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Potential of teff as alternative crop for Mediterranean farming systems: Effect of genotype and mowing time on forage yield and quality

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ABSTRACT

The introduction of alternative/innovative crops in the current Mediterranean cropping systems is a promising strategy to cope with climate change effects, which are threatening the food and feed security of that geographic area. Thanks to its large environmental adaptability and good nutritive value for humans (grains) and animals (biomass), teff is an excellent candidate to perform its role as alternative plant species for cereal/forage farming systems. However, the adoption of a "new" crop requires information about the adaptation to the target environment as well as details on the best management practices to apply. Very little knowledge is available regarding the performance of teff under Mediterranean climatic conditions. The aim of this study was to assess the effect of genotype and mowing time on the biomass yield (dry matter, DM) and proximate composition of teff (including the first regrowth). Grain yield potential was also evaluated. The study was carried out during two consecutive years in central Italy. Two different experiments were conducted in adjacent fields to gain information on both forage and grain potential of the crop. In both trials, six teff genotypes were used (namely T6, T7, T8, T11, T13 and T14). Plant height, forage yield and quality were assessed in different growth stages: flag leaf completely unrolled, booting, and heading. The regrowth of the first cut mowed at booting stage was also evaluated. Our study demonstrated that teff has potential as forage and grain crop under Mediterranean climatic conditions. Considering the total biomass production, teff genotypes yielded from 7 t DM ha^{-1} to 11 t DM ha^{-1}. If used as feed source, the best harvesting time is heading (GS: 57) since it allows to maximize both biomass yield and crude protein (CP) content. The teff accessions which deserve to be deeply explored as forage types were T8 and T14 (5–6 t DM ha^{-1}, with 150–160 g CP kg^{-1} DM), while T6, T7 and T13 were good grain producers (0.8–1.2 t ha^{-1}).

1. Introduction

Climate change is pushing farmers, policy makers and researchers to find new solutions for the preservation of natural resources while improving agriculture productivity and food security. The Mediterranean region is among the main vulnerable geographic areas facing such challenges [1]. New agronomic practices and eco-schemes should be assessed and implemented to transform traditional cropping systems into novel and resilient ones [2–5]. Diversifying global food and feed sources with minor (also called "orphan") crops is another strategy proposed to face food and nutrition insecurity [6]. The introduction of alternative/innovative plant species, which are climate-resilient and profitable for the farming systems, will be the core of the Common Agricultural Policy (CAP) of the European Union [7].

However, caution must be taken in identifying and introducing the appropriate innovative crop to different agricultural sites. The standard criteria including adaptation to pedoclimatic conditions, growth and yield, sustainability, and economic viability of the crop should be investigated as the major points for a suitable introduction of an innovative crop in a new growing area [8,9]. Quinoa, teff, tritordeum, camelina, nigella, chia, and sweet potato have been recently proposed as Mediterranean alternative crops able to accomplish the objectives of the European Union (EU) Green Deal [7].

Among these species, quinoa and sweet potato seem to not cope with

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EU's new Climate Law because of their high CO_2 emissions; chia is less versatile as compared to the other species and generally showed a low adaptability to new growing zones; nigella and tritordeum obtained the lowest score for the compliance of the alternative crops with EU directives and Green Deal principles; while camelina and teff proved to be the best candidates for their ability to adapt to different pedoclimatic conditions and their low requirements in agrochemical inputs [7].

Teff (*Eragrostis tef* (Zucc.) Trotter) is a C_4 annual small-grain cereal belonging to the *Poaceae* family, subfamily *Chloridoideae*. Teff is the sole species (among 350) of the *Eragrostis* genus that is cultivated for human consumption [10]. It represents the staple crop for over 50 million people in the Horn of Africa [11]. The interest for this crop is due to a wide environmental adaptability [12] and the composition of its grains, which are gluten-free and suitable for people with celiac disease [13–15]. Moreover, the nutritional value of its grains are fostering the popularity of tef as "super-food", thus raising global market of tef and its products [16]. The need for growing this crop outside its original borders has dramatically increased since 2006, when Ethiopia (that is the biggest teff-producing country) started to exert a strong monitoring action on the export of unprocessed teff grain and flour [11,17].

Teff highlighted a satisfactory ability in facing diverse challenging growing conditions: from salt and drought stress to waterlogged soils [18]. Regarding soil requirements, teff performs well in various soils, but it grows better in compacted vertisoils than andosoils, with relatively low nitrogen (N) inputs [19,20]. Even though teff withstands poorly drained soils better than other cereals [10], a large genetic diversity exists in waterlogging tolerance [21]. Teff is a fast-growing crop, relatively pest and disease resistant, able to provide a high-quality forage that can be harvested for hay or silage or used for grazing [22–25]. Due to these features and its versatility, teff can be usefully introduced into Mediterranean cereal/forage-based cropping systems, which are increasingly threatened by climate change [26]. Indeed, robust and consistent projections for the Mediterranean region indicate a general warming and drying especially during the summer season [27,28]. These predicted conditions will probably make the common summer-growing crops (*e.g.*, maize, sorghum, lucerne) less productive and sustainable in the future, thus causing an enlargement of the typical summer feed gap that already exists in the Mediterranean livestock systems [29,30]. As compared to other warm season crops (*e.g.*, maize and sorghum), teff can promote food and feed security using less resources [16,31]. As forage crop, teff can provide a first harvest 40–45 days after sowing and is able to persist for over 5 months with multiple mowings [32]. These features make this species ideal to be grown in the Mediterranean environment as: i) an emergency forage crop when other species fail to establish or survive; ii) a double cropping option immediately following wheat or barley; iii) a fodder crop providing livestock producers with high quality pasture or hay field during summer [23]. As for this latter point, previous studies showed that teff grown in the summer months provide favorable forage production with similar nutrition quality to that of cool season grasses, which generally have low yields following the spring harvest [33,34].

Additionally, teff hay inclusion in the rations of high-producing dairy cows was recently found to increase milk yield [35], thus reinforcing the opinion that this forage has potential to replace alfalfa and corn silage in the diets of lactating dairy cattle without loss of productivity [36]. Regarding monogastrics, even though McCown et al. [37] observed a discrimination against teff hay when multiple choices were offered to horses, some studies evidenced the good performance of teff as annual warm-season horse pasture forage, also lowering the glucose and insulin response of some horses [38,39].

However, adopting teff as an alternative crop in the Mediterranean region needs the understanding of its management practices [40]. Overall, detailed environmental and management data are rarely reported for teff field experiments [41] and information about the agronomic performance of this crop under Mediterranean climatic conditions is even scarcer. Kakabouki et al. [32], after studying for one season the effects of cutting frequency on biomass yield and quality of teff crop in two locations of Greece, concluded that it can be successfully integrated into Mediterranean forage systems with the aim to improve their nutritional quality. Appropriate nitrogen (N) fertilization was also investigated, and the authors found that the optimal N rate for teff crop (variety Kora) was 80–120 kg ha^{-1}. Ben-Zeev et al. [40] demonstrated the feasibility of teff production under irrigated conditions in Israel and the potential of a reduced sowing rate as a remedy for lodging. At the best of our knowledge, no studies were conducted to understand in which phenological phase teff crop should be cut to obtain the best trade-off between forage quantity and quality. Additionally, limited information on the agronomic characterization of teff genotypes is available out of Ethiopia and the United States, especially in Europe.

Therefore, our study aimed to fill this research gap by evaluating the effect of different teff accessions and mowing times on the biomass yield and quality of forage teff (including the first regrowth). Grain yield was also assessed to add precious information about its potential as alternative/innovative cereal crop under Mediterranean climatic conditions.

2. Materials and methods

2.1. Location, plant material and experimental design

The study was carried out during two consecutive years, 2016 and 2017, in the experimental farm of the University of Tuscia, Viterbo, central Italy (Lat 42°43′N, Lon 12°08′E, altitude 310 m above sea level). The growing area is characterized by a Mediterranean climate, with mean annual air temperature of about 14.5 °C and mean total annual precipitation of 755 mm. For both years, weather data were retrieved from the meteorological station located 50 m far from the experimental site and they are reported in Fig. 1. Two different experiments were conducted in adjacent fields to gain information on both forage and grain potential of teff. In both trials, six teff genotypes, hereinafter referred to as T6, T7, T8, T11, T13 and T14, were compared. Teff accessions were selected, multiplied and provided by the ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) – Casaccia Research Centre.

The experiment 1 was set-up to study the effect of mowing time and genotype on teff grass forage production and its quality. Mowing was made at the following secondary growth stages (GS), according to the extended BBCH-scale for cereals [42]: flag leaf completely unrolled (GS: 39, hereinafter referred to as FL), booting (GS: 45, hereinafter referred to as BT), and heading (GS: 57, hereinafter referred to as HD). The regrowth of the first cut (hereinafter referred to as RG) was also evaluated, mowing it at the BT stage. The cutting dates and the related phenological stages for each growing season were reported in Table 1.

A split-plot design with three replicates was used. The six genotypes were randomized in the main plots (7 m × 1.5 m), while the mowing times into three sub-plots (2 m × 1.5 m). A buffer area was left (0.5 m × 1.5 m) between two different mowing treatments.

The experiment 2 was laid out to study the effect of genotype on grain yield potential of teff. A randomized complete block design (RCBD) with three replicates was used. Dimension of each plot was 10.5 m^2 (7 m × 1.5 m). In both years and experiments the preceding crop was durum wheat.

2.2. Sowing and plot management

Soil was ploughed in early May in both years and then, clod size was reduced by using a disc harrow and rotovator until soil particles reached the proper dimensions to receive the very small teff seed. Finally, a double soil rolling (before and after sowing) was made to improve soil firmness and soil-seed contact. For both experiments, sowing was performed on June 1st and May 30th in 2016 and 2017, respectively. A plot seeder was used to distribute raw seeds in 5 rows per plot (30 cm row spacing), at 7 kg ha^{-1} seed rate. During the first ten days after sowing,

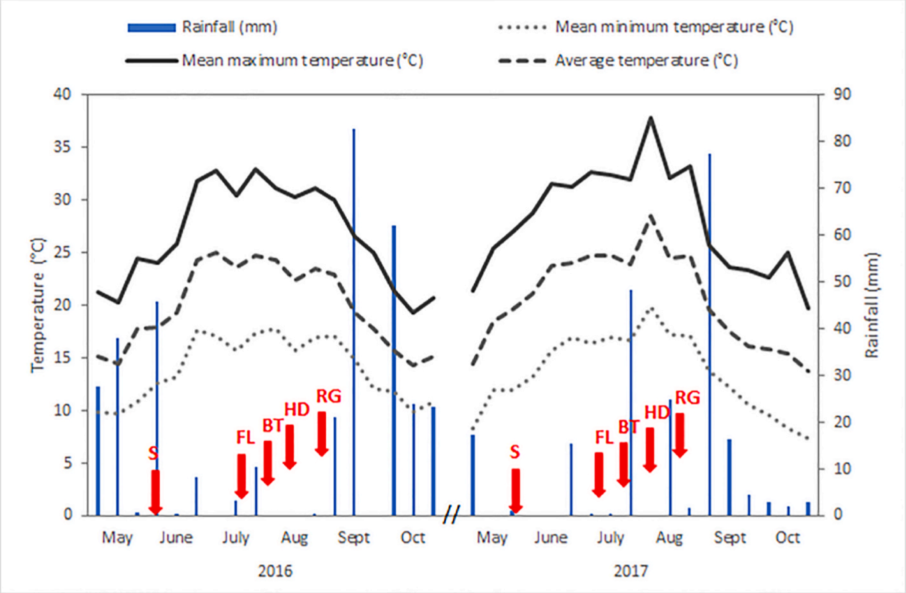

Fig. 1. Weather conditions during 2016 and 2017 seasons and time of completion (red arrows) of phenological stages of teff. S, sowing date; FL, flag leaf unrolled; BT, booting; HD, heading; RG, regrowth at booting. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Cutting dates and related phenological stages in each growing season.

2016		2017	
Cutting dates	Phenological stage	Cutting dates	Phenological stage
July 21st, 50 DAS	Flag leaf unrolled	July 11th, 42 DAS	Flag leaf unrolled
July 27th, 57 DAS	Booting	July 20th, 51 DAS	Booting
August 3rd, 64 DAS	Heading	August 2nd, 64 DAS	Heading
August 24th, 34 DAC	Booting (regrowth)	August 27th, 47 DAC	Booting (regrowth)

DAS = days after sowing; DAC = days after the first cutting.

both fields were irrigated frequently with low irrigation volumes to allow a uniform seedling emergence and good crop establishment. Subsequently, plots were watered when needed, replacing the total crop evapotranspiration (ETc) net of precipitations. Sprinkler irrigation was used to provide a seasonal amount of water of about 261 mm and 277 mm in 2016 and 2017, respectively. A total amount of 100 kg N ha^{-1} was distributed during crop cycle. Nitrogen was broadcasted in the form of ammonium nitrate (26–0–0), 50 % at tillering stage and 50 % at the beginning of stem elongation. Broadleaf herbicide was applied once a year, about four weeks after seedling emergence (July 6th, 2016, and July 4th, 2017).

2.3. Data collection and measurements – experiment 1

2.3.1. Plant height

Plant height was measured by a ruler from the ground level to the top of the plants before each mowing. Three random measures were taken along each plot.

2.3.2. Dry biomass production

To assess the effect of treatments on forage production, above-ground biomass was collected in each subplot excluding the external rows. A 10-cm stubble was left to ensure a prompt and vigorous regrowth. The samples were oven-dried at 65 °C until constant weight to calculate the dry biomass yield and the dry matter (DM) content at each mowing time.

2.3.3. Proximate analysis

For the first year only (2016), a chemical analysis of the forage was conducted in laboratory. Plant material was dried at 65 °C until constant weight in a forced air oven and then grinded through a Retsch mill (Haan, Germany) equipped with a 1 mm screen. Pre-grinding plant moisture was annotated. After thorough mixing, the ground samples were stored in sealed polyethylene bottles until analysis. A total of 72 ground dry samples were analyzed. The DM of ground samples was determined by gravimetry (AOAC method n. 934.01) [43]. Gravimetric determination of the ash content (ASH) was obtained after sample incineration by a muffle furnace (AOAC method n. 942.05) [43]. Organic matter was obtained by difference of DM and ASH. Crude protein (CP, g kg^{-1} DM) was assessed through the Kjeldahl method (AOAC method n. 978.04) [43], and the ethereal extract (EE) was determined by Soxhlet extraction (AOAC method n. 920.39) [43]. The neutral detergent fiber (NDF$_{OM}$, g kg^{-1} DM) was determined by boiling a 0.5 g sample for 1 h in 100 mL of neutral detergent plus 0.05 mL of heat-stable -amylase (ANKOM Technology, NY, USA) and 0.5 g of analytical grade sodium sulfite (Sigma-Aldrich, Darmstadt, Germany) (Van Soest et al., 1991). The non-fibrous carbohydrates (NFC, g kg^{-1} DM) were estimated according to the following equation:

$$NFC = 1000 - (CP + EE + NDF + ASH)$$

The gross energy (GE) content (Mcal kg^{-1} DM) of the teff samples was measured as described in Danieli et al. (2019).

2.4. Data collection and measurements – experiment 2

2.4.1. Assessment of grain yield

The plots managed for the determination of grain yield potential were harvested at physiological maturity on August 26th and August 24th in 2016 and 2017, respectively. Panicles were cut in a random 1 square meter area per plot, excluding the external rows. Biomass was left drying in metal boxes within a glasshouse to reach the appropriate moisture content and to easily separate the husk from the seed by manual threshing. Grains were oven-dried at 65 °C until constant weight to calculate humidity and determine grain yield (expressed in t ha^{-1}) at standard 13 % grain moisture.

2.5. Statistical analysis

Plant height, dry matter content, and biomass yield were subjected to the three-way analysis of variance (ANOVA); data from chemical analysis and grain yield were subjected to the two-way ANOVA.

The analysis was performed by using the 'Anova (.)' function in the 'car' package of R [44]. Fisher's least significant difference (LSD) was performed to determine significant difference between means at a significance level of $P \leq 0.05$. Data were reported as the mean ± standard error (SE).

3. Results

The ANOVA output for agronomic and quality traits is presented in Table 2. Treatments (Year, Y; Genotype, G; Mowing time, M) differently affected the measured traits. Third order interaction was never significant. Second order interactions were significant for grain yield (Y × G), plant height (Y × M), biomass yield (Y × M) and dry matter content (Y × M).

3.1. Experiment 1

3.1.1. Plant height

On average, the highest accessions were T13 and T14 (both around 84 cm), even though they did not differ statistically from T7 and T11, which were 80 cm tall (Fig. 2A). T8 was 78 cm in height, while T6 was the shortest genotype (75 cm). Plant height was significantly higher in 2017 than 2016 regardless the mowing time (Fig. 2B). The highest difference was detected in HD stage (127 cm *vs.* 75 cm), while the lowest during the regrowth (70 cm *vs.* 44 cm). Plant height significantly increased going ahead with growing stages in both years. Specifically, teff moved from 56 cm in FL stage to 70 cm in BT stage and up to 75 cm in HD stage during 2016 growing season. In 2017, the growth was slower between FL and BT stage (from 97 cm to 104 cm), but faster between BT and HD stage (from 104 cm to 127 cm). Regarding plant height at booting stage of regrowth (RG), it never reached the height of the original BT stage: 70 cm *vs.* 44 cm in 2016 and 104 cm *vs.* 70 cm in 2017.

3.1.2. Dry biomass production

Averaged over years and mowing dates, biomass yield ranged from 4.8 t DM ha^{-1} of T6 to 6.1 t DM ha^{-1} of T13 (Fig. 3A). Genotypes T11, T13 and T14 were the best performers for this trait (all above 5.7 t DM ha^{-1}), even though they did not differ statistically from T8 and T7 (5.5 and 5.4 t DM ha^{-1}, respectively). As in the plant height, biomass yield was significantly higher in 2017 than 2016 in each mowing time (Fig. 3B). The highest difference was detected in HD stage (10 t DM ha^{-1} *vs.* 5 t DM ha^{-1}), while the lowest during FL stage (4 t DM ha^{-1} *vs.* 2.5 t DM ha^{-1}). As expected, biomass yield significantly increased as growth development progressed. Specifically, yield moved from 2.5 t DM ha^{-1} in FL stage to 4 t DM ha^{-1} in BT stage and up to 5 t DM ha^{-1} in HD stage during 2016 growing season. In 2017, the biomass production was similar to 2016 between FL and BT stage (from 4 t DM ha^{-1} to 6.7 t DM ha^{-1}) but higher between BT and HD stage (from 6.7 t DM ha^{-1} to 10 t DM ha^{-1}). Unlike plant height, biomass yield at booting stage of regrowth (RG) showed results that were not significantly different from those of the original BT stage: 4 t DM ha^{-1} *vs.* 4.4 t DM ha^{-1} in 2016 and 6.7 t DM ha^{-1} *vs.* 7.3 t DM ha^{-1} in 2017.

Regarding the biomass' dry matter content, it increased over time moving from 21 % of FL stage to 34 % of regrowth at booting (Fig. 4). For each mowing time, dry matter percentage was similar in the two experimental years except for HD stage. Particularly, teff grass harvested at heading showed a dry matter content significantly higher in 2016 (32 %) than 2017 (28 %).

3.1.3. Teff grass proximate composition

Aimed at looking for the best teff genotype to be addressed to animal feeding, the nutritive values of teff plants harvested at different phenological stages were submitted to proximate analysis. As far as the organic matter (OM) content, a rather complex genotype × mowing time interaction was found (Fig. 5). Overall, the earlier vegetative stage was characterized by high OM content, with some exceptions. However, comparing the different genotypes, the T14 one showed a high OM content during all the growing season.

Looking at the crude protein (CP) contents of teff forage (Fig. 6), the genotype T8 (16 % CP) and T14 (15 % CP) performed better than the remaining ones. The forage harvested at the HD stage was richer in CP (15.5 %) than the FL stage and booting stage in regrown plants (both 14 %), but not in comparison with the same stage at first mowing (14.8 %). No genotype × mowing time interaction was found.

The lowest neutral detergent fibre content was found in T7 and T11 genotypes (both containing 62 % aNDF), while the other ones were all around 66–67 % aNDF (Fig. 7A). No significant differences were observed in plants mowed at the different phenological stages, nor was the genotype × mowing time statistically supported.

Consequently, the non-fiber carbohydrates (NFC) content follows a quasi-opposite pattern (Fig. 7B) with the T7 and T11 genotype showing the highest NFC content (13.4 % and 13.9 %, respectively). On the contrary, for the genotype T8 it was recorded the lowest NFC content (less than 5 %).

The gross energy content (Fig. 8) did not depend by the mowing time or the genotype-to-mowing time interaction. Overall, it was quite

Table 2
Significance levels of year (Y), genotype (G), and mowing time (M) effects and their interactions on different agronomic and quality traits.

	Plant height	Biomass yield	Grain yield	DM	CP	aNDF	NFC	OM	GE
Year (Y)	***	***	n.s.	n.s.	–	–	–	–	–
Genotype(G)	***	*	**	n.s.	*	**	***	**	**
Mowing time (M)	***	***	–	***	*	n.s.	n.s.	**	n.s.
Two-way interactions									
Y×G	n.s.	n.s.	*	n.s.	–	-.	–	–	–
Y×M	***	***	–	*	–	–	–	–	–
G×M	n.s.	n.s.	–	n.s.	n.s.	n.s.	n.s.	*	n.s.

ANOVA signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1; n.s.: not significant. DM: dry matter content; CP: crude protein; aNDF: neutral detergent fiber assayed with heat-stable amylase,; NFC: non-fibrous carbohydrates; OM: organic matter; GE: gross energy.

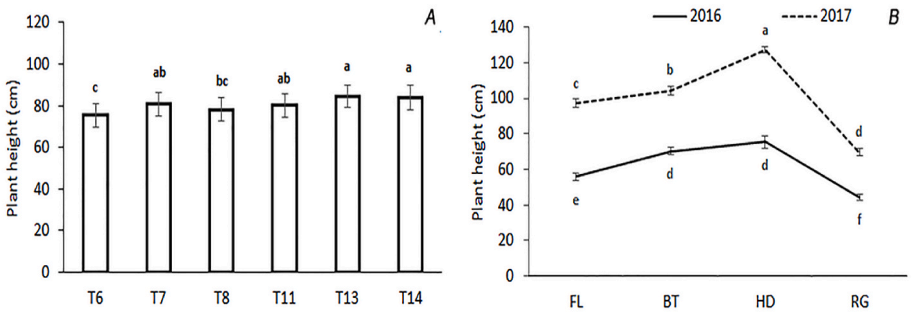

Fig. 2. Plant height as affected by (A) teff genotype (T6-T14) and (B) year × mowing time interaction. The vertical bars represent the standard error of the mean. Letters correspond to the ranking of the Fisher's protected test at $p < 0.05$. FL, flag leaf unrolled; BT, booting; HD, heading; RG, regrowth at booting.

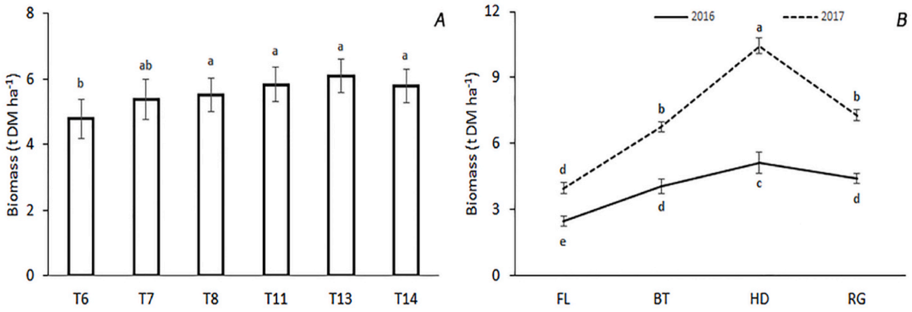

Fig. 3. Biomass yield of teff as affected by (A) genotype (T6-T14) and (B) year × mowing time interaction. The vertical bars represent the standard error of the mean. Letters correspond to the ranking of the Fisher's protected test at $p < 0.05$. FL, flag leaf unrolled; BT, booting; HD, heading; RG, regrowth at booting.

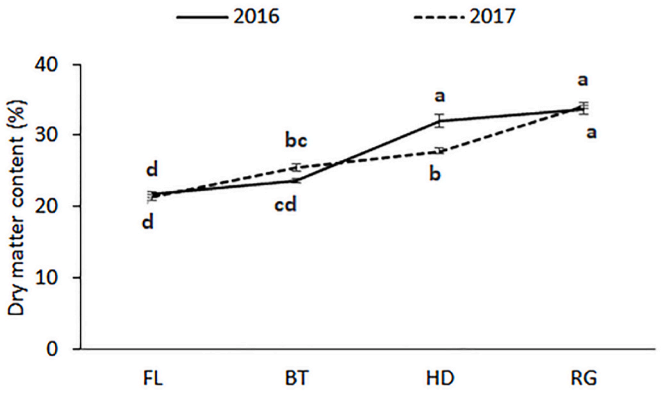

Fig. 4. Dry matter content of teff grass as affected by year × mowing time interaction. The vertical bars represent the standard error of the mean. Letters correspond to the ranking of the Fisher's protected test at $p < 0.05$. FL, flag leaf unrolled; BT, booting; HD, heading; RG, regrowth at booting.

levelled off among the different genotypes with the exception of T11 that performed better (4.35 Mcal kg^{-1} DM).

3.2. *Experiment 2*

3.2.1. *Grain yield*

Grain yield was significantly affected by year × genotype interaction ($P = 0.019$) and resulted much more variable in 2016 than 2017. Genotypes T6 and T13 were the best producers in 2016 while T7 in 2017, all outreaching 1 t ha^{-1} (Fig. 9). On the contrary, T8 constantly was the worst performer, never reaching 800 kg ha^{-1}. However, T6 only showed a significant yield variability between years (+40 % in 2016 than 2017).

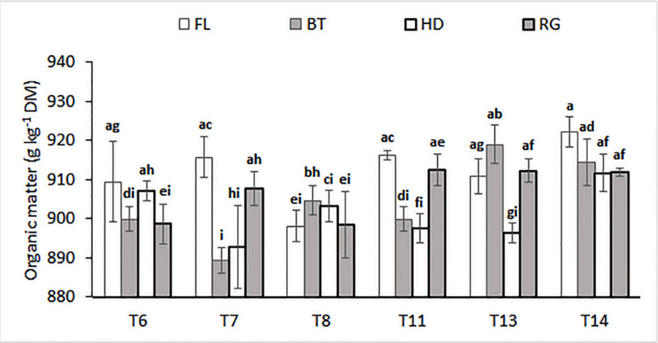

Fig. 5. Organic matter of teff grass as affected by genotype × mowing time interaction. The vertical bars represent the standard error of the mean. Letters correspond to the ranking of the Fisher's protected test at $P < 0.05$. T6-T14, teff genotypes. FL, flag leaf unrolled; BT, booting; HD, heading; RG, regrowth at booting.

4. Discussion

Results from our study showed that teff plant height, biomass yield and its dry matter content were affected by the year × mowing time interaction. Specifically, plant height and biomass yield were found to be significantly higher in 2017 than 2016 during all growing season, including the aftermath. This difference can be attributed to the heavy rainfalls (46 mm) occurred during the first decade after sowing in 2016 (Fig. 1). Precipitations, falling on a bare and compacted soil, can negatively affect the growth of plants owing to nutrient leaching [45] and reduction of oxygen availability around seeds and in the rootzone [46]. These temporary environmental conditions resulted in a slow and weak establishment of the teff seedlings as well as in a low crop competitiveness against weeds before the herbicide treatment. Exposure of the young teff plants to such abiotic and biotic stresses limited their

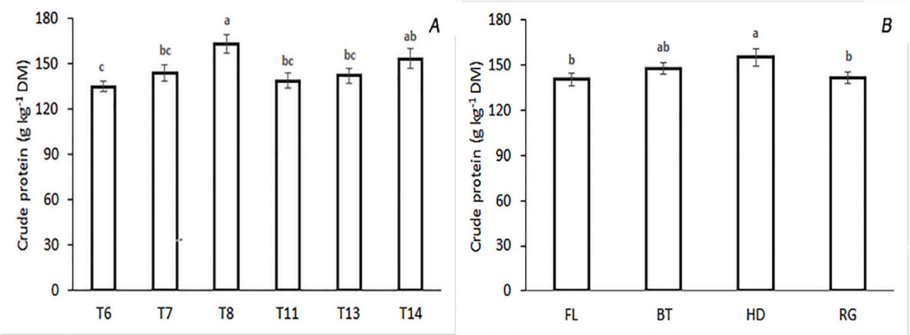

Fig. 6. Crude protein content of teff grass as affected by (A) genotype (T6-T14) and (B) mowing time. The vertical bars represent the standard error of the mean. Letters correspond to the ranking of the Fisher's protected test at $P < 0.05$. FL, flag leaf unrolled; BT, booting; HD, heading; RG, regrowth at booting.

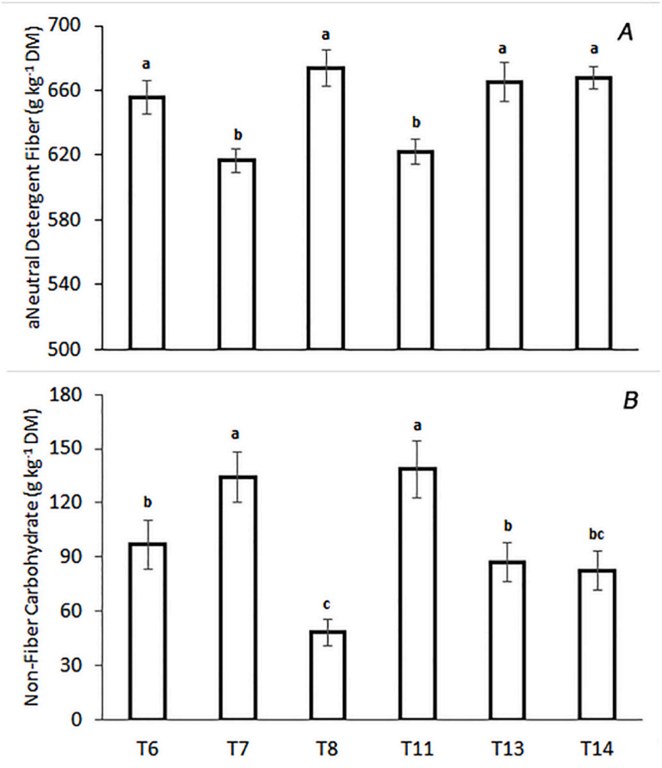

Fig. 7. Effect of teff genotype (T6-T14) on A) aNeutral Detergent Fiber and B) Non-Fiber Carbohydrate content. The vertical bars represent the standard error of the mean. Letters correspond to the ranking of the Fisher's protected test at $P < 0.05$.

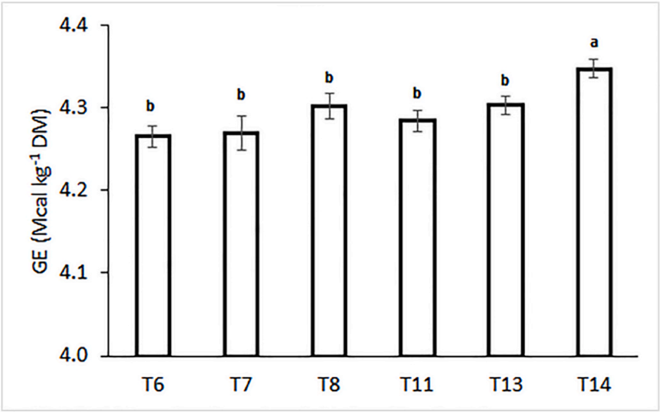

Fig. 8. Gross Energy (GE) of teff grass as affected by genotype (T6-T14) . The vertical bars represent the standard error of the mean. Letters correspond to the ranking of the Fisher's protected test at $P < 0.05$.

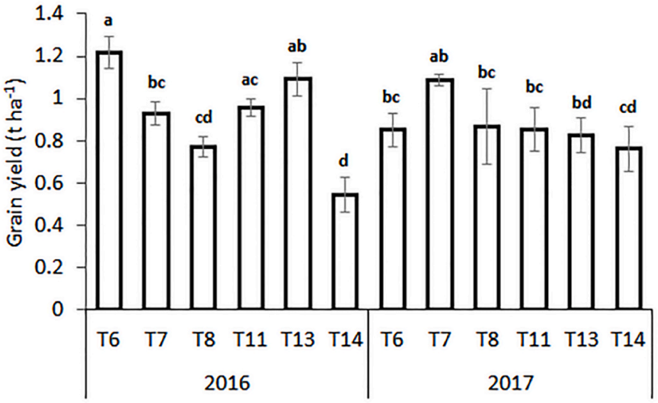

Fig. 9. Grain yield of teff as affected by genotype × year interaction. The vertical bars represent the standard error of the mean. Letters correspond to the ranking of the Fisher's protected test at $P < 0.05$. T6-T14, teff genotypes.

future growth as compared to that of 2017. However, it is worth noting that the response of teff to excess of moisture is dependent on genotype. For example, Cannarozzi et al. [21] found that waterlogged plants of cultivar "Tsedey" grew higher than normally watered plants, while "Quncho" and "Alba" varieties significantly suffered the excess of moisture. As expected, plant height and biomass yield increased moving from FL stage to HD stage while the aftermath reached values similar to those of the first growth at the same phenological stage (BT). Our results are within the ample range of reference values, which show teff height varying from about 40 cm to almost 140 cm, depending on many factors such as cutting frequency, plant density, nitrogen fertilization and genotype [19,32,47–50]. Shortening of plant is one of the main breeding target for teff, since it allows to reduce lodging [51]. In a study aiming at exploring factors involved in teff lodging tolerance, Blösch et al. [52] observed that the average height of the high lodging genotypes was 1.17 m, compared to 0.93 m of the low lodging genotypes. Accessions tested in our study reached the highest threshold (1.27 m) only during 2017 heading stage.

As for biomass yield, teff genotypes yielded 5 to 6 t DM ha^{-1} averaged over years and mowing times. However, considering the total biomass production given by the sum of the first cut and its regrowth, we obtained about 7 t DM ha^{-1} in 2016 and 11 t DM ha^{-1} in 2017. Those findings are comparable or even higher than values obtained by Kakabouki et al. [32] in two locations of Greece mowing teff every 10 days

(6–7 t DM ha^{-1}) as well as those reported for the United States [23,53,54]. It has to be noted that, for the objectives of this study, we stopped the experiment-1 with the harvest of the first aftermath (late August), but teff grass, in our environment, generally continues growing until mid-October, thus providing at least one additional harvest. Moreover, although we started the experiment in June, teff can be sown around mid-April under Mediterranean climatic conditions, with a marked extension of its growing season (up to 5–6 months) and, thus, with a higher yield potential.

Trends of dry matter (DM) content were very close between years except for HD stage, in which DM percentage of 2017 was significantly lower than that of 2016. This was probably due to the heavy precipitations (48 mm) occurred during the week preceding the 2017 harvest. DM percentage increased gradually in both years and reached 34 % at the booting stage of the aftermath. Wagali et al. [25], in a study aiming to evaluate the ability to preserve tef as silage, found DM content ranging from 28 % to 37 % depending on genotype and irrigation level, but mostly around 30 %. Considering that they harvested teff at grain-filling stage (10–14 days after heading), our results are perfectly consistent with their findings. While the possibility of using teff as silage crop was little explored in literature, it represents a good opportunity to enhance flexibility of that grass species especially when hay making is risky or not possible for adverse climatic conditions.

A timely harvest in the proper growth stage of the crop is one of the principal factors influencing forage quality and digestibility. With the progress of plant genetics, however, genotype too is playing a fundamental role in determining the nutritive value of a given forage crop. There are several teff varieties on the market today; some perform better as grain cultivars, others as forage ones. Grain types tend to mature earlier than forage types, resulting in lower DM yields and reduced nutritive value [23]. Therefore, the classification of a given accession is the first step not only to decide and apply the proper agronomic practices but also to choose the cropping system to which it adapts better.

In this experiment, grass from T8 genotype, and secondarily from T14, can be classified as good forage as it showed high values for biomass production, and also had the highest crude protein contents (140–160 g kg^{-1} DM) that fall in the upper part of the range (111.0–152.5 g kg^{-1} DM) reported by others for several teff varieties [55,56]. The aNDF content of teff grass in this work was also in line with the data published earlier that described a wide NDF range for teff grass spanning from 547.5 to 709.0 g kg^{-1} DM [39,55]. The NFC content of forages represents an estimate of the highly digestible carbohydrates including total starch and sugars, thus indicating the valuable quota of carbohydrates both for monogastric and ruminant livestock. From this standpoint, the genotype T7 worked well showing also promising yields. In the literature on teff as forage, rarely the NFC content is reported. However, from the few available reports resulted that the NFC content of teff grass recorded in this work was within the range from 70 [57] up to 168 g kg^{-1} DM [58], with the exception of the T8 genotype that was the lowest. To the best of our knowledge, the gross energy (GE) content of teff forage has very rarely reported earlier. It is worth noting that on the base of the data reported here, the GE content of grass from six different teff genotypes was about 4.3 Mcal kg^{-1} DM, that is about twice the digestible energy (DE) content reported by Ref. [59] and by Ref. [60] (2.2 and 2.1 Mcal kg^{-1} DM, respectively) for horses, about 15 % higher the average GE-to-DE ratio obtained for ruminants resorting to the FEEDEPEDIA database [61].

As for harvest timing, heading definitely represented the best phenological stage for both forage quantity and quality in this study. The cut at this stage resulted in about 0.8 t CP ha^{-1}, similar to that obtained in Greece, mowing teff every 20 days [32]. Our finding is not consistent with guidelines by Miller et al. [23] that suggest harvesting teff prior to seed head appearance (pre-boot to early-boot stage). Conversely, in a study aiming at evaluating nutrient composition, voluntary intake, and digestibility of teff hay cut at 3 different stages of maturity (boot, early and late heading), Staniar et al. [24] suggested that the early-heading maturity of teff hay offers the best balance between providing a palatable and digestible nutrient source for horses and a productive forage crop. Other authors reported the harvest timing as days after sowing (DAS) without specifying the phenological stage. More in detail, Kakabouki et al. [32] started to cut at 41 DAS in two field trials in Greece, while Saylor et al. [62] tested five harvest dates (40, 45, 50, 55 and 60 DAS) during a pot experiment under climate-controlled conditions in Kansas and concluded that the first cutting of teff should be harvested at 45 to 50 DAS to optimize forage yield, nutritive value, and digestibility. In our work, the CP content of teff grass from regrowth (BT stage) was not statistically different from the content of grass at the 1st cut for the same phenological stage. In another study [39], it has been shown that the NDF content of two teff genotypes (namely 6010 and Summer Lovegrass; 529 and 611 g kg^{-1} DM, respectively) and their NSC contents (71 and 101 g kg^{-1} DM, respectively), did not show any clear association with the cutting order also in connection with the phenological stage at mowing, as it was observed in the present study.

Regarding grain yield, a significant genotype × year interaction was found in our study. Interannual yield variability of different genotypes is a common feature of Mediterranean cereal crops [63]. As for teff, we are aware of just three field studies reporting grain yield in a Mediterranean environment, but no one showed the year effect [20]; [null]; [40]. However, Ben-Zeev et al. [40] found that genotype did not significantly affect grain yield, even though it varied from about 130 g m^{-2} to 181 g m^{-2} in 2018 and 81 g m^{-2} to 100 g m^{-2} in 2019. In our study, we obtained a grain yield ranging from 54 g m^{-2} to 122 g m^{-2} in 2016 and 76 g m^{-2} to 109 g m^{-2} in 2017. These values are consistent with those reported in other field studies, which show that grain yield of teff can grossly vary from 35 to 344 g m^{-2} [19,50,53,64–67], but more frequently around 80–130 g m^{-2} (0.8–1.3 t ha^{-1}).

5. Conclusions

Our study demonstrated that teff has great potential as forage and grain crop under Mediterranean climatic conditions. If used as feed source, the best harvesting time is heading (GS: 57) since this phenological stage allows to maximize both biomass yield and protein content.

The teff accessions which deserve to be deeply explored as forage types were T8 and T14, while T6, T7 and T13 were good grain producers.

Depending on the sowing date, T7, T8 and T14 can be considered also as double purpose genotypes, using the first and, possibly, the second cut for hay and the last harvest for grains.

Additional studies are needed to disentangle the complex relationships involving forage attributes, genotype, phenology, management practices and environment. In this view, experiments focusing on thermal sum of different genotypes under diverse climatic conditions will be of tremendous benefit to the optimization of agronomic practices for forage and grain teff. Experiments on water shortage tolerance will be important as well.

CRediT authorship contribution statement

Roberto Ruggeri: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Francesco Rossini:** Writing – review & editing, Visualization, Supervision, Resources, Investigation, Conceptualization. **Bruno Ronchi:** Writing – review & editing, Resources. **Riccardo Primi:** Writing – review & editing, Methodology. **Catia Stamigna:** Writing – review & editing, Resources. **Pier Paolo Danieli:** Writing – review & editing, Writing – original draft, Resources, Methodology, Formal analysis, 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.

Data availability

Data will be made available on request.

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