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Yield and lodging response of tef [*Eragrostis tef* (Zucc) trotter] varieties to nitrogen and silicon application rates

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A R T I C L E I N F O

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A B S T R A C T

Lodging, poor crop varieties and nitrogen management are among the main tef cultivation problems in acidic soils of northwestern Ethiopia. Though Si has been shown to improve crop yield and lodging resistance, knowledge of its effect on tef, along genotypes and nitrogen, is yet to be uncovered. Therefore, a 4 × 2 × 2 factorial field experiment was conducted on fixed experimental plot at the Koga irrigation scheme to assess yield and lodging responses of tef varieties to nitrogen and silicon fertilizer rates during two consecutive years of 2021 and 2022. The experiment comprised four nitrogen levels: 0 (N1), 23 (N2), 46 (N3), and 92 kg N ha^{-1}(N4), two Si levels: 0 (Si1) and 485 (Si2) kg ha^{-1}, and two improved varieties: Hiber-1 (V1) and Quncho (V2) treatment combinations, which were replicated four times. Results showed that regardless of silicon supply and variety, nitrogen had a significant effect ($p < .0001$) on agronomic attributes of tef grain yield, biomass yield, harvest index, chlorophyll content, plant height, panicle length, leaf area index, and the number of plants m^{-2} over the two years. Application of N4, N3, and N2 improved grain yield by 166.9, 126.2, and 75.2 % over N1, respectively. The harvest index showed a declining trend with nitrogen rates, which ranged from 36.1 to 26.5 %. Hiber-1 showed a significantly ($p < .01$) higher panicle length than Quncho. The interaction of nitrogen, silicon, and variety significantly ($p < .001$) affected lodging index, with a minimum lodging index of 0 % from V1Si1N1 and a maximum lodging index (71.9 %) from V2Si1N4. Maximum net return (2552.6 USD) was obtained from V1Si1N4, while the marginal rate of return (6961.7 %) from V1Si1N3. Therefore, it can be concluded that genotype and optimum nitrogen can maximize yield and lodging resistance of tef, while silicon in the form of carbonized rice husk results no significant effect on tef lodging.

1. Introduction

Tef [Eragrostis tef (Zucc) trotter] is one of the C_4 crop species in the Poaceae (formerly Gramineae) family, which is adapted to wider soil and climatic conditions [1]. It is the staple food crop for millions of people in Ethiopia, where the crop was first cultivated. It has been consumed in multiple ways, such as in pan-like flatbread called 'Injera', porridge, and fermented alcoholic drinks [2]. The high nutritional content, free of gluten, long storability of grains [3], wide use of the straw, including as livestock feed, traditional house construction [4], and extraction of organic silica nanoparticles [5], make the crop among the unique but underutilized crops of

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the world [6,7].

Tef has continued to dominate the total proportion of cultivated land in Ethiopia. In the 2021–22 cropping season, there was about 3.08 million ha of cultivated land, which accounted for 29.3 % of the overall area covered under cereals (nearly 10 million ha), followed by maize: 25.6 % [8]. The area covered by tef showed a decrement of 5.4 % and 6.23 % compared to the 2019–20 and 2020-21 growing seasons, respectively [8,9]. Nearly all the tef grain production in the country is obtained from a smallholder dry land farming system, which is vulnerable to crop failure caused by drought and nutrient loss.

Though there has been a growing interest in tef grain and straw both in the local and international markets, their productivity is low, with 1700 kg ha^{-1} of grain [1]. This may be attributed to erratic rainfall [10], poor fertilizer and seed management, and a lack of appropriate varieties [11]. Lodging, a permanent displacement of the stem or root, is also an important factor that has significantly affected yield and yield-related traits. Although there are many causes of lodging, lodging associated with environmental conditions [12] and morphological plant traits [13,14] is causing significant yield loss to the crop, accounting for up to 35 % of yield losses [15]. According to the above authors, high levels of soil nitrogen or nitrogen applied before the start of stem extension also produce longer internodes and weaker stems, which in turn cause lodging. A review [1] showed that lodging under natural conditions could cause up to 22 % tef yield loss, 35 % of 1000-kernel weight loss, and 51 % of grain yield per panicle. In addition to the inherently weak stem, heavy rainstorms or flooding could induce lodging of tef [16]. Other researcher [17] also indicated that tef lodging is attributed to plant height, mainly as the result of increased nitrogen fertilization.

There were efforts to improve the productivity of tef through the use of nitrogen and phosphorus fertilizers, gene editing [1,18], and other agronomic practices like tillage [19], seed rate, and method of planting [20] under the rainfed production system. However, the applicability of any technology varies significantly over the location, season, crop, variety, and management and production systems; thus, the majority of the farmers were forced to use blanket recommendations made at the national level for the rainfed system. This has been especially common for fertilizer management, which causes loss of nutrients, increases the cost of fertilizer, and hampers the productivity of the crop. For instance, an increased rate of N application resulted in the lodging of tef and, in turn, a reduction in yield. Researcher [21] stated that the application of 300 kg ha^{-1} urea increased the lodging of tef by about 99 %. Other reports also showed that application of 90 kg N ha^{-1} resulted in about 60 % of tef plant lodging [22]. According to Ref. [1] lodging could cause up to 22 % total grain yield loss, 35 % of 1000-kernel weight, and 51 % of grain yield per panicle. Thus, further research was required to optimize nutrient use, particularly nitrogen, for the tef crop under irrigated conditions.

On the other hand, much literature has presented the beneficial effects of silicon on various crops, particularly monocots, towards reducing lodging and other biotic and abiotic stresses [23]. Application of commercially available calcium silicate positively affected the yield of sugarcane and wheat [24] and beneficial soil microbes [25] in highly weathered acid soils and counteracted aluminum [26] and Mn toxicity [27] in acid sulfate soil. Crops in the Poaceae family get mechanical strength and inhibitory effects due to the deposition of silicon in their leaves [28]. Recently, an experimental study on pot revealed that the lodging tolerance of tef increased with the addition of sodium silicate [29]. Despite these facts, knowledge of the lodging reduction due to Si application on tef under field condition has been poorly documented. In addition, inorganic silicon fertilizers are either expensive, harm the environment, or not available in the local market [30]. Therefore, searching for locally available, inexpensive and eco-friendly materials such as carbonized rice husk, which contains 60–90 % silica [31,32], or diatomaceous earth with 80 % silicon content [33] could replace the role of inorganic silicon fertilizers.

Generally, we claimed that the application of nitrogen and silicon could affect the yield and lodging [34] of tef either independently or interactively. Genotypic variation could also have a potential difference in terms of the yield and lodging response to various inputs like nitrogen and silicon [35]. Furthermore, the treatments that provide significant effect might not be economical for practical use by the small holder farmers [36]. However, there have been limited empirical evidences toward this information specifically in the study

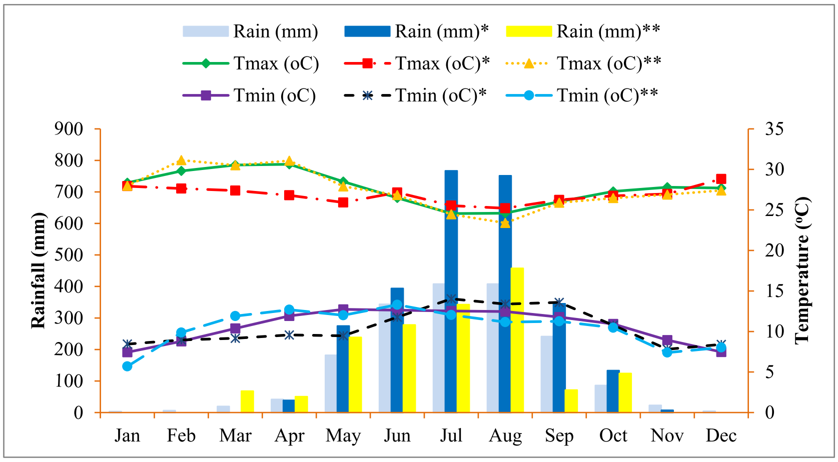

Fig. 1. Total monthly rainfall, mean monthly maximum and minimum temperatures averaged over 29 years' weather data (1994–2022) and specific to the growing season 2021 (*) and 2022 (**) (Source: Meray Meteorological Station, 2022).

area and generally in Ethiopia. Therefore, this study was designed to assess the main and interaction effect of nitrogen and silicon supplement on growth, yield and lodging of tef varieties, to select economically feasible treatments to small holder farmers.

2. Materials and methods

2.1. Description of study site

A two-year field experiment was conducted at *Kudmi,* Bahir Dar University experimental site, Koga irrigation scheme, Mecha district in 2021 and 2022 under irrigation condition. The site is located at 11°23′33″ N latitude and 37°6′43″ E longitude at an altitude of 1983 *m.* a.s.l. The area represents mid-highland agro-ecology [37]. Based on 29 years of weather data (January 01, 1994 to December 31, 2022), the study area receives a mean annual rainfall of 1768 mm with a mean maximum and minimum temperature of 27.7 and 10.7 °C, respectively (Fig. 1). Considering only the growing season (January to April), the mean monthly maximum temperature in 2021 was 27.1 °C and in 2022, it was 29.7 °C, while the minimum temperatures were (9.1 °C) and (10.43 °C), respectively. This indicated that the temperature was lower during 2021 and higher in 2022 than the historical average maximum and minimum temperature of 29.61 °C and 10.3 °C, which were recorded for the respective months of the growing season. The missing values of historical weather data were filled by calculating from means and variance of the observed data using DSSAT Weather Man Version 4.8.0.0 [38,39].

To characterize the soil property of the experimental site, soil samples of disturbed and undisturbed were collected in a zigzag fashion just prior to planting and after harvest from three different soil depths (0–20, 20–40, and 40–60 cm). During pre-plant sample collection, a total of 60 sample spots were considered to prepare three composite samples for each soil layer, while for post-harvest sampling, three spots were considered on an individual plot basis from 64 plots.

The undisturbed soil samples were used to determine the dry bulk density (BD_d), field capacity (FC) and permanent wilting point (PWP) and total available water (TAW), while the disturbed ones were used to analyse parameters, which were particle size distribution (PSD), soil pH, electrical conductivity (EC), total nitrogen (TN), available phosphorus, organic carbon (OC), organic matter (OM), cation exchange capacity (CEC) analysis.

The particle size distribution was analyzed by Bouyuocos hydrometer after dispersing the soil sample with sodium hexametaphosphate solution [40]. The BD_d was determined by the core method [41], after drying a defined volume of soil in an oven at 105 °C for 24 h, and then calculated as the ratio of the mass of oven-dried soil to the volume of the sampling core. The FC and PWP were determined gravimetrically with the help of a pressure plate extractor and oven drying as special apparatus [42]. From FC and PWP, the total available water was calculated (Equation (1)).

$$TAW = 10*(FC - PWP)*Zr \tag{1}$$

where, TAW is total available soil moisture content ($mm\ m^{-1}$); FC is field capacity ($m^3\ m^{-3}$), PWP is permanent wilting point ($m^3\ m^{-3}$); Zr is depth of root zone (m).

Soil pH was determined in water at 1:2.5 v/v soil/water [43]. The EC soil was measured in 1:5 supernatant solutions [44]. Total nitrogen content was determined by the Kjeldahl method [45]. Available phosphorus (AP) was extracted with a 0.5 M $NaHCO_3$ solution at pH 8.5 and determined colorimetrically [46]. The organic carbon (OC) was determined by the Walkley–Black method [47], whereas organic matter (OM) was determined by multiplying the OC with 1.9 [48]. Cation exchange capacity (CEC_{pH7}) was calculated as the sum of positively charged cations [49]. The physical and chemical analysis results are summarized below (Table 1).

2.2. Planting materials

Seeds of Quncho (Dz-CR-387 RIL-355), which has been widely cultivated by farmers and recently released Heber-1 (Dz-Cr-419), were collected from the Adet Agricultural Research Center (AARC). The earlier variety was released in 2006 by the Debre Zeit

Table 1
Pre-planting soil physical and chemical characteristics.

Zr	BD_d[a]	Sand	Silt	Clay	FC	PWP	TAW
cm	**g cm^{-3}**	%					**mm m^{-1}**
0–20	1.23	17	30	53	54.3	24.2	300.5
20–40	1.13	17	28	55	37.2	20.4	168.1
40–60	1.10	13	28	59	31.4	20.2	111.6
	pH **(H2O)**	**EC**	**A.P**	**TN**	**OC**	**OM**	**CEC**[b]
	-	**µS**	**ppm**	**%**			**Cmol$_c$kg^{-1}**
0–20	5.3	48.2	12.36	0.28	1.88	3.58	30.0
20–40	5.5	30.0	12.95	0.20	1.54	2.92	28.2
40–60	5.7	35.8	10.31	0.18	1.23	2.34	33.0

[a] Data averaged over 60 samples; Zr, root zone depth; BD_d, dry soil Bulk Density; FC, field capacity; PWP; Permanent Wilting Point; TAW, Total Available Soil Water; EC, Electrical Conductivity of Soil; TN, Total Nitrogen; A.P, Available Phosphorus; Organic Carbon; OM, Organic Matter; CEC, Cation Exchange Capacity; Available silicon

Agricultural Research Center (DZARC) and the latter was released in 2017 by AARC. Both varieties were characterized as having very white-colored seeds and high yields, the first being moderately tolerant to lodging, while the second is sensitive to lodging and early-set [1].

2.3. Treatments and experimental design

A 2 × 2*4 factorial experiment was arranged in a Randomized Complete Block Design (RCBD) consisting of two tef varieties (Heber-1 and Quncho), two levels of Si in the form of carbonized rice husk (0, 485 kg ha^{-1}), and four levels of nitrogen (0, 23, 46, and 92 kg ha^{-1}), with a total of sixteen treatment combinations to assess the main and interaction effect of nitrogen, silicon supplement and tef varieties. Each treatment combination was replicated four times on a plot area of 2 *m* by 3 *m*. The space between adjacent plots and blocks was 0.5 *m* and 1 *m*, respectively. The experiment was laid out on a 15 *m* by 39.5 m (592.5 m^2) net plot area; while the gross plot area including a 2 *m* buffer zone was 19 *m* by 43.5 m (826.5 m^2). Each treatment combination was applied to a fixed experimental unit over two consecutive years.

2.4. Agronomic practices and planting procedures

All the vegetation, including lupine (a cover crop), was removed, and three days before the first tillage, the land was soaked with water, which helped facilitate the practice of tillage. It was then tilled three times, with an oxen-driven tillage method and digging hoe in 2021 and 2022, respectively. The latter tillage method helped to control treatment contamination due to the mix-up of soils from adjacent plots. The clods were broken, and plot leveling was carried out to create favorable conditions for tef seeding. Bunds were made surrounding each plot, and furrows were constructed below each plot to control the overtopping of water and contamination. Prior to seeding, a CRH was then broadcast and mixed with hand hoes for each randomly assigned plot in each block. Further leveling was done by hand, and tiny furrows at a spacing of 20 cm were made for fertilizer application and seed sowing.

Seeds of the Heber-1 and Quncho varieties were sown at a rate of 15 kg ha^{-1} and left uncovered. The N treatment levels were also applied to each furrow in a split application; with 1/3 at sowing and 2/3 during stem elongation (about 6 weeks after planting). Additionally, the recommended rate of phosphorous (60 kg ha^{-1}) was applied uniformly for all experimental plots. Urea and Triple Super Phosphate (TSP), which are nutrient-specific fertilizers, were used as sources of N and P, respectively, with both fertilizers containing 46 % of the respective nutrient. Moreover, irrigation water was applied uniformly to all experimental plots on a regular basis, considering the soil moisture status. Weeding was done manually twice, at 35 and 50 DAP. Diazinon was sprayed during panicle initiation (41 DAP) to control aphids.

2.5. Data collection

The growth parameters of plant height (PH), panicle length (PL), and stem diameter (SD) were measured at the maturity stage on ten randomly selected plants from internal rows in each plot with a meter tape. Plant height was measured from the ground level to the tip of the panicle, while PL was measured from the node, where the first panicle branch emerges, to the tip of the panicle. The SD was measured at the second internal node of the stem using a digital caliper with 0.01 mm accuracy. Leaf area index (LAI) was measured once during the grain filling stage by a canopy analyzer (LI-COR Biosciences, LAI-2250, PCH-4750, Made in USA). The lodging index (LI) was evaluated just prior to harvest by observing the degree of stem inclination [22].

Yield and yield component data of grain yield (GY) and above-ground biomass yield (BY) were measured after harvest, which was done by placing 1 *m* by 1 *m* quadrants randomly, excluding border rows. The GY was measured by taking the weight of the grains from the net plot area and converting it to kg ha^{-1} after adjusting the moisture content of the grain to 12.5 % (Equation (2)). To quantify grain yield, samples were sun-dried for one week until a constant dry weight was obtained, and then they were manually threshed, where 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.

$$GY_{adj} = GY_m * \left({(100 - MC)}/{(100 - 12.5)} \right) \quad (2)$$

where GYadj is adjusted grain yield (kg ha^{-1}) at 12.5 % moisture content; GY_m is the actual grain yield; MC is the actual moisture content of measured grain yield (%). The BY was measured by weighing the sun-dried plant sample and converted to kg ha^{-1}. The harvest index (HI) was also calculated as the ratio of GY to BY and expressed as a percentage.

Chlorophyll content (CC) was measured using a Chlorophyll meter (SPAD-502 Plus, KONICA MINOLTA, INC, Made in Japan). Five plant samples were selected randomly from internal rows, and measurements were taken from flag leaves.

2.6. Data analysis

2.6.1. Statistical analyses

Data analysis was carried out using R statistical software version 4.1.1 [50]]. Before making the analysis of variance (ANOVA), data were checked for normality of the data distribution following the Shapiro-Wilk testing procedure [51]. The ANOVA was performed based on the procedure of the general linear model, whenever it showed a significant difference; mean separation was done using the least significant difference procedure at 0.05 probability level. However, when the number of means to be compared reached six and above, a comparison was made by the Tukey-Kramer HSD test when the F-test indicated factorial effects at a 0.05 significant level. One-, two-, and three-way ANOVA models were fitted to the corresponding design of the experiment. The data were analyzed with variety, silicon, and nitrogen as fixed effects and year and replication as random effects. The association between traits was determined by the Pearson correlation method [52]. Simple linear regression was applied to define the mathematical relationship between variables.

2.6.2. Partial budget analysis

A partial budget analysis of treatments was performed following the procedure provided by Ref. [53] to estimate the net return (NR) and marginal rate of return (MRR) from the variable input cost of urea, rice husk, and seed and the sale of grain and straw. Additional costs of labor for loading and unloading, transportation, preparation, and application were considered for the analysis. Other production costs, such as labor for land preparation, harvesting, and threshing, were considered uniform across treatments (fixed costs). 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 2021 and 2022 on a per-hectare basis. The costs of urea, rice husk, grain, and straw yields kg^{-1} were 0.5235, 0.0532, 0.8508, and 0.2694 USD, respectively, averaged over the two consecutive years of 2021 and 2022. Grain and straw yields were adjusted down by 10 % [53]. The total variable cost (TVC) collected in Ethiopian birr was converted to USD and calculated as the sum of the costs of inputs during sowing. Gross return (GR) was calculated as the sum of income obtained from the sale of grain and straw. The net return (NR) was calculated by subtracting GR from TVC. After treatments were arranged in ascending order by TVC value, treatments with a high NB and a lower TVC than the preceding treatment were selected for further analysis; treatments with a lower NR 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 NR to change in TVC of two consecutive treatments (Equation (3)). Selected treatments were ranked based on the NR value. The first-, second-, and third-ranked treatments were selected as the most economically feasible agronomic practices.

$$MRR(\%) = \frac{NRT2 - NRT1}{TVCT2 - TVCT1} * 100 \tag{3}$$

where, MRR is marginal rate of return ($US); NRT1 and NRT2 are the total net return ($US) of the first and the second consecutive treatments, respectively; TVC1 and TVC2 are the total variable costs ($US) for the first and second consecutive treatments, respectively.

Table 2
The effect of nitrogen on stem diameter (SD), plant Height (PH), NP, and its variability over the two years.

Nitrogen	SD			PH			NP			LAI		
kg ha^{-1}	mm			*Cm*				N m^{-2}				
	2021	2022	COY	2021	2022	COY	2021	2022	COY	2021	2022	COY
0	1.513	1.510^{c}	1.51^{c}	94.8^{c}	59.8^{d}	77.3^{d}	1162.8^{c}	2137.5^{b}	1650.1^{b}	1.44^{d}	1.03^{d}	1.23^{d}
23	1.47	1.732^{b}	1.60^{bc}	105.0^{b}	81.7^{c}	93.3^{c}	1203.0^{bc}	2228.8^{ab}	1715.9^{b}	2.21^{c}	1.78^{c}	1.99^{c}
46	1.52	1.733^{b}	1.63^{b}	108.3^{b}	93.8^{b}	101.0^{b}	1445.8^{ab}	2570.8^{a}	2008.3^{a}	2.75^{b}	2.53^{b}	2.64^{b}
92	1.58	1.88^{a}	1.73^{a}	114.5^{a}	105.3^{a}	109.9^{a}	1492.5^{a}	2508.3^{a}	2000.4^{a}	3.86^{a}	3.47^{a}	3.67^{a}
Mean	**1.52^{b}**	**1.71^{a}**	**1.62**	**105.7^{a}**	**85.1^{b}**	**95.4**	**1326.0^{b}**	**2361.3^{a}**	**1843.7**	**2.57^{a}**	**2.20^{b}**	**2.38**
SE	**0.05**	**0.04**	**0.04**	**1.27**	**1.68**	**1.06**	**113.8**	**113.8**	**80.5**	**0.15**	**0.12**	**0.10**
$LSD_{0.05}$		**0.11**	**0.10**	**3.61**	**4.80**	**2.97**	**64.0**	**88.1**	**56.5**	**0.42**	**0.34**	**0.29**
Sig.	**ns**	***	***	***	***	***	*	.	**	***	***	***
Y	–	–	***	–	–	***	–	–	***	–	–	
V	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Si	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Y × V	–	–	ns	–	–	ns	–	–		–	–	
Y × Si	–	–	ns	–	–	ns	–	–		–	–	
Y × N	–	–	*	–	–	***	–	–		–	–	
V × Si	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
V × N	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
Si × N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Y × V*Si	–	–	ns	–	–	ns	–	–		–	–	
Y × V*N	–	–	ns	–	–	ns	–	–		–	–	
Y × Si*N	–	–	ns	–	–	ns	–	–		–	–	
V × Si*N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Y × V*Si × N	–	–	ns	–	–	ns	–	–	ns	–	–	ns
CV (%)	**13.0**	**9.2**	**12.5**	**4.8**	**7.9**	**6.3**	**27.5**	**21.0**	**24.7**	**23.2**	**21.7**	**24.3**

SE, V, Si, N, CV, SD, PH, NP, LAI, are standard error, variety, silicon, nitrogen, coefficient of variation, stem diameter, plant height, and number of plants per m^{-2}, respectively; means connected with the same letter within the column were not significantly different; means for the main effect of nitrogen were separated using LSD *t*-test; sig, significance; *** significant at $p < .001$; ** significant at $p < .01$ *significant at $p < .05$; .significant at $p < .1$; ns, not significantly different.

3. Results

3.1. Effect of nitrogen and silicon on selected traits tef varieties

The main and interaction effects of nitrogen, silicon, and variety on SD, PH, NP, and LAI were presented below (Table 2). The combined analysis over years showed that SD was significantly influenced by the main effect of nitrogen ($p < .001$). The supply of nitrogen has also significantly influenced tef PH ($p < .0001$), NP ($p < .01$), LAI ($P < .0001$), and PL ($p < .0001$). However, either the main or interaction of variety and Si did not significantly ($p > .05$) affect all those traits except PL, which was significantly ($p < .01$) influenced by varietal difference (Table 3). Our result also showed that the LI of tef was significantly affected by the main effects of nitrogen ($p < .0001$) and silicon ($p < .05$) irrespective of the variety. The interaction of variety, silicon, and nitrogen was also significant ($P < .001$) (Table 4). The effect of N significantly interacted with the production year in all those growth traits, with SD ($p < .05$), PH ($p < .0001$), PL ($p < .0001$), LI ($p < .01$), except LAI, which was not significant ($p > .05$).

The maximum SD (1.73 mm) was recorded from the application of 92 kg ha^{-1}, while the lowest one (1.51 mm) was from 0 kg ha^{-1} nitrogen. The measured SD showed a declining trend with the decrease in the rate of N application (Table 2). The maximum PH of 114.5 cm, followed by 108.3 cm, was recorded from the application of 92 and 46 kg ha^{-1} nitrogen, respectively, during the first production year. The lowest PH 59.8 cm followed by 81.7 cm was measured at 0 and 23 kg ha^{-1} nitrogen, respectively, during the second season. The COY indicated that the highest LAI (3.67) was measured from the application of 92 kg ha^{-1} nitrogen, while the lowest (1.23) was obtained from 0 kg ha^{-1} nitrogen. The result generally showed that an increased application rate of nitrogen from 0 kg ha^{-1} to 92 kg ha^{-1} provided an actual mean difference in LAI of 2.44, which was higher by 198.4 %, while the minimum difference was 61.8 %. The application of 92 kg ha^{-1} nitrogen consistently provided the longest PL of any other nitrogen treatment level, with 43.5 and 37.7 cm in 2021 and 2022, respectively. The shortest PL of 23.9 cm, followed by 38.3 cm, was recorded from 0 kg ha^{-1} nitrogen in 2022 and 2021, respectively. Increasing nitrogen application from 0 to 92 kg ha^{-1} resulted in a 2.2–30.5 % increment change in tef PL. In terms of variety, Hebir-1 provided a larger PL (37.1 cm) than Quncho (35.8 cm). An overall mean performance of tef in terms of PL decreases significantly over the growing season by 9.7 cm, irrespective of nitrogen or silicon application, which could be due to the difference in cover crops. Maximum lodging of 71.9 %, followed by 65.6 %, was observed from V2Si1N4 and V1Si2N4. The lowest LI (0 %) was recorded from V1Si1N1, but it was not statistically different from V1Si1N2, V2Si1N1, V2Si1N2, V2Si2N1, and V1Si2N1. A medium level of LI was recorded from V1Si1N3 (25.0 %), followed by V2Si1N3 (31.3 %).

3.2. Yield and yield components of tef varieties

The ANOVA combined over years for the main effect of nitrogen and its interaction with Si application on GY and BY is presented below in Table 5, while the regression graph indicating their relationship with nitrogen is presented in Fig. 2. The result indicated that

Table 3
The main and interaction effect of variety, nitrogen, and silicon on tef panicle length (cm) and its variability over the years.

Factor	Unit	Factor level	Year 2021	Year 2022	Mean (COY)	$LSD_{0.05}$
N		**0**	38.3^{c}	23.9^{d}	31.1^{d}	
	kg ha^{-1}	**23**	41.7^{b}	30.6^{c}	36.1^{c}	
		46	42.0^{b}	34.6^{b}	38.3^{b}	
		92	43.5^{a}	37.7^{a}	40.6^{a}	
SE			**0.51**	**0.69**	**0.43**	
$LSD_{0.05}$			**1.44**	**1.96**	**1.2**	
V × N			*	**ns**	**ns**	
N × Si					**ns**	
Y			-	-	***	
Y × N			-	-	***	
V		**Hebir-1**	42.0^{a}	32.5^{a}	37.3^{a}	
		Quncho	40.7^{b}	30.9^{b}	35.8^{b}	
SE			**0.36**	**0.49**	**0.30**	
$LSD_{0.05}$			**1.02**	**1.38**	**0.85**	
V × Si			**ns**	**ns**	**ns**	
V × Y			-	-	**ns**	
Si	**kg ha^{-1}**	**0**	41.3	31.9	36.555	**ns**
		485	41.5	31.6	36.550	
SE			**0.36**	**0.49**	**0.30**	
Mean (Y)			**41.4^{a}**	**31.7^{b}**	**36.6**	**0.85**
Si × Y			*		**ns**	
V × Si*N				**ns**	**ns**	
Y × V*Si × N			-	-	**ns**	
CV (%)			**4.9**	**8.7**	**6.6**	

Means connected with the same letter are not significantly different (independently for each columns within factor); mean effects were compared through LSMeans student's for treatments below five (nitrogen, variety, and year) and Tukey HSD tests with treatments above five (N × Y interaction); *** significant ($p < .0001$); Y, V, N, and Si, COY are year, nitrogen, silicon, variety, and combined over years, respectively.

Table 4
The interaction effect of nitrogen, silicon and variety on lodging index of tef.

		Silicon Rate kg ha^{-1}									
Variety	Nitrogen rate	2021			2022			COY			
	kg ha^{-1}	0	485	Mean	0	485	Mean	0	485	Mean	Mean
Hiber-1	0	0.00^{e}	0.0^{e}	0.0^{d}	0.0^{e}	0.0^{e}	0.0^{d}	0.0^{f}	0.0^{f}	0.0^{c}	**26.6**
	23	0.00^{e}	25.0^{d}	12.5^{d}	0.0^{e}	0.0^{e}	0.0^{d}	0.0^{f}	12.5^{ef}	6.3^{c}	
	46	25.0^{d}	62.5^{ab}	43.8^{bc}	25.0^{d}	50.0^{bc}	37.5^{c}	25.0^{de}	56.3^{bc}	40.6^{b}	
	92	50.0^{bc}	62.5^{ab}	56.3^{ab}	56.3^{abc}	68.8^{ab}	62.5^{a}	53.1^{bc}	65.6^{ab}	59.4^{a}	
Quncho	0	0.0^{e}	0.0^{e}	0.0^{d}	0.0^{e}	0.0^{e}	0.0^{d}	0.0^{f}	0.0^{f}	0.0^{c}	**27.7**
	23	0.0^{e}	25.0^{d}	12.5^{d}	0.0^{e}	0.0^{e}	0.0^{d}	0.0^{f}	12.5^{ef}	6.3^{c}	
	46	37.5^{cd}	50.0^{bc}	43.8^{bc}	25.0^{d}	50.0^{bc}	. 37.5^{c}	31.3^{d}	50.0^{c}	40.6^{b}	
	92	75.0^{a}	56.3^{abc}	65.6^{a}	68.8^{ab}	56.3^{abc}	62.5^{a}	71.9^{a}	56.25^{bc}	64.1^{a}	
	Mean	**23.4^{c}**	**35.2^{a}**	**29.3^{a}**	**21.9^{c}**	**28.1^{b}**	**25.0^{b}**	**22.7^{b}**	**31.6^{a}**	**27.1**	**ns**
	SE	**4.4**	**4.4**	**2.68**	**3.2**	**3.2**	**2.68**	**2.68**	**2.68**	**1.9**	
	CV (%)	**29.7**			**25.8**			**28.0**			

SE, standard error; CV, coefficient of variation; means within the same year were compared by Tukey HSD test; means between varieties, silicon and year were compared using Least significance difference (LSD) student's *t*-test; means connected by the same letter were not significantly different with $LSD_{0.05} = 2.4026$.

GY and BY of tef responded significantly to the application of nitrogen ($p < .0001$), regardless of silicon application or tef variety (Table 5). The result also showed that the interaction of Si and N significantly ($p < .05$) influenced both GY and BY. Moreover, the effect of nitrogen varied over the growing season on both GY ($p < .0001$) and BY ($p < .001$) (Table 5). Furthermore, the result showed that there was a significant interaction effect of year, variety, and silicon on the BY of tef ($p < .05$) (Table 5). The HI of tef was significantly ($p < .0001$) influenced by the main effect of nitrogen in both 2021 and 2022. The interaction of silicon, variety, and nitrogen also significantly ($p < .05$) affected the HI of tef during 2022, but not in 2021 (Table 6). The mean HI of Quncho was significantly ($p < .01$) higher than the Hiber-1 variety (Table 6).

The COY showed that maximum GY (1789.8 kg ha^{-1}) was obtained from the application of Si1N4 but was not significantly different from Si2N4 (1739.5 kg ha^{-1}) followed by Si1N3 (1644.69 kg ha^{-1}). The lowest GY of tef (612.4 kg ha^{-1}) was recorded from the Si1N1 (Table 5). Though the difference was not significant, tef GY was reduced by about 7.7 % due to the application of Si compared to the

Table 5
The main and interaction effect of silicon, variety, nitrogen on grain and biomass yield of tef.

Silicon kg ha^{-1}	Nitrogen	GY			BY		
kg ha^{-1}		2021	2022	COY	2021	2022	COY
0	**0**	812^{fgh}	412^{h}	612^{d}	2655^{d}	1047^{e}	1851^{e}
	23	1429^{b-e}	1015^{efg}	1222^{c}	4643^{bc}	2756^{d}	3700^{cd}
	46	1670^{ab}	1619^{abc}	1645^{ab}	5995^{ab}	4474^{c}	5235^{b}
	92	1538^{bc}	2042^{a}	1790^{a}	7013^{a}	6327^{a}	6670^{a}
Mean		**1362^{a}**	**1272^{ab}**	**1317**	**5077^{a}**	**3651^{c}**	**4364**
485	**0**	854^{fgh}	566^{gh}	710^{d}	2780^{d}	1509de	2144^{e}
	23	1149^{c-f}	1041^{d-g}	1095^{c}	4195^{c}	2633^{d}	3414^{d}
	46	1186^{b-f}	1507^{bcd}	1347^{bc}	4572^{c}	4206^{c}	4389^{bc}
	92	1437^{b-e}	2042^{a}	1740^{a}	6366^{a}	6782^{a}	6574^{a}
Mean		**1157^{b}**	**1289^{ab}**	**1223**	**4478^{b}**	**3783^{c}**	**4130**
SE		**113.1**	**82.5**	**69.3**	**286.8**	**262.3**	**199.3**
Si		*	**ns**	**ns**	*	**ns**	**ns**
V		**ns**	**ns**	**ns**	**ns**	**ns**	**ns**
N		***	***	***	***	***	***
Si × N		**ns**	**ns**	*	**ns**	**ns**	*
Y × N				***			**
Y × Si		*		*	*		*
Y × V		**ns**			**ns**		
V × Si		**ns**	**ns**	**ns**	**ns**	**ns**	**ns**
V × N		**ns**	**ns**	**ns**	**ns**	**ns**	**ns**
Y × Si*N		**ns**			**ns**		
Y × V*Si		*			*		
Y × V*Si × N		**ns**			**ns**		

SE, Standard error; Y, Year; N, nitrogen; V, variety; Si, silicon, Si × V, interaction of silicon and variety; Y × N, interaction of year and nitrogen; Y × Si interaction of year and silicon; Y × V interaction of year and variety; V × Si, interaction of variety and silicon; V × N, interaction of variety and nitrogen; Y × Si*N, interaction of year, silicon, and nitrogen; Y × V*Si, interaction of year, variety and silicon; Y × V*Si × N, interaction of year, variety, silicon and nitrogen; ns, non-significant; ***significant at $p < .0001$; **Significant at $p < .001$; *significant at $p < .05$.

absolute control and increased rate of nitrogen. The GY of tef decreased marginally with the addition of Si, except for the N1 treatment (Table 5). The effect of nitrogen varied over the years, with the highest GY (2042.4 kg ha^{-1}) obtained from Y2Si2N4, but not significantly different from 2042.0 kg ha^{-1} from Y2Si1N3, whereas the lowest GY (412.4 kg ha^{-1}) was also recorded from Y2Si1N1, followed by Y2Si2N1 (565.9 kg ha^{-1}) (Table 5).

A maximum BY of 6669.8 kg ha^{-1} was obtained from Si1N4 followed by Si2N4 (6574.1 kg ha^{-1}), but that did not show any significant difference (Table 5). Our result also showed the variability of BY over the growing season: the highest BY was recorded from Y1Si1 (5076.6 kg ha^{-1}), followed by Y1Si2 (4478.3 kg ha^{-1}), while the lowest was measured from Y2Si1 (3651.2 kg ha^{-1}). In addition, the interaction of silicon with nitrogen was significant over the years, so Y1Si1N4 gave the highest BY of 7012.8 kg ha^{-1} but was not significantly different from Y2Si2N4, Y1Si2N4, Y2Si1N4, and Y1SiSi1N3, which provided 6781.9, 6366.4, 6326.8, and 5994.9 kg ha^{-1}, respectively. The lowest BY was obtained from Y2Si1N1 (1047.4 kg ha^{-1}), which was not significantly separated from Y2Si2N1 (1507.7 kg ha^{-1}).

The HI ranged from 20.4 to 42.1 %, with the maximum recorded HI being from Quncho in 2022, which received neither nitrogen nor Si treatments, while the minimum HI was obtained from the same variety with the application of 92 kg N ha^{-1} and 0 Si in 2021 (Table 6). The overall mean HI indicated an improvement in 2022 over 2021.

The fitted linear regression line graph (Fig. 2), constructed from data combined over both years, indicated the linear increment of GY with the change in the rate of nitrogen application. The highest ordered difference in GY (1103.3 kg ha^{-1}) was obtained between 92 and 0 kg N ha^{-1}, followed by 834.4 kg ha^{-1} from 46 to 0 kg N ha^{-1}, while the lowest GY difference (268.9 kg ha^{-1}) was recorded from 92 to 46 kg N ha^{-1}. The gain in GY of tef was about 166.9, 126.2, and 75.2 % through the application of 92, 46, and 23 kg N ha^{-1}, respectively, compared to the control treatment, which provided only 661.3 kg ha^{-1}. Generally, for the change in every single unit of nitrogen, GY increased by 11.519 kg. The simple linear regression graph (Fig. 2) showed that for each unit of change in nitrogen, the BY increases by about 49.4 kg. The changes in BY were also shown by the significantly strong positive correlation with the application of nitrogen ($r = 0.85$, $p < .0001$) (Supplementary Table 1).

3.3. *Chlorophyll content*

The chlorophyll content of tef was significantly ($p < .0001$) influenced by the main effect of nitrogen in both years. It was also affected significantly ($p < .05$) by the main effect of variety only during 2021. However, the interaction effect of all the factors was not significant ($p > .05$) during the two years. Maximum CC was observed from the application of N4, which was 28.7, 9.9, and 5.6 % more than N1, N2, and N3 treatments, respectively. Chlorophyll content had a significantly ($p < .0001$) positive correlation with N, PH, PL, LAI, LI, GY, and BY, expressed by r equal to 0.7338, 0.8102, 0.6933, 0.7081, 0.6217, 0.7445, and 0.8127, respectively, but its relation with HI was significantly ($p < .0001$) negative with r equal to −0.5074 (Supplementary Table 1).

3.4. *Partial budget analysis*

The net return and marginal rate of return were presented in Table 8. The maximum NR was recorded from treatment combinations of V1Si1N4, followed by V1Si2N4, with 2552.6 and 2460.8 USD, respectively. The lowest was recorded for V2Si1N1 (658.6 USD), followed by V1Si2N1 (778.7 USD). However, the marginal rate of return indicated that V1Si1N3 has dominated all other treatments with a MRR of 6961.7 %, followed by V2Si1N3 (6580.5 %). This means treatment V1Si1N3 was considered economically feasible for

Table 6
The effect of silicon and nitrogen application on the harvest index of tef varieties.

Variety	Nitrogen	2021			2022			COY		
		Silicon Rate								
		kg ha^{-1}								
	kg ha^{-1}	0	485	Mean	0	485	Mean	0	485	Mean
Hiber-1	0	29.5[a-e]	30.7[a-d]	30.1[ab]	36.5[a-d]	37.8[a-d]	37.1[ab]	33.0[a-d]	34.3[ab]	33.6[ab]
	23	32.3[ab]	28.1[a-e]	30.2[ab]	37.3[a-d]	38.4[ab]	37.9[ab]	34.8[ab]	33.3[abc]	34.0[ab]
	46	26.1[a-e]	26.5[a-e]	26.3[bcd]	35.6[bcd]	34.7[bcd]	35.2[bc]	30.9[b-e]	30.6[b-f]	30.7[b]
	92	23.1[cde]	21.6[de]	22.4[cd]	32.5[cde]	28.8[e]	30.6[d]	27.8[c-f]	25.2[f]	26.5[c]
Quncho	0	32.9[a]	31.3[abc]	32.1[a]	42.1[a]	38.1[abc]	40.1[a]	37.5[a]	34.7[ab]	36.1[a]
	23	28.7[a-e]	27.1[a-e]	27.9[ac]	36.4[a-d]	41.7[a]	39.0[a]	32.6[a-d]	34.4[ab]	33.5[ab]
	46	29.3[a-e]	25.3[a-e]	27.3[a-d]	37.1[a-d]	37.2[a-d]	37.2[ab]	33.2[a-d]	31.3[b-e]	32.2[b]
	92	20.4[e]	23.3[b-e]	21.8[d]	32.2[de]	32.0[de]	32.1[cd]	26.3[ef]	27.7[def]	26.9[c]
	Mean	27.8[a]	26.8[a]	27.3[b]	36.2[a]	36.1[a]	36.2[a]	32.0[a]	31.4[a]	31.7
	SE	1.80	1.80	1.27	1.15	1.15	0.81	1.1	1.1	0.79
	CV (%)	13.2			6.4			10.0		
V × Si		ns			*			ns		
V × Si*N		ns			.			.		

SE, CV, coefficient of variation; Standard Error; V × Si, interaction of variety and silicon; V × Si*N, interaction between variety, silicon and nitrogen; means represented with the same letter are not significantly different at $LSD_{.05}$, *interaction was significant at $p < .05$; interaction was significant at $P < .01$.

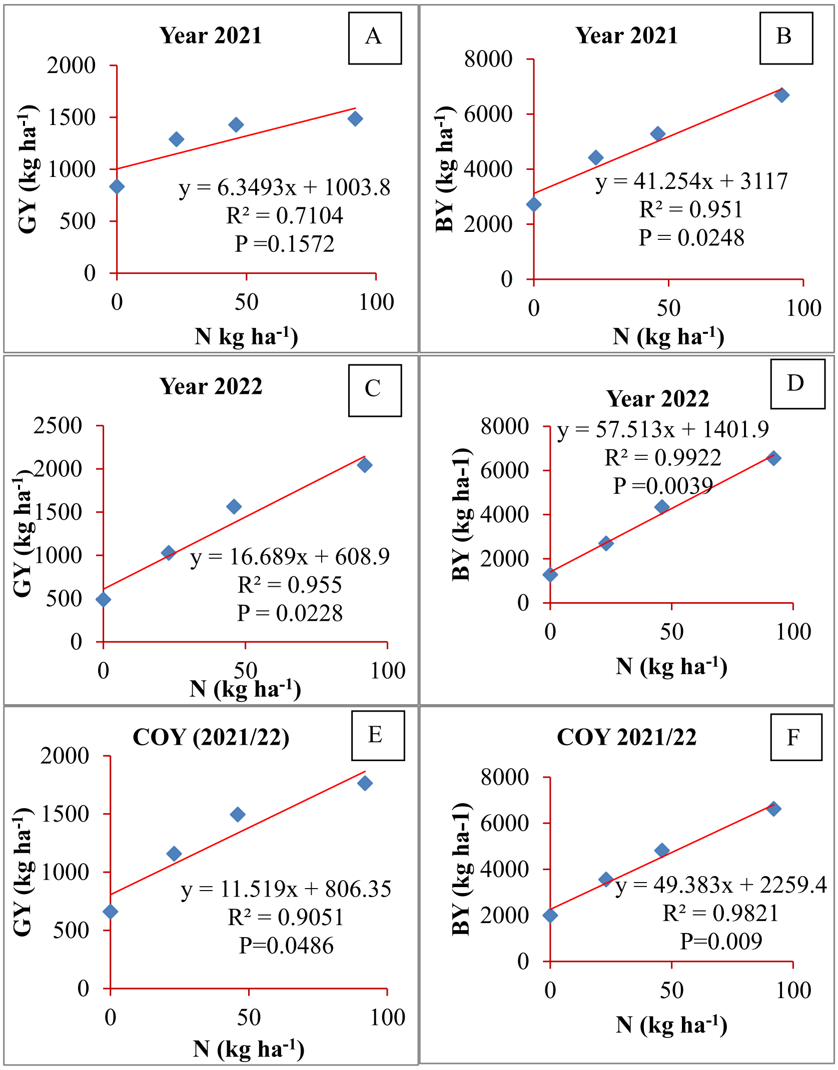

Fig. 2. The fitted linear regression showing the relationship between rate of nitrogen and mean yields of tef crop: A) nitrogen versus grain yield in 2021 growing season, B) nitrogen versus biomass yield in the year 2021, C) nitrogen versus grain yield in 2022 growing season, D) nitrogen versus biomass yield in 2022, E) nitrogen versus grain yield based on the pooled mean over the two growing seasons (2021/22), F) nitrogen versus biomass yield based on the pooled mean over the two growing season (2021/22); GY is Grain yield; BY is Biomass yield; R^2 is coefficient of determination; x and y represents the values of independent and dependent variables, respectively for the corresponding graph.

smallholder farms with financial constraints and seeking to maximize income with a minimum fertilizer because, for a unit kg of N supply, the Hiber-1 variety of treatment can provide 65.8 USD in additional benefits. For those farmers having no financial limitation V1Si1N4 treatment could be used for maximum net return with about 542.553 USD further incomes.

4. Discussion

An increased PH with a high rate of nitrogen was in agreement with [22], who found a longer PH (120.1 cm) at a high rate of nitrogen (90 kg ha^{-1}) application than the low rates. The effectiveness of soil nitrogen supply decreases with the season, as indicated by the decrease in PH in all of the applied nitrogen rates (Table 2). The decline in soil nutrients might be attributed to the difference in weather and lack of fertilization during the production of the rotating crop [54]. The result showed that the application of nitrogen could increase the plant population due to an increase in tiller numbers and maintain the stand performance of mother plants as compared to non-nitrogen treatment. The seasonal variability of plant populations could be attributed to the difference in available nitrogen resources in the soil. This was in line with the finding of [22], who found the highest plant tiller numbers per plant (13.8) of tef with the application of 97.5 kg ha^{-1} nitrogen. The reason for the seasonal variation in certain traits of tef could be attributed to the nature of the rotating cover crop [55], as tef was preceded by non-nitrogen-treated white lupine in the first year compared to non-nitrogen treated niger seed in the second year. Both separate and COY analysis results showed a similar trend of LAI increment due

Table 7
The main and interaction effect of nitrogen, silicon, and variety on the chlorophyll content (SPAD unit) of tef leaf.

Factor	Unit	Factor level	Year		Mean (COY)	$LSD_{0.05}$
			2021	2022		
Nitrogen		**0**	32.0^d	26.5^c	29.3^d	
	kg ha^{-1}	**23**	35.2^c	33.5^b	34.3^c	
		46	36.4^b	35.1^b	35.7^b	
		92	38.0^a	37.5^a	37.7^a	
SE			**0.30**	**0.55**	**0.31**	
$LSD_{0.05}$			**0.85**	**1.57**	**0.89**	
N			***	***	***	
N × Y			***			
Silicon	**kg ha^{-1}**	**0**	35.8^a	33.4	34.6	
		485	35.0^b	32.9	34.0	
SE			**0.21**	**0.39**	**0.22**	
$LSD_{0.05}$			**0.60**	**ns**	**ns**	
Si × Y			**ns**			
Variety		**Hiber-1**	35.6^a	32.9	34.2	**ns**
		Quncho	35.2^b	33.4	34.3	
SE			**0.21**	**0.39**	**0.22**	
Mean Y			**35.4^a**	**33.1^b**		**0.63**
V × Si			**ns**			
V × Si*N			**ns**			
CV (%)			**3.4**	**8.7**	**5.2**	

Y, Year; N × Y, interaction of nitrogen and year; Si × Y, interaction of silicon and year; V × Si, interaction of variety and silicon; V × Si*N, interaction effect of variety, silicon and Nitrogen; LSD, least significance difference; ns, not significant at p = .05; *** significant at p < .0001; letters represented with the same letters within the columns are not significantly different at $LSD_{0.05}$.

Table 8
The economic feasibility of silicon and nitrogen application on the net return and marginal rate of return from tef grown in Mecha district.

Silicon	Nitrogen	NR		MRR			
kg ha^{-1}		USD		%			
		V1	V2	V1	Rank	V2	Rank
0	0	798.2745	658.5985				
	23	1547.009	1390.325	2667.89	5	2607.286	6
	46	2010.06	2086.094	6961.724	1	6580.466	2
	92	2552.613	2369.289	4478.658	4	4489.819	3
582	0	778.651	922.123	−7404.86	13	−4512.18	11
	23	1370.817	1316.399	−6160.54	12	−7417.75	14
	46	1803.758	1618.567	1542.652	7	1076.686	8
	92	2460.773	2378.612	−238.913	10	24.25343	9

NR, net return; MRR, marginal rate of return; V1, Hebir-1; V2, Quncho; The price of urea, rice husk, tef grain and straw yield kg^{-1} per kilogram in ETB were averaged over years and converted to USD, thus their values were 0.5235, 0.0532, 0.8508, and 0.2694 USD, respectively (conversion was based on the average exchange rate of Commercial Bank of Ethiopia); 1 USD = 46.4997 ETB; Ranking was done for all the 16 treatment combinations.

to changes in nitrogen. This was confirmed by the strongly positive correlation (r = 0.841) between nitrogen rate and LAI (Supplementary material 1). The result similar with the earlier results obtained by Ref. [56] and it showed a positive correlation (r = 0.53) among LAI and nitrogen.

The observed difference among nitrogen treatments in terms of PL may be due to the increased availability and uptake of the nutrient, which has an effect on leaf expansion, chlorophyll concentration, and photosynthesis activity of the plant. Similar findings were observed by (22), who reported the longest tef PL (44.9 cm) at a rate of 97.5 kg N ha^{-1} application. The varietal change might be due to their genotypic variation [57].

The increase in LI could be mainly associated with an increase in LAI, BY, PH, and PL that facilitated the delicacy of tef to stem bending. This was confirmed by their strong positive correlations of r = 0.78, 0.76, 0.61, and 0.47, respectively (Supplementary Table 1). The result was in line with the findings of [17,22,58] who associated the lodging with the change in plant growth, which is affected by the nitrogen application rate [1]. However, the non-significance difference between Hiber-1 and Quncho varieties in terms of LI was in contrast with [1], who reported that Hiber-1 is a lodging-sensitive Tef variety. This might be attributed to their similarity to the nitrogen response expressed on plant traits of PH and LAI, which had a strong association with LI, with r values of 0.61 and 0.7818, respectively (Supplementary Table 1).

The increase in GY in relation to nitrogen supply alone could be attributed to the increase in photosynthetic activity caused by the increase in leaf chlorophyll content and leaf area index that enhance light interception [59,60]. The decline in GY observed in Y2N1 compared to Y1N1 might be attributed to the decrease in soil nitrogen in the control plot that was intensively taken by niger-seed (cover crop) in addition to the tef crop without any compensation for their requirement [61,62]. A significant GY improvement in wheat was obtained with the incorporation of legumes as a preceding crop [63] in addition to fertilization. Though the difference in GY was not significant in both years, a lower overall mean GY was recorded during the first production year than the second. This could be attributed to shattering and lodging, which caused regrowth and a molding effect because of the rain that fell during the late stage of the first season [64]. The residual nitrogen left from the previous cropping season might also contribute to the difference [65].

The non-significant effect of Si on BY was not in agreement with [29], who reported BY yield improvement from the application of Si in the form of sodium silicate. The silicon effect on the same variety reversed during the second season and showed trends of increment, but the change was not significant, whereas Quncho showed a similar trend over the years, which could be due to the variation in their genetic makeup [29].

The HI tef decreased with the application of nitrogen in both years, regardless of the variety as nitrogen is associated with biomass than grain yield [22,66]. The higher HI in 2022 than in 2021 might be attributed to either the decrease in nitrogen level in the soil [66] or the residual effect of CRH applied in the previous growing season which increase the maximum number of seeds per spike [67]. The significant difference observed in HI among tef varieties during 2022 could be associated with genetic variation [1,68].

The negative correlation among the CC and HI might be associated with nitrogen increment, which contributes more to biomass than grain yield. This result was in line with [69], who emphasized the importance of optimizing dry matter partitioning with appropriate traits like CC affecting the HI of wheat crops. Our result showed that CC had been negatively influenced by the application of Si (Table 7), which was not in line with the result of [29], who stated improvement of CC at a lower level of Si application. With an increased Si concentration in soil, its deposition in the leaf increases, this seems to improve the concentration of chlorophyll pigment with an increased rate of silicon [70]. The difference could be either due to the silicon rate or the source, which may vary in their Si content.

The increase in MRR for tef was significantly linked to the nitrogen application rate. An optimum amount of nutrient application particularly nitrogen is essential to maximize benefit from tef crop, while both minimum and excess supply could cause significant reduction on both grain and biomass yield, which result in low economic return. Our result is in line with [66] and showed maximum marginal rate of return of 801 and 566 % from the application of 46 kg ha^{-1} nitrogen under scenario 1 and 2, respectively. The significant reduction of the MRR due to the application of Si in the form of carbonized rice husk was because of the non-significant treatment effect on both grain and straw yield.

5. Conclusion

The authors concluded that panicle length and LI could be improved by the main effect of genotype. In addition, an optimum nitrogen rate can maximize yield and lodging resistance of tef, while silicon application in the form of carbonized rice husk results in no significant effect on tef lodging.

Data availability statement

All the data associated with this study are available without any restriction and are attached herewith to this manuscript as supplemental material. The data associated with this article has not been deposited into a publicly available repository.

CRediT authorship contribution statement

Mekonnen Gebru: Writing - review & editing, Writing - original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Getachew Alemayehu:** Writing - review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Yayeh Bitew:** Writing - review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation.

Declaration of competing interest

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

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Appendix A. Supplementary data

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