WATER USE EFFICIENCY OF TEFF (*ERAGROSTIS TEF* (ZUCC.) TROTTER) BREEDING LINES UNDER DIFFERENT IRRIGATION TREATMENTS

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Abstract

An ancient cereal crop indigenous to the Horn of Africa, teff (*Eragrostis tef* (ZUCC.) TROTTER) is becoming more and more popular worldwide because of its high nutritional content and capacity to adapt to a variety of ecological circumstances. This study aimed to evaluate the agronomic performance of three genotypes of *E. tef* and the species *E. curvula* under controlled pot conditions during two growing seasons (2023 and 2024), with and without additional watering.

Using standardized pot trials with humus-rich sandy soil and compost amendment, the experiment was carried out at the University of Nyíregyháza's demonstration garden. Four replicates per treatment were used to measure morphological and yield-related parameters, such as biomass, grain yield, thousand-kernel weight, and stem length.

The species' wide ecological tolerance was confirmed by the results, which showed that all genotypes could generate quantifiable yields in non-irrigated conditions. Irrigation generally improved biomass and grain production, although responses varied by genotype. Genotype PI-494237 yielded the most grain in dry conditions and did not benefit from irrigation, indicating strong drought adaptation. PI-442115 and *E. curvula*, on the other hand, did well in both treatments. PI-494455, on the other hand, did better with irrigation, which means it can handle moderate drought.

These results show that teff can grow well in Central Europe and that it is a good food and forage crop. The observed genetic variability offers opportunities for targeted selection and cultivation strategies in the context of climate-resilient agriculture.

Keywords: drought tolerance, genotype, yield, biomass, irrigation, pot experiment, gluten-free cereal

Introduction

Cereal crops are essential to the production of food worldwide and are therefore very important to Hungarian agriculture (Pepo & Sárvári, 2019). Alongside ordinary cereals, so-called alternative or ancient grains have received more attention in recent decades. Sometimes these species exhibit increased adaptability to extreme climatic conditions and may provide nutritional and physiological advantages (Comino et al., 2013; Chávez et al., 2018; Baillière et al., 2022). Ethiopia has been using teff (*Eragrostis tef* (Zucc.) Trotter) as a staple crop for thousands of years. The most common way to eat it is as injera, a sour flatbread that resembles pancakes (Ashoka, 2020).

Teff is one of the most important cereal crops in Ethiopia and Eritrea, where it is cultivated on over 3 million hectares, accounting for approximately 30% of the total area dedicated to cereal production. Teff cultivation has spread beyond of its traditional areas due to its increasing popularity, and it is currently found in nations like India and the United States. Due to its high nutritional value and lack of gluten, teff is a good choice for people with celiac disease (Spaenij-Dekking et al., 2005). It is also rich in essential minerals, such as iron, zinc, and calcium, often in higher concentrations than wheat, rice, or maize (Spaenij-Dekking et al., 2005). The grain contains 9–13% protein, including all essential amino acids, and is a notable source of calcium, iron, zinc, and magnesium (Abebe et al., 2007; Baye et al., 2014). Certain teff varieties exhibit significantly higher iron bioavailability compared to wheat, rice, or maize (Ligaba-Osena et al., 2021). This characteristic is of particular relevance in developing countries, where iron deficiency remains a major public health concern (Goedecke et al., 2018; Webb et al., 2018).

According to agrotechnical research, teff has a wide range of ecological adaptations. Ethiopia produces 1.5 to 1.7 tons per hectare on average (Ashoka, 2020). Several studies have shown that row planting and transplanting can result in higher yields, even if broadcasting is the most used sowing technique (Ashoka, 2020). Teff reacts favorably to fertilization with nitrogen and phosphate; however, integrated nutrient management systems yield the best results in terms of nutrient management (Habte & Boke, 2017).

Teff is an extremely adaptable crop. In addition to producing flour, the straw has significance as a building material and animal fodder. In animal husbandry, it is particularly beneficial for horses, as its low non-structural carbohydrate content makes it suitable for feeding animals with metabolic disorders (Staniar, 2010).

Teff has been used in international trade in recent years, mostly as a "superfood." Due to the growing need of gluten-free diets, sports nutrition trends, and health-consciousness, it has made an appearance in markets in the US, India, and Europe (Lee, 2018; Barretto, 2021). Although more production technology improvement is still needed, the initial cultivation trials in Hungary have produced encouraging results (Csabai & Szabó, 2023). Further study into teff and the modification of its growth techniques are warranted due to the increasing demand for gluten-free food products, which could present both consumers and producers with exciting prospects.

Materials and methods

The experiments were conducted in May 2023 and 2024 in the demonstration garden of the Institute of Engineering and Agricultural Sciences at the University of Nyíregyháza, which regularly provides research plots for agricultural students. The trials were set up in 40 cm diameter vegetation pots with a surface area of 0.125 m², with four replications, each containing two plants per pot.

The soil used was humus-rich sand, amended in the spring of 2022 with 50 t/ha of well-matured compost. According to soil analysis, the pH was approximately 7.2, the humus content was 0.5%, and the levels of phosphorus and potassium were found to be in the low to moderate range (Table 1).

Table 1. Soil properties of the vegetation pots

	Years		
Parameters	2021-2022	2022-2023	2023-2024
Sampling depth (cm)	0-30	0-30	0-30
pH (KCl)	7.08	7.2	7.22
Arany-type plasticity index (KA number)	28	31	34
Water-soluble total salts (m/m%)	0.02	<0.02	<0.02
Organic carbon – Humus content (m/m%)	1.03	0.299	0.5
AL-extractable phosphorus (P_2O_5) (mg/kg)	183	72.7	49.5
AL-extractable potassium (K_2O) (mg/kg)	242	69.8	61.7
KCl-extractable nitrate (NO_3^-) (mg/kg)	3.92	1.81	1.8

Source: Soil and Plant Testing Laboratory, Hungarian Horticultural Propagation Material Nonprofit Ltd. (Újfehértó)

In May 2023 and 2024, the experiment was carried out in the Institute of Engineering and Agricultural Sciences' demonstration garden at the University of Nyíregyháza. Trial plots for student-led agricultural research are frequently available in the research region. Four replicates of two plants each were cultivated in vegetation pots measuring 40 cm in diameter and having a surface area of 0.125 m². Professor John Cushman of the University of Nevada, Reno, supplied the teff genotypes used in this study.

The following four genotypes were studied:

1. *Eragrostis tef* PI-442115 (semi-dwarf, drought-tolerant, Rapid'),
2. *Eragrostis tef* PI-494237 (drought-tolerant, genome-sequenced, white-seeded),
3. *Eragrostis tef* PI-494455 (drought-tolerant, white-seeded),
4. *Eragrostis curvula* (drought-tolerant).

Sowing was performed at a depth of 0.5 cm, with 0.44 g of seeds (approximately 1,467 viable seeds) per pot, on May 8, 2023, and May 6, 2024, respectively. During the growing seasons of 2023 and 2024, the amounts of natural precipitation were 299 mm and 320 mm, respectively. To supplement this, a total of 96 mm of irrigation was applied (twice a week, 0.5 L per pot, 24 occasions), resulting in a total water input of 395 mm.

Harvesting was carried out at a stubble height of 10 cm on 13 November 2023 and 9 September 2024, respectively. Fresh biomass was weighed immediately after harvest, and then the samples were dried at 20 °C. Seeds were cleaned manually through a process of threshing, sieving, and air-blowing to achieve nearly 100% purity.

The following agronomic parameters were assessed:

- fresh and dry biomass weight,
- total grain yield,
- straw mass,
- thousand-kernel weight (TKW),
- plant height and stem length.

TKW was determined by weighing four subsamples of 500 seeds each. Stem length was measured from three bunches per replicate, with 10 randomly selected stems per bunch.

Throughout both growing seasons (2023 and 2024), no pests or diseases were observed, so no plant protection measures were required. Due to the crop's rapid early development, no weed control interventions were necessary.

Results

Within 10–12 days of seeding, all four genotypes showed effective emergence, with consistent shoot appearance across treatments. The more frequent irrigation schedule in 2024 probably contributed to the faster and denser germination that was seen.
Measurements of biomass showed significant annual fluctuation (Tables 2–3). Compared to 2023, aboveground biomass was significantly higher in 2024 for all genotypes. Higher residual moisture and earlier harvest timing are partially to blame for this, although irrigation and genotype-specific reactions also had a role. Interestingly, under irrigation, PI-494237 showed a decrease in biomass, indicating a potential vulnerability to overwatering. On the other hand, under irrigated conditions, *E. curvula* showed the strongest beneficial reaction, with biomass increasing by more than seven times.

These results imply that even though teff can withstand drought, harvest timing and water availability still affect biomass production, and genotype-specific patterns need more research.

Table 2. Aboveground biomass yield of teff genotypes under irrigated and control conditions in 2023 (measured on 13 November 2023)

Genotype	Value
1. *E.tef* PI-442115 semi dwarf (Rapid) drought-tolerant	53 g
2. *E.tef* PI-494237 drought-tolerant genome sequenced white seeds	61 g
3. *E.tef.* PI-494455 drought-tolerant (white)	45 g
4. *Eragrostis curvula* (drought-tolerant)	21 g

Table 3. Aboveground biomass of four *Eragrostis* genotypes under control and irrigated conditions (measured on 9 September 2024)

Genotype	Control	Irrigated
1. *E.tef* PI-442115 semi dwarf (Rapid) drought-tolerant	159 g	184 g
2. *E.tef* PI-494237 drought-tolerant genome sequenced white seeds	202 g	123 g
3. *E.tef.* PI-494455 drought-tolerant (white)	142 g	144 g
4. *Eragrostis curvula* (drought-tolerant)	131 g	149 g

Clear differences were observed in grain yield between the two experimental years under control conditions, as well as between the control and irrigated treatments in 2024 (Tables 4–5). This is also supported by the Independent-Samples T-test (Makszim, 2019). Despite a measured reduction in soil nutrient availability (Table 4), three of the four genotypes, PI-442115, PI-494237, and *E. curvula*, produced higher yields in 2024 than in 2023 under control conditions, suggesting good resilience to moderate nutrient depletion.
In contrast, genotype PI-494455 showed a reduction in yield under control conditions in 2024 compared to the previous year. However, it responded strongly to irrigation, reaching a yield of 6.5129 g, which indicates greater dependency on external water input.
These results support the presence of genotype-specific adaptability patterns in *Eragrostis* species. While PI-494237 and *E. curvula* appear more robust under limited-resource conditions, PI-494455 may be better suited for intensive or irrigated cultivation.

Table 4. Total grain yield of four *Eragrostis* genotypes under control conditions in 2023 (measured on 20 February 2024)

Genotype	Value
1. *E.tef* PI-442115 semi dwarf (Rapid) drought-tolerant	3.7403 g
2. *E.tef* PI-494237 drought-tolerant genome sequenced white seeds	1.7719 g
3. *E.tef.* PI-494455 drought-tolerant (white)	4.1691 g
4. *Eragrostis curvula* (drought-tolerant)	1.6202 g

Table 5. Total grain yield of four *Eragrostis* genotypes under control and irrigated conditions in 2024 (measured on 31 October 2024)

Genotype	Control	Irrigated
1. *E.tef* PI-442115 semi dwarf (Rapid) drought-tolerant	4.1070 g	9.4195 g
2. *E.tef* PI-494237 drought-tolerant genome sequenced white seeds	9.2745 g	6.2849 g
3. *E.tef.* PI-494455 drought-tolerant (white)	2.0029 g	6.5129 g
4. *Eragrostis curvula* (drought-tolerant)	5.1804 g	8.8909 g

Higher thousand-kernel weight (TKW) values were recorded in the first year of the study across all genotypes. This trend may have been influenced by the reduced availability of plant-available nutrients in the second year, as indicated by soil analysis results (see Table 4). A diminished nutrient supply may have limited grain filling, thereby affecting kernel weight.
Only *E. tef* PI-494455 (Genotype 3) responded favorably to irrigation in 2024, as evidenced by an increase in TKW from 0.3005 g to 0.3175 g. All other genotypes, however, either exhibited no change or had minor declines.
For teff and related species, the recorded values were consistent with previously published data, indicating that the experimental settings were within biologically relevant ranges (Tables 6–7).

Table 6. Thousand-kernel weight (TKW) of four *Eragrostis* genotypes in 2023 (measured on 26 February 2024)

Genotype	Value
1. *E.tef* PI-442115 semi dwarf (Rapid) drought-tolerant	0.3677 g
2. *E.tef* PI-494237 drought-tolerant genome sequenced white seeds	0.3177 g
3. *E.tef.* PI-494455 drought-tolerant (white)	0.3219 g
4.4. *Eragrostis curvula* (drought-tolerant)	0.2755 g

Table 7. Thousand-kernel weight (TKW) of four Eragrostis genotypes under control and irrigated conditions in 2024 (measured on 4 November 2024)

Genotype	Control	Irrigated
1. *E.tef* PI-442115 semi dwarf (Rapid) drought-tolerant	0.2961 g	0.2766 g
2. *E.tef* PI-494237 drought-tolerant genome sequenced white seeds	0.3015 g	0.2871 g
3. *E.tef.* PI-494455 drought-tolerant (white)	0.3005 g	0.3175 g
4. *Eragrostis curvula* (drought-tolerant)	0.2545 g	0.2459 g

In the second year of the experiment, a greater average stem length was noted. This tendency was probably influenced by agronomic variations between the two growth seasons. Compared to 2023, there was a modest increase in total precipitation, a longer period of sunshine, and less severe drought stress in 2024. It's possible that these environmental enhancements encouraged improved vegetative growth and stem elongation in all genotypes.
For teff cultivars, the four accessions examined in this study typically lie within the medium stem height range. There was a noticeable rise in stem length from year to year, even if the differences were not very noticeable. Furthermore, in 2024, genotype-specific responses to irrigation were noted: PI-494237 achieved its maximum height in the non-irrigated (control) treatment, while PI-442115 and PI-494455 displayed taller stems under irrigated circumstances. This variation demonstrates the intricate relationship between genotype expression and water availability (Tables 8 and 9).

Table 8. Stem length of four *Eragrostis* genotypes in 2023 (measured on 13 November 2023)

Genotype	Value
1. *E.tef* PI-442115 semi dwarf (Rapid) drought-tolerant	52.29 cm
2. *E.tef* PI-494237 drought-tolerant genome sequenced white seeds	47.81 cm
3. *E.tef.* PI-494455 drought-tolerant (white)	42.67 cm
4. *Eragrostis curvula* (drought-tolerant)	35.18 cm

Table 9. Stem length of four *Eragrostis* genotypes under control and irrigated conditions in 2024 (measured on 31 October 2024)

Genotype	Control	Irrigated
1. *E.tef* PI-442115 semi dwarf (Rapid) drought-tolerant	50.50 cm	58.40 cm
2. *E.tef* PI-494237 drought-tolerant genome sequenced white seeds	62.55 cm	60.05 cm
3. *E.tef.* PI-494455 drought-tolerant (white)	53.15 cm	58.80 cm
4. *Eragrostis curvula* (drought-tolerant)	51.85 cm	52.90 cm

Straw mass measurements showed considerable variation between years, as well as between control and irrigated plants within the 2024 experiment. As with biomass data, part of the variability may be attributed to differences in harvest dates and corresponding plant moisture content at the time of sampling.
A particularly large difference was observed between control plants in 2023 and 2024, with straw mass values being 5 to 6 times higher on average in the second year. Within the 2024 trial, Genotypes 1 and 2 displayed the most significant variation between irrigation treatments:

- *E. tef* PI-442115: 79 g (control) vs. 96 g (irrigated)
- *E. tef* PI-494237: 124 g (control) vs. 56 g (irrigated)

Conversely, Genotypes 3 and 4 showed relatively stable straw yields across treatments:

- *E. tef* PI-494455: 68 g (control) vs. 64 g (irrigated)
- *E. curvula*: 53 g (control) vs. 58 g (irrigated)

These findings suggest genotype-specific responses to water availability, and possibly varying allocation of assimilates between reproductive and vegetative tissues. In particular, the substantial drop in straw mass in *E. tef* PI-494237 under irrigation may indicate a shift in resource partitioning towards grain production or altered growth dynamics under supplemental water (Table 10-11).

Table 10. Straw mass of four Eragrostis genotypes in 2023 (measured on 20 February 2024)

Genotype	Value
1. *E.tef* PI-442115 semi dwarf (Rapid) drought-tolerant	16 g
2. *E.tef* PI-494237 drought-tolerant genome sequenced white seeds	20 g
3. *E.tef.* PI-494455 drought-tolerant (white)	15 g
4. *Eragrostis curvula* (drought-tolerant)	10 g

Table 11. Straw mass of four *Eragrostis* genotypes under control and irrigated conditions in 2024 (measured on 25 November 2024)

Genotype	Control	Irrigated
1. *E.tef* PI-442115 semi dwarf (Rapid) drought-tolerant	79 g	96 g
2. *E.tef* PI-494237 drought-tolerant genome sequenced white seeds	124 g	56 g
3. *E.tef.* PI-494455 drought-tolerant (white)	68 g	64 g
4. *Eragrostis curvula* (drought-tolerant)	53 g	58 g

The extrapolated grain yield values per hectare, calculated from pot trials, are shown in Table 12. The data reveal significant differences between the years and treatments.
In 2023, yields were consistently lower across all genotypes, ranging from 1.30 to 3.34 q/ha, which is expected due to less favorable environmental conditions and reduced vegetative

development. In contrast, the 2024 control and irrigated treatments both resulted in markedly improved yields.
Genotype 1 (*E. tef* PI-442115) achieved the highest yield under irrigation (7.54 q/ha), showing clear responsiveness to additional water input. *E. curvula* (Genotype 4) also responded well, nearly tripling its 2023 output.
Genotype 2 (E. tef PI-494237) produced its best result in the control group in 2024 (7.42 q/ha), suggesting a possible sensitivity to irrigation or altered nutrient uptake. Meanwhile, Genotype 3 (E. tef PI-494455) performed best under irrigation (5.21 q/ha), more than tripling its yield compared to the control treatment of the same year (1.60 q/ha).
These results underscore the importance of genotype-environment interactions and indicate that irrigation had both positive and variable effects depending on the accession. Yield differences also align with observations in biomass and straw mass, further supporting the physiological diversity among the tested *Eragrostis* types.

Table 12. Extrapolated grain yield per hectare (q/ha) based on pot experiments in 2023 and 2024 under control and irrigated conditions

Genotype	2023.	2024. Control	2024. Irrigated
1. *E.tef* PI-442115 semi dwarf (Rapid) drought-tolerant	2.99	3.27	7.54
2. *E.tef* PI-494237 drought-tolerant genome sequenced white seeds	1.42	7.42	5.03
3. *E.tef.* PI-494455 drought-tolerant (white)	3.34	1.60	5.21
4. *Eragrostis curvula* (drought-tolerant)	1.30	4.14	7.11

Discussion

The broad ecological adaptability of teff is well established. In Ethiopia, it is cultivated under both humid highland and arid savanna conditions, which represents one of its most important adaptive traits (Baye et al., 2014; Ligaba-Osena et al., 2021). The findings of our 2023–2024 pot experiments reinforce this observation. Under irrigated conditions, most genotypes produced greater biomass and grain yield. However, even in the absence of supplemental irrigation, stable growth and acceptable yields were observed. These results support the notion that teff could serve as a promising crop for sustainable grain production under changing climatic conditions. Similar genotype-specific physiological responses under drought were reported by Mengistu et al. (2022), who observed significant variation in water use efficiency and adaptive traits across teff accessions (Mengistu – Cushman, 2024)
In terms of grain yield, genotype PI-494237 was outstanding. It achieved its highest yield under non-irrigated conditions and did not respond positively to irrigation; on the contrary, in some cases, its yield actually decreased. This behaviour aligns with its described drought tolerance and suggests that the genotype is particularly well adapted to water-limited environments. As a white-seeded type, PI-494237 has potential for direct human consumption and may represent a marketable, gluten-free grain alternative.
Genotype PI-442115 ('Rapid') and *Eragrostis curvula* both showed balanced performance, with moderate yields under control conditions and markedly higher outputs under irrigation. Their consistent response across treatments indicates their suitability for cultivation under a wide range of environmental conditions. In addition to high grain yields, both accessions produced substantial biomass and straw mass, enhancing their value for forage use alongside their role in food production. Although *E. curvula* had a lower thousand-kernel weight, reducing its significance as a food grain, its stable and high vegetative yield underscores its utility as a fodder crop.

Under dry conditions, genotype PI-494455 performed worse; however, it responded favorably to irrigation, showing a significant increase in grain output. This implies that it might have a moderate tolerance for drought, but it might do well in intensive farming systems with access to water supplements or irrigation.

Conclusion

All things considered, the experiment demonstrated that teff is a very hardy crop that can provide respectable yields without irrigation while demonstrating notable yield gains when irrigated. *E. curvula* and PI-442115 produced the most balanced performance across both treatments, while PI-494237 showed the highest drought tolerance among the investigated genotypes.

The genetic diversity within the *Eragrostis* genus is shown by the found genotype differences. Because of its diversity, it is possible to choose and use particular kinds for a variety of applications, such as fodder use (biomass and straw yield) or food production (grain yield).

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