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Research Article

Optimizing sowing rates and methods for irrigated Tef *(Eragrostis tef* (Zucc.) (Trotter) production in North Western Ethiopia

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Abstract: *Tef is considered the major crop in Ethiopia, serving as a staple food for the majority of the population and occupying the largest area under cultivation among cereal crops in the country. However, crop management for tef produced under irrigation is mainly based on its recommended rates for the respective tef production under rain-fed conditions. A field experiment was conducted at the Koga irrigation scheme during the 2020/2021 dry season to determine the effects of sowing methods and seeding rates on the yield of tef produced under irrigation conditions. The treatments consisted of two sowing methods (broadcast and drill row) and five seed rate levels (5, 10, 15, 25, and 30 kg ha^{-1}), which were laid out in a randomized complete block design with three replications. Data on growth, yield, and yield component parameters were collected. The data were analysed using SAS-JMP13 software. Results showed that the row and broadcast sowing methods at a seed rate of 5 kg ha^{-1} and 15 kg ha^{-1}, respectively, gave the maximum plant height, panicle length, grain yield, and harvest index. Sowing tef in broadcasting with a seed rate of 15 kg ha^{-1} is a profitable sowing method as compared to others. Thus, it could be concluded that sowing tef in broadcasting method with a seed rate of 15 kg ha^{-1} gave both maximum grain yield and net benefit for irrigated tef production and recommended for the farmers in the study area. Further extensive research needs to be conducted in all agro-ecologies of the country as far as the irrigation water is available.*

Keywords: Broadcasting; Irrigation; Seeding rate; Sowing method; Tef yield
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1. Introduction

Tef [*Eragrostis tef* (Zucc) Trotter] is a cereal crop and indigenous in Ethiopia (Assefa, 2005). The area devoted to tef cultivation is larger as compared to other major cereal crops. Although tef is found in almost all cereal-growing areas of Ethiopia, the major areas of its production are *Gojam, Shewa, Gondar, Wellega, and Wello,* in the central highlands of the country (Atsbaha and Tessema, 2008). Tef performs well in '*Weina dega'* (mid-altitude) agro-ecological zones or medium altitude (1700-2400 meters above sea level). According to Berhe (2009), mean temperature and optimum rainfall for tef during the growing season range from 10 to 27 ^{0}C and 450 to 550 mm, respectively. It occupies about 24.11% of the total area and 17.11% of the grain production (CSA, 2020). Ethiopian farmers grow Tef for a number of merits, which are mainly attributed to the socioeconomic, cultural, and agronomic benefits (Seyfu, 1993). It is a gluten-free grain (Zhu, 2018), relatively drought-tolerant (Seyfu, 1997), and waterlogging (Kebebew *et al.*, 2015) compared to other cereals except rice. Tef is the staple food crop in Ethiopia, and its straw is a preferred feed for livestock (Kebebew *et al.*, 2011). Teff is used to make the traditional flatbread *injera*, as well as bread, pancakes, porridge, and alcoholic beverages. When grown on vertisols, tef gives better grain yield and possesses higher nutrient contents, especially protein, rather than on andosols (Seyfu, 1997).

Tef performs well above any other major crops grown under unfavorable circumstances, such as low moisture and waterlogged conditions, and is better than that of many other cereals, including maize, wheat, and barley, making it a preferred cereal by farmers, often considered as a rescue crop in seasons when crops fail due to moisture stress and waterlogging conditions (Hailu and Seyfu, 2001). Moreover, demand for tef grain products is increasing worldwide due to their increasing popularity as gluten-free grains (Zhu, 2018).

There is a shortage of crop production in the country to meet the demand. For instance, Ethiopia continually remains a net importer of about 1.7 million tons of wheat, draining the national treasury (EIAR, 2020).To minimize these challenges, currently, the government has given due attention to low- and high-land irrigated agriculture to attain food security (Abiot, 2017). In these circumstances, based on this attention, irrigated agricultural technologies have been created, and efforts have been made to hasten the diffusion and adoption of these innovations (Getinet *et al*., 2020). Among the strategies, improving crop management technologies for tef production under irrigation conditions is getting priority.

Despite the aforementioned advantage and high area coverage, adaptation to different environmental conditions and requirements as a staple food in Ethiopia, the yield of tef grain is very low (national average grain yield of 1.85 t ha^{-1}) (CSA, 2020) as compared to the potential yield (1.7-2 t ha^{-1}) (Gebru *et al.*, 2021). Some of the factors contributing to the low yield of tef as compared to other cereals in both production systems could be associated with the use of poor soil fertility management, weeds, unimproved varieties, traditional sowing methods, high seeding rates, insects, and diseases (Delelegn and Fassil, 2011; Abu and Teddy, 2001). Among these, lack of appropriate seeding rates and sowing methods are greatly affecting the production and productivity of tef in northwest Ethiopia (EIAR, 2020). Desperately, there is no special recommended planting method and seed rate for Tef production produced under irrigation conditions. Rather, crop management for tef produced under irrigation is mainly based on its recommended rates for the respective tef production under rain-fed conditions.

The sowing method and seeding rate are the most important agronomic factors that need great emphasis for maximum yield of crops (Amare and Mulatu, 2017). The use of inappropriate sowing methods and seed rates by smallholder farmers leads to low yields as compared to research fields. Research results conducted under irrigation conditions indicated that the use of proper sowing methods and seed rates encourages nutrient availability, proper sunlight penetration for photosynthesis, a good soil environment for the uptake of soil nutrients, and water use efficiency, all necessary for crop vigor and consequently increasing the production and productivity of the crop (Amare *et al*., 2015). This indicates that there is a need to conduct research on the various production systems, such as under dry seasons with irrigation, to determine the appropriate sowing method and the optimal seed rate in each growing area as one of the important agronomic management practices to improve production and productivity of tef. As many research works have been carried out in Ethiopia to increase the productivity of tef under rain-fed conditions, little or no research has been done in irrigated agriculture to develop appropriate crop management practices such as optimum seed rates.

Row sowing method combined with optimized seeding rates could potentially improve grain yield. A preliminary observation by Berhe *et al.* (2011) reported that Tef yield increased by 20–50% when planted at a row spacing of 20 cm. Row planting has multiple advantages over broadcast planting, for example, by permitting efficient use of resources (light, moisture, and nutrients), enhancing light interception and gas exchange capacity, and facilitating farm operations such as weeding. Row planting maintains a uniform population per unit area and provides easy access for carrying out cultural practices (Donnenfeld *et al.*, 2017). Berhe *et al.* (2011) suggested that row planting of tef will improve crop establishment during drought and reduce tillering capacity, seed distribution, root development, and lodging. The Ethiopian government has been promoting tef row planting, but adoption has been low (Vandercasteelen *et al.*, 2014). This might be due to a lack of evidence on yield and economic advantages of tef row planting as compared to broadcast planting methods.

There is also an absolute lack of information on optimized seeding densities planted under both row and broadcasting methods for tef production using irrigation. Government agricultural extension systems have been promoting row planting at a density of 2.5 to 5.0 kg seed ha^{-1} at 20 cm row spacing (BoA, 2018). However, the most common method of sowing used by farmers is the broadcasting planting method, which is traditional and greatly reduces the labour cost as compared to the row planting method. However, Refissa (2012) revealed that the broadcasting planting method greatly reduces Tef grain yield due to higher competition for resources and also lodging problems. For broadcasting, the usual density is 25–50 kg seed ha^{-1} (Vandercasteelen *et al.,* 2014). This is believed to be above the optimum seeding density. A possible reduction in seeding density below 25 kg ha^{-1} will save large amounts of tef grain yield that could be used as food. Unfortunately, according to the impact assessment conducted in all parts of the country, the efforts of the government to presale up the drill row planting method have been unsuccessful (Minten *et al.,* 2013; Mizan et *al.*, 2016).

Seed rate is also one important factor in achieving optimum levels of plant density and has considerable effects on the growth and development of crops under all production types (Sate, 2012). Seed rate greatly affects the productivity of crops when combined with sowing methods. Although some studies have investigated the optimum seeding density and row spacing, most were inconclusive (Vandercasteelen *et al.*, 2014). Most observations for different planting methods and seeding rates, as well as economic comparisons, are absent in those studies. For instance, little is known about the response of tef yield to very high seeding densities (~30 kg ha^{-1}) under different planting methods and irrigation conditions. Data on these parameters are available for other cereals such as wheat and rice (Ashoka *et al.*, 2020; Mekonnen, 2020). There has been an interest in determining the effect of seed rate and sowing methods on tef yield in order to establish optimum population to enhance tef productivity under irrigation production systems. Aiming at increasing tef productivity through strategic manipulation of sowing methods and seed rates at the Koga irrigation scheme and similar agro-ecological areas of northwestern Ethiopia is of paramount importance. Therefore, the study was conducted to determine the optimum seed rate and appropriate sowing methods for maximum tef production under irrigation production.

2. Materials and Methods

2.1. Description of the study area

A field experiment was conducted in the *Mecha* district at the Koga irrigation scheme in northwestern Ethiopia in the 2019/2020 dry season. The experimental site is located at 11023'29.24" N latitude and 3706'29.69" E longitude with an altitude of 1981 meters above sea level. The study area is found in the agro-ecological zone of moist 'Wayena *Dega*'' (mid-altitude) (Azene *et al.,* 2005). The historical average total annual rainfall was 1144 mm. The average daily minimum and maximum temperatures were 11 °C and 28 °C, respectively. Generally, the rainfall in the study area follows a dominantly uni-modal distribution with a peak in June, July, and August, during which more than 80% of the annual rainfall is received. Smaller peaks occur in May, September, and October. The remaining months are dry, and rain-fed crop production has been based on these months (Bitew *et al.*, 2020).

At the experimental site, soil samples were taken prior to planting time at five points diagonally at 0–20 cm soil depth and composited. The composite samples were submitted to the Soil Chemistry and Water Quality Laboratory Section of Amhara Design and Supervision Works Enterprise (2020) for soil analyses, including soil texture, total nitrogen, pH, available phosphorus, organic carbon and electrical conductivity, cation exchange capacity using the hydrometer method (Gee and Bauder, 1986), micro-Kjeldahl method (Bremner and Mulvaney, 1982), a pH meter (H2O 1:2·5), Bray II method (Bray and Kurtz, 1945), Walkley and Black method (Heanes, 1984), unfiltered 1:5 soil: distilled water suspension (EC 1:5) at 25 °C (FAO, 2008) and Ammonium acetate, respectively. Soil bulk density was also measured using the soil core method (Blake and Hartge, 1986) from undisturbed sampled soils. The results of the soil analysis (Table 1) before the start of the experiment indicated that the study site soil pH was found in the acidic range (Landon, 1991). The authors also indicated that the bulk density (BD), total nitrogen (TN), organic carbon (OC) and available phosphorus (Ava. P) of the soil were found to be low. The soil textural class of the experimental area is Clay (66.5%) (Bitew *et al.*, 2020).

Table 1: Major soil properties of the study site before the start of the experiment

Soil properties	Values	Rating	**Reference**
pH (H_2o)1:2.5	4.57	Acidic	Landon (1991)
CEC ((cmol (+) kg^{-1})	31.40	High	Landon (1991)
EC (ds m^{-1})	0.075	Low	FAO (2008)
OC (%)	2.07	Intermediate	Landon (1991)
TN (%)	0.20	Medium	Landon (1991)
Ava. P (ppm)	9.81	Low	Landon (1991)
BD (g cm^{-3})	1.03	Low	Landon (1991)
Soil texture			
Sand (%)	12.33	-	
Silt (%)	22.12	-	
Clay (%)	66.50	-	
Soil textural class	Clay	Clay	Hazelton & Murphy (2007)

OC = -organic carbon, TN = total nitrogen, Ava. P = available phosphorus, CEC = cation exchange capacity, BD = bulk density

2.2. Experimental materials

The Tef variety, namely *Quncho (Dz-CR-387),* was used as a test crop. It was developed from crossing between two parental tef lines, Dukem (DZ-01-974) and Magna (DZ-01-196). It was released by *Debre Zeit* Agricultural Research Center in 2014. *It* has a maturity period ranging from 86 to 151 days with an average yield potential of 2.5–2.7 t ha^{-1} under research field and altitudinal adaptation from 1800 to 2500 meters above sea level (Assefa *et al.,* 2011).

2.3. Treatments and experimental design

The treatments consisted of five seed rates (5, 10, 15, 25, and 30 kg ha^{-1}) and two sowing methods (broadcast and row), which were arranged in a randomized complete block design (RCBD) with three replications. The gross area of the experimental plot was 2m x 2m (4m²) with a 40 cm furrow (Figure 1), and the distance between each adjacent plot and block was 1m each. The net plot size was 0.8 m x 1.5 m. For row sowing treatments, four rows were taken (two rows from the centre of the right and left of the furrow). For the broadcast planting method, data were taken by installing two quadrants, having a size of 0.25 m x 0.25 m, in the net plot (one on the left and one on the right of the furrow). For treatments planted in rows, seeds were drilled in 20 cm row spacing. A Single plot showing how to drill row (A) and broadcasting (B) sowing methods were prepared in the irrigated field as indicated in Figure 1.

2.4. Experimental procedures and cultural practices

This experiment was conducted under irrigation conditions. Experimental plots were ploughed four times using an oxen plough. The first and the second plough were done in October; the third and the fourth plough were done in November. Smoothing and leveling of the experimental plots were done mechanically on the same date that planting was done on 20 December 2020. In row-planted tef treatments, seeds of tef were drilled in rows at their recommended inter-row spacing of 20 cm (Figure 1 A). In broadcast-sown tef treatments, seeds were uniformly broadcasted in the respective plots (Figure 1B). Tef planted in both sowing methods received N and P_2O_5 fertilizers at the rates of 64 kg P ha^{-1} (in the form of NPS) and 46 kg N ha^{-1} (in the form of UREA), respectively. All recommended amounts of P_2O_5 and half of the N fertilizers were applied at the sowing time of tef, while the remaining half of the N was applied at its tillering stage. The fertilizer application method for row-sown crops was in bands with a depth of 2 cm, while for tef sown in broadcasting, fertilizer was in broadcasting. Irrigation was done at the frequency of a 7-day interval. Weeding was done 30 days after planting, at the tillering and flowering stages of tef.

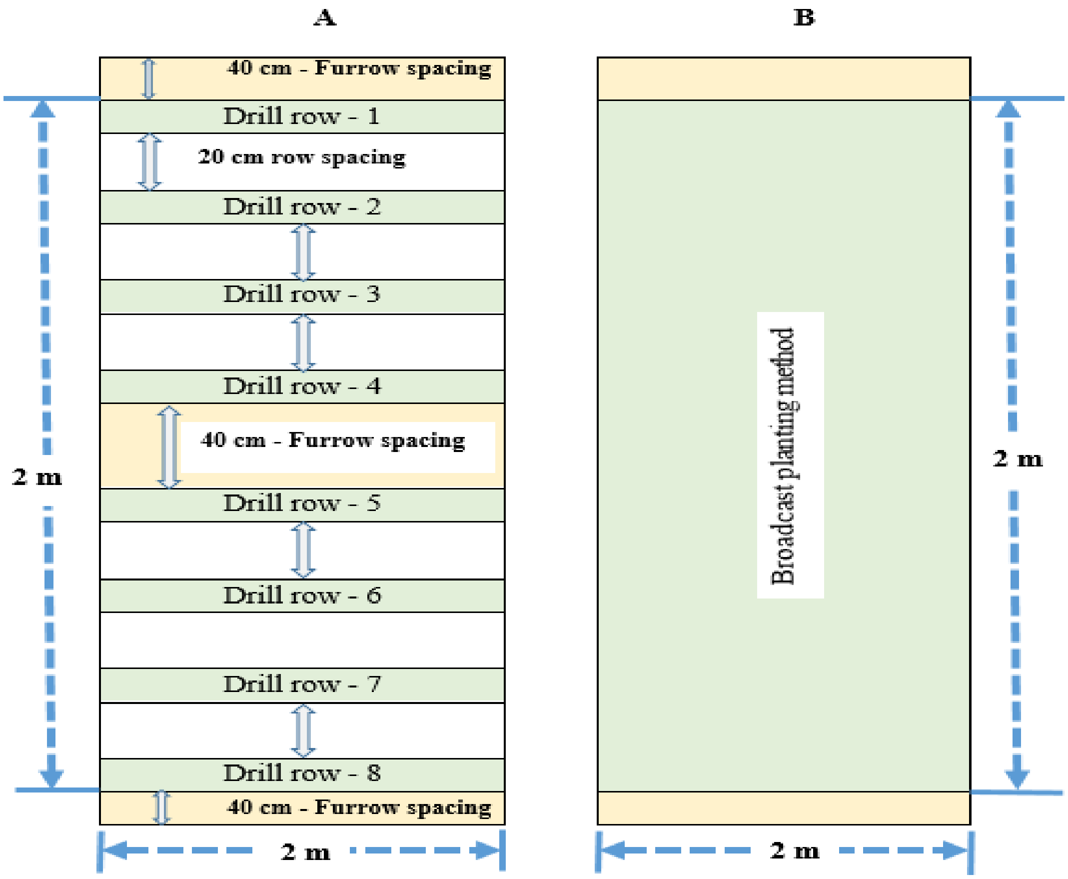

Figure 1: Single plot showing how to drill row (A) and broadcasting (B) sowing methods were prepared in the irrigated field

2.5. Data collection

2.5.1. Growth and yield components

Plant height was measured in centimeters from the base of the main stem to the tip of the panicle at physiological maturity from ten randomly selected plants. Panicle length was recorded by measuring the length of the panicle from the node where the first panicle branch starts to the tip of the panicle in centimeters at their physiological maturity, and the average of ten randomly selected plants in net plot was used for statistical analysis.

The average panicle weight of the main panicle at harvest was recorded from the average of ten randomly selected plants from the net plot. At physiological maturity, the total tillers per plant were recorded from ten randomly taken samples in each plot. To estimate the leaf area index (LAI) of tef, field photographs were taken at 1 m² quadrat using a digital camera (Coolpix 4500, Nikon, Tokyo, Japan) from 1 m above ground. Measurements were carried out shortly before sunset at the full tillering stage of tef. All the photographs were imported to the computer and saved as uncompressed, high-resolution files. All these files were directly imported to the LAI calculator to analyze the LAI (Bitew *et al*., 2020). At full crop maturity, plant population was determined by estimating the number of plants in each plot. Two sample counts were randomly taken per plot using a 0.25m x 0.25m quadrat in the case of the broadcast planting. Similarly, for total dry biomass and grain yield measurements at physiological maturity, four rows were harvested from row-planted treatments, while two 0.25 m x 0.25 m quadrants were used to randomly sample each broadcasted treatment. Total dry biomass yield was measured in the field immediately after harvest. To quantify grain yield, samples were sun-dried for one week till constant dry weight was obtained and finally manually threshed, and grains were separated from husks and adjusted to 12.5% moisture content. The harvest index (HI) for each treatment was obtained by dividing the economic yield by the biomass yield.

2.5.2. Loading Index percentage

The lodging/index percentage of tef was calculated using the formula developed by Caldicott and Nuttall (1979).

$$\sum \frac{LS * \%AL}{5} \quad [1]$$

Where, LS = lodging score and %AL = the respective % of area lodged. The lodging scale was from 0 to 5 where, 0-1 = no lodging, 2 = 25% lodging, 3 = 50% lodging, 4 = 75% lodging & 5 = 100% lodging.

2.6. Data collection

2.6.1. Statistical data analysis

Quantitative data from the experimental field was entered into Microsoft Office Excel. The same software was used for data management. Data analyses for all data were conducted using the statistical software, SAS-JMP13 (SAS, 2016). Before analysis, data were checked for normal distribution following the scatter plot technique. Analysis of variance (ANOVA) was performed, and means were separated using the Tukey-Kramer HSD test when the F-test indicated statistical effects at a 5% significance level. A factorial ANOVA model was used according to the design of the corresponding experiment. Data were analyzed with sowing methods and seed rate as fixed effects and replication as random effects. Linear and polynomial regressions were used to define mathematical relationships among parameters.

2.6.2. Partial budget analysis

To calculate the costs and benefits associated with each treatment, the partial budget procedure (CIMMYT, 1988) was applied. Seed and labour for planting and fertilization costs were considered the input costs; income from tef grain and straw yields were used as output elements. Other production costs, such as labour for land preparation, harvesting, and threshing, were considered uniform across treatments (fixed costs) and not considered in the analysis. The partial budget analysis was performed using the prevailing costs of inputs during sowing and farm-gate prices for outputs during the harvest period. All costs were calculated as the average value of 2019 and 2020 on a per-hectare basis. The cost of Tef seed, grain, and straw yield per kg were 50, 43, and 10 ETB (Ethiopian birr), respectively. Grain and straw yields were adjusted down by 10% as suggested by CIMMYT (988). Total variable cost (TVC) was calculated as the sum of costs (in Ethiopian Birr) of inputs during sowing.

Gross benefit (GB) was calculated as the sum of outputs (income obtained from selling grain and straw). Net benefit (NB) was calculated by subtracting GB from TVC. After treatments were arranged in ascending order by TVC value, treatments with high NB and lower TVC than the preceding treatment were selected for further analysis; treatments with a lower NB value and a greater TVC than the preceding were excluded. Selected treatments were subjected to marginal rate of return (MRR) analysis, which was calculated as the ratio of change in NB to change in TVC of two consecutive treatments (Equation 2). Selected treatments were ranked based on NB value.

$$\text{MRR (\%)} = \left(\frac{\text{NBT2} - \text{NBT1}}{\text{TVCT2} - \text{TVCCT1}}\right) \text{x} 100 \quad [2]$$

Where T2 and T1 are consecutive treatments (T) arranged in ascending order based on their TVC after excluding dominated treatments.

3. Results and Discussion

3.1. Agronomic attributes and lodging index

Analysis of variance indicated that the main effect (PM) *(P<0.01)* and the interaction between Pm and SR (P<0.001) significantly affected the plant population, while SR *(P>0.05)* had no significant effect on the plant population per meter square (PPPMS) (Table 2). The highest PPPMS (6544.44) was observed when tef was sown in the broadcasting planting method at the highest seed rate (30 kg ha-1), but the response of tef at this treatment was statistically similar when it was planted in the broadcasting planting method at 25 (6525.93) and 15 kg ha^{-1} (6340.74) seed rate (Table 2). Significantly, the lowest PPPMS was recorded when tef was sown in the row planting method with a seed rate of 10 kg ha^{-1} (3851.85), but this treatment had a statistically similar effect on PPPMS when it was sown in the row planting method with a seed rate of 15 kg ha^{-1} (3866.60) (Table 2). This result suggested that the number of plant populations was inconsistent across treatments indicates that in lower seed rate treatments the number of total tillers grown per plant was increased and comparable with the higher seed rate treatments at both sowing methods. Parallel to this result, Mihretie *et al.* (2020) aimed that the Tef plant population increased when SR was increased from 2.5 to 10 kg ha^{-1} for both row and broadcast sowing methods.

Analysis of variance indicated that panicle weight was significantly *($P < 0.05$)* affected by the seeding rate but was not affected *($P > 0.05$)* by the main effect of the sowing method and the interaction between seed rate and planting methods (Table 2). This is in agreement with the findings of Yonas *et al.* (2016). Contrary to this finding, Abraha *et al.* (2020) and Fekremariam *et al.* (2020) reported that tef planted in rows under a rain-fed production system showed high panicle weight as compared to the broadcasting sowing method. The panicle weight was the highest at the seed rate of 15 kg ha^{-1} (0.35 gram), followed by 5 kg ha^{-1} (0.33 gram). However, seeding rates of 5 (0.33 gram), 10 (0.33 gram), and 25 (0.29 gram) kg ha^{-1} had statistically similar panicle weights. The lowest panicle weight (0.28 gram) was observed when tef was sown at a 30 kg ha^{-1} seed rate. The highest panicle weight at the lower seed rates at both planting methods might be due to lower plant growth resource competition between plants throughout the whole plant growth stages. Parallel to this finding, Abraha *et al.* (2020) demonstrated that in rain-fed tef production systems, as the seeding rate increased, panicle weight was reduced.

Plant height is an essential growth character directly linked with the productive potential of plants in terms of fodder and grain yield (Abraham *et al.*, 2018). An optimum plant height is claimed to be positively correlated with the productivity of plants (Getahun *et al.*, 2018). Analysis of variance indicated that the sowing method (SM) ($P < 0.01$) and the interaction between sowing and seed rate (SR) *($P < 0.01$)* significantly affected plant height of tef, while it was not significantly affected by SR (Table 2). The highest plant height of tef was recorded when tef was planted in the row sowing method with the seed rate of 15 kg ha^{-1} (89.20 cm) (Table 2). However, this treatment had a statistically similar effect when tef was planted in row SM at the seed rate of 5 (87.33 cm) and 10 (88.0 cm) kg ha^{-1} (Table 2). Overall, irrespective of the seed rate, the plant height of Tef was much higher when it was sown in rows than when it was planted in the broadcasting method. Tef plant height increased in line with the seed rate up to 15 kg ha^{-1} but further increases above this seed rate reduced the plant height. Similar to the present results, Hasan and Songul (2010) found that a high seeding rate promoted plant height to a certain level at the early stage of growth, while elongation was slightly depressed at the later stage of growth. Soomro *et al.* (2009) also reported that the maximum plant height in wheat occurred at higher seed rates and row-sowing methods. In contrast, Abraham *et al.* (2018) reported that increasing the seeding rate significantly increased plant height of tef. The lowest plant height was recorded when tef was planted in the broadcast sowing method at the seed rate of 25 kg ha^{-1} (7.13 cm), followed by the other treatments (Table 2), which is also contrary to the finding of the above author. At the start, increasing seed rate per unit area might have caused nutrient competition between standing crops of tef, thereby resulting in a decrease in vertical vegetative growth in height.

Analysis of variance indicated that both the main and interaction effects of SM and seed rate highly significantly affected the panicle length (Table 2). Sowing tef in the row planting method with a seed rate of 5 kg ha^{-1} gave the maximum panicle length (41.48 cm), which had a statistically similar effect when tef was sown in the broadcasting sowing method with a seed rate of 15 kg ha^{-1} (40.91 cm). On the other hand, sowing tef in broadcasting SM with a seed rate of 30 kg ha^{-1} gave the lowest panicle length (24.80 cm), and it had a statistically similar effect with a 25 kg ha^{-1} (27.00 cm) in the same planting method. Contrary to this study, Abraha *et al.* (2020) reported that the interaction of planting methods and seed rate did not affect the panicle length. Regression analysis indicated that panicle length slowly declined in row SM decreased rapidly and then increased slowly in the broadcast sowing method as the seed rate increased (Figure 3c). The increased panicle length from the combination of row sowing and reduced seeding rate might be the result of more space provided for the crop to utilize more growth resources. This finding is similar to Berhe (2008), who reported that significantly higher panicle length was observed under low seeding rates than in high seeding rates. This result is also in agreement with Jemal *et al*. (2015), who reported that with increasing seeding rate, the panicle length declined by 8.57%. Similarly, Alemayehu (2015) reported that increasing the seeding rate from 10 kg ha^{-1} to 15 kg ha^{-1} decreases the panicle length by 3.35%.

Table 2: Effect of sowing method and seed rate on plant population, tiller per plant and growth parameters of tef during 2020/2021 under irrigation condition

Sowing method	Seed rate (kg ha^{-1})	PPPMS	PW	PH	PL
Broadcast sowing	-	5754.81^{a}	0.30	75.76^{b}	30.04^{b}
Row sowing	-	4174.81^{b}	0.33	86.48^{a}	32.82^{a}
Significant level		**	Ns	**	**
±SE		349.26	0.01	1.75	0.66
Seed rate (kg ha^{-1})					
-	5	5129.63	0.33^{ab}	83.53	38.12^{a}
-	10	3520.37	0.33^{ab}	84.63	29.27^{b}
-	15	5103.70	0.35^{a}	82.23	35.01^{a}
-	25	5555.56	0.29^{ab}	73.77	27.80^{b}
-	30	5514.81	0.28^{b}	81.43	26.93^{b}
Significant level		Ns	**	Ns	***
±SE		552.23	0.02	2.76	1.05
*Interaction effect (*Sowing *method x seed rate)*					
Broadcast sowingg	5	5511.11^{ab}	0.33	79.73^{ab}	28.53^{bc}
Broadcast sowing	10	3851.85^{bc}	0.3	80.67^{ab}	28.53^{bc}
Broadcast sowing	15	6340.74^{a}	0.33	75.27^{ab}	40.91^{ac}
Broadcast sowing	25	6525.93^{a}	0.29	67.00^{b}	27.40^{c}
Broadcast sowing	30	6544.44^{a}	0.27	76.13^{ab}	24.80^{c}
Row sowing	5	4748.15^{abc}	0.34	87.33^{a}	35.33^{ab}
Row sowing	10	3188.89^{abc}	0.36	88.60^{a}	30.00^{bc}
Row sowingg	15	3866.67^{bc}	0.37	89.20^{a}	41.48^{a}
Row sowingg	25	4585.19^{abc}	0.29	80.53^{ab}	28.20^{bc}
Row sowingg	30	4485.19^{abc}	0.29	86.73^{ab}	29.07^{bc}
Significant level		*	Ns	**	***
±SE		780.97	0.02	3.91	1.48
CV (%)		27.25	11.75	8.35	8.18

PPPMS = Plant population m^{-2}; PW = panicle weight (gram); PH = plant height; Pl = panicle length; *, **, *** are the significant differences at probability levels of, 0.05, 0.01 and 0.001, respectively and ns = non-significant at 0.05 probability level. Means with the same letter at column are not significantly different

Analysis of variance showed the main effect of seeding rate and the interaction of SM and seeding rate significantly affected the leaf area index (LAI), while LAI was not significantly (P > 0.05) affected by PM (Table 3). The highest LAI was obtained when tef was planted in drill row SM with 15 kg ha^{-1} (5.4) and broadcast planting method with a seed rate of 5 kg ha^{-1} (5.29), whereas the lowest LAI (2.82) was recorded in the row planting method with a seeding rate of 10 kg ha^{-1} (Table 3). The polynomial regression analysis also indicated that LAI (Figure 3b) slowly declined in the row planting method decreased rapidly and then increased slowly in broadcast SM as the seed rate increased. Simple linear regression analysis also showed that LAI was significantly and positively related to panicle length (Figure 3c) in both sowing methods. The highest LAI in lower seeding rates might be due to the number of tillers that have relatively broader leaves, which are important for photosynthesis, as compared to higher seed rates. Contrary to this result, Fekremariam et al. (2021) reported that the LAI of tef was significantly affected by planting methods in which LAI in the broadcast was higher than row planting methods. Bavec and Bavec (2008) also reported that under optimal water and nutrient supply, increased plant population under row planting methods results in smaller cobs, but the increased number of cobs per area usually results in higher grain yields. Leaf area is influenced by genotype, seed rate, planting methods, climate, and soil fertility (Tollernar et al., 1994; Tollenaar and Bruulsema, 1988; Murphy et al., 1996).

Results of the experiment revealed that total dry biomass yield was not significantly *(P < 0.05)* affected by both the main and interaction effects of SM and seed rate (Table 3). Consistent with this result, Fekremariam *et al.* (2020) reported that tef total dry biomass yield was not significantly influenced by both the main and interaction of SM and seed rate. However, Abraha *et al.* (2020) described that biological yield was significantly affected by the main effects of seeding rate and method of sowing as well as by the interaction of both treatment factors. This could be due to the higher tiller per plant at the lower seed rate at both planting methods, which gave comparable plant populations with the higher seed rate treatments.

Grain yield was significantly affected by the main effect of seeding rate and the interaction effects of the sowing method and seed rate (*P < 0.01*), while the planting method had no significant (*P > 0.05*) effect on the grain yield of tef (Table 3). The highest grain yield was obtained from a seeding rate of 5 kg ha^{-1} combined with the row (4850.81 kg ha^{-1}) method but statistically similar effect with a seeding rate of 15 kg ha^{-1} combined with the broadcast sowing method (4819.38 kg ha^{-1}). The lowest grain yield (2687.96 kg ha^{-1}) was recorded from a seeding rate of 25 kg ha^{-1} combined with the broadcast planting method. The row sowing method with a seeding rate of 5 kg ha^{-1} is greater by 81% as compared to the broadcast sowing methods with a 25 kg ha^{-1} seeding rate. The maximum yield obtained from the lower seeding rate with row SM might be due to better field management practice and resource use in row SM and lowering interspecific competition for growth resources among plants in a relatively lower seeding rate that contributed to a lesser plant population. This result is similar to Shiferaw (2012), who reported that row SM with a relatively lower seeding rate gave the highest grain yield of tef. Similar to this result, Mitiku (2008) and Abraha *et al.* (2020) reported that there was a significant increase in yield and yield components of tef with decreasing seed rates to a certain extent. Moreover, Fanuel *et al.* (2012) conducted an experiment on participatory farmer's group evaluation of seed rates of tef and reported that most of the participating farmers preferred relatively lower seeding rates when mixed with sand than higher seeding rates. The production of greater-yielding components of tef can be attributed to improved light penetration and utilization because of the well-spaced plant population. The polynomial regression analysis also indicated that grain yield (Figure 3a) slowly declined in row SM decreased rapidly and then increased slowly in the broadcast planting method as the seed rate increased. Simple linear regression analysis also showed that grain yield was significantly *(P < 0.05)* and positively related to leaf area index (Figure 3a) and panicle length in both sowing methods (Figure 3b).

The relationship between total biological yields of crops was expressed in terms of the harvest index, which ultimately determines the ability to convert the dry matter into the economic yield (Marschener, 1995). The harvest index was significantly (P *< 0.05)* affected by the main effect of the seeding rate and the interaction effects of the sowing method and seed rate, while SM had no significant *(P > 0.05)* effect on the harvest index (Table 3). The highest harvest index (25.25%) was recorded with row sown at a seeding rate of 15 kg ha^{-1}, while the lowest harvest index (15.18%) was obtained with row planting at a seeding rate of 10 kg ha^{-1} (Table 3). The higher harvest index obtained in the lower seeding rate and row SM can be attributed to more light penetration through the plant canopy and improved nutrient supply. In agreement with this result, Abrham *et al.* (2018) and Abraha *et al.* (2020) indicated that the harvest index increased as the seed rate decreased. Similarly, this finding is in agreement with the results obtained by Zeng and Shannon (2000), who reported that at high seed rates, carbohydrate supply was limited because of shading among plants and the competition between shoot growth and panicle growth. However, Mollah *et al.* (2009) reported that seed rate did not have a significant effect on the harvest index of wheat in bed planting conditions. Both main and interaction effects of SM and seed rate significantly *($P < 0.05$)* affected the lodging index of tef (Table 3). The highest lodging index (3.70) was recorded in broadcast sowing with a 30 kg ha^{-1} seeding rate, while the lowest (0.07) was recorded in broadcast sowing with a 5 kg ha^{-1} seeding rate. The lower lodging index was obtained from both sowing methods with lower seeding rates (Table 3). The higher lodging percentage in the case of the broadcast sowing method with a 30 kg ha^{-1} seeding rate might be due to higher intra-specific competition for moisture, nutrients, and air among plants that led them to weak and succulent stems prone to strong wind and rainfall. This result is in line with the finding of Sahle and Tafese (2016), who reported an increase in lodging percentage in Tef crop in the case of the broadcast sowing method with a 25 kg ha^{-1} seeding rate. Similar to this finding, Fekremariam *et al.* (2021) claimed that lodging was significantly lower with row sowing than with broadcast sowing at the highest seed rate. Mobasser *et al.* (2009) and Abraham *et al.* (2018) also reported that higher planting density enhanced stem length and thereby the lodging index. Polynomial regression analysis also indicated that the lodging index of tef increased as the seed rate increased in both sowing methods, though the increment was rapid in the broadcast sowing method (Figure 2d). This is also clearly explained by its indirect relationship with panicle length (Figure 3d). However, Abraha *et al.* (2020) reported that the highest lodging index was observed from the low seeding rate (10 kg ha^{-1}), although it was at par with the seeding rate of 15 kg ha^{-1}.

Table 3: Effect of planting method and seed rate on the yield component, and lodging index of tef during 2020/2021 under irrigation conditions

Sowing method	Seed rate (kg ha^{-1})	LAI	TDB	GY	HI	LI
Broadcast sowing	-	3.80	18518.50	3315.54	19.17	1.65[a]
Row sowing	-	3.56	18333.30	3507.00	19.27	0.95[b]
Significant level		Ns	Ns	Ns	Ns	*
±SE		0.1	1317.07	146.66	1.31	0.21
Seed rate (kg ha^{-1})						
-	5	4.18[a]	21296.30	4073.86[a]	20.08[ab]	0.26[b]
-	10	3.05[b]	18981.50	2836.71[b]	15.76[b]	0.18[b]
-	15	4.41[a]	18981.50	4042.07[a]	22.40[a]	0.61[ab]
-	25	3.71[ab]	14583.30	2842.87[b]	19.50[ab]	2.48[a]
-	30	3.07[b]	18287	3260.83[ab]	18.39[ab]	2.99[a]
Significant level		*	Ns	**	*	*
±SE		0.17	2082.48	231.88	2.07	0.34
Interaction effect (Planting method x seed rate)						
Broadcast sowing	5	5.29[a]	23148.15	3233.33[ab]	19.55[ab]	0.07[c]
Broadcast sowing	10	3.29[b]	18518.52	2764.81[b]	16.33[b]	0.15[c]
Broadcast sowing	15	3.42[b]	18518.52	4819.38[a]	23.09[ab]	1.13ab[c]
Broadcast sowing	25	3.90[b]	13888.89	2687.96[b]	19.35[ab]	3.20[a]
Broadcast sowing	30	3.13[b]	18518.52	3072.22[b]	17.55[b]	3.70[a]
Row sowing	5	3.07[b]	19444.44	4850.81[a]	25.25[a]	0.45b[c]
Row sowing	10	2.82[b]	19444.44	2908.61[b]	15.18[b]	0.20[c]
Row sowing	15	5.40[a]	19444.44	3328.33[ab]	17.06[ab]	0.08[c]
Row sowing	25	3.52[b]	15277.78	2997.78[b]	19.65[ab]	1.75[ab]
Row sowing	30	3.01[b]	18055.56	3449.44[ab]	19.23[ab]	2.28[a]
Significant level		*	Ns	**	*	*
±SE		0.23	2945.07	327.93	2.92	0.48
CV (%)		5.26	27.68	16.65	26.33	6.85

LAI = Leaf area index; TDB = total dry biomass yield (kg ha^{-1}); GY = grain yield (kg ha^{-1}); HI = harvest index (%); LI = lodging index; *, **, *** are the significant difference at a probability level of 0.05, 0.01 and 0.001, respectively and ns = non-significant at 0.05 probability level. Means with the same letter within column are not significantly different

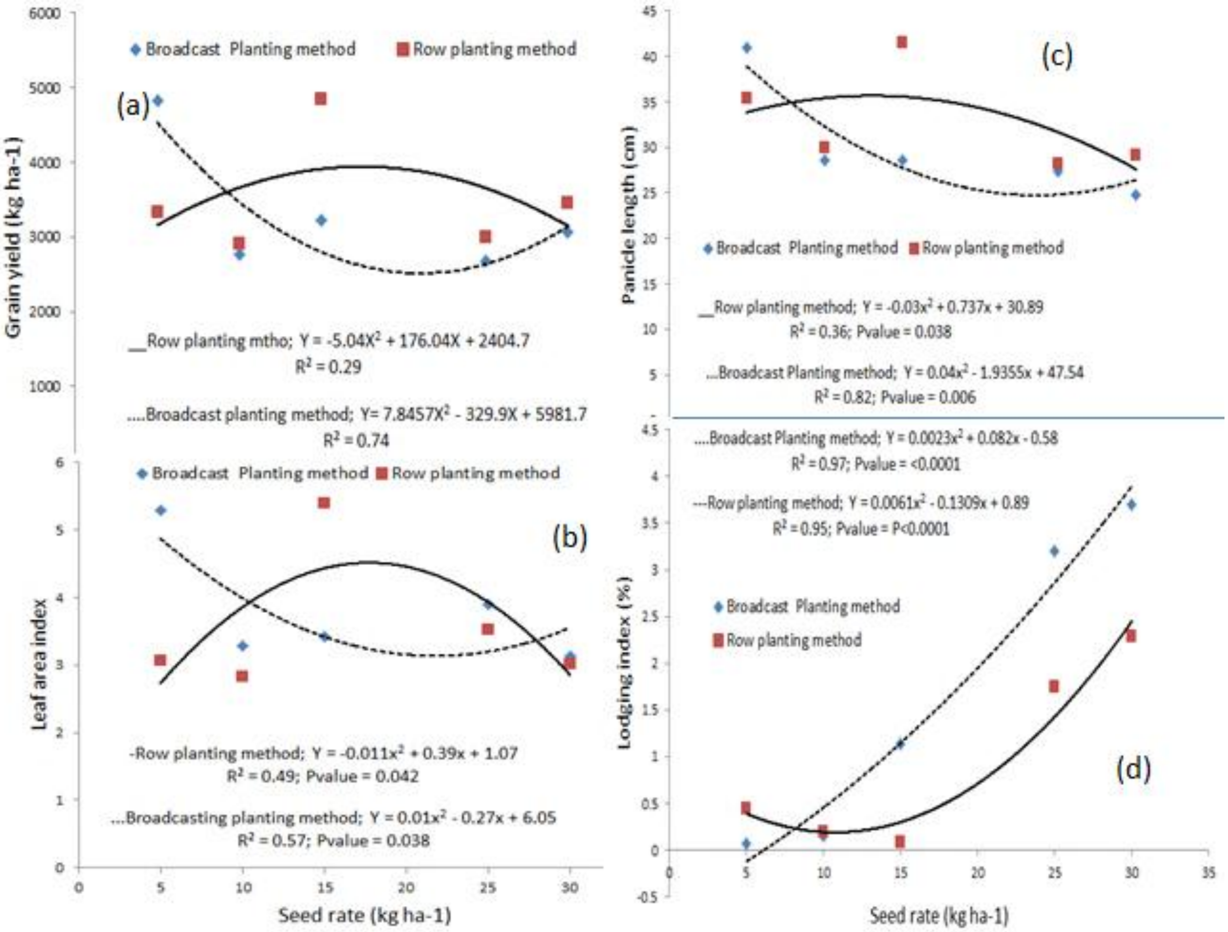
(a)
Broadcast Planting method
Row planting method
Grain yield (kg ha-1)
__Row planting mtho; Y = -5.04X² + 176.04X + 2404.7
R² = 0.29
....Broadcast planting method; Y= 7.8457X² - 329.9X + 5981.7
R² = 0.74
(b)
Leaf area index
-Row planting method; Y = -0.011x² + 0.39x + 1.07
R² = 0.49; Pvalue = 0.042
...Broadcasting planting method; Y = 0.01x² - 0.27x + 6.05
R² = 0.57; Pvalue = 0.038
Seed rate (kg ha-1)
(c)
Panicle length (cm)
__Row planting method; Y = -0.03x² + 0.737x + 30.89
R² = 0.36; Pvalue = 0.038
...Broadcast Planting method; Y = 0.04x² - 1.9355x + 47.54
R² = 0.82; Pvalue = 0.006
(d)
Lodging index (%)
....Broadcast Planting method; Y = 0.0023x² + 0.082x - 0.58
R² = 0.97; Pvalue = <0.0001
---Row planting method; Y = 0.0061x² - 0.1309x + 0.89
R² = 0.95; Pvalue = P<0.0001
Seed rate (kg ha-1)

Figure 2: Polynomial regression showing the response of (a) grain yield (b) leaf area index (c) panicle length and (d) lodging index to planting methods and seeding rate of tef. Each grain yield values are the means of the three replication

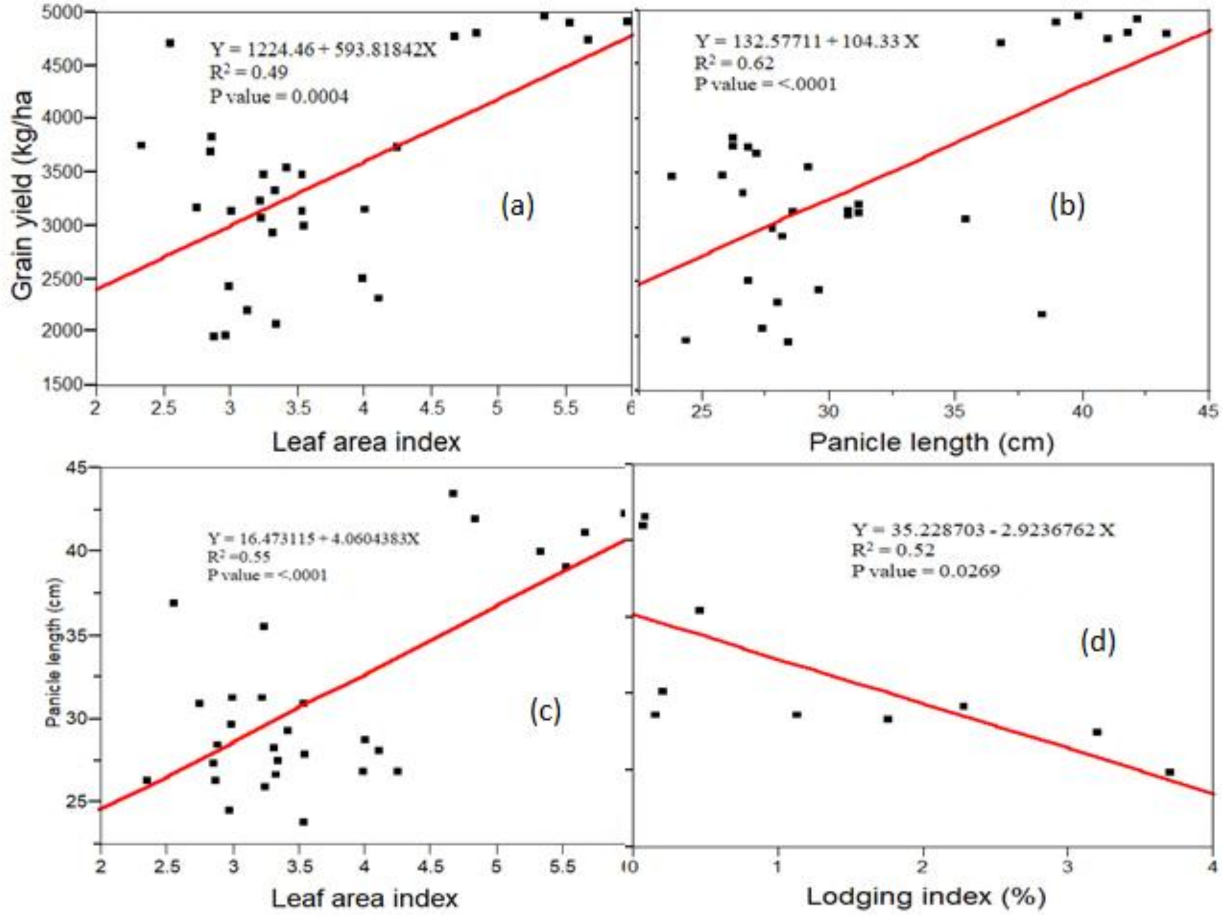

Figure 3: Simple linear regression shows the relationship between (a) grain yield and leaf area index, (b) grain yield and panicle length, (c) panicle length and leaf area index and (d) panicle length and lodging index of Tef as affected by sowing methods and seeding rates of Tef

3.2. Partial budget analysis

Partial budget analysis showed that sowing Tef in the broadcasting method with a seed rate of 15 kg ha^{-1} (net benefit = 349058.94 Ethiopian Birr with MRM = 41175) was the only most profitable method (Table 4). Therefore, sowing Tef in the broadcasting method with a seed rate of 15 kg ha^{-1} was ranked first based on economic feasibility, with the highest net benefit and marginal rate of return, and optimized the economics of Tef production in the study area. Fekremariam *et al.* (2020) pointed out that at rain-fed production season partial budget analysis showed that the broadest SM with a seed rate of 2.5 and 5.0 kg ha^{-1} gave the most profitable methods. Despite the grain yield advantage offered by row SM, the labour cost for sowing, fertilizer application, weeding, and broadcast planting of Tef with a 15 kg ha^{-1} seed rate causes the difference in the net and marginal rate of return between the two sowing methods. When devising strategies for the improvement of agronomic technologies for growing tef, the economic return obtained from Tef straw and the labour required for sowing and fertilizer application should be considered in addition to grain yield.

Table 4: Net return and marginal rate of return (partial budget analysis) from irrigated tef production system in northwestern Ethiopia

Planting method	Seed rate (kg ha^{-1})	adj.GY	adj.SY	GY (birr/ha)	SY (birr/ha)	TVC	GB	NB	MRR (%)
Broadcast	5	4337.44	16495.89	186510.01	164958.93	2410.00	351468.94	259786.58	-
Broadcast	10	2488.33	14178.34	106998.15	141783.39	2660.00	248781.54	246121.54	D
Broadcast	15	2910.00	13756.67	125129.87	137566.71	2910.00	262696.58	349058.9	41175
Broadcast	25	2419.16	10080.84	104024.05	100808.37	3410.00	204832.42	201422.42	D
Broadcast	30	2765.00	13901.67	118894.91	139016.70	3660.00	257911.61	254251.61	D
Row	5	2995.50	14504.50	128806.37	145044.99	4690.00	273851.36	313879	D
Row	10	2617.75	14882.25	112563.21	148822.47	4940.00	261385.68	256445.68	D
Row	15	4365.73	13134.27	187726.35	131342.67	5190.00	319069.02	269161.36	D
Row	25	2698.00	11052.00	116014.09	110520.00	5690.00	226534.09	220844.09	D
Row	30	3104.50	13145.51	133493.33	131455.08	5940.00	264948.41	259008.41	D

Cost of tef seed = 50 ETB (Ethiopian birr) kg^{-1}; cost of tef grain yield = 43ETB kg^{-1} and cost of tef straw yield =10 ETB kg^{-1}; D = dominated treatment. Man day^{1} for row and broadcast planted tef were 15 and 1, respectively; Man day^{-1} for fertilizer application of row and broadcast planted tef14 and 1, respectively; Man day^{-1} for weeding for row and broadcast planted tef 8 and 17, respectively. The cost of Man day for planting, and fertilizer application was 120 Ethiopian

4. Conclusion Recommendations

In this study, the highest grain yield in the irrigated tef production system was obtained at two production systems: (1) when tef was drilled in rows with a 5 kg ha^{-1} seeding rate and (2) when Tef was broadcasted with 15 kg $^{-1}$ ha seed rates, which is completely different from what farmers currently use (25-30 kg ha^{-1} seeding rate with the broadcast sowing method under rain-fed conditions). However, according to the partial budget analysis, sowing of tef in broadcasting with a seed rate of 15 kg ha^{-1} was the only most profitable sowing method in the irrigated tef production system. Thus, it could be concluded that sowing tef in the broadcasting method with a seed rate of 15 kg ha^{-1} gave both the highest grain yield and net benefit for irrigated Tef production and was recommended for the farmers in the study area. The following research gaps were suggested for further research: (i) the present study has to be repeated over years and locations to reach more conclusive recommendations for use in the study area; (ii) the comparison between the labour costs of tef sowing and fertilizer application in rows and broadcast planting should be conducted in a large plot of area

Data availability statement

Data will be made available on request.

Conflicts of interest

The authors declared that there is no conflict of interest.

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