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Fertilizer-nitrogen use optimization for Tef in South Wollo Zone of Ethiopia

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Tef [Eragrotis tef] is a major staple cereal crop in Ethiopia but yields are low due to inadequate nutrient supply and other constraints. A field study was conducted in 2014 and 2015 in Jamma district of South Wollo Zone of Amhara Region to determine the economic optimum rate of fertilizer-N for tef. Fertilizer-N rates of 0, 23, 46, 69, 92, 115 and 138 kg ha^{-1} were evaluated. The randomized complete block design with three replications was used. The fertilizer-N rate means fit a quadratic yield response function with R^2=0.25**. The maximum mean grain and straw yields were recorded with 138 kg N ha^{-1} which was not statistically different from the 92 and 115 kg ha^{-1} N rates. The net economic returns to N were optimized with the 115 and 92 kg ha^{-1} N rates with respective net benefits of Ethiopian Birr 30508 and 28971 ha^{-1} and with marginal rate returns of 236 and 288%, respectively. The highest value to cost ratio (VCR) and highest benefit to cost ratio (BCR) of 10.9 and 5.2, respectively were obtained with 46 kg N ha^{-1}. Using the yield response function determined, the profit-maximizing optimal rate of N was found to be 117 kg N ha^{-1}. Therefore, for financially constrained farmers 46 kg N ha^{-1} is recommended, while for farmers without financial constraints 92 to 117 kg N ha^{-1} can be recommended for economic optimum return from tef production on the Vertisols in Jamma District and similar agroecologies.

Key words: Economic optimum, Jamma district, nitrogen fertilizer, yields response of tef.

INTRODUCTION

Tef [*Eragrostis tef (Zucc.)]* is the most important cereal crop in Ethiopia covering 30% of the area and 20% of the total cereal production (CSA, 2015). It is an excellent source of essential amino acids, including lysine which is commonly deficient in cereal grain (Doris, 2002). It is gluten-free (Spaenij et al., 2005). However, tef has the lowest productivity as compared to the other cereal crops as the national average yield is meager, ranging between 1.28 and 1.58 t ha^{-1} (CSA 2015).

Vertisols account for 23% of the cropland in Ethiopia and are the dominant soil type in the highlands where Jamma District of South Wollo Zone is located (Kamara and Haque, 1988). These soils are characterized by very low water infiltration rate or low saturated hydraulic conductivity and, therefore, are susceptible to waterlogging under high intensity rainfall conditions. Tef is the most important food crop in Jamma District (Getachew, 1991). However, tef yield in the District is

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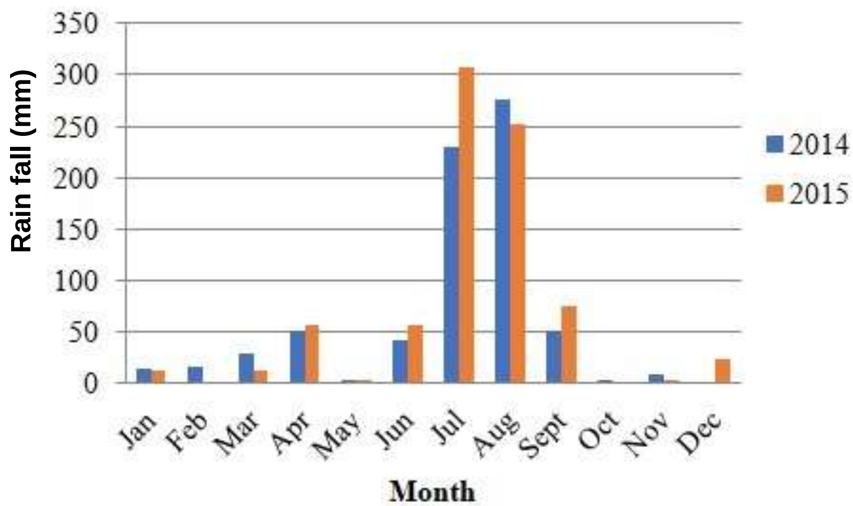

Figure 1. Monthly rainfall distribution of Jamma District in 2014 and 2015.

below the national average, at least partly due to inadequate supply of plant nutrients (Stoorvogel and Smaling, 1990; Asnakew, 1994; Fassil and Charles, 2009; Tulema et al., 2005). In addition, the Ethiopia highland Vertisols tend to exhibit low total N mainly due to leaching and denitrification (Tekalign et al., 1988) limiting cereal production.

The current blanket fertilizer recommendation for tef and other cereal crops in Jamma District is to apply 64 kg N and 46 kg P_2O_5 ha^{-1} (NFIU, 1992). Therefore, refinement of the previous fertilizer recommendations is essential from the basis of dynamic property of soils as a result of different natural and man-made factors. However, nutrient fertilization recommendations must be based on crop yield optimization and profit maximization. Fertilization recommendations are usually based on results from field crop nutrient response trials which were lacking for Jamma District. The recent soil fertility assessment map produced by Ethiopian Soil Information System (EthioSIS) showed that in addition to N and P, K, S, B and Zn deficiencies are widespread in Ethiopian soils (EthioSIS 2014). Therefore, this research was conducted to develop a yield response curve of tef to fertilizer-N under adequate supply of all nutrients and determine the economically optimum N rate for tef.

MATERIALS AND METHODS

Description of the study area

The study was carried out in 2014 and 2015 main cropping seasons in Jamma District of South Wollo Zone of the Amhara Region in Ethiopia. The district is situated within the geographical boundaries of 10° 06' 24'' - 10° 35' 45'' N latitudes and 39° 04' 04'' - 39° 23' 03'' E longitudes and altitudinal ranges of 1428 - 2752 m above sea level (masl). The district receives a mean annual rainfall of 1130 mm rainfall with approximately 60% falling in July and August (Figure 1); with 10.3°C mean minimum temperature; and 21.6°C mean maximum temperature. The cropping season is from June to November. The soil type for the study sites is Pellic Vertisol with some of the physico-chemical properties mentioned in Table 1. The previous crop produced on the study sites had been wheat.

Treatments and experimental design

The treatments comprised fertilizer-N at rates of 0, 23, 46, 69, 92, 115 and 138 kg ha^{-1} with uniform application of 69/80/30/2/1 kg ha^{-1} P_2O_5/K_2O/S/Zn/B. In addition, there was a zero fertilizer treatment and the recommended 69/46 kg ha^{-1} N/P_2O_5. The randomized complete block design (RCBD) with three replications was used on each of three representative farmers' fields in 2014 and 2015. The gross plot size was 3 x 3 m and 2 x 2 m was the harvested area for data collection.

Experimental materials and procedures

Tef variety with local name *dega tef* - *DZ675* was planted in rows of 20 cm spacing at a seed rate of 10 kg ha^{-1} on flat fine seed beds. Phosphorus, K and S fertilizers were band-applied at basal as triple super phosphate (TSP), muriate of potash (KCl) and calcium sulfate ($CaSO_4$) straight fertilizers, respectively. Fertilizer-N was applied as urea with 50% at planting and 50% at 45 days after planting. The micronutrients Zn as zinc sulphate ($ZnSO_4$) and B as borax ($Na_2B_4O_7.5H_2O$), each weighed in plot level, each dissolved in 16 L volume tap water in a knapsack sprayer were sprayed at foliage 45 and 60 days after planting, respectively.

Data collection

Fresh biomass yield was measured by weighing the total above ground biomass of the entire harvestable area. The dry biomass weight was obtained by drying a sample of plants, with seed panicles, in an oven at 105°C for 12 h and adjusting the fresh biomass weight into dry weight basis. Grain yield was determined from harvested grain weight and straw yield was calculated by subtracting the grain weight from the dry biomass weight. Harvest index was obtained by dividing the grain yield by the dry biomass

Table 1. Range of physico-chemical properties of surface soil (0-30 cm) of the study sites.

Soil property*	Value	Rating**
pH (H_2O)	6.5-6.8	Slightly acidic to neutral
Organic matter (OM) (%)	1.36-1.75	Low
Total N (TN) (%)	0.10-0.11	Low
Olsen extractable P (mg kg^{-1} soil)	3.08-5.20	Low
Exchangeable Ca ($cmol_C$ kg^{-1})	30.6-46.3	Very high
Exchangeable Mg ($cmol_C$ kg^{-1})	9.9-12.9	Very high
Exchangeable K ($cmol_C$ kg^{-1})	0.6-0.7	High
Cation exchange capacity (CEC) ($cmol_C$ kg^{-1})	52.0-61.7	Very high
Percent acid saturation (PAS) %	82.5-97.6	Very weakly leached
Sand %	16.3-17.5	
Silt %	20.0-21.3	
Clay %	62.5	
Textural class	Clay	

The soil analysis was conducted at the Ethiopian National Soil Research Center.
*Source: Abebe et al. (2013). **Ratings are based on pH (Jones, 2003), OM and TN (Tekalign, 1991), available P (Cottenie, 1980), exchangeable Ca, Mg and K (FAO, 2006), CEC and PAS (Hazelton and Murphy, 2007).

weight.

Data analysis

The collected data were subjected to analysis of variance (GLM procedure) using SAS software version 9.00 (SAS, 2004). The mixed model procedure was used for the combined analysis over the testing sites with treatments as a fixed variable and with site and replication as random variables. Treatment means separation was done with Duncan's Multiple Range test (DMRT) at P ≤0.05. Simple non-linear regression analysis was run using SAS to determine the goodness of fit of the yield response curve to N. The farm-gate prices of Ethiopian Birr (ETB) 20, 2 and 23.9 per kg for variable factors; tef grain, tef straw and N (derived from cost of urea, ETB 11.0 kg^{-1}), respectively, were used for partial budget analysis following the CIMMYT procedure (CIMMYT, 1988). The other factors were constant as they were applied uniform to all treatments. The mean grain and straw yields used in the partial budget analysis were adjusted to 90% of the measured yield.

RESULTS AND DISCUSSION

Yield response of Tef to N fertilizer

A highly significant (P≤ 0.01) grain and straw yield response to N was found at all testing sites in 2014 (Table 2). There was no significant difference in the response to fertilizer-N across testing sites. The grain yield was increased from 0.6 - 0.8 t ha^{-1} to 1.3 - 1.4 t ha^{-1} while the straw yield was increased from 1.6 - 1.8 t ha^{-1} to 2.7 - 3.4 t ha^{-1} by applying N_{115}. The significant yield response of tef to N was attributed to the low indigenous soil N supply (Table 1; Tekalign 1991). The results agree with other reports of tef response to fertilizer-N especially in the highland Vertisols (NFIU, 1993; Tekalign et al., 2001; Minale et al., 2004). The combined analysis of the yield data pooled over the testing sites in 2014 indicated that N had significant (P≤0.05) effect on the yield of tef with a mean maximum grain yield of 1.2 t ha^{-1} and mean maximum straw yield of 2.9 t ha^{-1} with N_{115} and N_{138} which were statistically at par with N_{69} and N_{92} (Table 4). However, treatments did not affect the harvest index (HI).

Tef grain yield was increased with fertilizer-N at only one of the three sites in 2015 (Table 3). The lack of response for the two sites was attributed to these being newly cultivated fields which were previously range land had better soil fertility. Fertilizer-N application decreased grain yield at Site 6. However, straw yield was increased at all testing sites in 2015. This result is supported by Alkamper (1973) and Legesse (2004) who concluded that straw compared with grain yield is more responsive to N while P encourages good tef grain production. The mean grain yield of 1.9 t ha^{-1} in 2015 was above the then national average yield (CSA, 2015). Grain yield was not affected by N rate in the pooled analysis in 2015 (Table 4). The non-significant grain yield response to N and significant treatment by site interaction effect in 2015 was due to the non-significant grain yield response to N at two of the testing sites. The highest mean straw yield was 7.8 t ha^{-1} with N_{155} which was statistically at par with the straw yield from N_{92} and N_{138}. The HI declined with increased N rate in 2015 due to relatively great straw compared with grain yield response to N rate.

On average across the two years, grain yield increased from 0.7 to 1.5 t ha^{-1} and straw yield increased from and 1.8 to 4.0 t ha^{-1} due to fertilizer-N application, but HI was not affected (Table 4). The average grain yield increase due to fertilizer-N of 0.8 t ha^{-1} was higher than the mean yield increase from 52 sites in Amhara Region of 0.59 t ha^{-1} (Wakene and Yifru, 2013). The mean grain and straw yields were not significantly increased with N rate > 92 kg ha^{-1}.

Table 2. Mean grain and straw yields of tef obtained in the three testing sites as affected by fertilizer treatments in 2014.

Treatment* (kg N ha^{-1})	Grain yield (kg ha^{-1})			Straw yield (kg ha^{-1})		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
No fertilizer	642.8^{b}	603.7^{c}	827.0^{d}	1632.2^{d}	1813.0^{cd}	1839.7^{b}
0	633.9^{b}	708.8^{bc}	898.6^{cd}	1699.4^{d}	1874.5^{cd}	1768.1^{b}
23	960.1^{ab}	704.3^{bc}	1041.6^{bcd}	2123.3^{cd}	1629.0^{d}	1858.4^{b}
46	1050.3^{ab}	948.2^{ab}	1063.1^{bc}	2366.4^{bcd}	2051.8^{cd}	2603.6^{a}
69	1087.5^{ab}	920.3^{ab}	1163.4^{ab}	2745.8^{abc}	2246.3^{bc}	2336.6^{a}
92	1397.7^{a}	1004.8^{a}	1133.9^{ab}	2727.3^{abc}	2745.2^{ab}	2491.1^{a}
115	1390.8^{a}	1049.1^{a}	1309.8^{a}	3442.6^{a}	2700.9^{ab}	2590.3^{a}
138	1497.6^{a}	1062.2^{a}	1186.3^{ab}	3169.1^{ab}	3104.5^{a}	2605.3^{a}
69/46 N/P_2O_5	1235.5^{a}	878.0^{abc}	1145.3^{ab}	2681.2^{abc}	2038.7^{cd}	2338.0^{a}
Mean	1099.6	875.5	1085.4	2509.7	2244.9	2270.1
CV (%)	26.5	17.3	11.3	17.4	13.8	11.3
SEM	292.0	151.5	122.5	435.7	310.7	256.8

Treatment means within a column followed by the same letter are not significantly different at p > 0.05. The N rate treatments had a uniform band application of 69/80/30 P_2O_5/K_2O/S kg ha^{-1} and a uniform foliar application of 2/1 Zn/B kg ha^{-1}.

Table 3. Mean grain and straw yields of tef obtained from the three testing sites as affected by application of N in 2015

Treatment* (kg N ha^{-1})	Grain yield (kg ha^{-1})			Straw yield (kg ha^{-1})		
	Site 4	Site 5	Site 6	Site 4	Site 5	Site 6
No fertilizer	683.3^{d}	2152.5	1765.0^{ab}	2407.5^{de}	3098^{e}	4151.7^{e}
0	725.0^{d}	2243.3	1858.3^{ab}	1775.0^{e}	4668^{cde}	4308.3^{e}
23	1318.3^{c}	2015.0	1881.7^{ab}	3848.3^{cd}	3318de	6285.0^{bcd}
46	1841.7^{b}	1935.0	2066.7^{a}	5491.7^{abc}	5732^{bcd}	5766.7^{d}
69	2203.3^{ab}	2189.9	1531.7^{bc}	5713.3^{abc}	5977^{bc}	7468.3^{ab}
92	2228.3^{ab}	2053.3	1546.7^{bc}	6771.7^{ab}	7613^{ab}	7370.0^{abc}
115	2346.7^{a}	2038.3	1686.7^{ab}	6903.3^{ab}	8128^{ab}	8313.3^{a}
138	2356.7^{a}	1970.0	1260.0^{c}	7560.0^{a}	8863^{a}	5906.7^{cd}
69/46 N/P_2O_5	1861.7^{b}	2495.0	1826.7^{ab}	4888.3^{bc}	6672^{abc}	7173.3^{abcd}
Mean	1729.4	2120.2	1713.7	5141.1	6177.6	6304.8
CV (%)	14.1	17.6	12.1	20.9	21.1	12.8
SEM	243.9	372.4	207.4	1078.5	1303.8	806.0

*Treatment means within a column followed by the same letter are not significantly different at p > 0.05. The N rate treatments had a uniform band application of 69/80/30 P_2O_5/K_2O/S kg ha^{-1} and a uniform foliar application of 2/1 Zn/B kg ha^{-1}.

Minale et al. (2004) and Alemayehu et al. (2007) recommended 60-80 kg N ha^{-1} with 18-20 kg P_2O_5 ha^{-1} for maximum tef production on Vertisols in Northwest Ethiopia. Application of 80 kg N ha^{-1} plus 80 kg ha^{-1} P_2O_5 with tef row spacing of 10 cm gave the highest tef yield (Kumela and Thomas, 2016) while Fissehaye et al. (2009) reported maximized tef grain yield with 69 kg N ha^{-1} on Vertisols. In contradiction to these findings, Miller (2009) and Nosberg et al. (2009) stated that tef requires only 32 to 46 kg N ha^{-1} and that excessive N rate results in increased lodging.

Wakene and Yifru (2013) showed that optimal N rates for tef in Ethiopia varied from 15-90 kg ha^{-1} due to diversity in agro-ecology, climate and soil type and recommended 15-60 kg ha^{-1} N for Nitisols, Luvisols, Fluvisols and Andosols, but 60-90 kg ha^{-1} N for Vertisols. However, N fertilization for tef could be either omitted or reduced by half when the precursor crops are legumes (Tekalign et al., 2001; Alemayehu et al., 2010) or oil crops (Abedenna et al., 2006; Alemayehu et al., 2010).

Yield response function analysis

The mean grain yield response to N rate over two years fit a quadratic function. The adjusted $R^2 = 0.25^{**}$ when the

Table 4. Mean grain and straw yields (kg ha^{-1}) and harvest index pooled over testing sites in 2014 and 2015 and pooled over two experimental years.

Treatment* (kg N ha^{-1})	2014			2015			Pooled over years		
	GY	SY	HI	GY	SY	HI	GY	SY	HI
No fertilizer	691.2^{e}	1761.6^{c}	0.28	1456.3	3352.1^{d}	0.31^{a}	721.6^{e}	1950.3^{de}	0.27
0	747.1^{de}	1780.7^{c}	0.29	1608.9	3448.1^{d}	0.31^{ab}	741.6^{e}	1779.3^{e}	0.29
23	902.0^{cd}	1870.2^{c}	0.32	1738.3	4483.9^{d}	0.29^{abc}	975.1^{d}	2371.4^{d}	0.30
46	1020.5^{bc}	2340.6^{b}	0.30	1947.8	5663.3^{c}	0.26^{bcd}	1273.9^{c}	3203.4^{bc}	0.30
69	1057.1^{abc}	2442.9^{b}	0.30	1975.0	6386.1^{bc}	0.24^{def}	1343.6^{bc}	3260.5^{bc}	0.30
92	1178.8^{ab}	2654.5^{ab}	0.31	1942.8	7251.7^{ab}	0.21^{def}	1441.2^{ab}	3683.8^{ab}	0.29
115	1249.9^{a}	2911.3^{a}	0.30	2023.9	7781.7^{a}	0.21^{ef}	1539.4^{a}	3893.9^{a}	0.30
138	1248.7^{a}	2959.6^{a}	0.30	1862.2	7443.3^{ab}	0.20^{f}	1544.0^{a}	4091.4^{a}	0.29
69/46 N/P_2O_5	1086.3^{abc}	2352.6^{b}	0.32	2061.1	6244.4^{bc}	0.26^{cde}	1290.4^{bc}	3087.2^{c}	0.30
Mean	1020.2	2341.6	0.30	1851.1	5876.2	0.25	1213.3	3067.8	0.29
CV (%)	19.5	15.4	11.4	14.9	19.7	18.9	14.8	17.9	10.49
SEM	198.9	360.3	0.03	276.2	1157.8	0.05	179.5	551.5	0.03
Trt*Site	ns	ns	ns	**	*	*	**	**	ns

GY = Grain yield; SY = Straw yield; HI = Harvest index; Treatment means within a column followed by the same letter are no significantly different at p > 0.05. * and **- significant at 0.05 and 0.01 probability levels, respectively. ns = non-significant at p > 0.05.

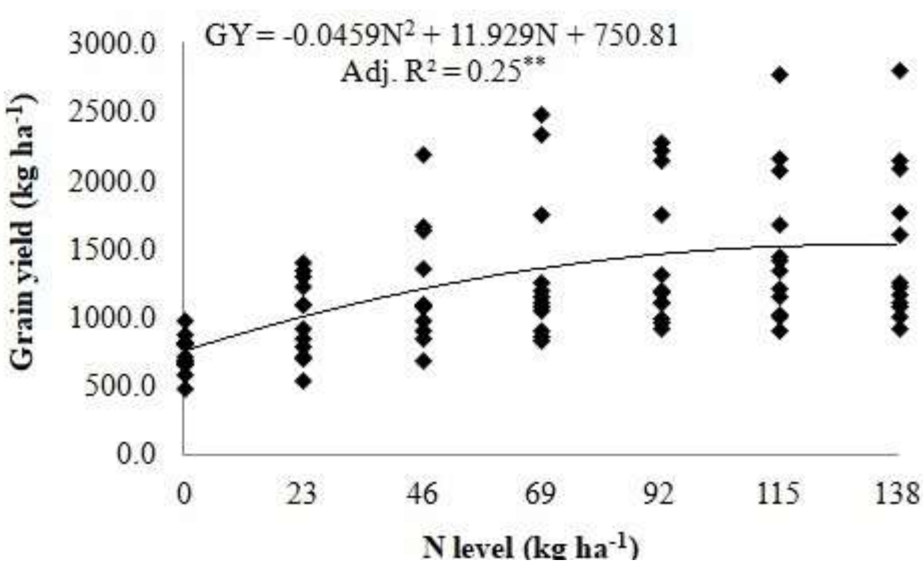

Figure 2. The quadratic response curve of the plot yield data to fertilizer-N in the six sites in 2014and 2015 on Vertisols in Jamma District of Ethiopia.

analysis was with plot data but 0.988 where the regression analysis was with overall N rate means (Figures 2 and 3). This generally agrees with tef responses reported for the central highlands of Ethiopia with Vertisols (Tekalign et al., 2001; Minale et al., 2004). Others have reported good fits of quadratic yield response to N fertilizer including for potato (Gilles et al., 2000), wheat (Cassman and Plant, 1992; Zhejun et al., 2014) and rice (Cassman and Plant 1992; Dobermann et al., 1992).

Economic analysis

The partial budget analysis showed that the highest net economic return of Ethiopian Birr (ETB) 30508 per ha with MRR of 236% was estimated from N_{115} followed by the net economic return of 28971 ETB per ha and MRR of 288% from N_{92} (Table 5). The dominance analysis showed that application of N_{138} was dominated and thus was excluded from the analysis. The sensitivity analysis with the assumption of increasing fertilizer price and labor

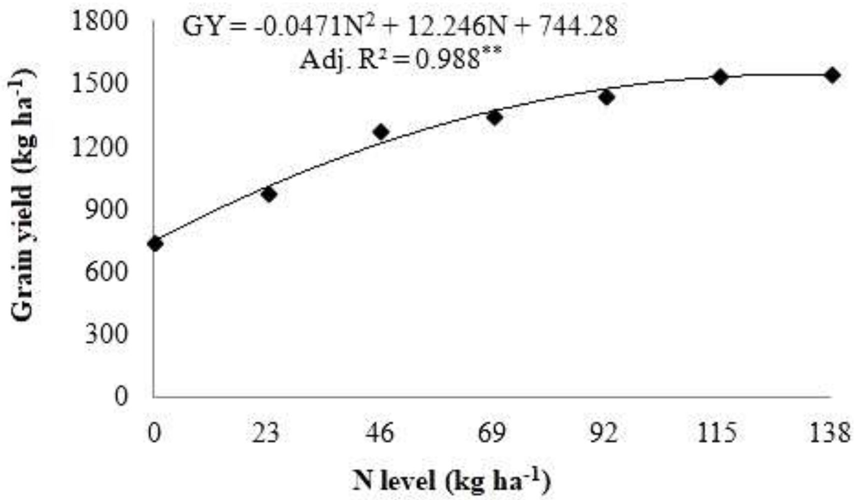

Figure 3. The quadratic response curve of the mean grain yield to N pooled over six sites in 2014and 2015 on Vertisols in Jamma District of Ethiopia.

Table 5. Partial budget analysis for overall mean grain and straw yields with grain value of 20 Ethiopia birr (ETB), straw value of 2, fertilizer-N cost of 23.9 for scenario 1 and grain value of 17 ETB, straw value of 1.7 ETB and fertilizer-N cost of 27.5 ETB for scenario

N	AGY	ASY	GR	LC	FC	TVC	NR	MRR (%)	VCR	BCR
					Scenario 1					
0	667	1601	16542	0	0	0	16542	-	-	-
23	878	2128	21816	1000	550	1550	20266	240	9.6	3.4
46	1147	2816	28572	1200	1099	2299	26273	801	10.9	5.2
69	1209	2935	30050	1300	1649	2949	27101	127	8.2	4.6
92	1297	3315	32570	1400	2199	3599	28971	288	7.3	4.5
115	1386	3518	34756	1500	2749	4249	30508	236	6.6	4.3
					Scenario 2					
0	667	1601	14060.7	0	0	0	14061	-	-	-
23	878	2128	18543.6	1150	632	1782	16761	152	7.1	1.5
46	1147	2816	24286.2	1380	1264	2644	21642	566	8.1	2.9
69	1209	2935	25542.5	1495	1896	3391	22151	68	6.1	2.4
92	1297	3315	27684.5	1610	2529	4139	23546	187	5.4	2.3
115	1386	3518	29542.6	1725	3161	4886	24657	149	4.9	2.2

AGY=Adjusted grain yield (kg ha^{-1}); ASY=Adjusted straw yield (kg ha^{-1}); BCR=Benefit to Cost Ratio; FC=Fertilizer-N Cost (TEB); GR=Gross Returns (ETB); LC=Labor Cost (ETB); MRR=Marginal Rate of Return; N=N level (kg N ha^{-1}); NR=Net Return (ETB); TVC=Total Variable Cost (ETB); VCR=Value to Cost Ratio.

cost by 15% while decreasing grain and straw yields' price by 15% also showed that the highest net economic returns were obtained from application of N_{115} and N_{92}. However, the highest value to cost ratio (VCR) and highest benefit to cost ratio (BCR) of 10.9 and 5.2, respectively, in the first scenario and 8.1 and 2.9, respectively, in the second scenario were obtained from application of N_{46} (Table 5). Using the yield response function determined, the profit-maximizing optimal rate of N, calculated by setting the first derivative of the response function that is, $GY = -0.0459N^2 + 11.929N + 750.81$ to the price ratio of the fertilizer-N to the grain price, that is, (ETB 23.9/ETB 20) was found to be $23.9/20 = -0.0918N + 11.929$; $N = 117$ kg ha^{-1} for scenario 1, while in the case of scenario 2, $27.5/17 = -0.0918N + 11.929$; N = 112 kg ha^{-1}. Therefore, for the financially constrained farmers seeking maximum profits with least fertilizer costs, application of 46 kg N ha^{-1} is recommended. However, for the farmers without financial constraints seeking for maximum net economic returns, application of 92-117 kg N ha^{-1} is recommended. This result is supported by previous studies by Tekalign et al.

(1996) and Wakene and Yifru (2013) who recommended application of 60-90 kg N ha^{-1} on Vertisols in the highlands of Ethiopia.

Conclusion

The result revealed that quadratic response curve was the best fitting curve for the mean grain yield response of tef to application of N. The highest net economic returns and highest marginal rate of returns were obtained with 115 and 92 kg N ha^{-1}. However, the highest VCR and highest BCR were found with 46 kg N ha^{-1}. The profit-maximizing optimal rate of N using the yield response function determined in the study was found to be 117 kg N ha^{-1} in scenario 1 and 112 kg N ha^{-1} in scenario 2. However, taking the limited resource endowment of small holder farmers in the Jamma District in to consideration, 46 kg N ha^{-1} is recommended for financially constrained farmers seeking maximum profits with least fertilizer costs, while 92-117 kg N ha^{-1} is recommended for farmers without financial constraints seeking maximum net economic returns with higher investment.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests

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