

Article

Weed-Competitive Ability of Teff (*Eragrostis tef* (Zucc.) Trotter) Varieties

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Abstract: Teff is a staple and well adapted crop in Ethiopia. Weed competition and control have major effects on yields and economic returns of the crop in the country. Among the weed management methods, development and use of weed competitive teff varieties remain the cheapest and most sustainable weed management option. Ten teff varieties were tested for their weed competitive ability in two locations. Treatments were applied using a split plot design with three blocks at each location for two consecutive seasons. Hand weeding and non-weeded treatments were applied to whole plot treatments with teff varieties assigned as split plots within the whole plot. The main objective was to determine relative competitive ability among teff varieties. Results showed that teff varieties showed significant variation in their weed competitive abilities. The varieties ‘Kora’ and ‘DZ-Cr-387’ significantly reduced weed density, dry weight, and cover more than the other teff varieties. They also had the lowest yield losses with a loss of 6% in biomass yield and 18% in grain yield recorded from ‘Kora’ and a loss of 17% in biomass yield and 21% in grain yield recorded from ‘DZ-Cr-387’. Therefore, they showed the highest weed competitive ability compared to the other varieties.

Keywords: teff; teff varieties; weeds; weed competitive ability

1. Introduction

Teff (*Eragrostis tef* (Zucc.) Trotter) is a well-adapted and widely grown staple in Ethiopia [1]. The crop adapts to a range of climatic and edaphic conditions. It grows from the sea level to as high as 3300 m a.s.l., although it performs best at an altitudinal range from of 1500 to 2300 m a.s.l. [1]. Being a staple food to more than 60% of the population in Ethiopia, around 3 million hectares of the arable land is allocated to its production [2].

Teff has a broad phenotypic and genetic diversity [3–5]. It shows a high diversity at different development stages in terms of its morphological, physiological, and phenological traits. Most of the varieties differ widely in seed color (which determines the consumer preference), seed emergence, panicle type, panicle length, tillering potential, plant height, leaf area, flowering, maturity, lodging potential and overall dry weight [3–5]. These traits also enable it to adapt to various moisture conditions, so that it can perform well under both drought and water-logged conditions [4,5].

Weed competition has major impacts on teff yields in the small-scale production systems of Ethiopia. There are many direct and cultural control methods used by farmers to reduce weed

competition [6]. Frequent tillage and hand weeding are among the most common practices during teff production [6]. Some control methods, such as the use of herbicides, have potential disadvantages. They may not be economically affordable to most small-scale farmers [7,8]. As a solution to these challenges, the use of competitive varieties as part of integrated non-chemical control options is a cheap and sustainable component of weed-management strategies. In contrast to increasing knowledge about the potential for competitive varieties in cereal crops as in wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and oat (*Avena sativa* L.), no studies that we are aware of have focused on the potential use of competitive teff varieties.

Crop weed competitive ability is an important tool in low-input, integrated weed management systems. Crop competitiveness is divided into two aspects—(i) the ability of the crop to reduce the fitness of a competitor and (ii) the ability of the crop to withstand the competitive impact of its neighbors and to resist yield loss [9]. They indicated that these aspects are referred to with different terms in the literature and have been described, respectively, as ‘suppressive ability’ and ‘tolerance ability’ in the same way as presented by Hansen et al. [10]. Similar to the definition used by Violle et al. [11] and Andrew et al. [9], we will in this paper use the term ‘traits’; this term being reserved for any feature that is a morphological, physiological, or phenological characteristic of cereal crops and that can be identified and measured at the level of the individual crop plant.

Several traits might explain differences in suppressive or tolerance ability between cereal species [9]. The height of the cereal varieties has been included in numerous studies. Wicks et al. [12] compared winter wheat varieties in their ability to suppress weeds and found a negative correlation between total weed number and plant height [12]. Another finding in their study, however, was that two relatively short varieties suppressed the weeds more than many of the taller varieties. This was an indication that competitive ability cannot be attributed to a single trait [9]. Another group of traits that frequently explain differences among varieties is different indicator traits of early vigor, including fast germination, early crop height, cover, and biomass. Bertholdsson found that early cover, but also allelopathic potential, explained differences between varieties significantly both in barley and wheat [13]. Tillering, canopy architecture and belowground biomass might contribute to different varieties’ competitive ability against weeds [9].

Another aspect is the change in yield potential due to weed competition. Traits or plant functions that can increase the ability of varieties to suppress weeds persistently require energy allocated from the crop plants during growth and development, which detracts from their final yield potential [9,14]. The change in yield potential of the varieties between weeded and unweeded plots can show such an allocation among the teff traits during weed competition. As far as we are aware, no studies have been done clarifying whether this change in yield potential is true for all teff varieties.

The hypothesis of our study were:

Hypothesis 1. *There are differences between teff varieties in terms of traits commonly considered to be important for variety competitiveness in other cereal species.*

Hypothesis 2. *Weeds respond differently to various teff varieties.*

Hypothesis 3. *There is a change in yield potential of teff varieties due to their weed competitiveness.*

Hypothesis 4. *The competitiveness of the variety influences the weeding time of teff.*

2. Materials and Methods

2.1. Description of the Study Areas

The experimental sites were selected based on their suitability for teff production. They are found in the same altitudinal range but with different soil types.

Axum is located 245 km northwest of the Mekelle. The research site is located 4 km east of Axum town, and the experiments were laid on deep black Vertisols with small patches of Cambisol with sandy clay texture (the soil description was made based on WRB (World Reference Base for Soil Resources) 2014 [15]). The experimental fields were located at 14°07'37" N and 38°45'51" E at an altitude of 2098 m a.s.l. It has a tepid to cool sub-moist mid-highlands with an annual rainfall ranging from 401 mm to 800 mm, and the average temperature ranges from 15 °C to 28 °C.

Mekelle research site was situated at the Mekelle University and is located at 13°28'48" N and 39°29'25" E at an altitude of 2224 m a.s.l. The soil at the site is characterized as Cambisol dominated by sandy loam texture with patches of Vertisols (the soil description was made based on WRB 2014 [15]). It has a moderate temperature ranging from 12 °C to 30 °C with an average around 20 °C. The site receives an annual rainfall ranging from 400 mm to 600 mm.

In both Axum and Mekelle, the highest rainfall during the experiment period was recorded in July and August with the warmest months being April, May, and June (Table 1).

Table 1. Rainfall, minimum temperature, and maximum temperature in Axum and Mekelle during 2015 and 2016.

Location	Year	Rainfall (mm)	Min. Temperature (°C)	Max. Temperature (°C)
Axum	2015	725	11	27
	2016	675	11	27
Mekelle	2015	580	11	28
	2016	560	11	28

Source: [16].

2.2. Experimental Design and Treatments

The experiment had a randomized complete block (RCB) design with three blocks with split plot containing two levels of weeding (without weeding and hand weeding) on the main plots and the 10 teff varieties (Table 2) as sub-plot treatments. Both main and sub-plots were randomized independently. The plot sizes were 2 m × 3 m for the sub-plots and 2 m × 39 m for the main plot. There was a space of 1 m between the subplots, 1 m between main plots within blocks, and 1.5 m between blocks to control border effects (to avoid mixture of the seeds from the plots of the different teff varieties).

These teff varieties are commonly produced by small scale farmers in Ethiopia and are adapted to wide altitudinal ranges (i.e., from the lowlands (below 1500 m a.s.l.) all the way to the extreme highlands—as high as 3200 m a.s.l.). A local landrace had been used as a control. A local landrace is a landrace with no known phenotypic and genetic description but commonly sown by the farmers around the experimental sites. It is considered the most adaptable to the condition of the research sites because it has been produced by the farmers for more than a decade. The management and assessment operations of these teff varieties are described in Table 3. Most of these dates describing the period of the crop and weed management operations were within the range of the teff cropping calendar commonly used by farmers in Tigray, Northern Ethiopia, particularly the farmers in the experimental sites. Prior to sowing, ploughing was done four times in Axum as it has vertic soil and three times in Mekelle as it has sandy loam soil using the traditional Ethiopian ard plough. Fertilizing of the field was done by applying DAP (Di-ammonium phosphate) and urea at a rate of 60 kg N/ha and 60 kg P₂O₅/ha for black Vertic soils and 40 kg N/ha and 40 kg P₂O₅/ha for light sandy loam soils. Axum had vertic black soils and Mekelle had a light sandy loam soil type. Sowing was done at the nationally recommended seed rate of 25 kg/ha. Crop assessment had been done beginning 7 days after planting until final harvest in both locations. The researchers undertook management and thorough follow up of the experiments.

Table 2. General description of the teff varieties used for the experiments.

Varieties	Year of Release	Seed Colour	Maturity (Days)	Height (cm)	On-Station Yield (kg/ha)	On-Farm Yield (kg/ha)
Boset	2012	Very White	75–86	75–90	1800–2000	1400–1800
DZ-01-1681	2002	Dark Brown	84–93	74–85	2500	1600–2000
DZ-01-2675	2004	Pale White	112–123	47–91	1800–2800	1600–2000
DZ-Cr-387	2005	White	86–151	72–104	2500–2700	1600–2000
DZ-01-974	1995	White	76–138	84–123	2400–3400	2000–2500
DZ-Cr-385	2009	White	65–88	82–90	1600	1000
DZ-01-354	1970	Pale White	85–130	53–115	1800–2800	1800–2200
DZ-Cr-358	1995	White	76–138	70–109	2100–3600	1800–2400
Kora	2012	White	88–95	90–110	2400–3400	2000–2500
Local						

Source: [17].

Table 3. Description of crop and weed management and assessment operations in the two experimental sites.

Operations	2015	2016
Axum research site		
Land preparation	12 May–20 July	15 May–18 July
Seed bed preparation and sowing	20 July	18 July
Weed assessment		
First weeding and assessment	18 August	21 August
Second weeding and assessment	30 September	2 October
Third weeding and assessment	18 November	25 November
Crop harvesting	20 November	29 November
Crop and weed biomass measurement	3 December	8 December
Crop threshing and grain weighing	3–5 December	8–12 December
Mekelle research site		
Land preparation	23 May–25 July	25 May–29 July
Seed bed preparation and sowing	25 July	29 July
Weed assessment		
First weeding and assessment	2 September	4 September
Second weeding and assessment	28 September	04 October
Third weeding and assessment	26 November	25 November
Crop harvesting	30 November	1 November
Crop and weed biomass measurement	7 December	9 December
Crop threshing and grain weighing	7–12 December	9–12 December

2.3. Data Collection

The collected data can be classified within three classes, that is, (i) data related to crop traits, (ii) weed data and (iii) data related to weeding time.

2.3.1. Data Related to Crop Traits

The crop data include crop phenology (days to emergence, heading/flowering, and maturity), tillering (total tiller number/plant), plant height, biomass yield, and grain yield. The phenology data were obtained by recording the dates when the teff plants covering 50% of the plot area emerged, flowered, and matured. Tillering and plant height were measured as the average of 10 random teff plants from each plot. Tillering was recorded by counting the number of tillers in a single teff plant. Plant height (i.e., height of the teff plant from node separating root and shoot up to the tip of the panicle) was measured using a meter and centimeter graduated flexible metal ruler. Biomass yield was the sum of the straw or the vegetative part and the seed/grain or the reproductive part of the crop plant.

2.3.2. Effects of Different Teff Varieties on Weeds

Density and Biomass

Weed plant density and aboveground weed biomass (dry weight) were assessed three times (Table 3) before harvest in one randomly placed quadrat (25 cm × 25 cm) per plot. Weed cover was estimated visually (coverage) by weeding time (first, second, and third weeding). The space occupied by the crop and the most abundant weed species on all small plots was expressed as the percentage of ground coverage. The areas covered by crop, weed species, and bare soil were summed up to 100%. The biomass samples were dried at 65 °C for 48 h to determine the dry weight of both the monocot and dicot weeds.

2.3.3. Identification of Dominant Weed Species

The main purpose of identifying dominant weed species was to determine the weed species composition, which might have fierce competition with teff. From all parts of the experimental fields in both Axum and Mekelle, 12 samples were taken randomly using a 50 cm × 50 cm quadrat before sowing. The weed species were identified and counted from each sample. Six weed species from Axum and five weed species from Mekelle were identified, and their frequency, abundance, and dominance were calculated based on the most commonly used procedures [18–21]. The first three weed species from each location that had the highest values of frequency, abundance, and dominance were considered the dominant weed species in the experimental areas of both locations.

2.3.4. Change in Yield Potential of Teff Varieties Due to Their Weed Competitiveness

The yield potential of the teff varieties in our study refers to the yield obtained from plots with hand weeding and receiving all the recommended teff agronomic practices applied under the prevailing seasonal climatic conditions. The competitiveness of the varieties was measured in terms their ability to reduce weed density, dry weight, and cover in times of weed infestation during production. To determine if there was a change in yield potential of teff varieties, the yield difference between the weeded and unweeded plots was calculated for each variety. This is the loss due to weed competition in unweeded plots. We used the following formula to calculate the loss in yields of the varieties:

$$\text{Yield loss (\%)} = \frac{\left(\text{Yield} \left(\frac{\text{kg}}{\text{ha}}\right) \text{from weeded plots}\right) - \left(\text{yield} \left(\frac{\text{kg}}{\text{ha}}\right) \text{from unweeded plots}\right)}{\left(\text{yield} \left(\frac{\text{kg}}{\text{ha}}\right) \text{from weeded plots}\right)} \times 100. \quad (1)$$

The yield loss of each variety and the weed response were compared to determine if there was a change in yield potential of the varieties due to weed competitiveness. Yield was measured in kg/ha.

2.3.5. Weeding Time and Competitiveness of Teff

Estimation of Hand Weeding Time

This estimation was based on the weeding time required by a single person to hand weed the 6 m² subplots. This was recorded as minutes/person/plot and was averaged from all replications and weeding times of the experiment in each location. This average value of the weeding time was converted into hours/ha.

2.4. Data Analysis Procedures

Combined analysis of the teff variety experiments was done by year and location using the MIXED procedure of SAS (SAS version 9.4). The crop data included hand weeding, variety, year, and location as factors. The weed data also included weeding frequency (weeding time—first, second, and third).

All factors from both data groups were considered to be fixed. Weed assessment was performed in two successive years and with three weeding times. A repeated-measurement mixed model was used during weed data analysis to determine if there was a correlation among the assessments recorded at the different times. For the correlation analysis, two widely known serial structures—unstructured (un) and first-order autoregressive (ar (1)) model structures—were used. The final model for the analysis was chosen based on the Akaike information criterion (AIC) and Schwarz Bayesian information criterion (BIC). The model with the lowest AIC and BIC value was considered to be the final model for analysis. Model assumptions for the split plot analysis were that the data were normally distributed and that the errors were independent with homogeneous variances. Any outliers within the dataset were checked using standardized residual plots generated during analysis. These plots were composed of normal probability plots and plots with residuals versus fitted values of the response variables. The least square means of factors were separated using the Tukey–Kramer test at a level of significance of 5%.

3. Results

3.1. Traits of Teff Varieties

The main factors of hand weeding, variety, year and location all appeared significant for all crop traits with the exception of location and grain yield (Table 4). Because the two-factor interactions, variety \times year, variety \times location, and year \times location, for most crop traits were also significant (Table 4), the subsequent analyses were performed separately for locations and years (Table 5). The results from these analyses were separated by sites and years in the presentation below.

3.1.1. Emergence and Maturity

There were variations in days to emergence among the varieties in both locations and years (Table 5). The general picture was that the varieties belonged to two groups, one big group with, for example, 'Boset,' that was early emerging, and the second group of 'DZ-01-354' and 'DZ-Cr-358' with late-emerging varieties (Figure 1). The least number of days taken to emerge was 5.7 for Boset in both Axum and Mekelle in 2016, and the greatest number of days to emergence was 16 for 'DZ-Cr-358' in Mekelle in 2015.

Differences among the teff varieties were observed in days to maturity (Table 4). The early-emerging variety 'Boset' matured in most cases significantly earlier than the other teff varieties. 'Boset' took, on average, 90 days in Axum and Mekelle in 2015 and 2016 (Figure 1). Both 'DZ-01-354' and 'DZ-Cr-358' matured later, but not always significantly later than the other varieties. The variety 'DZ-01-354' took an average of 112 days to maturity, and 'DZ-Cr-358' took an average of 113.5 days (Figure 1). Weeding had a significant effect on days to maturity of the crop (Table 4). Earlier maturity of teff was observed in unweeded plots taking an average of 106.5 days compared to 109 days in weeded plots.

3.1.2. Plant Height

The teff varieties differed in plant height (Table 4). The varieties 'Boset' and 'DZ-01-1681' had, although not always significantly, the shortest plant height with an average value of 76 cm across locations and seasons (Figure 1). Taller plants were observed from the varieties 'DZ-Cr-387' and 'DZ-01-974,' having an average value of 97 cm. Teff plants were taller (on average 93 cm) on unweeded plots compared to 89 cm in plots with hand weeding.

3.1.3. Tiller Number per Plant

The varieties 'DZ-Cr-358' and 'DZ-01-354' had the highest number of tillers per plant with average values of 5.82 and 4.48, respectively, but only 'DZ-Cr-358' in weeded plots in Axum 2015 had significantly more tillers than all the others. Other than in 2016 in Mekelle, the tillering of the varieties was significantly different in all the locations and seasons (Table 5). The teff varieties 'DZ-Cr-358' and

'DZ-01-354' had the highest number of tillers per plant in both Axum and Mekelle in 2015 and 2016 on weeded plots (Figure 2). Hand weeding significantly affected the number of tillers per plant (Table 4), and a greater number of total tillers per plant was observed in weeded plots with an average value of 4.53, which was 28.3% higher than in plants from the unweeded plots.

3.1.4. Biomass Yield and Grain Yield

Teff varieties were different in terms of biomass and grain yield (Table 4). They also showed significant differences in Axum and Mekelle in both 2015 and 2016 (Table 5). The varieties 'DZ-Cr-358' and 'DZ-01-354' had the least biomass and grain yield (Figure 3). In particular 'DZ-Cr-358' showed significantly lower biomass and grain yield values compared to most other varieties. The average biomass yields of 'DZ-Cr-358' (4223.6 kg/ha) and 'DZ-01-354' (5286.8 kg/ha) were 48% and 35%, respectively, lower than the highest-yielding variety 'Kora' having an average biomass yield of 8118.1 kg/ha (Figure 3). Similarly, the average grain yields of 'DZ-Cr-358' (813.2 kg/ha) and 'DZ-01-354' (1001 kg/ha) were 40.4% and 26.6%, respectively, lower than the highest-yielding variety 'Kora' having an average grain yield of 1364.1 kg/ha (Figure 3). Generally, the varieties had higher biomass and grain yields in Axum than in Mekelle (Figure 3). At the same time, they had higher biomass and grain yields in 2015 than in 2016 except in some varieties (Figure 3). Weeding had a significant effect on these yields with the highest being recorded from plots with hand weeding. The teff biomass yield harvested from weeded plots was 7295 kg/ha, which was 15.3% higher than the yield obtained from the plots without weeding. The average grain yield from hand-weeded plots was 1448 kg/ha, which was 32% higher than that obtained from plots without hand weeding.

Table 4. ANOVA table with P-values for the main factors hand weeding, teff variety, year, and location, and their interactions on different teff traits.

Fixed Factors	DF	Teff Traits					
		Days to Emergence	Days to Maturity	Plant Height (cm)	Total Tiller No./Plant	Biomass Yield (kg/ha)	Grain Yield (kg/ha)
Hand weeding ^a (HW) **	1		0.0256 *	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***
Variety (VAR)	9	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***
HW × VAR	9		0.6599 ns	0.1239 ns	0.0001 ***	0.6068 ns	0.3965 ns
Year (YR)	1	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	0.0007 ***	0.0797 ns
HW × YR	1		0.2979 ns	0.0121 *	0.0005 ***	<0.0001 ***	<0.0001 ***
VAR × YR	9	<0.0001 ***	<0.0001 ***	0.0049 **	<0.0001 ***	<0.0001 ***	<0.0001 ***
HW × VAR × YR	9		0.8387 ns	0.824 ns	<0.0001 ***	0.3227 ns	0.1585 ns
Location (LOC)	1	<0.0001 ***	0.0012 **	<0.0001 ***	<0.0001 ***	<0.0001 ***	0.4654 ns
HW × LOC	1		0.0699 ns	0.6995 ns	0.0181 *	0.9343 ns	0.5317 ns
VAR × LOC	9	<0.0001 ***	<0.0001 ***	0.0162 *	0.3026 ns	0.8262 ns	0.7325 ns
HW × VAR × LOC	9		0.6255 ns	0.6381 ns	0.2726 ns	0.6335 ns	0.2716 ns
YR × LOC	1	<0.0001 ***	<0.0001 ***	<0.0001 ***	0.4889 ns	<0.0001 ***	0.005 **
HW × YR × LOC	1		0.2449 ns	0.4912 ns	0.7361 ns	0.0148 *	0.024 *
VAR × YR × LOC	9	<0.0001 ***	<0.0001 ***	0.016 *	0.3669 ns	0.0131 *	0.2639 ns
HW × VAR × YR × LOC	9		0.8457 ns	0.3339 ns	0.6737 ns	0.6299 ns	0.8752 ns
Transformation of Y Type ^b		-	-	-	-	-	-
		-	un	un	un	un	un

* Significant at $p < 0.05$, ** significant at $p < 0.01$, *** significant at $p < 0.001$, ns: not significant; ^a Hand weeding—refers to uprooting of weeds from the field of the crop (Teff) using the hands; ** Hand weeding did not have an effect on days to emergence because it was applied after teff sprouting. ^b Among the commonly used serial structures used for correlations, “unstructured” (un, in SAS) was used. This was used during analysis because it resulted in models with lower values of Akaike information criterion (AIC) and Schwarz Bayesian information criterion (BIC).

Table 5. ANOVA table with P-values for the main factors hand weeding and variety on different teff traits.

Crop (teff) Responses	Fixed Factors											
	Axum						Mekelle					
	2015			2016			2015			2016		
	Hand Weeding (HW)	Variety (VAR)	HW × VAR	Hand Weeding (HW)	Variety (VAR)	HW × VAR	Hand Weeding (HW)	Variety (VAR)	HW × VAR	Hand Weeding (HW)	Variety (VAR)	HW × VAR
Days to 50% emergence		<0.0001 ***		<0.0001 ***			<0.0001 ***			<0.0001 ***		<0.0001 ***
Days to 50% maturity	0.0634 ns	<0.0001 ***	<0.0001 ***	0.436 ns	<0.0001 ***	0.7895 ns	0.0056 **	<0.0001 ***	0.915 ns	0.0574 ns	<0.0001 ***	0.4818 ns
Plant height (cm)	0.0002 ***	<0.0001 ***	0.962 ns	0.3788 ns	<0.0001 ***	0.5385 ns	0.0005 ***	<0.0001 ***	0.0181 *	0.0946 ns	<0.0001 ***	0.6292 ns
Total tiller no./plant	0.0005 ***	<0.0001 ***	<0.0001 ***	0.1181 ns	0.004 **	0.0244 *	<0.0001 ***	0.0003 ***	0.0245 *	<0.0001 ***	0.931 ns	0.6258 ns
Crop biomass (kg/ha)	<0.0001 ***	<0.0001 ***	0.4988 ns	0.0105 *	<0.0001 ***	0.7955 ns	<0.0001 ***	<0.0001 ***	0.231 ns	0.9559 ns	0.1138 ns	0.1627 ns
Grain yield (kg/ha)	<0.0001 ***	<0.0001 ***	0.6986 ns	0.8003 ns	0.2931 ns	0.8378 ns	0.0149 *	<0.0001 ***	0.1626 ns	0.2522 ns	0.5321 ns	0.4654 ns
Degree of freedom	1	9	9	1	9	9	1	9	9	1	9	9

* Significant at $p < 0.05$, ** significant at $p < 0.01$, *** significant at $p < 0.001$, ns: not significant; Hand weeding—refers to uprooting of weeds from the field of the crop (teff) using the hands.

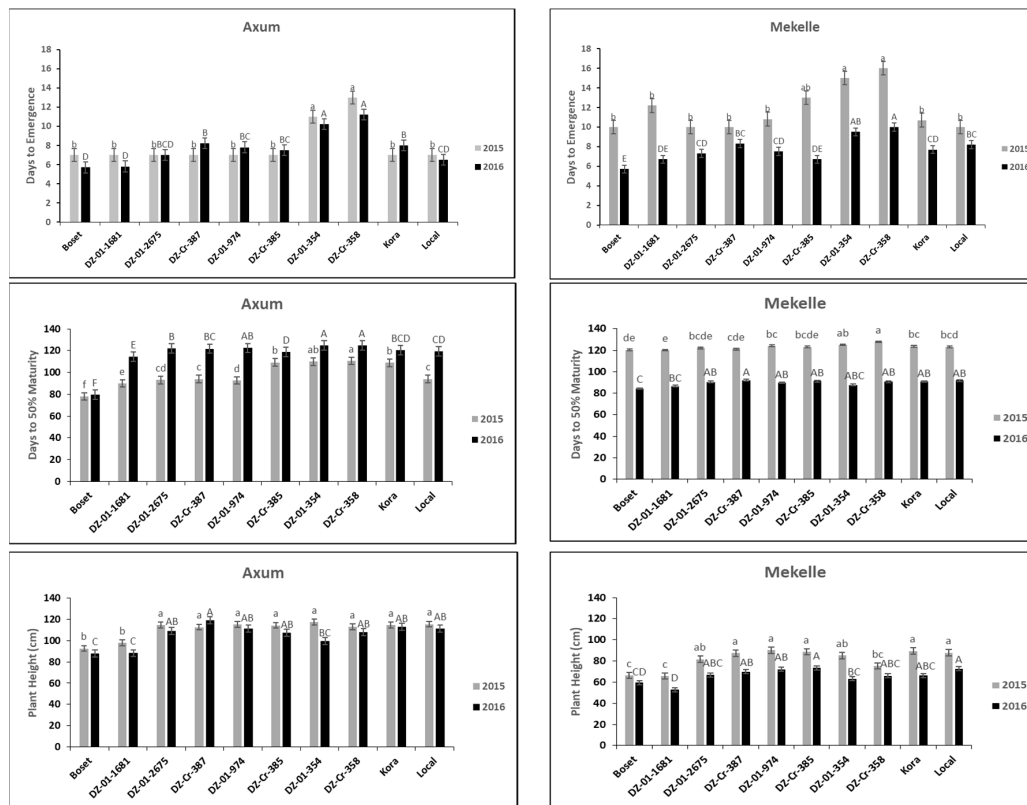


Figure 1. Differences of teff varieties in days to emergence, days to maturity, and plant height in Axum and Mekelle in 2015 and 2016. Means of the teff varieties were compared separately within each location and year considering the main effect of variety. Means with the same letter are not significantly different.

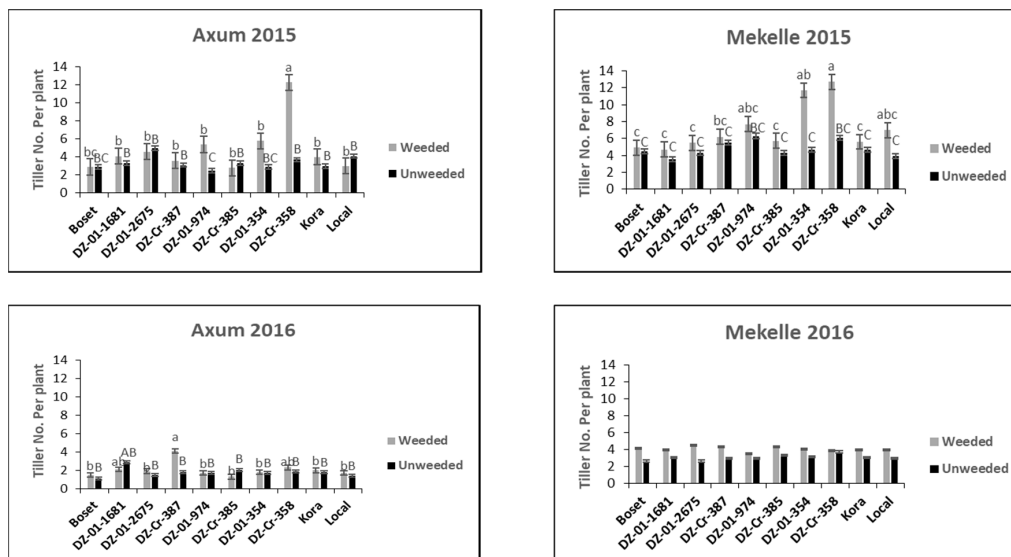


Figure 2. Differences of teff varieties in tiller number per plant in Axum and Mekelle in 2015 and 2016. Means of the teff varieties were compared separately within each location and year considering the HW×VAR interaction. Means with the same letter are not significantly different.

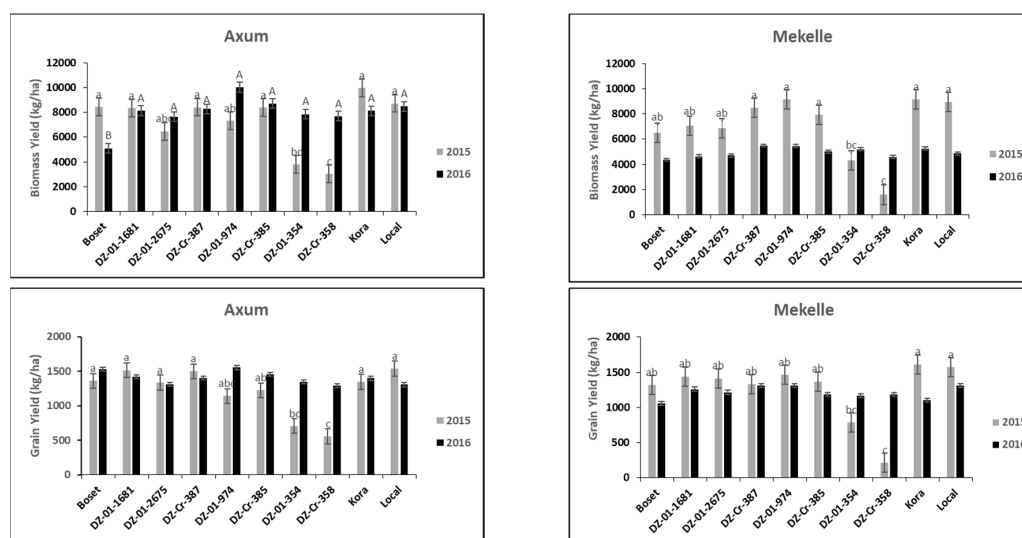


Figure 3. Differences of teff varieties in biomass and grain yields in Axum and Mekelle in 2015 and 2016. Means of the teff varieties were compared separately within each location and year considering the main effect of variety. Means with the same letter are not significantly different.

3.2. Influence of Teff Varieties on Weeds

In most cases the main factors of hand weeding, variety, year, and location appeared significant for most weed assessments with some few exceptions (Table 6). Because most of the two-factor interactions, variety \times year, variety \times location, and year \times location, as well as the three and four-factor interactions, for weed assessments were not significant (Table 6) the analyses were not further split up.

3.2.1. Weed Density

The different teff varieties resulted in significant variation in weed density (Table 6), but only for the density of monocot weeds and the total weed density. The highest total weed density (sum of the densities of the monocot and dicot weeds) was recorded from plots with the varieties DZ-Cr-358 (349 shoots/m²) and DZ-01-354 (328 shoots/m²), while the lowest density was from plots with DZ-Cr-387 (263 shoots/m²) and DZ-Cr-385 (262 shoots/m²) (Table 7). The latter reduced the weed density by 25% of that recorded from the plot with DZ-Cr-358. The effect of the different teff varieties was comparable to the effect of hand weeding. Such an effect of the varieties was not variable spatially or temporally because the interaction of the teff varieties with location and year was not statistically significant for any of the parameters of weed density (Table 6). Hand weeding had a significant effect on weed density, with the highest average value of 364 shoots/m² from unweeded plots (Table 7). Compared to the monocot weeds, hand weeding significantly affected the dicots and reduced their density by 29.7%.

3.2.2. Weed Dry Weight

The teff varieties affected weed dry weight significantly (Table 6), but again only for monocots and total weed biomass. The highest weight was recorded from the plots with the varieties DZ-01-354 and DZ-Cr-358 with average values of 347.2 g/m² and 356.4 g/m², respectively (Table 7). The lowest weed dry weight was obtained from plots with DZ-01-2675 with an average value of 150.1 g/m² (Table 7). The latter was not significantly different from the weed dry weight obtained from plots with the varieties DZ-Cr-387 and DZ-Cr-385. The varietal difference resulted in significantly reduced dry weight of monocot weeds. Their dry weight from weeded plots (121.64 g/m²) was higher than that from plots with the varieties DZ-01-2675 (94.92 g/m²) and Kora (108.1 g/m²) (Table 7). DZ-Cr-387 ('Quncho') reduced the dry weight of dicot weeds (43.72 g/m²) to a level comparable with the weight recorded from hand-weeded plots (42.65 g/m²). Hand weeding had a significant effect on the dry

weight of weeds (both monocots and dicots) (Table 6). It reduced the dry weight by 39.6% for total weeds and by 29.6% and 57.1% for monocot and dicot weeds, respectively (Table 7).

3.2.3. Weed Cover

Like density and dry weight, weed cover was also significantly influenced due to the varietal differences in teff (Table 6). The varieties Kora and DZ-Cr-387 reduced the weed cover to as low as 13.7%, with the highest cover being observed from plots with DZ-01-354 (22.24%) and DZ-Cr-358 (23.4%) (Table 7). In other words, the high-yielding varieties reduced the weed cover by 41.8% when compared to the cover in plots consisting of DZ-Cr-358 and by 33.9% when compared with the cover in unweeded plots. Weeding also significantly affected weed cover (Table 6) and reduced it from 20.6% in unweeded plots to 12.89% in weeded plots, that is, it reduced weed cover by 59.8% (Table 7).

3.2.4. Dominant Weeds

The most dominant weeds identified in the research sites were *Plantago lanceolata* L., *Cyperus esculentus*, and *Setaria pumila* (poir.) Roem. and Schult in Axum and *Avena abyssinica* Hochst, *Galinsoga parviflora* Ca, and *P. lanceolata* L. in Mekelle.

3.3. Changes in Yield Potential of Teff Varieties Due to Their Weed Competitiveness

Most of the teff varieties showed wide variation in their biomass and grain yields due to hand weeding (Table 8). The greatest yield losses due to weed competition in unweeded plots was 36% in biomass yield of the local landrace and 38% in grain yield of the variety 'DZ-01-354' (Figure 4). The lowest yield losses were recorded from the varieties 'Kora' (with a loss of 6% in biomass yield and 18% in grain yield) and 'DZ-Cr-387' (with a loss of 17% in biomass yield and 21% in grain yield) (Figure 4). On average, the losses in grain yields of the varieties were higher than losses in biomass yields.

3.4. Weeding Time and Competitiveness on Teff

The time taken to weed was longer in Mekelle than in Axum (Figure 5). It was also longer in 2015 than in 2016. The longest time was recorded in Mekelle with an average of 1950 h/ha in 2015, which was lowered to 889 h/ha in 2016, that is, a reduction of 54.4%. In Axum, the longest time for weeding was 574.1 h/ha in 2015, and this was reduced by 39.5% to 347.2 h/ha in 2016. Such a reduction was attributed to the effect of the different teff varieties on weed density, dry weight, and cover. The greatest reduction in weeding time, by 50.6% in Axum and by 54.4% in Mekelle, was observed in plots with the teff variety DZ-Cr-387. The lowest reduction was observed in Mekelle, which was 1.22% in plots with DZ-Cr-358, i.e., the weeding time was almost the same in 2015 and 2016. The average weeding time in plots with DZ-Cr-358 in Mekelle was 1066.7 h/ha in 2015 and 1053.7 h/ha in 2016. There was also a 3.76% increase in weeding time in plots with DZ-01-354 in Axum.

Table 6. ANOVA table with P-values for the effects of the main factors of hand weeding, teff variety, location, and year and their interactions on weed assessments.

Fixed Factors	DF	Weed Assessments						
		Monocot Density (Shoots/m ²)	Dicot Density (Shoots/m ²)	Total Density (Shoots/m ²)	Monocots DW (g/m ²)	Dicots DW (g/m ²)	Total DW (g/m ²)	Weed Cover (%)
Hand weeding (HW)	1	0.2175 ns	0.0197 *	0.0306 *	0.0195 *	0.0004 ***	<0.0001 ***	<0.0001 ***
Variety (VAR)	9	0.0108 *	0.1665 ns	0.0061 **	0.0034 **	0.2829 ns	0.001 ***	<0.0001 ***
HW × VAR	9	0.5878 ns	0.6069 ns	0.7291 ns	0.0994 ns	0.4166 ns	0.0347 *	0.0933 ns
Year (YR)	1	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***
HW × YR	1	0.8377 ns	0.5756 ns	0.6063 ns	0.0492 *	0.0022 **	0.0007 ***	0.0006 ***
VAR × YR	9	0.0951 ns	0.4643 ns	0.0533 ns	0.0029 **	0.262 ns	0.001 ***	<0.0001 ***
HW × VAR × YR	9	0.0684 ns	0.236 ns	0.014 *	0.0747 ns	0.3074 ns	0.0204 *	0.2295 ns
Location (LOC)	1	<0.0001 ***	0.0028 **	0.0003 ***	<0.0001 ***	0.0012 **	<0.0001 ***	0.1635 ns
HW × LOC	1	0.9398 ns	0.1464 ns	0.5213 ns	0.1574 ns	0.1746 ns	0.7045 ns	0.0002 ***
VAR × LOC	9	0.0271 *	0.645 ns	0.2053 ns	0.2256 ns	0.8689 ns	0.5378 ns	0.0699 ns
HW × VAR × LOC	9	0.7699 ns	0.4824 ns	0.7974 ns	0.2853 ns	0.7797 ns	0.7973 ns	0.6023 ns
YR × LOC	1	<0.0001 ***	0.0746 ns	<0.0001 ***	<0.0001 ***	0.0073 **	<0.0001 ***	<0.0001 ***
HW × YR × LOC	1	0.4346 ns	0.2121 ns	0.8701 ns	0.1359 ns	0.2019 ns	0.6292 ns	0.8513 ns
VAR × YR × LOC	9	0.3921 ns	0.4951 ns	0.1571 ns	0.2075 ns	0.8612 ns	0.5657 ns	0.0364 *
HW × VAR × YR × LOC	9	0.0892 ns	0.1316 ns	0.008 **	0.3467 ns	0.7874	0.8529 ns	0.6821 ns
Transformation of Y Type ^b		-	-	-	-	-	-	-
		un	un	un	un	un	un	un

* Significant at $p < 0.05$, ** significant at $p < 0.01$, *** significant at $p < 0.001$, ns: not significant; Hand weeding—refers to uprooting of weeds from the field of the crop (teff) using the hands;

^b Among the commonly used serial structures used for correlations, “unstructured” (un, in SAS) was used. This was used during the analysis because it resulted in models with lower values of the Akaike information criterion (AIC) and Schwarz Bayesian information criterion (BIC).

Table 7. Effects of teff varieties and hand weeding on weed assessments.

Fixed Factors	Monocot Density (Shoots/m ²)	Dicot Density (Shoots/m ²)	Total Density (Shoots/m ²)	Monocot DW (g/m ²)	Dicot DW (g/m ²)	Total DW (g/m ²)	Weed Cover (%)
Variety							
Boset	135.11ab	135.78	270.89ab	131.66ab	56.81	188.48abc	15.43b
DZ-01-1681	156ab	131.11	287.11ab	125.93ab	60.33	186.26abc	16.65b
DZ-01-2675	138.89ab	132	270.89ab	94.92b	55.19	150.11c	16.22b
DZ-Cr-387	136ab	127.11	263.11b	131.48ab	43.72	175.21abc	13.61b
DZ-01-974	169.33ab	142.44	311.78ab	134.98ab	61.34	196.32abc	15.07b
DZ-Cr-385	116b	146	262.0b	113.39ab	55.12	168.51bc	16.24b
DZ-01-354	174.22ab	154.22	328.4ab	247.67ab	99.50	347.17a	22.24a
DZ-Cr-358	186.67a	162.22	348.89a	262.27a	94.10	356.37a	23.40a
Kora	141.11ab	129.78	270.89b	108.07b	57.08	165.15bc	13.79b
Local	140.22ab	124.67	264.89ab	121.39ab	126.24	247.63abc	14.74b
Hand weeding							
With	150.71	130.89b	281.6b	121.64b	42.65b	164.29b	12.89b
Without	178	186.18a	364.18a	172.71a	99.24a	271.95a	20.6a

Means with the same letter are not significantly different. DW = Dry Weight.

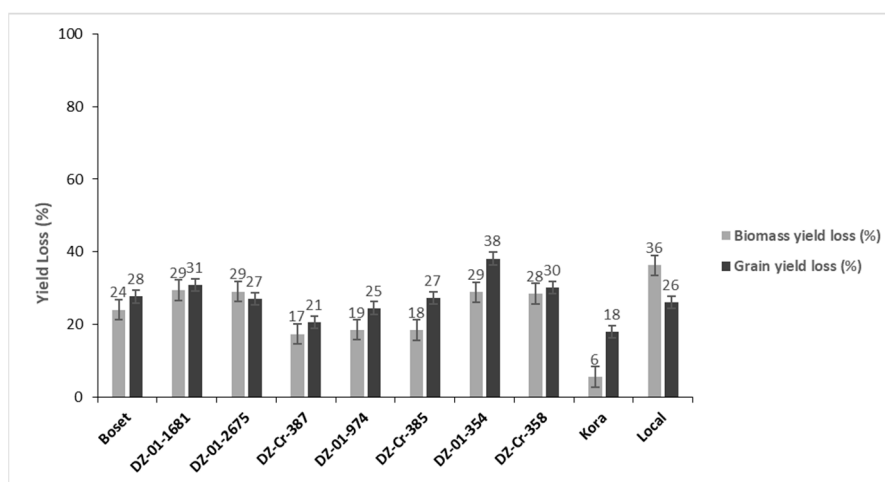


Figure 4. Biomass and grain yield losses of teff varieties due to weed competition in unweeded plots. N.B. Yield loss (%) = % of the yields obtained from weeded plots and lost due to the weed competition in unweeded plots

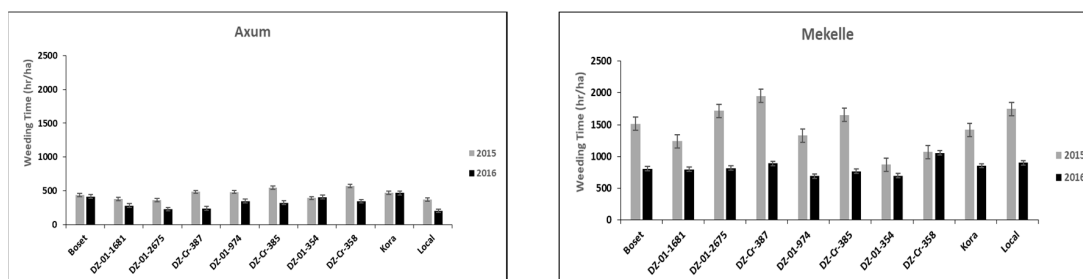


Figure 5. The effect of the different teff varieties on weeding time.

Table 8. Variation in biomass and grain yields of teff varieties due to weeding.

Variety	Biomass Yield (kg/ha)		Difference (kg/ha)	Grain Yield (kg/ha)		Difference (kg/ha)
	With Weeding	Without Weeding		With Weeding ^{rank}	Without Weeding ^{rank}	
Boset	6940.25	5270.86	1669.4	1413.95 ⁸	1021.6 ⁸	392.3
DZ-01-1681	7268.03	5126.42	2141.6	1489.16 ⁶	1029.1 ⁷	460.1
DZ-01-2675	6459.75	4581.92	1877.8	1444.02 ⁷	1053.2 ⁶	390.8
DZ-01-387	8398.58	6940.28	1458.3	1600.85 ¹	1270.5 ¹	330.3
DZ-01-974	8415.58	6855.61	1560.0	1530.71 ³	1155.5 ⁴	375.2
DZ-Cr-385	7950.03	6482.45	1467.6	1515.54 ⁴	1101.2 ⁵	414.4
DZ-01-354	6180.56	4393.06	1787.5	1236.69 ⁹	765.12 ⁹	471.6
DZ-Cr-358	4925	3522.17	1402.8	957.59 ¹⁰	668.72 ¹⁰	288.9
Kora	8352.81	7883.31	469.5	1499.34 ⁵	1228.8 ²	270.6
Local	8062.5	5137.5	2925.0	1591.19 ²	1175.6 ³	415.6

N.B. Yield difference = (yield obtained from weeded plots) – (yield obtained from unweeded plots). The biomass and grain yield values of teff varieties described in this table were an average from across locations and seasons.

4. Discussion

4.1. Traits of Teff Varieties

4.1.1. Emergence and Maturity

A huge variation in how quickly the varieties emerge was found, from the early-emerging variety Boset to late varieties such as DZ-Cr-358 and DZ-01-354. This result is consistent with the characteristics of these varieties described in the Ethiopian Crop Varieties annual bulletin [17]. Rapid emergence and early biomass accumulation are examples of ruderal traits [22]. Rapidly emerging varieties start photosynthesis early, and this is a crucial factor in the weed-competitive ability of cereal crops [23]. The varieties described above showed the same trend in flowering and maturity as well, that is, Boset matured early and DZ-Cr-358 and DZ-01-354 matured late. Those that emerged early flowered and matured early. The early-emerging varieties have earlier access to water, nutrients, and sunlight for their vegetative and reproductive growth and development. Thus, weeding might have caused delayed maturity of the varieties because it allowed the varieties to use soil resources more efficiently and with less competition from weeds. On the other hand, early maturity of teff varieties in unweeded plots might be a mechanism for escaping the stress (due to limited availability of water and nutrients in the soil) that could occur due to the competition of the crop with weeds. In most cases, plants allocate their limited water and nutrient supplies to their various structures to facilitate their growth and development during stress as a survival mechanism [24]. Teff varieties differ in their response to water, nutrients, light, and heat stress [25–27]. Many early vigor traits like early emerging, early coverage, early biomass, and early height are among plant properties frequently mentioned to be important for competition against weeds in wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and oats (*Avena sativa* L.) [9].

4.1.2. Plant Height

Plant height is also among the crop agronomic traits contributing to the weed-competitive ability of cereal crops [9,23]. In our study there were differences among the varieties in their heights. The early emerging and maturing varieties Boset and DZ-01-1681 had shorter plants than other varieties, whereas taller plants were observed in DZ-Cr-387 and DZ-01-974. Plant height of a single variety, however, is spatiotemporally variable depending on the availability of water, nutrients, and sunlight, and most commonly in teff production a good supply of water, nutrients and sunlight results in taller plants and longer panicles for a cultivar. It is also very common to observe late-maturing varieties having taller plants than early-maturing varieties [4,5,17,26,28]. Not only genotypic variability, but also agronomic management practices of cereal crops have a conspicuous effect on plant height and panicle length [23]. In our study, significantly taller teff plants were found in unweeded plots. The taller heights of teff in

plots without hand weeding are attributed to the competition of the crop plant with weeds for sunlight. Plants respond to restricted sunlight as a result of weed competition by elongating their stalks [29–31].

4.1.3. Tillering

Weeding teff plots significantly increased tillering in this experiment, and this is in agreement with the finding that tillering of cereal crops such as wheat increases with decreased weed density [23,32]. In addition, the rate of tiller production is plastic and density dependent and that tiller numbers are reduced with increased inter and intraspecific competition [9]. Not only weeding, but also genotypic variance influenced the tillering. Tillering refers to the number of productive and non-productive tillers from a single teff plant. The late emerging, flowering, and maturing varieties, that is, DZ-Cr-358 and DZ-01-354, had significantly more tillers than other varieties. The interaction of the two factors (hand weeding and variety) also had a significant effect on the tillering of teff, and most of the varieties had more tillers on weeded plots. The reason is that when weeds are removed from teff plots, they leave an open space enabling the crop to get sufficient access to water, nutrients and sunlight to support itself and its newly emerging tillers from its basal nodes.

4.1.4. Biomass and Grain Yields

Genotypic variation also resulted in significant difference in biomass and grain yields. Among all the varieties, Kora gave the highest biomass yield. This variety was also the highest yielder followed by DZ-Cr-387 (Quncho) in previous studies [33,34]. The late emerging varieties, that is, DZ-Cr-358 and DZ-01-354, had the lowest yields because those varieties not only emerged late, but also matured late. This low yield might be attributed to the competition among the tillers at the end of the production season, especially for water, and thus there is less time for the productive tiller to reach the final stage of seed filling and physiological maturity. The other reason for the low yield might be due to the suppression of late-emerging varieties by weeds during their early growth stage. The teff yield was significantly higher from the weeded plots and the tillering of teff was higher in plots with hand weeding. This was likely as a result of improved access to water and plant nutrients as well as less competition for sunlight. The difference in biomass yield (15.3%) and grain yield (32%) in weeded plots compared to plots without hand weeding can be considered as losses as a result of higher weed competition.

Similarly to other cereal species, there are differences between teff varieties in terms of traits commonly considered to be important for variety competitiveness, and thus hypothesis 1 was clearly supported.

4.2. Influence of Teff Varieties on Weeds

4.2.1. Weed Density, Dry Weight, and Cover

In our experiment, hand weeding had a greater effect on dicots compared to monocots, probably because most of the dicots were more easily removed during weeding, especially at their early growth stage. Weeding significantly reduced the density and dry weight of dicots in particular and the cover of all weed types in general. Cover was highly related with weed density, and it was highly influenced by the removal of weeds because it was higher in unweeded plots. Weed dry weight is attributed to the ability of weeds to compete with crops for water, nutrients, and sunlight.

The differences between varieties were generally large and comparable with the effect of hand weeding. For instance, the average total weed density from the plot with variety 'DZ-Cr-387' ('Quncho') (obtained by calculating the mean weed density from the plots with and without hand weeding consisting of this variety, that is, 263.11 weeds/m²) was 6.7% lower than the average total density from weeded plots (i.e., 281.6 weeds/m²) and 27.8% lower than that from unweeded plots (i.e., 364.18 weeds/m²). Such an effect of the varieties did not vary spatially and temporally because the interaction of the teff varieties with location and year was not significant for any of the parameters of weed density (Table 4). The high-yielding varieties (i.e., biomass and grain yields) reduced the

weed cover by 41.8% when compared to the cover in plots consisting of DZ-Cr-358 and by 33.9% when compared with the cover in unweeded plots. Unlike hand weeding, genotypic difference had a significant effect only on monocot density and biomass, not on dicot weeds. Such a variability might be attributed to the difference in emergence, tillering potential, plant height, and biomass of the varieties [5,17]. Crops with different growth habits such as different root systems, plant heights, tillering potential, and foliar architecture have different competitive potential against weeds [23,35–38]. The late emerging varieties, that is, 'DZ-Cr-358' and 'DZ-01-354', allowed weed growth and were more infested than other varieties. The high yielding and the early emerging varieties 'DZ-Cr-387', Kora, and 'DZ-Cr-385' had a very strong competitive response to weeds and reduced the weed density, dry weight, and cover. These varieties not only gave taller plants, but also had the ability to dominate their space through their strong-standing tillers.

There were dominant weed species found in both experimental locations. The weed species *P. lanceolata* and *C. dactylon* were among these. *Cyperus esculentus*, and *Setaria pumila* were specifically dominant in Axum and *Avena abyssinica*, and *Galinsoga parviflora*, were dominantly found in Mekelle. Two of the three dominant weed species in Axum were monocots, and two of the three dominant weed species in Mekelle were dicots.

As described above, there were significant differences in weed density and biomass between teff varieties, and thus hypothesis 2, "Weeds respond to various teff varieties differently," was supported.

4.2.2. Changes in Yield Potential of Teff Varieties Attributed to Their Weed Competitiveness

The teff varieties 'Kora' and 'DZ-Cr-387' compete strongly with weeds as seen by their effect on weed density, dry weight and cover, and they also have higher yields at the end of the growing season than other varieties. However, they sacrifice some of their yields during their competition with both monocot and dicot weeds. For instance, the variety 'Kora' lost as much as 6% of its biomass yield and 18% of its grain yield. Similarly, the variety 'DZ-Cr-387' lost as much as 17% of its biomass yield and 21% of its grain yield. Relatively smaller changes were observed in the teff varieties 'Kora' and 'DZ-Cr-387', and they lost less of their biomass and grain yields than other varieties as a cost of their competitiveness, and they significantly reduced density, dry weight, and cover of weeds.

Hypothesis 3, "There is a trade-off between yield potential and weed competitiveness in teff varieties," was supported.

4.2.3. Weeding Time and Competitiveness on Teff

The competitive ability of the teff variety 'DZ-Cr-387' resulted in a 50–55% reduction in the weeding time in both locations, which can be considered as a compensation for the yield reduction of the variety due to competition with weeds.

Thus, hypothesis 4, "The competitiveness of the variety influences the weeding time of teff," was supported.

5. Conclusions

The different teff varieties had different emergence, heading, and maturity dates, plant height, tillering, and yields.

Weeds responded differently to different teff varieties. The teff varieties 'Kora' and 'DZ-Cr-387' significantly lowered weed density, dry weight and cover and thus were more competitive against weeds than, for example, the varieties 'DZ-Cr-358' and 'DZ-01-354.' Generally, teff varieties had greater effects on monocots than on dicots.

Hand weeding caused delayed flowering and maturity, taller plants, enhanced tillering, reduced weed biomass, and enhanced yields of teff. It decreased weed density and biomass in both locations and seasons, but the efficiency was higher for dicots than for monocot weeds.

There was a trade-off between the yield potential and weed competitiveness in most of the varieties, especially for ‘Kora’ and ‘DZ-Cr-387’ as they lost less of their yields while significantly reducing weed infestation.

The competitive ability of the teff variety ‘DZ-Cr-387’ resulted in shortened weeding time in both locations.

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