Original scientific paper
Journal of Central European Agriculture, 2024, 25(3), p.725-735
DOI: /10.5513/JCEA01/25.3.4344

Influence of sowing and nitrogen rates on teff (*Eragrostis tef* (Zucc.) Trotter) productivity under the conditions of South Central Bulgaria

Влияние на сеитбените и азотните норми върху продуктивността на теф (*Eragrostis tef* (Zucc.) Trotter) в условията на Южна Централна България

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Received: March 29, 2024; accepted: June 14, 2024

ABSTRACT

In 2021 - 2023, in the region of South Central Bulgaria, the influence of three sowing rates (10, 15 and 20 kg/ha) and four levels of nitrogen fertilization (0, 30, 60 and 90 kg/ha) on the productivity of teff (*Eragrostis tef* (Zucc.) Trotter) in two stages of development (milk and dough maturity) has been studied. The experiment was based on the method of fractional plots, with the size of the harvest plot 10 m^2, under non-irrigated conditions. The statistical processing was carried out with the ANOVA LSD test and the MS Excel software package - 2010. Fertilization with 90 kg/ha of nitrogen resulted in the highest yields (up to 56.7% more green mass and up to 55.5% more dry matter) in all tested sowing rates (10, 15, 20 kg/ha) and harvesting phases (milk and dough maturity). The increase in the sowing rate from 10 to 15 kg/ha increased the yield of green mass and dry matter by up to 5.9% and 3.6%, respectively in the dough maturity phase. Teff productivity is positively correlated with the amount of vegetation precipitation (r = 0.745 – 0.766) and nitrogen fertilization (r = 0.535 – 0.541) and negatively correlated (r = -0.526 – -0.543) with vegetation temperatures. The conditions of the year (68.58 – 72.18%) and nitrogen fertilization (20.25 – 22.81%) have the main influence on the teff productivity. The influence of the sowing rate is weaker - 1.73 - 2.62% of the total variation. The harvesting phase has been shown to affect dry matter yield.

Keywords: *Eragrostis tef* (Zucc.), green mass yield, dry matter yield, sowing rate, nitrogen fertilization, harvesting phase

РЕЗЮМЕ

През 2021 – 2023 г. в района на Централна Южна България е изпитано влиянието на три посевни норми (10, 15 and 20 kg/ha) и четири нива на азотно торене (0, 30, 60 and 90 kg/ha) върху продуктивността на Теф (*Eragrostis tef* (Zucc.) Trotter) в две фази на развитие (млечна и восъчна зрялост). Опитът е заложен по метода на дробните парцелки, с големина на реколтната парцелка 10 m^2, при неполивни условия. Статистическата обработка е извършена с ANOVA LSD test и пакетът програми MS Excel software – 2010. Азотното торене влияе положително върху продуктивността на теф. Най-високи добиви се получават при торене с 90 kg/ha азот (до 56.7% повече зелена маса и до 55.5% повече сухо вещество) при всички изпитани посевни норми (10, 15, 20 kg/ha) и фази на прибиране (млечна и восъчна зрелост). Увеличението на посевната норма от 10 на 15 kg/ha води до повишение на добива на зелена маса и сухо вещество съответно с до 5.9% и 3.6% във фаза восъчна зрелост. Продуктивността на теф е в добра положителна корелационна зависимост с количеството на вегетационните валежи (r = 0.745 - 0.766) и азотното торене (r = 0.535 - 0.541), а отрицателна корелационна зависимост (r = -0.526 – -0.543) с вегетационните температури. Основно влияние върху продуктивността на теф оказват условията на годината (68.58 – 72.18%) и азотното торене (20.25 – 22.81%). По-слабо е влиянието на посевната норма - 1.73 – 2.62% от общото вариране. Фазата на прибиране доказано влияе върху добива на сухо вещество.

Ключови думи: *Eragrostis tef* (Zucc.) Trotter, добив на зелена маса, добив на сухо вещество, посевна норма, азотно торене, фаза на прибиране

INTRODUCTION

Climatic and resource challenges are of particular importance for the development of agriculture and, in particular, the cultivation of forage crops. More frequent and intense droughts are likely to reduce water supplies, which combined with hot winds will increase the risk of wind erosion and soil degradation. In certain areas, this is a limiting factor for the cultivation of main forage crops that require fertile soils. To reduce the negative impact of climate anomalies on agriculture, growing alternative ecologically flexible crops is an appropriate approach (Miller, 2009; Yumbya et al., 2014; Kakabouki et al., 2021; Wagali et al., 2023). The African crop teff is considered a potential forage crop during the summer months, especially for the USA (Twidwell et al., 2002; Roseberg et al., 2005; Norberg et al., 2008; Miller, 2009; Saylor, 2017).

Several authors point to teff as an ancient and forgotten crop with the prospect of producing food for humans and animals, due to its valuable qualities: drought resistance, ecological flexibility, short vegetation period, higher nutritional value than some cereals and indispensable nutritional qualities of the grain with the possibility for production of gluten-free bakery products (Ketema, 1997; Mengistu and Mekonnen, 2011; Stoyanov, 2014; Sang-Hoon et al., 2015; Barretto et al., 2021; Chochkov et al., 2022).

Teff can be grown for green mass, hay, silage, and straw, as well as for pasture (Miller, 2009; Saylor, 2017; Tadele, 2018; CSA 2020; Kakabouki et al., 2021; Wagali et al., 2023). At certain stages of animal growth and development, teff feed can supplement or replace feeding with other staple feeds (Miller, 2009; Wagali et al., 2023). According to Saylor (2017), feeding cattle with teff hay does not reduce the amount of milk and fat content, while increasing its protein content. Due to the great drought tolerance of the crop and its cultivation without irrigation, a reduction in water consumption is also achieved in the livestock farm, which increases the profitability of production. The residual plant mass of teff - the straw, mainly studied in its homeland Ethiopia (Ketema, 1993, 1997), stands out for its better quality than that of other annual cereal crops.

In recent years, some authors have reported the potential of the crop to produce silage and hay harvested at different phenological phases and studied the influence of different factors on productivity (Norberg et al., 2008; Young et al., 2014; Nakata et al., 2018; Vinyard et al., 2018; Ream et al., 2020; Billman et al., 2022). Research shows that the main factors influencing the productivity of forage teff are nitrogen fertilization (Tadele, 2019; Tesfaye et al., 2019), harvesting phase, sowing rate (Ream et al., 2020) and climatic conditions of the area. Harvesting for forage can be done at different stages of the crop development – from flag leaf to dough maturity (Roseberg et al., 2005; Saylor, 2017; Ream et al., 2020; Laca et al., 2021). In literature, the harvesting stage is registered as days after sowing the crop – 45 to 120 days after sowing, early or late heading, or 50-90% occurrence of the flag leaf, heading and maturity stages (Norberg et al., 2008; Kakabouki et el., 2020; Ream et al., 2020).

Several authors have established effective nitrogen fertilization rates to be from 20 to 90 kg/ha of active substance in green mass and grain production (Gebretsadik et al., 2009; Abay et al., 2011; Girma et al., 2012; Dereje et al., 2018). According to Habtegebrial et al. (2007), grain and dry matter yield increased linearly with the application of fertilization from 0 to 60 kg/ha of nitrogen. With an increase in the nitrogen rate to 90 kg/ha, no increase in yield has been observed, due to losses from leaching in the lower soil layers. Hunter et al. (2009)

and Miller (2009) established that fertilization with 30 to 90 kg/ha of nitrogen was necessary before sowing and for each subsequent swathing. According to Gebretsadik et al. (2009), the highest grain and green mass yield were obtained by fertilization with 92 kg/ha of nitrogen. High nitrogen fertilization rates and irrigation can result in lodging (Saylor, 2017; Barretto et al., 2021).

An important element of crop technology affecting productivity is the seeding rate. For Ethiopian conditions, many authors recommend a seeding rate of 10 to 25 kg/ha (Asagrew et al., 2014; Bultosa, 2016; Arefaine et al., 2020; Mihretie et al., 2020). For green mass production in the California region, Miller (2009) indicated sowing rates of 6 to 8 kg/ha as appropriate. Roseberg et al. (2005), indicated a sowing rate of 5 to 10 kg/ha for the Oregon region, USA. According to Arefaine et al. (2020), the highest grain and biomass yield was obtained at a seeding rate of 10 kg/ha. In the conditions of Western Bulgaria Ivanova (2018), found that in the production of teff for grain, a sowing rate of 0.8 kg/ha and soil and leaf fertilization was necessary to increase yields.

Currently, there are limited studies on teff in Bulgaria, and their main focus is the production of the grain and its nutritional potential (Stoyanov, 2014; Ivanova, 2018; Chochkov et al., 2022).

The objective of the present study was to determine the influence of sowing rate, nitrogen fertilization and harvesting phase on the productivity of teff grown for forage in the conditions of South Central Bulgaria.

MATERIALS AND METHODS

The study was conducted in the period 2021-2023 in the area of the village of Tulovo, Stara Zagora district, located in the region of South Central Bulgaria with geographical coordinates 42°33'15.1"N and 25°33'09.8"E and with an altitude of 332 m. A three-factor field experiment based on the method of fractional plots, with a harvest plot size of 10 m^2, was performed. The experiment was carried out under non-irrigated conditions, after a wheat predecessor, using white teff variety Veronica of the Dutch company "Millets place".

The soils in the area are alluvial, slightly to moderately stocked with humus (1.6% – 2.6%), with a slightly acidic to neutral reaction, slightly stocked with nitrogen (31.0 – 35.0 kg/ha) and phosphorus (8.0 – 27.0 ppm) and slightly to well stocked with potassium (93.0-136.0 ppm).

The influence of sowing rate and nitrogen fertilization on the productivity of teff (*Eragrostis tef* (Zucc.) Trotter) in two phases of development (milk and dough maturity) was tested. The studied factors and their levels are as follows: factor A: sowing rate, kg/ha (A1 – 10; A2 – 15; A3 – 20); factor B: nitrogen fertilization rate, kg/ha, against the background of 50 kg/ha P_2O_5 (B1 – 0; B2 – 30; B3 – 60; B4 – 90). Variant 1 (A1B1) has been adopted as a control – harvested at the milk maturity phase, with a sowing rate of 10 kg/ha and without nitrogen fertilization.

The technology of teff production

It includes basic soil tillage - immediately after harvesting the predecessor, basic soil tillage was made - deep ploughing (20 - 25 cm) in the period August - September and subsequent cultivation (10 - 15 cm) in the second half of November and the beginning of December. In the spring, two cultivations were performed - the first in March, and the second was a pre-sowing one (in May) at a depth of 5 - 6 cm. Before sowing, to create a suitable seedbed, the area was rolled. With the main soil tillage, background fertilization with 50 kg/ha P_2O_5 in the form of triple superphosphate was applied. With the pre-sowing cultivation, nitrogen was introduced according to the levels of factor B (0, 30, 60 and 90 kg/ha active substance nitrogen in the form of ammonium nitrate). Sowing was carried out in May when the soil was warmed up to 18-20 °C at the sowing depth, with sowing rates according to the levels of factor A (10, 15 and 20 kg/ha). The row spacing was 15 cm, and the sowing depth was 0.5 cm. After sowing, the area was fenced. Weed control was done manually by weeding. Disease and pest control was not carried out due to no attack present during the years of the experiment. Biomass harvesting was carried out at the milk and dough maturity of the crop.

Reported indicators

Green mass (GM) and dry matter (DM) yields have been reported - in kg/ha and relative in %. For the meteorological assessment of the experimental period, the degree of availability of the vegetation precipitation amount and the average vegetation temperature of the air (P) have been calculated. The formula P = i x 100 / n + 1 was used, where: P – degree of availability, %; i – sequence number of the individual members in the row (arranged in descending order for precipitation amounts and in ascending order for the average annual and vegetation temperatures); n – total number of members in the row. Years with availability from 0 to 25% are considered to be very wet and cool, medium wet and medium cool - from 25 to 50%, medium dry and medium warm - from 50 to 75%, dry and warm - 75 to 100 %.

Statistical analysis

The investigated parameters were measured in four replicates and the average results are presented in the experimental results. To establish the influence of sowing rate, nitrogen fertilization rate and development phases on the yields of green mass and dry matter statistical procedures were obtained by an ANOVA LSD test for statistical significance of the differences. After significant results were obtained by the ANOVA test, Tukey's HSD test was applied to all pairwise differences between means. The significant differences were tested and *P* values <0.05 were considered statistically significant. To establish correlation dependencies and factor analysis, the software package for statistical data processing MS Excel software - 2010 was used.

RESULTS AND DISCUSSION

Meteorological conditions during the study period are given in Table 1. Regarding precipitation, the study years were characterized as relatively favourable except for 2022, in which the annual precipitation total was 40.8% below that of the multi-annual period. Precipitation totals during the vegetation period of teff in all three years of the study were below the multiannual average. The greatest vegetation amount of precipitation was recorded in 2023 – 189.7 mm (10.0% below normal). The lowest vegetation amount of precipitation was recorded in 2022 – 85.5 mm (54.9% below normal). During the multi-annual period (1987 - 2020), precipitation was distributed unevenly during the teff vegetation, with their highest values occurring in the month of June. During the study years, this irregularity was also well expressed, especially in 2022. That year was characterized by a severe spring drought that lasted throughout the whole month of May when the monthly precipitation totaled 10.6 mm (84.7% below normal). The drought in July 2022 was particularly drastic when there was only 2.1 mm of precipitation (96.6% below normal). In all three years of the experiment, the predominant part of vegetation precipitation (76.7 - 97.5%) was in May and June. Regarding vegetation precipitation, 2021 is characterized as moderately dry with 60% availability, 2022 as dry with 80% availability, and 2023 as moderately wet with 40% availability.

The average air temperature during teff vegetation for the multi-annual period (1987 - 2020) was 19.5 °C. In 2021 and 2023, the average air temperatures for the vegetation season did not differ significantly from the multi-annual average ones - the excess is 0.2-0.3 °C. Greater deviation from the norm was found in 2022 when the average air temperatures for the vegetation period were 1.7 °C above normal. During that year of the study, the average daily air temperatures in the initial phases of plant development (June) were 3.0 °C above the multi-annual average. In July of the same year (2022), during the heading and ripening phases, the average monthly air temperatures were 2.1 °C above the multi-annual average.

Regarding the vegetation temperatures, 2021 was characterized as moderately cool (P = 40%), 2022 as warm (P = 80%), and 2023 as moderately warm (P = 60%).

According to Yumbya et al. (2014), it is agronomically justified to grow teff in areas with average vegetation temperatures from 13.2 to 25.2 °C. Based on the analysis of climatic factors, it can be seen that the established temperature conditions in the region of South Central Bulgaria are favorable for the cultivation of the teff crop, but moisture supply may prove to be a limiting factor for obtaining high productivity.

Table 1. Climate conditions of South-Central Bulgaria

Years	Months														P%
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I-XII	V-VII	
Rainfall, mm															
2021	97.2	22.5	42.8	56.9	52.9	54.9	32.7	120.2	20.3	79.3	13.6	83.8	677.1	140.5	60.0
2022	20.2	9.7	14.4	67.0	10.6	72.8	2.1	67.0	23.3	3.1	22.0	28.8	341.0	85.5	80.0
2023	103.7	3.9	19.4	79.5	73.7	88.6	27.4	32.4	22.0	8.9	69.3	22.7	624.3	189.7	40.0
1987-2020	35.7	30.2	36.7	39.1	69.4	79.5	61.9	36.7	53.4	46.0	38.9	48.5	575.9	210.8	
Average temperature, °C															
2021	2.2	6.0	4.6	9.4	16.6	19.0	23.8	23.2	16.4	9.3	6.9	3.5	11.7	19.8	60.0
2022	1.7	3.9	3.1	10.5	16.2	23.0	24.3	24.1	12.6	17.4	9.1	5.2	13.3	21.2	80.0
2023	5.2	4.5	7.3	12.9	14.5	19.8	24.6	24.0	20.3	14.5	7.9	4.2	13.1	19.6	40.0
1987-2020	0.7	2.7	6.1	11.2	16.0	20.0	22.4	20.4	15.1	9.9	4.6	1.6	11.4	19.5	

P% - Degree of vegetation availability of the climatic factors – precipitation and temperature

Productivity is the most important and synthesizing indicator of the application of a given technology. Average annual yields of green mass (GM) of teff depending on the sowing rate and nitrogen fertilization for the study period ranged from 9249.5 to 14149.5 kg/ha in the milk stage and from 8845.4 to 13561.3 kg/ha in the dough stage (Table 2).

GM yields were lowest in the dry and warm year 2022, when the amount of vegetation precipitation was 59.4% below normal, and average vegetation temperatures were 1.7 °C above normal. The harvest year 2023 was characterized by more favourable weather conditions, which created a prerequisite for a more optimal course of growth and reproductive processes and the formation of higher GM yields - 14149.5 kg/ha in the milk maturity phase and 13561.3 kg/ ha in the dough maturity phase, on average, which is 32-34% above the yields achieved in 2021 and 2022.

With an increase in the sowing rate from 10 to 15 and 20 kg/ha, green mass yields increased from 2.1% to 3.9% in the milk maturity phase and from 4.6% to 9.5% in the dough maturity phase, and the differences compared to the control are statistically proven ($P < 0.01$ - $P < 0.001$) only for dough maturity phase.

The results for the obtained GM yields showed that, both by year and on average for the reviewed period, the lowest yield was obtained in the unfertilized control. Among the variants without nitrogen fertilization, in all experimental years, the yields of green mass were the lowest in both tested harvest phases, but the difference compared to the control was proven only in 2021. The application of increasing nitrogen fertilization rates leads to an increase in the yields of green mass at all tested sowing rates. Both by years and on average for the experimental period, the highest statistically very well-proven ($P < 0.001$) yield of GM was obtained from the variants fertilized with 90 kg/ha of nitrogen and a sowing rate of 15 kg/ha. The GM yield of these variants exceeded the control in the milk phase by 56.7% and in the dough phase by 38.4%.

Average annual dry matter (DM) yields of teff for the study period ranged from 3758.3 to 5903.1 kg/ha in the milk phase and from 4028.9 to 6409.1 kg/ha in the dough stage (Table 3). Analogous to the results for GM yields, DM yields were the lowest in 2022 and the highest in 2023, characterized by more favourable climatic conditions.

As the sowing rate increased from 10 to 15 and 20 kg/ha, dry matter yields increased from 1.4% to 1.6% in the milk maturity phase, but differences compared to the lowest tested sowing rate (10 kg/ha) were not proven. In the dough maturity phase, the increase was from 1.8% to 3.6% compared to the lowest sowing rate tested, and the differences were not statistically proven either.

The results for the obtained DM yields showed that, both by year and on average for the reviewed period, the lowest yield was obtained in the unfertilized control. Fertilization with increasing nitrogen rates during both tested phases (milk and dough maturity) and the three tested sowing rates had a positive effect on DM yields in teff. The highest, statistically very well-proven ($P < 0.001$) yield of DM in individual years and on average for the study period was obtained from the variants fertilized with 90 kg/ha of nitrogen. Averaged over the study period, the DM yield of these variants exceeded the control by 38.9 to 47.3% at milk maturity and by 45.3 to 55.5% at dough maturity.

Analogous to the present study, an increase in productivity with an increase in the nitrogen fertilization rate was found by Roseberg et al. (2005), Gebretsadik et al. (2009), Abay et al. (2011), Girma et al. (2012), Dereje et al. (2018). According to other authors, no increase in teff productivity was observed when fertilizing with higher nitrogen fertilization rates due to losses from biomass lodging (Saylor, 2017; Barretto et al., 2021) or due to losses from leaching nitrogen in the lower soil layers (Habtegebrial et al., 2007).

When calculating the correlations between the productivity of GM and DM in teff and the studied sowing rates, nitrogen fertilization rates, harvesting

Table 2. Yields of green mass by the years and average for the period 2021 – 2023, kg/ha

Variant	Years			Average	
	2021	2022	2023	kg/ha	%
			Phase of milk maturity		
1 A_1B_1 (control)	7405.5	7655.5	11664.2	8908.4[a]	100.0
2 A_1B_2	7957.3***	8117.2*	12325.3**	9466.7***[b]	106.3
3 A_1B_3	9669.9***	9432.7***	14249.7***	11117.4***[ef]	124.8
4 A_1B_4	11607.4***	10398.4***	16390.9***	12798.9***[ij]	143.7
5 A_2B_1	7935.7**	7893.0	11464.6	9097.8[a]	102.1
6 A_2B_2	9670.4***	9215.0***	15282.1***	11389.2***[fg]	127.8
7 A_2B_3	11117.9***	9457.3***	15902.3***	12159.2***[hi]	136.5
8 A_2B_4	12746.1***	11615.4***	17518.4***	13959.9***[k]	156.7
9 A_3B_1	7876.8*	7989.2	11890.1	9252.0[ab]	103.9
10 A_3B_2	8483.5***	9120.6***	12146.8*	9917.0***[c]	111.3
11 A_3B_3	9355.5***	9379.9***	15142.4***	11292.6***[fg]	126.8
12 A_3B_4	10954.9***	10720.0***	15816.8***	12497.2***[ij]	140.3
Average of phase	9565.1	9249.5	14149.5	10988.0	123.3
			Phase of dough maturity		
13 A_1B_1	8521.9***	7736.9	11426.7	9228.5[ab]	103.6
14 A_1B_2	8640.8***	7836.9	11958.4	9478.7**[b]	106.4
15 A_1B_3	9162.5***	8685.5***	13728.4***	10525.5***[de]	118.2
16 A_1B_4	10299.6***	9937.3***	14364.9***	11533.9***[fg]	129.5
17 A_2B_1	8749.1***	7740.7	12775.3***	9755.1***[bc]	109.5
18 A_2B_2	9665.0***	8385.0***	14093.4***	10714.4***[de]	120.3
19 A_2B_3	10302.9***	9703.8***	15228.5***	11745.1***[gh]	131.8
20 A_2B_4	11146.0***	10513.9***	15318.8***	12326.3***[hi]	138.4
21 A_3B_1	8735.7***	7535.7	11674.5	9315.2**[b]	104.6
22 A_3B_2	9317.4***	8412.5***	12659.4***	10129.8***[cd]	113.7
23 A_3B_3	10051.8***	9505.1***	13718.4***	11091.8***[ef]	124.5
24 A_3B_4	10915.2***	10152.1***	15789.8***	12285.7***[hi]	137.9
Average of phase	9625.7	8845.4	13561.3	10677.5	119.9
LSD $P < 0.05$	396.5	397.8	390.1	394.8	4.4
LSD $P < 0.01$	526.5	528.3	518.1	524.3	5.9
LSD $P < 0.001$	683.0	685.3	672.0	680.1	7.6

*A - sowing rates, kg/ha (A_1 – 10, A_2 – 15, A_3 – 20); B - nitrogen rates, kg/ha (B_1 – 0, B_2 – 30, B_3 – 60, B_4 – 90); *, **, *** Statistically significant differences of the variants and control at $P < 0.05$, 0.01 and 0.001, respectively; a-l – Different letters indicate statistically significant differences among variants at $P < 0.05$

Table 3. Yields of dry matter by the years and average for the period 2021- 2023, kg/ha

Variant	Years			Average	
	2021	2022	2023	kg/ha	%
Phase of milk maturity					
1 A_1B_1 (control)	3209.0	3192.6	4847.8	3749.8[a]	100.0
2 A_1B_2	3465.3***	3378.2**	5090.1***	3977.9**[b]	106.1
3 A_1B_3	3891.8***	3749.1***	6046.3***	4562.4***[e]	121.7
4 A_1B_4	4605.9***	4311.6***	6704.4***	5207.3***[i]	138.9
5 A_2B_1	3268.9	3238.2	4904.9	3804.0[a]	101.4
6 A_2B_2	3820.9***	3604.4***	6251.2***	4558.8***[e]	121.6
7 A_2B_3	4403.4***	3911.1***	6802.9***	5039.1***[h]	134.4
8 A_2B_4	4804.7***	4602.3***	7166.4***	5524.5***[k]	147.3
9 A_3B_1	3297.0	3269.9	4863.9	3810.4[a]	101.6
10 A_3B_2	3751.5***	3575.2***	5197.5***	4174.7***[c]	111.3
11 A_3B_3	4245.2***	3804.2***	6194.8***	4748.1***[f]	126.6
12 A_3B_4	4729.5***	4463.1***	6766.9***	5319.8***[j]	141.9
Average of phase	3957.8	3758.3	5903.1	4539.7	121.1
Phase of dough maturity					
13 A_1B_1	3890.0***	3382.1**	5596.8***	4289.6***[d]	114.4
14 A_1B_2	3913.1***	3620.6***	5709.8***	4414.5***[d]	117.7
15 A_1B_3	4141.6***	3890.4***	6309.2***	4780.4***[f]	127.5
16 A_1B_4	4726.7***	4543.8***	7077.7***	5449.4***[jk]	145.3
17 A_2B_1	3978.0***	3418.9***	5872.5***	4423.2***[d]	118.0
18 A_2B_2	4433.6***	3821.9***	6536.0***	4930.5***[g]	131.5
19 A_2B_3	4605.8***	4513.1***	6999.3***	5372.7***[j]	143.3
20 A_2B_4	5095.1***	4846.6***	7547.9***	5829.9***[l]	155.5
21 A_3B_1	4005.2***	3429.9***	5639.4***	4358.2***[d]	116.2
22 A_3B_2	4165.0***	3732.4***	5884.3***	4593.9***[e]	122.5
23 A_3B_3	4594.9***	4440.5***	6577.9***	5204.5***[i]	138.8
24 A_3B_4	4956.4***	4705.9***	7157.9***	5606.8***[k]	149.5
Average of phase	4375.5	4028.9	6409.1	4937.8	
LSD $P < 0.05$	90.1	116.5	111.1	105.9	2.8
LSD $P < 0.01$	119.6	154.7	147.5	140.6	3.7
LSD $P < 0.001$	155.2	200.6	191.4	182.4	4.9

*A - sowing rates, kg/ha (A_1 – 10, A_2 – 15, A_3 – 20); B - nitrogen rates, kg/ha (B_1 – 0, B_2 – 30, B_3 – 60, B_4 – 90); *, **, *** Statistically significant differences of the variants and control at $P < 0.05$, 0.01 and 0.001, respectively; a-l – Different letters indicate statistically significant differences among variants at $P < 0.05$

phase and climatic factors, it has been found that there is a significant positive dependence of productivity with the nitrogen fertilization rate (r = 0.535 – 0.541) and high with vegetation precipitation (r = 0.745 – 0.766), and negative significant correlation with vegetation temperatures (r = -0.526 – -0.543) (Table 4). There is also a correlation between DM yields of teff and the harvest phase, but it is of a lower value (r = 0.465). It has been found that the relationship between sowing rate and dry matter yield is stronger (r = 0.334) than that between sowing rate and green mass yield (r = 0.218).

The dispersion analysis shows that the strongest, very well-proven ($P < 0.001$) influence on teff productivity was exerted by climatic factors - 68.58 - 72.18% of the total data variation (Table 5). The influence of the nitrogen rate on yields is very well-proven ($P < 0.001$), but significantly lower – 20.25 - 22.81%, respectively, and it is the second most influential factor after climate. Sowing rate is the third most important factor affecting teff productivity.

The interaction between the factors year and nitrogen fertilization has a low (0.80%), but well-proven influence on teff productivity. The harvesting phase has been shown to affect only dry matter yield. There is no proven effect on teff yields from the interaction between year and sowing rate and the year and phase of crop harvest.

Table 4. Correlation (r) between yields and factors, n = 288

	Yields of green mass	Yields of dry matter	Sowing rate	Nitrogen rate	Phase	Temperature V-VII	Rainfall V-VII
Yields of green mass	1						
Yields of dry matter	0.958*	1					
Sowing rate	0.218	0.334	1				
Nitrogen rate	0.535*	0.541*	0.174	1			
Phase	0.304	0.465*	0.332	0.333	1		
Temperature V-VII	-0.526*	-0.543*	0.113	-0.212	0.211	1	
Rainfall V-VII	0.745*	0.766*	-0.076	0.432	0.010	-0.909*	1

*V-VII – rainfall and temperature during the growing season (May – July); * Correlation is significant at the $P < 0.05$ level

Table 5. Influence of factors on yields, average for the period 2021-2023, %

Factors	Green biomass yields	Dry matter yields
Year	68.58***	72.18***
Nitrogen rate	22.81***	20.25***
Sowing rate	2.62***	1.73***
Phase of maturity	0.36	2.81***
Year*nitrogen rate	0.80***	0.79***
Year*sowing rate	0.41	0.48
Year*phase	0.28	0.17
Other factors	4.14	1.59

*** - Statistical significance at $P < 0.001$

CONCLUSIONS

In the conditions of South Central Bulgaria, teff yields up to 10988.0 kg/ha GM and up to 4937.8 kg/ha DM on average. Fertilization with 90 kg/ha nitrogen results in the highest yields (up to 56.7% more green mass and up to 55.5% more dry matter) at all tested sowing rates (10, 15, 20 kg/ha) and harvesting phases (milk and dough maturity).

The increase in the sowing rate from 10 to 15 kg/ha leads to an increase in the yield of green mass and dry matter by up to 5.9% and 3.6%, respectively, in the dough maturity phase, but the differences from the lower sowing rate have not been statistically proven.

Teff productivity has a good positive correlation with the amount of vegetation precipitation (r = 0.745 - 0.766) and nitrogen fertilization (r = 0.535 - 0.541) and a negative correlation (r = -0.526 – -0.543) with vegetation temperatures. The conditions of the year (68.58 – 72.18%) and nitrogen fertilization (20.25 – 22.81%) have the main influence on teff productivity. The influence of the sowing rate is weaker - 1.73 - 2.62% of the total variation. The harvesting phase has been shown to affect dry matter yield.

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