

Bozhimirov, S., Nenova, R., Enchev, S. (2026). Green mass yield potential of sweet sorghum (*Sorghum bicolor* (L.) Moench var. *saccharatum*) as affected by nitrogen fertilization and sowing density. *Agriculture and Forestry*, 72 (3): 105-118. <https://doi:10.17707/AgricForest.72.3.07>

DOI: 10.17707/AgricForest.72.3.07

Stanislav BOZHIMIROV¹, Radena NENOVA¹, Stanimir ENCHEV¹

GREEN MASS YIELD POTENTIAL OF SWEET SORGHUM (*Sorghum bicolor* (L.) Moench var. *saccharatum*) AS AFFECTED BY NITROGEN FERTILIZATION AND SOWING DENSITY

SUMMARY

During 2023-2025, a field experiment took place at the Agricultural Institute-Shumen, under rainfed conditions on Calcic Chernozem soil, evaluating the effects of sowing density and nitrogen fertilization on the green mass yield of sweet sorghum. Productivity assessment relied on three cuttings at the sweeping stage and two cuttings at the flowering stage. Results indicate significant differences between fertilized and unfertilized treatments, as well as between the two sowing densities. Under dense sowing, nitrogen fertilization increased the mean cumulative yield at the sweeping stage from 74.13 to 84.12 t ha⁻¹. The Shumen Sweet variety achieved the highest seasonal total under the fertilized dense treatment, reaching 105.18 t ha⁻¹ at the sweeping stage (+33.9%) and 98.15 t ha⁻¹ at the flowering stage (+52.3%). Sparse sowing reduced yields by approximately 22-28% relative to dense sowing across all cutting schemes. These findings identify the most productive genotypes and the optimum agronomic management for maximizing green mass yield, providing a practical basis for selecting raw material for stem juice extraction.

Keywords: Sweet sorghum, nitrogen fertilization, sowing density, green mass yield, rainfed conditions, harvest stage

INTRODUCTION

Sweet sorghum (*Sorghum bicolor* (L.) Moench var. *saccharatum*.) is a high-yielding annual crop of subtropical origin that serves as both a forage and an industrial plant, with considerable importance in South-Eastern European agriculture. Its C4 photosynthetic metabolism (Wang *et al.*, 2009), deep root system and strong tolerance to heat and water deficit make it well suited to the agro climatic conditions of North-Eastern Bulgaria (Kikindonov, Enchev and Slanev, 2013, Enchev, Kikindonov and Slanev, 2016).

Sweet sorghum is characterized by its succulent stems, which accumulate sugars at concentrations that frequently reach or exceed 20% (Kawahigashi *et al.*,

¹Stanislav Bozhimirov (corresponding author: bozhimirov@gmail.com), Radena Nenova, Stanimir Enchev, Agricultural Academy, Sofia, Agricultural Institute - Shumen, BULGARIA

Notes: The authors declare that they have no conflicts of interest. Authorship Form signed online.

Received:21/05/2026

Accepted:26/07/2026

2013, Soleymani, Almodares and Shahrajabian, 2013, Vinutha *et al.*, 2014). The crop ranks among the most efficient biomass accumulators under drought and high temperature conditions (Rooney, 2000). A large proportion of cultivated materials derives from local populations shaped by natural selection and traditional cultivation (Smith and Frederiksen, 2000), while modern hybrids with sudangrass and grain sorghum exploit heterosis to combine high biomass productivity, robust regrowth potential and elevated carbohydrate content (Enchev, Kikindonov and Slanev, 2016). Genotype strongly determines plant height, stem diameter, juice sugar concentration and juice yield (Figueiredo *et al.*, 2015) and the balance among stem mass, leaf area and grain formation governs both green mass quality and the capacity for sugar storage in the stems (Tovignan *et al.*, 2016).

Beyond its established role as a forage crop, sweet sorghum has attracted growing scientific and practical attention as a source of carbohydrate rich stem juice, which is pressed at appropriate developmental stages to produce extracts with high sugar content (Kikindonov and Enchev, 2015, Enchev, 2023). The stem juice is particularly rich in readily fermentable sugars, sucrose, glucose and fructose (Zhao *et al.*, 2009, Kawahigashi *et al.*, 2013), making sweet sorghum extracts a promising candidate for managing neonatal hypoglycemia in livestock, a novel and practically significant application. The favorable sucrose-to-monosaccharide ratio also makes the crop attractive for both animal feeding and potential human food use (Varbanov and Hristova, 1996). This multipurpose nature underscores the necessity of optimizing production agronomy to satisfy the specific requirements of both forage and industrial end uses.

Nitrogen is the primary nutrient limiting sorghum productivity and adequate supply is essential for achieving high green mass yields (Leghari *et al.*, 2016, Bartzialis *et al.*, 2023). The magnitude of the yield response to nitrogen fertilization varies according to site-specific climatic and soil conditions, as well as the genetic potential of the genotype (Muchow, 1998, Ostmeyer *et al.*, 2022). Nitrogen fertilization consistently improves vegetative growth and overall crop productivity across sorghum types (Schlegel and Bond, 2021, Bartzialis *et al.*, 2023), but economically optimum rates are set by the yield cost balance, since excessive applications produce negligible returns and reduce profitability (Holman, Obour and Mengel, 2019, Schlegel and Bond, 2021). Practical application rates range from 55 to 150 kg N ha⁻¹ depending on soil fertility status (Holman, Obour and Mengel, 2019, Wang *et al.*, 2024). Sowing density is an equally important management factor that dictates inter plant competition for light, water and nutrients, and directly shapes canopy structure and determining yield components (Donchev and Enchev, 2024, Benson *et al.*, 2025).

The aim of this study was to evaluate green mass productivity in sweet sorghum varieties and local populations harvested at the sweeping and flowering stages under two sowing densities, with and without nitrogen fertilization, over the period 2023-2025. Furthermore, the study seeks to identify the most productive genotypes and the optimum agronomic management for supplying raw

material for stem extract production. While the effects of nitrogen fertilization and sowing density on grain and forage sorghum have been studied previously, comparable multi-year data for sweet sorghum genotypes evaluated specifically for green mass remain limited. This study addresses that gap by combining eight sweet sorghum genotypes, two sowing densities and two nitrogen fertilization rates across three growing seasons (2023-2025). Since fresh stalk yield is one of the strongest predictors of juice yield in sweet sorghum (Nazli *et al.*, 2024), agronomic practices that increase green mass yield are expected to translate directly into greater juice, and therefore sugar, output per hectare. This is further supported by evidence that stalk weight, stalk volume, stalk diameter and plant height are all strongly and consistently associated with juice yield across diverse sorghum ideotypes, including sweet types (Carvalho and Rooney, 2017).

MATERIAL AND METHODS

The experiment took place during 2023-2025 at the experimental fields of the Agricultural Institute-Shumen, North-Eastern Bulgaria (43°18'51.3"N, 27°01'41.8"E). The soil is a Calcic Chernozem (WRB, 2022) with 3.3% organic matter, very high CaCO₃ content and a slightly alkaline reaction (pH 7.4-7.8). The baseline chemical properties of the experimental soil (0-20 cm depth) are summarized in Table 1. The site showed deficiency in nitrogen, phosphorus and zinc, while soil analysis indicated sufficient potassium and magnesium. The experiment took place under rainfed conditions, with sugar beet as the preceding crop.

Table 1. Chemical characteristics of the experimental soil

Macronutrients	Concentration (mg kg ⁻¹)	Micronutrients	Concentration (mg kg ⁻¹)
CaO	5988.00	Fe	25.40
MgO	678.00	Mn	6.34
K ₂ O	438.00	Na ₂ O	31.40
P ₂ O ₅	39.00	Cu	1.37
N	18.70	B	1.30
S	7.43	Zn	0.31

The 2023-2025 period showed significant year-to-year variability. Temperature sums during the peak summer months (July-August) consistently exceeded long-term averages in all three seasons, providing favorable thermal conditions for crop growth (Figure 1a). Rainfall distribution, however, was irregular and frequently fell below optimal levels, serving as the primary limiting factor for green mass productivity (Figure 1b).

In May, temperatures remained below the climatic norm across all three years and rainfall was optimal in 2023 and 2025 but insufficient in 2024 (37.2 mm). June demonstrated a general moisture deficit across the entire study period, with precipitation failing to reach the historical norm (41.0 mm) in all years (26.4 mm in 2023, 33.3 mm in 2024, and a critical low of 13.6 mm in 2025). Thermal dynamics varied, with an exceptionally warm June in 2024 (752.0°C vs. 687.0°C

norm) accelerating early vegetative transitions, while 2023 and 2025 remained closer to or below the thermal norm.

Throughout July-September, temperatures were consistently above the long-term norm in all three years. The accompanying rainfall deficit was most severe in 2024, with cumulative precipitation reaching only 39.1 mm, far below the 159.0 mm norm. Consistent with previous observations in North-Eastern Bulgaria, this drought stress overlapped with active vegetative growth, creating a combined heat and water deficit that inhibited stem elongation and biomass accumulation. This is consistent with field evidence that water deficit during stem elongation significantly reduces sorghum stem dry weight, stem diameter and internode length, an effect attributable to shorter internodes rather than reduced internode number (Perrier *et al.*, 2017, Ssebulime *et al.*, 2025). Overall, favorable temperatures but limited moisture characterized the three-year study period, with the seasonal distribution of rainfall acting as the critical constraint on green mass productivity.

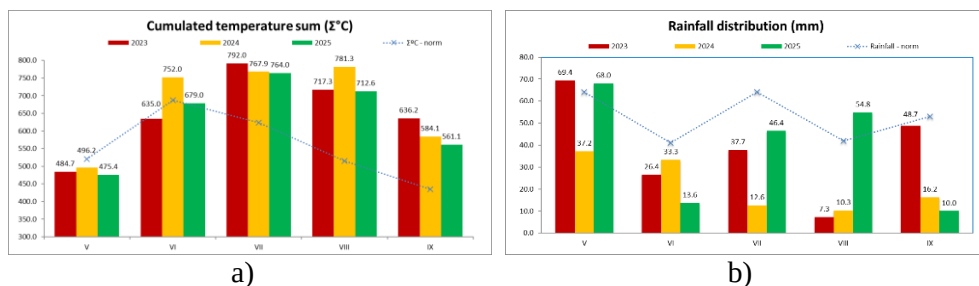


Figure 1. a) Cumulated temperature sum ($\Sigma^{\circ}\text{C}$) by month during the growing season; b) Rainfall distribution (mm) by month during the growing season

The experiment used a long-plot design with four replications, with a harvested area of 10.8 m² per plot. Sowing took place mechanically at 45 cm row spacing on 20 April (2024) and 25 April (2023 and 2025), at a seed rate of 30 kg ha⁻¹ and a sowing depth of 4-5 cm, giving an initial plant density of 110-130 plants m⁻². To compare density effects, the experiment included two treatments, the standard sowing density and a sparse-sowing treatment produced through manual thinning at the early growth stage by removing every other plant. A single post-sowing application supplied nitrogen through incorporation of ammonium nitrate (NH₄NO₃, 34% N) at 200 kg ha⁻¹, delivering 70 kg active N ha⁻¹. Unfertilized plots served as controls.

The trial evaluated eight sweet sorghum genotypes, comprising international commercial varieties and experimental lines from the Agricultural Institute-Shumen breeding program. The SZW and SZD populations are stabilized lines developed through the hybridization of sweet sorghum with grain sorghum genotypes. Yantar is a Ukrainian sweet sorghum population used commercially as a standard cultivar. Super Sweet is a U.S. sweet sorghum x grain sorghum hybrid serving as a standard for combined green mass and silage

production. SZE is a stabilized population developed through the hybridization of sudangrass and sweet sorghum. The SAxSZ population is a stabilized line derived from a cross between a grain sorghum male-sterile (MS) line (SA) and a sweet sorghum x sudangrass hybrid (SZ) serving as the pollinator. SZT is a local sweet broomcorn population with a distinctive panicle form. Shumen Sweet is a registered sweet sorghum variety of the Agricultural Institute-Shumen, developed by recurrent selection from a local sweet sorghum population (Enchev and Kikindonov, 2023).

Productivity assessment relied on three cuttings at the sweeping stage and two cuttings at the flowering stage. Each cut took place in the morning to minimize turgor loss, once 50% of plants in a given plot had reached the target developmental phase. Weighing of the freshly cut material from each plot took place immediately, with yields expressed as t ha^{-1} . Statistical evaluation used analysis of variance (ANOVA) for long-term split-plot experimental designs. The least significant difference (LSD) test at the $p < 0.05$, $p < 0.01$ and $p < 0.001$ probability levels evaluated treatment significance. The coefficient of variation (CV %), calculated for each cutting, indicated experimental precision (Welham *et al.*, 2014). Values reported in the tables (Tables 2-4) are means across the three growing seasons (2023-2025).

RESULTS AND DISCUSSION

Green mass yield at the sweeping stage

Mean green mass yields for three successive cuttings at the sweeping stage, averaged over 2023-2025, are presented in Table 2. The sweeping stage harvest scheme maximizes the number of cuttings per season and fully exploits the tillering capacity of the tested genotypes. This strategy is particularly valuable under the conditions of moisture limitation that characterized the period of the study. Treatment differences were statistically significant across all three cuttings, as indicated by the LSD values.

Under dense sowing, the first cutting produced the highest yields of the season. The unfertilized mean was 35.70 t ha^{-1} , which increased to 43.29 t ha^{-1} with nitrogen fertilization (21.3% increase). SZT, SAxSZ and Shumen Sweet recorded the highest first cutting yields. Notably, nitrogen fertilization boosted first cutting yields by 47.7% in SAxSZ and 44.3% in Shumen Sweet. Although Yantar recorded the lowest initial yield under unfertilized conditions, it showed the strongest relative response to fertilization of any genotype, an increase of 87.3%.

Yields at the second and third cuttings declined progressively as the regrowth period shortened and cumulative summer moisture deficits intensified. Nevertheless, several genotypes demonstrated high regenerative capacity. Shumen Sweet outperformed other entries with the highest fertilized yields at both the second and third cuttings.

Table 2. Green mass yield of sweet sorghum at the sweeping stage - 3 cuttings, by sowing density and nitrogen fertilization, t ha⁻¹ (mean 2023-2025)

Variant	I cutting		II cutting		III cutting	
	unfertilized	fertilized	unfertilized	fertilized	unfertilized	fertilized
Dense sowing, mean 2023-2025						
SZW	34.81	38.52	23.33	25.56	13.33	15.56
Yantar	20.37	38.15	15.93	17.78	9.26	12.59
Super Sweet	38.15	37.78	29.26	27.78	19.63	15.56
SZE	40.00	43.70	27.41	27.04	15.56	12.59
SAXSZ	32.59	48.15	25.56	23.70	13.33	12.59
SZT	45.93	48.52	22.98	31.85	17.04	15.56
SZD	37.78	39.63	20.74	23.70	11.48	11.48
Shumen Sweet	35.93	51.85	27.41	32.96	15.19	20.37
Average	35.70	43.29	24.08	26.30	14.35	14.54
Sparse sowing, mean 2023-2025						
SZW	24.07	27.04	18.89	14.07	10.74	8.89
Yantar	23.33	25.19	18.15	24.44	11.48	9.63
Super Sweet	28.89	27.78	23.33	18.89	18.52	8.15
SZE	29.26	36.67	18.52	18.89	10.74	10.74
SAXSZ	26.67	42.59	18.52	22.96	8.52	10.74
SZT	29.63	31.11	21.85	25.93	13.33	14.07
SZD	22.59	27.41	14.07	14.44	7.04	8.52
Shumen Sweet	28.52	32.59	23.33	26.67	9.26	16.67
Average	26.62	31.30	19.58	20.79	11.20	10.93
LSD 0.05	8.11		5.53		4.46	
LSD 0.01	10.79		7.35		5.93	
LSD 0.001	14.02		9.55		7.71	
CV %	9.68		9.95		14.29	

Under sparse sowing, mean yields were lower across all three cuttings. However, several genotypes demonstrated physiological plasticity, partially compensating for reduced stand density through greater individual plant biomass. Super Sweet produced strong first cutting yields, consistent with the rapid growth dynamics typical of hybrids. Shumen Sweet displayed a strong fertilizer response under sparse conditions achieving the highest third cutting value in this density variant. Similarly, SAXSZ showed a marked response to nitrogen at the first cutting.

Our results show that nitrogen fertilization and sowing density both significantly increased green mass yield at the sweeping stage, with pronounced genotypic variation in the nitrogen response. The magnitude of the nitrogen effect at the first cutting (21.3%) is broadly consistent with yield gains reported for sorghum under comparable nitrogen rates (Holman, Obour and Mengel, 2019; Bartzialis *et al.*, 2023). This reflects the disproportionate importance of nitrogen during early vegetative growth, when the critical nitrogen requirement of the crop for maximal biomass accumulation is highest (Van Oosterom, Carberry and Muchow, 2001). This places our applied rate of 70 kg active N ha⁻¹ within the efficient response range for this soil type, rather than the diminishing returns

range described by Schlegel and Bond (2021) for higher rates. The pronounced genotypic spread in fertilizer response agrees with the genotype dependent nitrogen use efficiency reported by Ostmeyer *et al.*, (2022) and Muchow (1998). SAxSZ and Shumen Sweet gained far more than Yantar, consistent with Thapa *et al.*, (2025), who found the yield benefit of nitrogen in sorghum is conditional on adequate soil moisture. The ability of Shumen Sweet to sustain the highest yields across all three cuttings, together with strong second cutting performance from SZT and Super Sweet, points to substantial regenerative capacity under repeated defoliation. This is consistent with recent evidence that sorghum genotypes differ markedly in their ability to sustain forage yield across successive cuts under water limited conditions (Nour-El-Din *et al.*, 2026).

Green mass yield at the flowering stage

Table 3 presents the mean green mass yields from two successive cuttings at the flowering stage, averaged over 2023-2025. This harvest scheme uses an extended interval between cuttings, resulting in higher initial yields compared to the sweeping stage.

Table 3. Green mass yield of sweet sorghum at the flowering stage - 2 cuttings, by sowing density and nitrogen fertilization, t ha⁻¹ (mean 2023-2025)

Variant	Flowering stage			
	I cutting		II cutting	
	unfertilized	fertilized	unfertilized	fertilized
Dense sowing, mean 2023-2025				
SZW	52.96	56.30	38.15	29.26
Yantar	31.11	38.15	22.59	24.44
Super Sweet	47.78	45.93	31.85	34.07
SZE	50.00	49.26	32.22	31.85
SAxSZ	49.26	54.07	27.04	28.15
SZT	49.63	51.11	32.96	36.30
SZD	42.59	43.70	25.56	24.81
Shumen Sweet	41.48	60.37	22.96	37.78
Average	45.60	49.86	29.17	30.83
Sparse sowing, mean 2023-2025				
SZW	38.15	42.59	24.44	25.93
Yantar	24.07	30.37	14.81	14.44
Super Sweet	32.22	38.89	26.67	25.93
SZE	28.52	35.56	21.11	19.26
SAxSZ	38.89	40.74	18.89	18.52
SZT	41.85	47.78	32.96	31.48
SZD	26.30	27.41	14.07	11.85
Shumen Sweet	34.81	34.81	17.78	20.00
Average	33.10	37.27	21.34	20.93
LSD 0.05	3.34		2.07	
LSD 0.01	4.42		2.74	
LSD 0.001	5.70		3.54	
CV %	5.06		4.98	

Under dense sowing, the mean first cutting yield was 45.60 t ha⁻¹ under unfertilized conditions and 49.86 t ha⁻¹ with fertilization, representing an increase of 9.3%. Shumen Sweet achieved the highest first cutting yield when fertilized. SZW, SZT and SAxSZ also demonstrated robust growth. Super Sweet and SZE showed slight yield declines under fertilization (-3.9% and -1.5%, respectively) rather than a positive response. Treatment differences were statistically significant at the 1% probability level (LSD_{0.01}=4.42 t ha⁻¹).

Shorter regrowth periods and intensifying summer moisture deficits restricted second cutting yields, with dense sowing means of 29.17 t ha⁻¹ (unfertilized) and 30.83 t ha⁻¹ (fertilized). Shumen Sweet, SZT and Super Sweet maintained the highest outputs. An anomalous result was observed for SZW, whose second cutting yield was lower in fertilized plots compared to unfertilized plots.

Under sparse sowing, first cutting yields averaged 33.10 t ha⁻¹ (unfertilized) and 37.27 t ha⁻¹ (fertilized), representing a reduction of approximately 27-28% relative to dense sowing. SZT proved most stable, achieving the highest yields at both cuttings. Fertilization reduced second cutting yield in six of the eight genotypes, from a marginal decline in Yantar and SAxSZ to a substantial drop in SZD (a 15.8% reduction).

The nitrogen response weakened at the flowering stage (9.3% versus 21.3%), agreeing with reports that sorghum's nitrogen response is strongest during early vegetative growth and diminishes toward reproductive development (Ostmeyer *et al.*, 2022). The slight yield declines under fertilization in Super Sweet and SZE likely reflect the same genotype-dependent ceiling on nitrogen use efficiency documented across sorghum genotypes, rather than a plateau specific to these two (Ostmeyer *et al.*, 2022). By contrast, the density effect grew larger over a longer growth interval, reaching 27-28% at flowering compared with 22-28% at sweeping. This pattern agrees with density-effect patterns described for sorghum by Benson *et al.*, (2025) and for sweet sorghum specifically, by Soleymani, Almodares and Shahrajabian (2013), where a longer growth interval between cuttings amplifies the yield cost of an understocked canopy. This agrees with evidence that higher water use efficiency drives much of the yield benefit from increased sowing density in sorghum, an effect that would likely matter more over the longer growth interval between flowering stage cuttings (Pilloni *et al.*, 2024). Shumen Sweet showed a markedly higher first cutting yield under this longer interval, reflecting the same pattern. A single, less frequent harvest accumulates more biomass than repeated, closely spaced cuts, as documented directly for sweet sorghum by Wei *et al.*, (2026). The ability of Shumen Sweet, SZT and Super Sweet to sustain the highest second-cutting yields under this scheme further points to strong regenerative capacity following an extended regrowth interval, consistent with the documented capacity of sweet sorghum for productive regrowth across successive harvests under semi-arid conditions (Nour-El-Din *et al.*, 2026).

SZW stands out as a genuine anomaly at dense sowing. Its second cutting yield was lower under fertilization than without it (29.26 t ha⁻¹ compared with 38.15 t ha⁻¹ unfertilized). Under sparse sowing, this reversal was far more

widespread, with fertilization reducing second cutting yield in six of the eight genotypes. This pattern is consistent with reports that water-deficient conditions reduce the efficiency with which sorghum converts applied nitrogen into yield, so that higher nitrogen rates fail to translate into a proportional yield gain once water becomes limiting (Thapa *et al.*, 2025). Under sparse sowing, fertilization likely increased canopy nitrogen demand without a matching water supply across most genotypes, while at dense sowing SZW appears to be an individual exception to an otherwise consistent fertilizer response.

Cumulative green mass yield by harvesting scheme

Table 4 presents seasonal cumulative green mass yields for each harvesting scheme, averaged over 2023-2025.

Under the sweeping scheme (three cuttings), dense sowing totals averaged 74.13 t ha⁻¹ (unfertilized) and 84.12 t ha⁻¹ (fertilized), representing a 13.5% gain from nutrient application. Shumen Sweet, under fertilized dense sowing, produced the highest seasonal total in the study (105.18 t ha⁻¹), followed by SZT. Super Sweet and SAxSZ also produced notably high totals.

Table 4. Cumulative green mass yield at the sweeping and flowering stages by sowing density and nitrogen fertilization, t ha⁻¹ (mean 2023-2025)

Variant	Total green mass yield, t ha ⁻¹ at:			
	Sweeping - 3 mowings		Flowering - 2 mowings	
	unfertilized	fertilized	unfertilized	fertilized
Dense sowing, mean 2023-2025				
SZW	71.47	79.64	91.11	85.56
Yantar	45.56	68.52	53.70	62.59
Super Sweet	87.04	81.12	79.63	80.00
SZE	82.97	83.33	82.22	81.11
SAxSZ	71.48	84.44	76.30	82.22
SZT	85.95	95.93	82.59	87.41
SZD	70.00	74.81	68.15	68.51
Shumen Sweet	78.53	105.18	64.44	98.15
Average	74.13	84.12	74.77	80.69
Sparse sowing, mean 2023-2025				
SZW	53.70	50.00	62.59	68.52
Yantar	52.96	59.26	38.88	44.81
Super Sweet	70.74	54.82	58.89	64.82
SZE	58.52	66.30	49.63	54.82
SAxSZ	53.71	76.29	57.78	59.26
SZT	64.81	71.11	74.81	79.26
SZD	43.70	50.37	40.37	39.26
Shumen Sweet	61.11	75.93	52.59	54.81
Average	57.41	63.01	54.44	58.19
LSD 0.05	10.78		3.93	
LSD 0.01	14.34		5.20	
LSD 0.001	18.63		6.71	
CV %	6.31		3.49	

Sparse sowing reduced cumulative yields under the sweeping scheme to 57.41 t ha⁻¹ under unfertilized conditions and 63.01 t ha⁻¹ with fertilization, representing decreases of 22.6% and 25.1%, respectively. Genotypic responses to reduced stand density varied considerably. SZT maintained comparatively high yields under both sparse sowing variants. SAxSZ showed the strongest nitrogen response under sparse sowing, with yields rising from 53.71 to 76.29 t ha⁻¹. Shumen Sweet maintained the highest absolute yield among all genotypes under sparse sowing, despite a decline of 27.8% from its dense sowing yield, the largest relative decline among the top performing genotypes. For SZW and Super Sweet, nitrogen fertilization offered no consistent yield advantage under sparse sowing, with Super Sweet showing a slight decline under this variant.

Under the flowering scheme involving two cuttings, dense sowing cumulative yields averaged 74.77 t ha⁻¹ under unfertilized conditions and 80.69 t ha⁻¹ with fertilization. Cumulative yields were comparable to those of the sweeping scheme, though the flowering scheme achieved this output via fewer cuttings at higher individual harvest yields. Shumen Sweet again led the trial under this scheme (98.15 t ha⁻¹ with fertilization). SZW and SZT also demonstrated robust performance.

Sparse sowing cumulative yields at the flowering stage averaged 54.44 t ha⁻¹ under unfertilized conditions and 58.19 t ha⁻¹ with fertilization, representing a decrease of 27% compared to dense sowing. SZT delivered the highest cumulative yields under sparse sowing at this stage. SAxSZ and SZW also maintained relatively stable yields at reduced density, with SAxSZ showing the most substantial nitrogen response. The remaining genotypes showed sharper yield depressions under sparse sowing.

Taken together, these results indicate that under the rainfed, moisture limited conditions of North-Eastern Bulgaria, genotype selection, not fertilization rate alone, sets the practical ceiling on green mass yield. Shumen Sweet and SZT combined the strongest, most consistent responses to nitrogen and density, making them the clearest candidates for immediate adoption. In the longer term, breeding toward genotypes that maintain nitrogen and water use efficiency under sparse stands, following the density-tolerant ideotype outlined by Pilloni *et al.*, (2024), would extend these gains further.

The three cutting structure of the sweeping scheme allowed genotypes to express their full regenerative capacity across successive harvests. This agrees with reports that sorghum genotypes differ in how well they tolerate repeated cutting under water limited conditions (Nour-El-Din *et al.*, 2026). Water use efficiency under denser stands also varies by genotype, and this difference explains much of the variation in density response (Pilloni *et al.*, 2024). SZT performed comparatively steadily across both sowing densities, at both the cumulative sweeping stage and the flowering stage, suggesting low sensitivity to stand density in this genotype. Shumen Sweet showed the opposite pattern. It had the largest yield increase from sparse to dense sowing among the top performing genotypes, despite retaining the highest absolute yields under sparse sowing.

Shumen Sweet therefore appears to depend more heavily on adequate stand density to express its full yield potential. The advantage of the flowering scheme in achieving comparable cumulative yields through fewer, higher yielding cuttings agrees with evidence that less frequent harvesting increases biomass accumulation per cut in sweet sorghum (Wei *et al.*, 2026). The strong cumulative performance of Shumen Sweet under this scheme mirrors the pattern observed at the flowering stage first cutting, reinforcing that this genotype benefits disproportionately from longer regrowth intervals.

CONCLUSIONS

Three years of field experimentation established clear and consistent differences in green mass productivity among sweet sorghum genotypes in response to sowing density, nitrogen fertilization and harvest frequency. The recurrent moisture deficit experienced across all three growing seasons served as a stringent test of genotypic adaptability.

A single application of ammonium nitrate (200 kg ha⁻¹) resulted in a consistent, statistically significant yield increase across all genotypes, density treatments and harvest stages. Under dense sowing, the cumulative response was +13.5% at the sweeping stage and +7.9% at the flowering stage. Under sparse sowing, the corresponding increases were +9.8% and +6.9%, confirming that the fertilization effect is more effectively expressed at higher stand densities.

Dense sowing consistently outperformed sparse sowing across all harvest schemes. At the sweeping stage, dense crop stands reached 74.13 t ha⁻¹ (unfertilized) and 84.12 t ha⁻¹ (fertilized), compared with 57.41 t ha⁻¹ and 63.01 t ha⁻¹ under sparse sowing, representing reductions of 22.6% and 25.1%, respectively. At the flowering stage, the yield advantage of dense sowing was 27.2% (unfertilized) and 27.9% (fertilized).

Shumen Sweet and SZT were the most productive genotypes under both harvest schemes when combined with dense sowing and fertilization. Shumen Sweet achieved the highest values recorded in this study, 105.18 t ha⁻¹ at the sweeping stage and 98.15 t ha⁻¹ at the flowering stage. SZT demonstrated consistently high and stable productivity across all management systems.

Based on these findings, we recommend that farmers use the agronomic combination of dense sowing (110-130 plants m⁻²) and a single nitrogen application (200 kg ha⁻¹ NH₄NO₃) as a practical management strategy to maximize green biomass production in sweet sorghum under the environmental conditions of North-Eastern Bulgaria. This approach provides a sound basis for optimizing raw material supply for stem extract production.

ACKNOWLEDGMENTS

This work was carried out within the framework of project KII-06-M96/1/09.12.2025 “Testing the effect of sweet sorghum extract (*Sorghum bicolor* (L.) Moench) on overcoming neonatal hypoglycemia in farm animals”, funded by the National Science Fund - Ministry of Education and Science, Republic of Bulgaria.

REFERENCES

- Bartzialis, D., Giannoulis, K.D., Gintsiodis, I., & Danalatos, N.G. (2023). Assessing the efficiency of different nitrogen fertilization levels on sorghum yield and quality characteristics. *Agriculture*, 13(6): 1253.
- Benson, I., Lofton, J., Rice, J., & Cannon, B. (2025). The impact of planting density and intermediate skips on grain sorghum yields. *Crops*, 5(3): 25.
- Carvalho, G., & Rooney, W.L. (2017). Assessment of stalk properties to predict juice yield in sorghum. *Bioenergy Research*, 10(3): 657-670.
- Donchev, V., & Enchev, S. (2024). Effect of different mowing and fertilization schemes on productivity of sudangrass (*Sorghum sudanense* (Piper) Stapf.). *Journal of Mountain Agriculture on the Balkans*, 27(2): 108-123.
- Enchev, S. (2023). Productivity of sweet sorghum under ecological production conditions. *Bulgarian Journal of Agricultural Science*, 29(5): 800-804.
- Enchev, S., & Kikindonov, T. (2023). Breeding of the first Bulgarian sweet sorghum variety Shumen Sweet. *Scientific Papers. Series A. Agronomy*, LXVI(1): 318-321.
- Enchev, S., Kikindonov, G., & Slanev, K. (2016). Productive potential of varieties and elite populations of sweet sorghum for silage production. *Journal of Mountain Agriculture on the Balkans*, 19: 124-134.
- Figueiredo, U.J., Nunes, J.A.R., Parrella, R.A.C., Souza, E.D., Silva, A.R., Emygdio, B.M., Machado, J.R.A., & Tardin, F.D. (2015). Adaptability and stability of sweet sorghum genotypes assessed by GGEbiplot and Toler methods. *Genetics and Molecular Research*, 14(3): 11211-11221.
- Holman, J.D., Obour, A.K., & Mengel, D.B. (2019). Nitrogen application effects on forage sorghum production and nitrate concentration. *Journal of Plant Nutrition*, 42(20): 2794-2804.
- IUSS Working Group WRB (2022). World reference base for soil resources: international soil classification system for naming soils and creating legends for soil maps (4th ed.). Vienna, International Union of Soil Sciences (IUSS).
- Kawahigashi, H., Kasuga, S., Okuizumi, H., Hiradate, S., & Yonemaru, J. (2013). Evaluation of Brix and sugar content in stem juice from sorghum varieties. *Grassland Science*, 59(1): 11-19.
- Kikindonov, T., & Enchev, S. (2015). Testing sweet sorghum as a raw material for the production of sweeteners. *Bulgarian Journal of Agricultural Science*, 52(6): 33-36.
- Kikindonov, T., Enchev, S., & Slanev, K. (2013). Influence of variety and sowing rate on the green mass productivity of sudangrass and Sorghum x sudangrass hybrids. *Agricultural Science and Technology*, 5(1): 11-18.
- Leghari, S.J., Wahocho, N.A., Laghari, G.M., Talpur, K.H., Wahocho, S.A., & Lashari, A.A. (2016). Role of nitrogen for plant growth and development: a review. *Advances in Environmental Biology*, 10(9): 209-218.
- Muchow, R.C. (1998). Nitrogen utilization efficiency in maize and grain sorghum. *Field Crops Research*, 56(1-2): 209-220.
- Nazli, R.I., Aslankaciran, C., Yang, D., Liaqat, W., Polat, M., Cavdar, A.S., Tansi, V., & Baloch, F.S. (2024). Assessment of sweet sorghum genotypes for bioethanol production potential and bagasse combustion characteristics in a semi-arid Mediterranean climate. *Agronomy*, 14(11): 2626.

- Nour-El-Din, N., Attia, M.A., El-Hashash, E.F., El-Absy, K.M., El-Shaer, H.M., Youssef, A.M.A., Sallam, S.M.A., Khafaga, H.S., Abdelghany, F.I., & Abdelatty, S.A.A. (2026). Application of various agricultural practices on sorghum forage yield and its association with water use efficiency under deficit irrigation conditions. *Scientific Reports*, 16: 3271.
- Ostmeyer, T.J., Bahuguna, R.N., Kirkham, M.B., Bean, S., & Jagadish, S.V.K. (2022). Enhancing sorghum yield through efficient use of nitrogen - challenges and opportunities. *Frontiers in Plant Science*, 13: 845443.
- Perrier, L., Rouan, L., Jaffuel, S., Clément-Vidal, A., Roques, S., Soutiras, A., Baptiste, C., Bastianelli, D., Fabre, D., Dubois, C., Pot, D., & Luquet, D. (2017). Plasticity of sorghum stem biomass accumulation in response to water deficit: a multiscale analysis from internode tissue to plant level. *Frontiers in Plant Science*, 8: 1516.
- Pilloni, R., Kakker, A., Kholova, J., Tardieu, F., & Vadez, V. (2024). The genotypic variation in the positive response of sorghum to higher sowing density is linked to an increase in water use efficiency. *European Journal of Agronomy*, 158: 127207.
- Rooney, W.L. (2000). Genetics and cytogenetics. In C.W. Smith & R.A. Frederiksen, eds. *Sorghum: origin, history, technology and production*, pp. 261-307. New York, USA, Wiley. 840 pp.
- Schlegel, A., & Bond, D. (2021). Irrigated grain sorghum response to long-term nitrogen, phosphorus and potassium fertilization. *Kansas Agricultural Experiment Station Research Reports*, 7(7): 1-13.
- Smith, C.W., & Frederiksen, R.A. (Eds.) (2000). *Sorghum: origin, history, technology and production*. New York, USA, Wiley. 840 pp.
- Soleymani, A., Almodares, A., & Shahrajabian, M.H. (2013). Effect of increasing plant density on stem yield, sucrose content and ethanol yield in two sweet sorghum cultivars. *International Journal of Agronomy and Plant Production*, 4: 642-646.
- Ssebulime, S., Nuwamanya, E., Kakeeto, R., Opolot, E., Echodu, E., Alinaitwe, H.O., Migamba, L., Biruma, M., & Adikini, S. (2025). Drought recovery responses in grain sorghum: insights into genotypic variation and adaptation. *Agronomy*, 15(10): 2356.
- Thapa, B., Awal, R., Fares, A., Veetil, A.V., Elhassan, A., & Rahman, A. (2025). Optimized irrigation and nitrogen fertilization enhance sorghum yield and resilience in drought-prone regions. *Plants*, 14(18): 2913.
- Tovignan, T.K., Fonceka, D., Ndoye, I., Cisse, N., & Luquet, D. (2016). Sowing date and post-flowering water status affect sugar and grain production in photoperiodic sweet sorghum through regulation of sink size and leaf area dynamics. *Field Crops Research*, 192: 67-77.
- Van Oosterom, E.J., Carberry, P.S., & Muchow, R.C. (2001). Critical and minimum N contents for development and growth of grain sorghum. *Field Crops Research*, 70(1): 55-73.
- Varbanov, M., & Hristova, L. (1996). Biological features and productive capabilities of sweet sorghum. In *Proc. Jubilee Scientific Session "25 Years of Shumen University"*, Shumen, Bulgaria, pp. 129-132.
- Vinutha, K.S., Rayaprolu, L., Yadagiri, K., Umakanth, A.V., Patil, J.V., & Srinivasa Rao, P. (2014). Sweet sorghum research and development in India: status and prospects. *Sugar Tech*, 16(2): 133-143.

- Wang, X., Gowik, U., Tang, H., Bowers, J.E., Westhoff, P., & Paterson, A.H. (2009). Comparative genomic analysis of C4 photosynthetic pathway evolution in grasses. *Genome Biology*, 10: R68.
- Wang, Z., Nie, T., Lu, D., Zhang, P., Li, J., Li, F., Zhang, Z., Chen, P., Jiang, L., Dai, C., & Waller, P.M. (2024). Effects of different irrigation management and nitrogen rates on sorghum growth, yield and soil nitrogen accumulation under drip irrigation. *Agronomy*, 14(1): 215.
- Wei, K., Ma, R., Jiang, C., Li, Z., Shen, Y., & Yang, X. (2026). Effects of irrigation level and cutting frequency on yield, quality, and water-nitrogen use efficiency in forage sweet sorghum: evidence from auto-weighted lysimeters. *Plant Soil*, 519(1): 813-832.
- Welham, S.J., Gezan, S.A., Clark, S.J., & Mead, A. (2014). *Statistical methods in biology: design and analysis of experiments and regression*. Boca Raton, Florida, USA, CRC Press. 582 pp.
- Zhao, Y.L., Dolat, A., Steinberger, Y., Wang, X., Osman, A., & Xie, G.H. (2009). Biomass yield and changes in chemical composition of sweet sorghum cultivars grown for biofuel. *Field Crops Research*, 111(1-2): 55-64.