns	0.019ns	4.60ns
P	3	36734^{**}	339315^{**}	144.62^{*}	515^{**}	326^{**}	310^{**}	11.21ns	0.114^{**}	34.92^{*}
Error (a)	6	696	19968	29.95	45	19.05	8	4.38	0.008	5.30
Variety	2	2941^{**}	38030^{**}	93.20^{**}	109ns	2.33ns	3.86ns	3.36ns	0.026ns	3.03ns
P × Variety	6	267ns	14817^{*}	21.46^{*}	10ns	9.63ns	9.75ns	11.21ns	0.004ns	5.15ns
Error (b)	16	436	5033	6.99	49	14.93	41.24	4.33	0.010	5.80
CV(a), %		14.66	16.30	27.36	7.99	8.91	4.16	11.01	13.87	21.41
CV(b), %		11.60	8.18	13.22	8.33	7.89	9.44	10.95	15.41	22.40

[1]harvest index was multiplied by 10^{-4}; [2]seed weight was multiplied by 10^{-3}; GY = grain yield; TB = total biomass; PHT = plant height; DTF = days to flowering; DTM = days to maturity; GFP = grain filling period; PW = panicle weight; SW = seed weight; * = significant at $p < 0.05$; ** = significant at $p < 0.01$; ns = not significant.

Table 2. **Mean values of grain yield and yield related parameters at four phosphorus (P) rates and three tef varieties.**

P rate (g/m^2 P_2O_5)	GY (g/m^2)	TB (g/m^2)	HI (ratio)	PHT (cm)	DTF	DTM	GFP	PW (g/plant)	SW (g/plant)
0	84	586	0.14	73	58	76	18	0.49	0.25
3	203	897	0.23	86	49	69	20	0.68	0.36
6	213	971	0.22	89	46	64	18	0.72	0.36
9	218	1016	0.22	90	44	63	19	0.73	0.38
$LSD_{0.05}$	30	163	0.063	8	5	3	ns	0.10	0.08
Variety									
DZ-Cr-37	194	810	0.24	81	49	68	19	0.69	0.33
DZ-Cr-82	182	922	0.19	87	50	69	19	0.60	0.33
DZ-Cr-255	163	871	0.18	85	50	68	18	0.67	0.36
Mean	180	867	0.20	84	49	68	19	0.65	0.34
$LSD_{0.05}$	18	61	0.023	ns	ns	ns	ns	ns	ns

GY = grain yield; TB = total biomass; HI = harvest index; PHT = plant height; DTF = days to flowering; DTM = days to maturity; GFP = grain filling period; PW = panicle weight; SW = seed weight.

Table 3. **Significance of mean squares for grain and total plant N, P, Ca and K across four phosphorus (P) rates and three tef varieties.**

Source of variation	d.f	GN (g/m^2)	TN (g/m^2)	GP (g/m^2)	TP (g/m^2)	GCa (g/m^2)	TCa (g/m^2)[1]	GK (g/m^2)	TK (g/m^2)
Replication	2	0.34ns	4.14ns	0.018ns	0.038ns	0.89ns	0.027ns	0.028ns	12.08ns
P	3	11.70^{**}	80.20^{**}	0.523^{**}	2.065^{**}	31.68^{**}	0.145^{**}	0.731^{**}	65.15^{**}
Error (a)	6	0.19	1.40	0.012	0.023	1.47	0.012	0.008	3.39
Variety	2	1.11^{**}	1.24ns	0.060^{**}	0.134^{**}	28.10^{**}	0.262^{**}	0.085^{*}	16.42^{**}
P × Variety	6	0.11ns	0.96ns	0.008ns	0.025ns	2.43^{**}	0.005ns	0.019ns	1.36ns
Error (b)	16	0.12	1.09	0.008	0.021	0.58	0.009	0.018	1.51
CV(a), %		14.92	14.72	18.72	12.38	31.02	34.62	12.88	22.58
CV(b), %		11.86	12.98	15.28	11.87	19.43	29.98	19.31	15.07

[1]Grain Ca was multiplied by 10^{-4}; GN = grain N; TN = total plant N; GP = grain P; TP = total plant P; TCa = total plant Ca; GK = grain K; TK = Total plant K; * = significant at $p < 0.05$; ** = significant at $p < 0.01$; ns = not significant.

Increasing P rate increased grain and total plant N, P, Ca and K. Total plant N increased from 3.92 to 10.80, P 0.57 to 1.66, Ca 0.16 to 0.45, and K 4.45 to 10.50 when P rate was increased from 0 to 9 g/m^2 P_2O_5. However, the maximum increase in total nutrient uptake was occurred between 0 and 3 g/m^2 P_2O_5 and it was low between 6 and 9 g/m^2 P_2O_5. Total plant P for varieties DZ-Cr-37, DZ-Cr-82 and DZ-Cr-255 was 1.11, 1.26 and 1.31, respectively. There were also considerable variations among varieties for grain N, P, Ca and K, and total plant Ca and K (**Table 4**).

3.3. Phosphorus Efficiency

Physiological efficiency (PE), apparent recovery (AR), and agronomic efficiency (AE) were significantly affected by P application and variety. However, the effect of P × variety interaction was only significant for PE. With increasing P rate from 3 to 9 g/m^2 P_2O_5, PE deceased from 224 to 127, AR 0.49 to 0.28, and AE 92 to 35. The respective PE, AR, and AE were 248, 0.28 and 68 for variety DZ-Cr-37; 130, 0.44 and 57 for variety DZ-Cr-82; and 126, 0.41 and 51 for variety DZ-Cr-255 (**Table 5**).

Table 4. Mean values of grain and total plant N, P, Ca and K for four phosphorus (P) rates and three tef varieties.

P rate (g/m^2 P_2O_5)	GN (g/m^2)	TN (g/m^2)	GP (g/m^2)	TP (g/m^2)	GCa (g/m^2)	TCa (g/m^2)	GK (g/m^2)	TK (g/m^2)
0	1.25	3.92	0.23	0.57	0.013	0.16	0.28	4.45
3	3.18	7.95	0.63	1.20	0.040	0.27	0.74	7.96
6	3.54	9.49	0.73	1.49	0.048	0.38	0.84	9.70
9	3.72	10.80	0.75	1.66	0.056	0.45	0.92	10.50
$LSD_{0.05}$	0.50	1.37	0.13	0.18	0.014	0.13	0.10	2.12
Variety								
DZ-Cr-37	3.18	7.67	0.60	1.11	0.042	0.47	0.61	7.82
DZ-Cr-82	3.00	8.17	0.65	1.26	0.053	0.29	0.70	9.45
DZ-Cr-255	2.59	8.28	0.51	1.31	0.022	0.18	0.78	7.19
Mean	2.92	8.04	0.59	1.23	0.039	0.32	0.69	8.15
$LSD_{0.05}$	0.30	ns	0.09	0.13	0.008	0.095	0.12	1.06

GN = grain N; TN = total plant N; GP = grain P; TP = total plant P; GCa = grain calcium; TCa = total plant Ca; GK = grain K; TK = Total plant K.

Table 5. Significance of F-ratios, and mean values of physiological efficiency (PE), apparent recovery (AR), and agronomic efficiency (AE) for three phosphorus (P) rates and three tef varieties.

P rate (g/m^2 P_2O_5)	PE	AR	AE
3	224	0.49	92
6	153	0.36	50
9	127	0.28	35
$LSD_{0.05}$	39	0.13	11
Variety			
DZ-Cr-37	248	0.28	68
DZ-Cr-82	130	0.44	57
DZ-Cr-255	126	0.41	51
Mean	168	0.38	59
$LSD_{0.05}$	37	0.09	11
F-ratio[1]			
Replication (2)	0.22ns	1.09ns	1.24ns
P(2)	25.19**	9.72*	118.19**
Error (a) (4)	884	0.01	68
Variety (2)	33.77**	9.14**	5.98*
P × Variety	4.37*	0.79ns	1.63ns
Error (b) (12)	1286	0.007	111
CV(a), %	17.70	26.32	13.98
CV(b), %	21.35	22.02	17.86

[1]numbers in the parentheses are degree of freedom; * = significant at $p < 0.05$; ** = significant at $p < 0.01$; ns = not significant.

4. Discussion

As to the present experiment, the increase in P rate increased grain yield in tef [24] and soybean [25]; grain yield and total biomass in maize [19], wheat [26], amaranth [27] and sorghum [28]; total biomass in rice [20,29]; and plant height in soybean [25], sorghum [28] and tef [30], because P is involved in several energy transformation and biochemical reactions for plant growth and development. Such an increase in tef performance observed in present experiment with P supply would also indicate the deficiency of P in this particular soil. On the other hand, low and non-significant increase in yield of tef beyond 3 g/m^2 P_2O_5 besides the low soil P content (4.60 ppm) could be related to the reaching of P supply to the optimal level or the limitation of yield potential of tef relative to high P supply. It has also been reported that when the supply of one nutrient is increased, the other nutrients or the genetic potential of the plants become the limiting factors [7]. In present experiment, the yield increase with the increase in P rate was related to the increase in total biomass, harvest index, panicle weight and seed weight/plant.

In the present experiment, the delay in days to maturity at low P supply was mainly attributed to the delay in days to flowering than the grain filling period. Indeed, limited P supply reduces leaf area duration, and limits supply of P and photosynthates to the grain subsequently reducing grain filling period [7]. As to the present experiment, early flowering with the supply of P has been reported for tomato [31] and wheat [32]. This could be because P supply increases cytokinins synthesis [33] and supply of photosynthates [7] for flower formation.

As to the present experiment, the increase in P supply increased grain P in maize [19,34], amaranth [27] and sorghum [28], grain N and K in maize [34], total plant P in maize [19], soya bean [25], wheat [26], rice [20,29] and sorghum [28], and total plant N and K in sorghum [28]. The increase in nutrient accumulation with the increase in P supply could be related to improved root system development [25], and increased availability of nutrients due to increased soil pH [27].

As to the present experiment, the decline in P physiological efficiency for soybean [25], and apparent recovery and agronomic efficiency for maize [19] and soybean [25] with the increase in P supply has also been reported. This could be due to the limiting effect of other nutrients with increasing level of P [6,19]. It has also been reported that high nutrient efficiency is generally obtained at low soil nutrient supplies or when rate of nutrient application is not too high [6].

As to the present experiment, varietal differences in grain P in maize [19], total plant P in maize [19] and rice [29], and P efficiency in amaranth [27] have also been reported. Moreover, the differences in apparent recovery could be related to the differences in root characteristics [7]. The present experiment suggests that excess P supply beyond 3 g/m^2 could result in low grain yield increase and low P recovery requiring soil P assessment prior to fertilizer application. Moreover, variety DZ-Cr-37 may be incorporated in future breeding programs for P efficiency in tef.

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