

Article

Physiological Trade-Offs Between Biomass Yield and Nutritional Quality of Sweet Sorghum Regulated by Planting Density and Mowing in Semiarid Drylands

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Abstract

Feed shortage and water scarcity critically constrain livestock production in semiarid regions, yet the interactive mechanism of growth by which planting density and mowing shape the trade-off between biomass yield and nutritional quality remain poorly quantified for rainfed sweet sorghum (*Sorghum bicolor* L. Moench). The Loess Plateau is located in the north-central part of China. It belongs to the semiarid continental monsoon climate and is mainly rainfed by agriculture. A two-year field experiment (2023–2024) was conducted in this region to investigate how four planting densities (50,000, 70,000, 90,000 and 110,000 plants·ha^{−1}) and two mowing regimes regulate plant morphology, root development and comprehensive nutritional traits. Compared with a mowing treatment, a non-mowing treatment significantly increased dry matter yield from 8.54 t·ha^{−1} to 21.59 t·ha^{−1} (an increase of 152.7%) in 2023 and from 10.32 t·ha^{−1} to 20.91 t·ha^{−1} (an increase of 102.6%) in 2024. Increasing planting density elevated population biomass, with the 90,000 plants·ha^{−1} treatment optimally balancing individual growth and interplant resource competition. Mowing reduced stem diameter, leaf area index, and root biomass, thereby lowering fiber concentration but suppressing total dry matter accumulation. Structural equation modeling (GFI = 0.937) quantified this dual effect: mowing exerted a strong negative direct effect on dry matter yield (path coefficient = −4.211, explaining 94.9% of the yield variance) but indirectly improved nutritional quality by thinning stems to optimize leaf allocation. Integrated random forest and radar chart multi-index evaluation identified non-mowing at 90,000 plants·ha^{−1} as the optimal cultivation regime (comprehensive score $Y = 0.917$), which coordinated population biomass and nutritional performance while delivering a 23.3% higher net profit than conventional mowing treatments. This study revealed the physiological trade-off path between biomass productivity of sorghum and its quality under drought stress under rainfed conditions on the Loess Plateau and provides a quantitative, replicable evaluation framework to optimize agronomic management for sweet sorghum and analogous C4 crops in global semiarid rainfed ecosystems, offering practical strategies for sustainable forage production.

Keywords: semiarid region; mowing; planting density; forage sweet sorghum; biomass allocation; forage quality



Academic Editor: Othmane Merah

Received: 8 August 2026

Revised: 7 September 2026

Accepted: 12 September 2026

Published: 15 September 2026

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1. Introduction

In recent years, the production of traditional feed crops in semiarid areas has faced multiple constraints, such as water shortage, barren soil and frequent extreme weather events, and the stability of yield and quality is difficult to guarantee [1]. At the same time, the demand for high-quality forage in animal husbandry continues to rise, and the contradiction between supply and demand is becoming increasingly acute. According to China's first national forage development plan, more than 120 million tons of high-quality forage is needed to ensure the self-sufficiency of beef, mutton and milk, with a gap of nearly 50 million tons [2]. Therefore, mining alternative forage crops adapted to local ecological conditions and establishing supporting agronomic optimization schemes have become the key path to ensure the safety of regional animal husbandry.

Forage sweet sorghum (*Sorghum bicolor* L. Moench), a typical C4 crop, is widely recognized as a promising alternative forage in semiarid regions due to its outstanding drought tolerance, salinity–alkalinity tolerance, low soil fertility requirement, and high photosynthetic efficiency [3]. Compared with maize and other water-intensive crops, sweet sorghum can maintain relatively high biomass production under water-limited conditions, with stems rich in soluble sugars and leaves containing relatively high crude protein, giving it excellent forage value [4]. Nevertheless, the specific precipitation and soil conditions of semiarid regions limit its productive potential, and optimizing agronomic regulation to unlock yield and quality potential has become a research priority.

Among various agronomic practices, planting density and mowing regime are two key manageable factors affecting the productivity and quality of forage sweet sorghum [5]. Density directly affects the utilization efficiency of light, water and nutrients by regulating the balance between individual growth and resource competition, which in turn affects stem elongation, dry matter accumulation and lodging risk [6,7]. Mowing affects the digestibility and palatability of forage by regulating plant regeneration, biomass allocation and nutritional quality [8,9].

Although studies have explored the effects of density and mowing on forage production, systematic studies on the interaction between the two are still very limited, especially under semiarid rainfed conditions. Density determines the initial resource competition pattern, while mowing reshapes the canopy structure and material distribution strategy during the regeneration process, and the interaction between the two is complex. In addition, most of the existing studies focus on dry matter yield, and a coordinated analysis of quality traits, such as crude protein and fiber composition, is relatively insufficient [10]. Nutritional quality is directly related to animal feed intake and weight gain efficiency, and its importance is no less than yield [11]. Therefore, in the sweet sorghum production system in semiarid areas, it is urgent to comprehensively evaluate the synergistic effect of planting density and mowing mode on yield and quality under a unified framework, in order to provide optimal management strategies for forage production in the region.

Given this, based on a two-year field experiment, the present study systematically investigated the effects of planting density and mowing regime on key agronomic traits (plant height, stem diameter, leaf area index, and tiller number per plant), dry matter yield, and forage quality indicators (crude protein, starch, neutral detergent fiber, and acid detergent fiber) of forage sweet sorghum grown under typical semiarid ecological conditions, with a particular focus on their interactive effects. The study aimed to answer the following: (1) Under semiarid water limitation, how do density and mowing independently affect yield formation and quality characteristics? (2) Given the resource constraints of semiarid regions, can an optimal density–mowing combination be identified to coordinate yield, quality, and resource efficiency? This study is expected to provide a theoretical basis and practical guidance for efficient, high-quality, and sustainable cultivation of forage sweet

sorghum in semiarid regions and to promote the coordinated development of regional animal husbandry and ecological conservation.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted from April 2023 to October 2024 at the National Field Scientific Observation and Research Station of Qingyang Grassland Agroecosystem in Gansu Province, northwest China (latitude 35° 39' N, longitude 107° 51' E, altitude 1297 m). The station is located in the western Loess Plateau and has a temperate continental monsoon climate, representing a typical semiarid rainfed agricultural region. Based on long-term meteorological data (2001–2024), the annual mean precipitation and temperature in this region are 581.2 mm and 10.1 °C, respectively, with a humidity of 61.8%, a wind speed of 2.2 m·s^{−1}, and a frost-free period of 165 days. The test site is flat, and the slope is 0°, so there is no aspect problem. Before sowing in 2023, the soil texture of a 0–60 cm soil layer in the test site was silt loam. The soil physical and chemical properties of the 0–60 cm soil layer in the experimental site are as shown in Table 1. Monthly precipitation in 2023 and 2024 and long-term (2001–2024) average monthly precipitation and temperature are shown in Figure 1.

Table 1. Soil physicochemical properties in the 0–60 cm layer at the experimental site.

Soil Depth (cm)	Bulk Density (g·cm ^{−3})	Organic Matter (g·kg ^{−1})	Total N (g·kg ^{−1})	Available N (mg·kg ^{−1})	Available P (mg·kg ^{−1})	Available K (mg·kg ^{−1})	pH
0–20	1.38	17.4	1.0	19.78	15.7	110.0	8.1
20–40	1.41	14.3	0.9	21.05	12.7	97.1	8.2
40–60	1.29	16.5	0.9	18.11	11.4	96.2	8.2

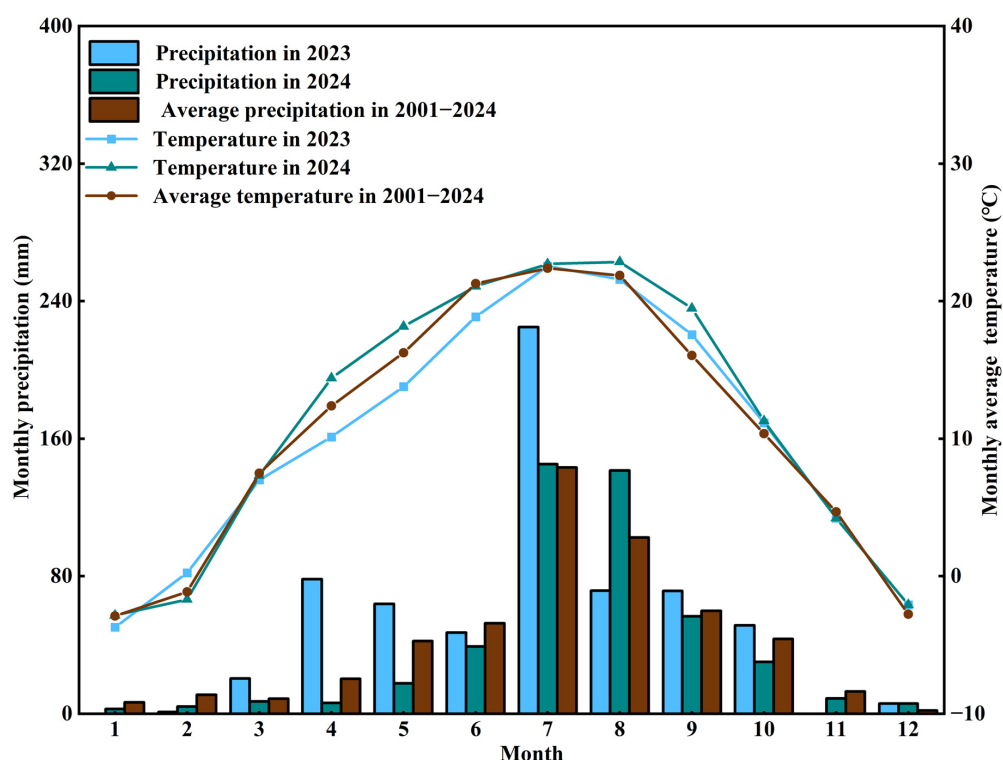


Figure 1. Monthly precipitation and temperature at the experimental site in 2023 and 2024, and long-term (2001–2024) average precipitation and temperature.

2.2. Experimental Design

The experiment used a two-factor randomized complete block design. The factors were planting density (D) and mowing regime (M). Four planting densities were set: 50,000 (D_5), 70,000 (D_7), 90,000 (D_9), and 110,000 (D_{11}) plants·ha⁻¹. The row spacing was 0.5 m for all densities, with a within-row spacing of 0.4, 0.29, 0.22, and 0.18 m, respectively. Two mowing regimes were applied: non-mowing (NM), in which the crop was harvested only once at maturity, and mowing (M), in which the crop was cut once when plants reached approximately 1.8 m in height (stubble height, 5 cm), and the regrowth was harvested at the same time as the non-mowed treatment. The tested variety was “Hunnigreen”, a commercial forage sorghum hybrid widely planted by local farmers for its short growth cycle and high biomass yield. In this experiment, a total of 8 treatments were carried out, with 4 replicates each time, a total of 32 plots, and the plot area was 15 m² (3 m × 5 m). A randomized complete block design was chosen because both planting density and mowing are whole-plot factors with no hierarchy for subplot assignment, providing balanced replication and a single error term suitable for our analyses.

2.3. General Agrotechnical Parameters of the Experiment

The former crop was forage corn, which was deep-ploughed to a depth of 20 cm by a rotary tiller after harvest and then raked flat. No other tillage was carried out before sowing. On 27 April 2023 and 1 May 2023, artificial sowing was carried out using on-demand seeders. The first mowing was carried out on 7 August 2023 and 13 August 2024, respectively. The last harvest was completed on 21 September 2023 and 27 September 2024, respectively. Each treatment was applied in the way of strip application, and the amount of fertilizer was the same: 150 kg of N·ha⁻¹, 120 kg of P₂O₅·ha⁻¹, and 150 kg of K₂O·ha⁻¹. All phosphorus (superphosphate, 16% P₂O₅) and potassium (potassium sulfate, 51% K₂O) fertilizers, together with 30% of the nitrogen fertilizer (urea, 46% N), were applied at the seedling stage. An additional 40% nitrogen fertilizer was applied at the jointing stage, and the remaining 30% was applied after mowing (for mowed treatments).

2.4. Measurements and Calculations

2.4.1. Determination of Agronomic Traits

In each experimental plot, five plants were randomly selected and tagged for repeated measurement of plant height and stem diameter. Measurements were taken every 30 days. Plant height was measured using a ruler (range, 5 m; precision, 0.1 cm), stem diameter with a vernier caliper (range, 150 mm; precision, 0.1 mm), and LAI with a plant canopy analyzer (LAI-2000, LI-COR, Lincoln, NE, USA). The tiller number per plant was determined by counting the total tillers of each plant in the two central rows of the plot (approximately 40 plants on average) during the growing season and then calculating the average.

2.4.2. Root Distribution

After harvest, the soil cores of the 0–20 cm and 20–40 cm soil layers were collected with a root drill (inner diameter of 9 cm) at a fixed position in each plot. Three drills were taken from each layer, and the same layer was mixed into one sample, and the average value was taken. For each of the four replicated plots, the sampling points were arranged diagonally in the plot. The soil samples were placed in a 0.25 mm aperture nylon mesh bag and gently rinsed with deionized water to avoid rubbing damage to fine roots until the water became clear and no visible sediment residue was observed. According to the morphological criteria of living/dead roots, the living roots were sorted: the color of the living roots was bright (yellowish brown), the tissue was full and elastic, and the center of the transverse section was milky white; the dead roots were dark brown or black and

fragile and easy to break, and the cortex fell off. Absorbent paper was used to absorb water from the surface of the sorted roots. The roots were then scanned using an EPSON Scanner (Expression 11000XL, Markham, ON, Canada), and parameters including root length (RL) and root volume (RV) were extracted using the WinRHIZO Pro 2019b image analysis software. After scanning, roots were oven-dried at 65 °C to constant weight and weighed using a precision electronic balance (0.0001 g) to obtain the root biomass (RB). The following formulas were used [12]:

$$RB \text{ (g} \cdot \text{cm}^{-3}) = MD \text{ (g)} / V \text{ (cm}^{-3}) \quad (1)$$

$$RL \text{ (cm} \cdot \text{cm}^{-3}) = \text{TRL (cm)} / V \text{ (cm}^{-3}) \quad (2)$$

$$RV \text{ (mm}^3 \cdot \text{cm}^{-3}) = \text{TRV (mm}^3) / V \text{ (cm}^{-3}) \quad (3)$$

where MD is the root dry mass (g), TRL is the total root length (cm), TRV is the total root volume (mm³), and V is the sampled soil volume (cm^{−3}).

2.4.3. Determination of Dry Matter Yield

After the first mowing and at the final harvest, three representative plants were sampled from each plot, and fresh weights were recorded. Subsequently, they were dried at 105 °C for 30 min for deactivation and then at 75 °C to constant weight to determine the water content (or fresh-to-dry ratio). After sampling, the entire aboveground biomass of each plot was harvested and weighed to obtain the fresh plot yield. The dry matter yield per hectare (DM yield) was then calculated based on fresh weight and plant water content. For the mowing treatment, the DM yield was the sum of the first cutting and the regrowth harvested at the final harvest.

2.4.4. Determination of Forage Quality Indices

Dried plant samples were ground to pass through a 0.425 mm sieve. Standard methods [13,14] were used to determine the crude protein (CP), starch (STA), neutral detergent fiber (NDF), and acid detergent fiber (ADF) contents of forage sweet sorghum. Total digestible nutrients (TDNs), relative feed value (RFV), and relative forage quality (RFQ) are widely used indices for comprehensive forage quality assessment, with higher values indicating better quality. The forage grading index (GI) and food equivalent unit (FEU) are indices that quantify the grain value of forage and evaluate the efficiency of different food production systems. GI integrates the available energy and protein content of roughage, combined with NDF to reflect physical characteristics, providing a more objective measure of nutritional value for ruminants. FEU quantifies edible value based on energy, crude protein content, digestibility, and metabolic efficiency, facilitating comparisons across different food production systems. Voluntary dry matter intake (VDMI) is a key parameter for calculating GI. The above indices (RFQ, TDNs, GI, and FEU) were calculated using the following formulas [15]:

$$\text{DMI (\%)} = 120 / \text{NDF} \quad (4)$$

$$\text{DDM (\%)} = 88.9 - 0.779 \times \text{ADF} \quad (5)$$

$$\text{RFV (\%)} = \text{DMI} \times \text{DDM} / 1.29 \quad (6)$$

$$\text{RFQ (\%)} = 1.9499 \times \text{RFV} - 67.038 \quad (7)$$

$$\text{TDN} = 81.38 + (\text{CP} \times 0.36) - (\text{ADF} \times 0.77) \quad (8)$$

$$\text{NE}_1 \text{ (MJ} \cdot \text{kg}^{-1}) = [1.044 - (0.0124 \times \text{ADF})] \times 9.29 \quad (9)$$

$$\text{VDMI (kg} \cdot \text{d}^{-1}) = 1.2 \times \text{BW} / \text{NDF} \quad (10)$$

$$GI (MJ \cdot d^{-1}) = NE_l \times VDMI \times (CP/NDF) \quad (11)$$

$$FEU = DDM \times (H \times 0.042 + CP \times 0.0033) \quad (12)$$

where DDM is digestible dry matter, DMI is dry matter intake, NE_l is the net energy for lactation, VDMI is voluntary dry matter intake, BW is the body weight of dairy cattle (taken as 600 kg), H is the energy of silage sorghum ($12.94 \text{ MJ} \cdot \text{kg}^{-1}$), and CP is the crude protein content of silage sorghum ($\text{g} \cdot \text{kg}^{-1}$).

2.4.5. Calculation of Economic Benefits

Economic benefits were calculated using the following formula:

$$EB (\text{CNY} \cdot \text{ha}^{-1}) = PS \times FY - N \times PN - P \times PP - K \times PK - C_s - C_l \quad (13)$$

where PS is the unit price of fresh silage sweet sorghum ($500 \text{ CNY} \cdot \text{t}^{-1}$), FY is the fresh yield ($\text{t} \cdot \text{ha}^{-1}$), N is the nitrogen fertilizer rate, PN is the price of urea ($2.2 \text{ CNY} \cdot \text{kg}^{-1}$), P is the phosphorus fertilizer rate, PP is the price of superphosphate ($3.3 \text{ CNY} \cdot \text{kg}^{-1}$), K is the potassium fertilizer rate, PK is the price of potassium sulfate ($3.6 \text{ CNY} \cdot \text{kg}^{-1}$), C_s is the seed cost (540, 756, 972, and $1080 \text{ CNY} \cdot \text{ha}^{-1}$ for D₅, D₇, D₉, and D₁₁, respectively), and C_l is the labor cost (500, 700, 900, and $1000 \text{ CNY} \cdot \text{ha}^{-1}$ for NMD₅, NMD₇, NMD₉, and NMD₁₁, respectively; 1000, 1400, 1800, and $2000 \text{ CNY} \cdot \text{ha}^{-1}$ for MD₅, MD₇, MD₉, and MD₁₁, respectively).

2.4.6. Comprehensive Evaluation and Analysis Method

To systematically evaluate the combined effects of different treatments on the yield and forage quality of sweet sorghum, six core indicators—dry matter yield, starch content, total digestible nutrients, forage grading index, food equivalent unit, and economic benefit—were linearly transformed to a 0–1 scale, where 0 represents the worst performance and 1 the best. The transformation formula for each indicator is as follows [16]:

$$A_{ij} = A'_{ij} / A'_{ij\max} \quad (14)$$

where i is the number of evaluation objects (treatments), j is the number of evaluation indicators, A'_{ij} is the original value of the j -th indicator for the i -th treatment, $A'_{ij\max}$ is the maximum value among treatments for that indicator, and A_{ij} is the transformed value.

To comprehensively reflect the overall performance and balance among indicators, the area (S_i) and perimeter (L_i) of the radar chart were extracted as feature vectors to construct a two-dimensional feature vector for calculating the comprehensive evaluation function value. The formulas are as follows:

$$S_i = \sum_{(j=1)}^K \frac{1}{2} A_{ij} A_{i(j+1)} \sin \alpha \quad (15)$$

$$L_i = \sum_{(j=1)}^K \sqrt{(A_{ij}^2 + A_{i(j+1)}^2 - 2A_{ij} A_{i(j+1)} \cos \alpha)} \quad (16)$$

where S_i is the sum of the areas of the triangles formed by adjacent axes in the radar chart, L_i is the perimeter of the radar chart, k is the number of evaluation indicators, A_{ij} is the transformed value of the j -th indicator for the i -th treatment, and α is the angle between adjacent axes ($\alpha = 2\pi/k$).

An evaluation vector V_i (V_{i1} , V_{i2}) was then constructed to reflect the overall performance of each treatment and the balance among indicators:

$$V_{i1} = S_i / S_{\max} \quad (17)$$

$$V_{i2} = (4\pi S_i)/L_i^2 \quad (18)$$

where V_{i1} is the area evaluation value (larger values indicate better overall performance), and V_{i2} is the perimeter evaluation value (larger values indicate better balance among indicators).

Finally, an evaluation function, Y , was constructed from the evaluation vector, and treatments were ranked according to Y :

$$Y = \sqrt{(V_{i1} \times V_{i2})} \quad (19)$$

Larger Y values indicate better overall performance and greater balance among indicators.

2.5. Statistical Analysis

Data were organized and summarized using Excel 2021 (Microsoft, Redmond, WA, USA). Two-way analysis of variance (ANOVA) was performed using SPSS 21.0 (SPSS Inc., Chicago, IL, USA). Means were compared using Duncan's multiple range test. Graphs were created using Origin 2021 (OriginLab, Corporation, Northampton, MA, USA). Random forest analysis was conducted using the "rfPermute" package in R 4.5.0, and variables were ranked by the percentage increase in mean squared error. Structural equation modeling (SEM) was performed using partial least squares path modeling, with model fit evaluated by the goodness-of-fit index (GFI). Radar chart-based comprehensive evaluation was used for multi-indicator assessment. Significance was declared at $p < 0.05$.

3. Results

3.1. Plant Height, Stem Diameter, Leaf Area Index, and Tiller Number per Plant

The plant height of the forage sweet sorghum increased continuously with growth stage in both 2023 and 2024, whereas LAI, stem diameter, and tiller number per plant increased rapidly in the early stages and then stabilized (Figure 2). Plant height and LAI increased with an increasing planting density in both years, while stem diameter and tiller number per plant showed the opposite trend. Compared with non-mowing, the mowing treatment resulted in a lower plant height, LAI, and stem diameter but a higher tiller number per plant in both years. During the period from cutting to harvesting, LAI and tiller number per plant showed significant differences among treatments.

Note: D_5 , D_7 , D_9 and D_{11} represent the four planting densities of 50,000, 70,000, 90,000, and 110,000 plants·ha⁻¹, respectively, while M and NM represent mowed and non-mowed, respectively.

3.2. Root Biomass, Root Length, and Root Volume

Both planting density and mowing significantly affected the root biomass, root length, and root volume of the forage sweet sorghum (Figure 3). In 2023, density significantly affected root biomass and root length in both the 0–20 cm and 20–40 cm soil layers; in 2024, density significantly affected root volume in the 0–20 cm layer and root biomass in the 20–40 cm layer. Specifically, in the 0–20 cm layer in 2023, root biomass at D_7 was significantly higher than at D_5 by 92.9% but not significantly different from D_9 or D_{11} . Root length at D_7 and D_9 was significantly higher than at D_5 by 45.9% and 77.1%, respectively. In the 20–40 cm layer, root biomass at D_5 , D_7 , and D_9 was significantly higher than at D_{11} , and root length at D_5 , D_9 , and D_{11} was significantly higher than at D_7 . In 2024, in the 0–20 cm layer, root volume at D_9 was significantly higher than at D_5 and D_7 by 31.8% and 28.5%, respectively but not significantly different from D_{11} . In the 20–40 cm layer, root biomass at D_{11} was significantly higher than at D_5 but not significantly different from D_7 or D_9 .

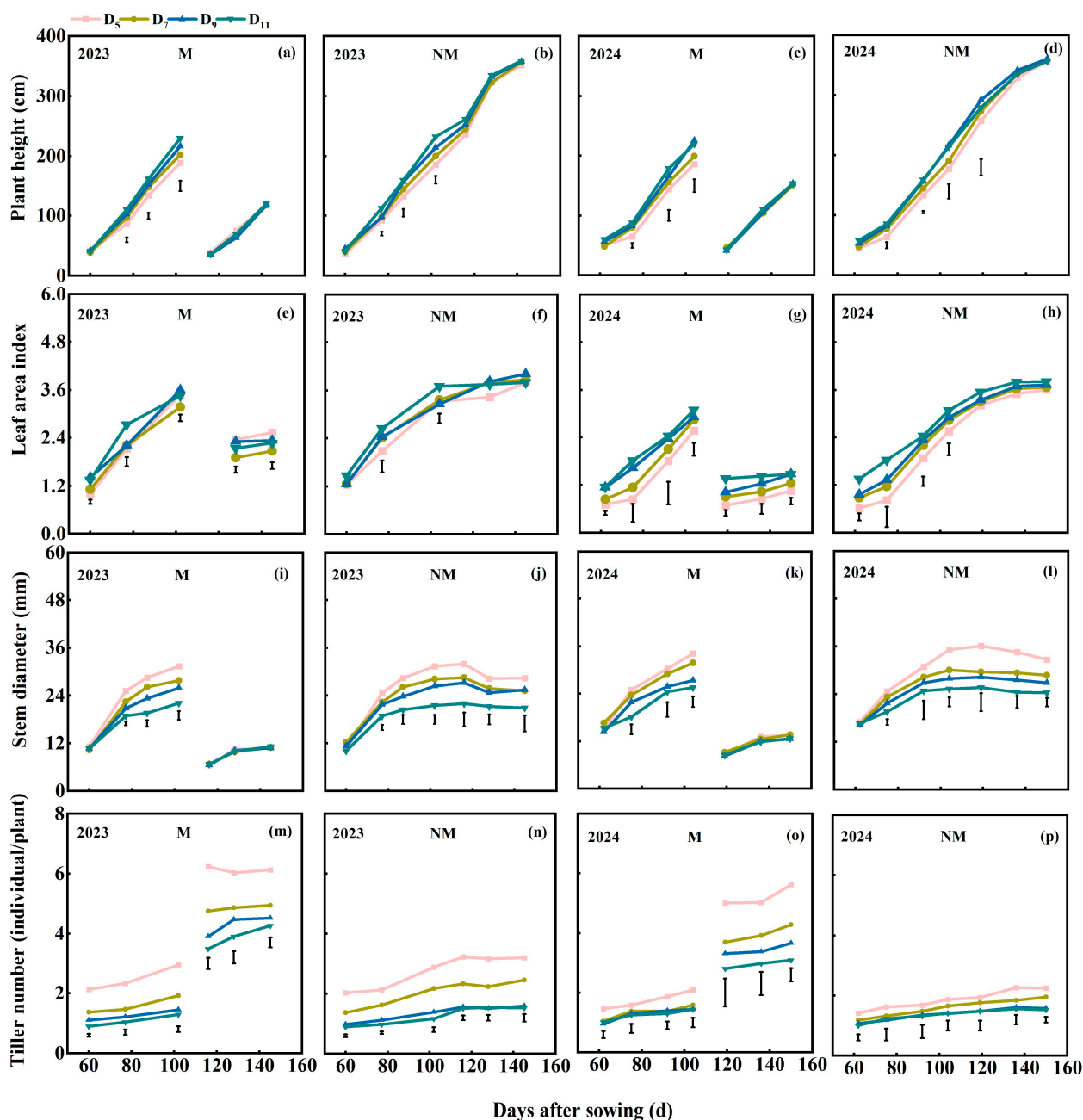


Figure 2. Effects of different planting densities and mowing regimes on plant height, stem diameter, leaf area index, and tiller number per plant of forage sweet sorghum in 2023 and 2024. (a–d) Plant height; (e–h) Stem diameter; (i–l) Leaf area index; (m–p) Tiller number per plant. The error bar represents the least significant difference (LSD) at the $p < 0.05$ level.

For mowing, in 2023, in the 0–20 cm layer, root biomass, root length, and root volume were significantly higher under non-mowing than under mowing; in the 20–40 cm layer, root biomass and root length were significantly higher under non-mowing. In 2024, in the 0–20 cm layer, root biomass and root volume were significantly higher under non-mowing; in the 20–40 cm layer, root length was significantly higher under non-mowing. No significant planting density $\times$ mowing interactions were observed for any root parameter in either year.

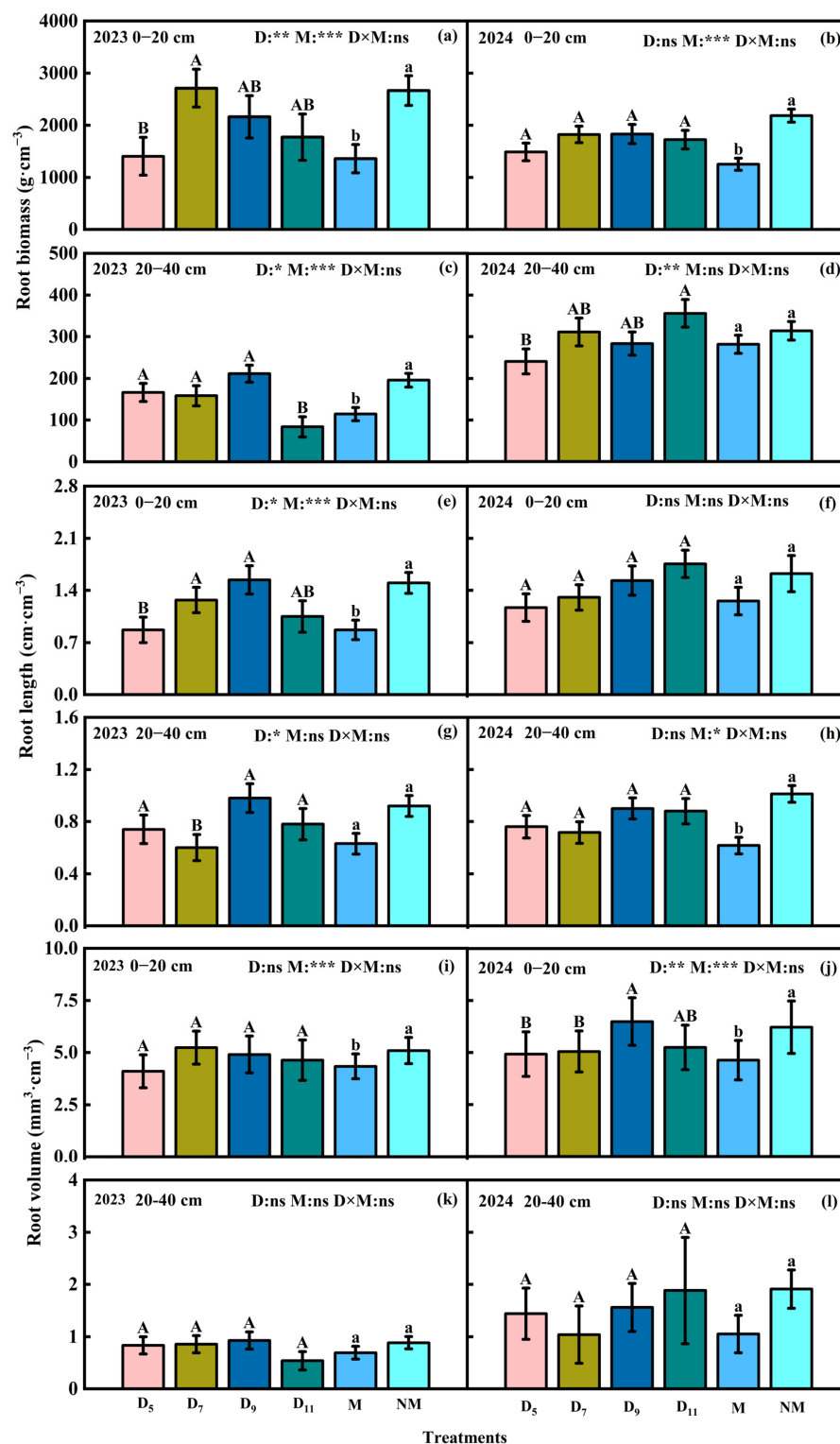


Figure 3. Effects of different planting densities and mowing regimes on root biomass, root length, and root volume of forage sweet sorghum in 2023 and 2024. (a–d) Root biomass; (e–h) Root length; (i–l) Root volume; Asterisks *, **, *** indicate significance at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively. Note: D₅, D₇, D₉ and D₁₁ represent the four planting densities of 50,000, 70,000, 90,000, and 110,000 plants·ha⁻¹, respectively, while M and NM represent mowed and non-mowed, respectively. Different lowercase letters indicate that under the same planting density, the difference between different mowing treatments reaches the $p < 0.05$ significant level; different capital letters indicate that under the same cutting treatment, the difference between different planting densities reaches the $p < 0.05$ significant level.

3.3. Dry Matter Yield

Both planting density and mowing significantly affected the dry matter yield of the forage sweet sorghum (Figure 4). For density, in 2023, the dry matter yield at D₉ was significantly higher than at D₅ by 22.1% but not significantly different from D₇ or D₁₁. In 2024, the dry matter yield at D₁₁ was significantly higher than at D₅ by 42.6% but not significantly different from D₇ or D₉. For mowing, in 2023, the dry matter yield of the non-mowing treatment was significantly increased by 152.7% compared with the mowing treatment, and in 2024, it was significantly increased by 102.6%. No significant planting density × mowing interaction was observed in either year.

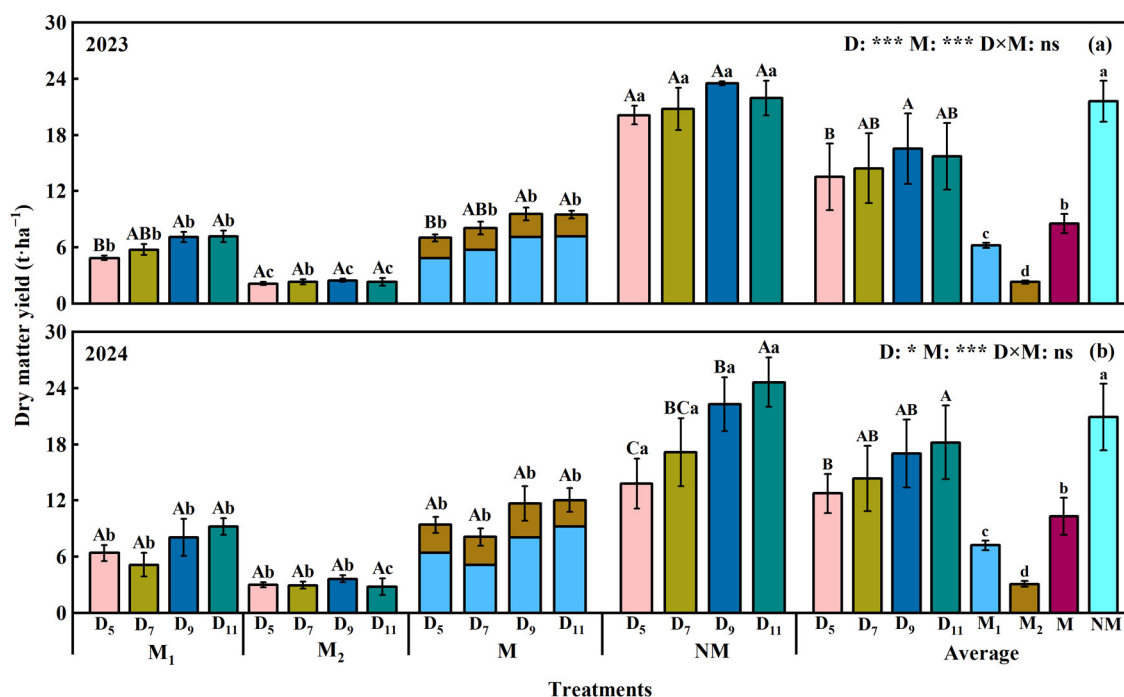


Figure 4. Effects of different planting densities and mowing regimes on dry matter yield of forage sweet sorghum in 2023 and 2024. (a) Dry matter yield in 2023; (b) Dry matter yield in 2024. Note: D₅, D₇, D₉ and D₁₁ represent the four planting densities of 50,000, 70,000, 90,000, and 110,000 plants·ha⁻¹, respectively, while M and NM represent mowed and non-mowed, respectively. Different lowercase letters indicate that under the same planting density, the difference between different mowing treatments reaches the $p < 0.05$ significant level; different capital letters indicate that under the same cutting treatment, the difference between different planting densities reaches the $p < 0.05$ significant level; * indicates a significant difference at $p < 0.05$, *** indicates a significant difference at $p < 0.001$, and ns indicates no significant difference.

3.4. Forage Quality

Both planting density and mowing significantly affected the crude protein, starch, NDF, and ADF contents of the forage sweet sorghum (Figure 5). Density significantly affected only NDF content in both years. In 2023, NDF content at D₅ was significantly lower than at D₇ and D₉ by 2.7% and 2.6%, respectively. In 2024, NDF content at D₅ was significantly lower than at D₇ and D₉ by 3.7% and 2.7%, respectively. Mowing significantly affected all quality parameters in both years. In 2023, compared with non-mowing, the first and second cuttings significantly increased crude protein content by 64.4% and 58.3%, respectively, and significantly reduced starch content by 16.3% and 14.5%, respectively. Compared with the first cutting, non-mowing significantly reduced NDF content by 3.58%. In 2024, compared with non-mowing, the first and second cuttings significantly increased crude protein content by 76.9% and 55.7%, respectively, and significantly reduced starch

content by 17.2% and 9.7%, respectively. Compared with the first cutting, non-mowing significantly reduced both NDF and ADF contents. No significant planting density $\times$ mowing interactions were observed for any quality parameter in either year.

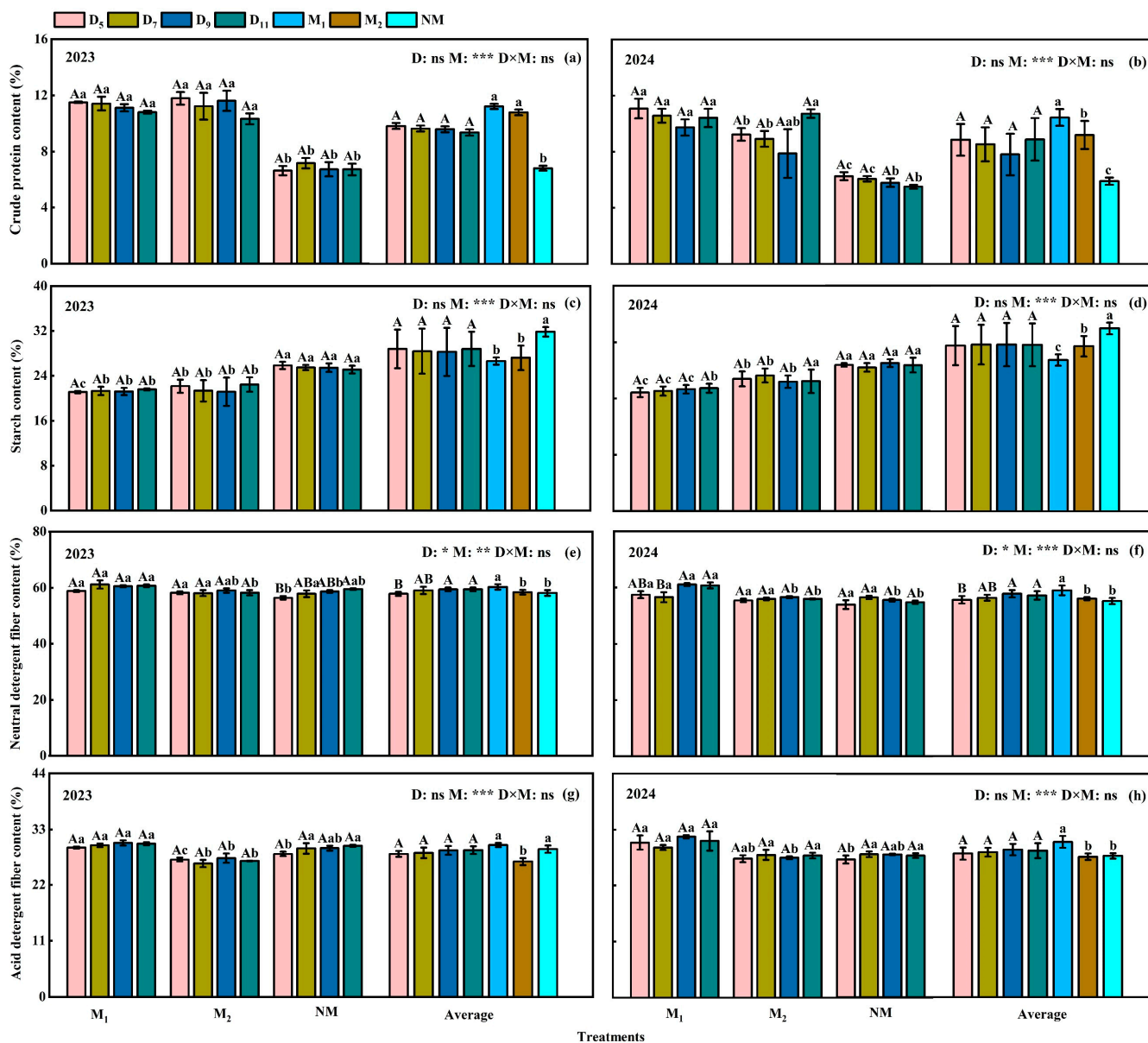


Figure 5. Effects of different planting densities and mowing regimes on crude protein, starch, neutral detergent fiber, and acid detergent fiber contents of forage sweet sorghum in 2023 and 2024. (a,b) Crude protein content; (c,d) Starch content; (e,f) Neutral detergent content; (g,h) Acid detergent content. Note: D₅, D₇, D₉ and D₁₁ represent the four planting densities of 50,000, 70,000, 90,000, and 110,000 plants·ha⁻¹, respectively, while M and NM represent mowed and non-mowed, respectively. Different lowercase letters indicate that under the same planting density, the difference between different mowing treatments reaches the $p < 0.05$ significant level; different capital letters indicate that under the same cutting treatment, the difference between different planting densities reaches the $p < 0.05$ significant level; * indicates a significant difference at $p < 0.05$, ** indicates significance $p < 0.01$, *** indicates a significant difference at $p < 0.001$, and ns indicates no significant difference.

Both planting density and mowing significantly affected various forage quality indices (Table 2). Density significantly affected only RFQ and GI in 2023. In 2023, RFQ under M₁D₅ was significantly higher than under M₁D₇, M₁D₉, and M₁D₁₁ by 6.5%, 6.1%, and 6.2%, respectively, and under NMD₅ was significantly higher than under NMD₁₁ by 11.3%. GI

under M₁D₅ was significantly higher than under M₁D₁₁ by 15.8%. Mowing significantly affected all indices in both years. In 2023, RFQ under NMD₉ was significantly higher than under M₁D₉ by 6.7%; TDNs under M₂D₉ were significantly higher than under M₁D₉ and NMD₉; and GI and FEU under M₁D₉ were significantly higher than under NMD₉. Similar results were observed in 2024. No significant planting density × mowing interactions were observed for any index in either year.

Table 2. Effects of different planting densities and mowing regimes on relative forage quality (RFQ), total digestible nutrients (TDNs), forage grading index (GI), and food equivalent unit (FEU) of forage sweet sorghum in 2023 and 2024.

Treatments	2023				2024			
	RFQ (%)	TDNs (%)	GI (MJ·d ^{−1})	FEU	RFQ (%)	TDNs (%)	GI (MJ·d ^{−1})	FEU
M ₁ D ₅	136.33Ab	62.83Ab	23.13Aa	0.68Ab	138.97Aa	61.86Aa	23.59Aa	0.67Aa
M ₁ D ₇	127.90Bb	62.46Ab	21.30ABa	0.68Aa	144.69Aa	62.42Aa	23.14Aa	0.66Aa
M ₁ D ₉	128.53Bb	62.01Ab	21.10ABa	0.67Aa	123.76Ab	60.50Ac	18.15Aa	0.63Aa
M ₁ D ₁₁	128.39Bb	61.91Ab	19.97Ba	0.66Aa	126.99Ab	61.39Aa	19.60Ab	0.65Ab
M ₂ D ₅	144.42Aa	64.76Aa	24.28Aa	0.71Aa	154.20Aa	63.63Aa	20.94Aa	0.65Aa
M ₂ D ₇	146.84Aa	65.11Aa	23.21Aa	0.70Aa	150.20Aa	62.95Aa	19.84Aa	0.64Aa
M ₂ D ₉	140.79Aa	64.46Aa	23.23Aa	0.70Aa	148.89Aa	63.56Aa	20.50Aa	0.65Aa
M ₂ D ₁₁	145.01Aa	64.52Aa	21.73Aa	0.68Aa	150.35Aa	63.70Aa	23.78Aa	0.68Aa
NMD ₅	148.29Aa	62.04Ab	14.54Ab	0.58Ac	161.24Aa	62.68Aa	15.11Ab	0.58Ab
NMD ₇	140.66ABab	61.41Ab	14.89Ab	0.59Ab	147.78Aa	61.82Aa	13.23Ab	0.57Ab
NMD ₉	137.19ABa	61.21Ab	13.63Ab	0.58Ab	151.42Aa	61.76Ab	13.05Ab	0.57Ab
NMD ₁₁	133.23Bb	60.83Ac	13.22Ab	0.58Ab	155.12Aa	61.83Aa	12.73Ac	0.56Ac
D	*	ns	*	ns	ns	ns	ns	ns
M	***	***	***	***	***	**	***	***
D × M	ns	ns	ns	ns	ns	ns	ns	ns

Note: Different lowercase letters indicate that under the same planting density, the difference between different mowing treatments reaches the $p < 0.05$ significant level; different capital letters indicate that under the same cutting treatment, the difference between different planting densities reaches the $p < 0.05$ significant level; * indicates a significant difference at $p < 0.05$, ** indicates significance $p < 0.01$, *** indicates a significant difference at $p < 0.001$, and ns indicates no significant difference.

3.5. Economic Benefits

Both planting density and mowing significantly affected the economic benefits of the forage sweet sorghum (Table 3). Density significantly affected total output (TO) in 2023 and net profit (NP) in both years. In 2023, TO under NMD₉ was significantly higher than under NMD₅ and NMD₇ by 22.6% and 18.4%, respectively but not significantly different from NMD₁₁. Under MD₉, TO was significantly higher than under MD₅ by 30.1%. NP under NMD₉ was significantly higher than under NMD₅ and NMD₇ by 23.3% and 19.7%, respectively. In 2024, NP under NMD₁₁ was significantly higher than under NMD₅ and NMD₇ by 67.3% and 47.1%, respectively. Mowing significantly affected TO, NP, and return on investment (ROI) in both years. In 2023, under non-mowing, TO, NP, and ROI were significantly higher than under mowing across all four densities. In 2024, under non-mowing, TO, NP, and ROI were significantly higher than under mowing at D₅, D₇, and D₉. No significant planting density × mowing interactions were observed for any economic indicator in either year.

Table 3. Effects of different planting densities and mowing regimes on economic benefits of forage sweet sorghum in 2023 and 2024.

Treatments	2023						2024					
	TO (CNY·ha ⁻¹)	TFI (CNY·ha ⁻¹)	TS (CNY·ha ⁻¹)	LI (CNY·ha ⁻¹)	NP (CNY·ha ⁻¹)	ROI	TO (CNY·ha ⁻¹)	TFI (CNY·ha ⁻¹)	TS (CNY·ha ⁻¹)	LI (CNY·ha ⁻¹)	NP (CNY·ha ⁻¹)	ROI
MD ₅	31,762.5 d	4230.8	540	1000	25,991.7c	5.4b	29,425.1bc	4230.8	540	1000	23,654.2cd	5.1bc
MD ₇	35,166.6cd	4230.8	756	1400	28,779.8c	5.5b	23,208.3c	4230.8	756	1400	16,821.5d	3.6c
MD ₉	41,313.3c	4230.8	972	1800	34,310.5c	5.9b	35,566.6bc	4230.8	972	1800	28,563.8cd	5.1bc
MD ₁₁	40,300.1cd	4230.8	1080	2000	32,989.2c	5.5b	35,566.6bc	4230.8	1080	2000	28,255.8cd	4.9bc
NMD ₅	51,937.5b	4230.8	540	500	46,666.7b	9.8a	35,112.2bc	4230.8	540	500	29,841.7cd	6.6ab
NMD ₇	53,758.3b	4230.8	756	700	48,071.5b	9.5a	39,633.3b	4230.8	756	700	33,946.5bc	6.9ab
NMD ₉	63,679.1a	4230.8	972	900	57,576.3a	10.4a	54,266.6a	4230.8	972	900	48,163.8ab	8.9a
NMD ₁₁	64,620.8a	4230.8	1080	1000	58,309.9a	10.2a	56,245.8a	4230.8	1080	1000	49,934.9a	8.9a
D	**				*	ns	ns				*	ns
M	***				***	***	***				***	***
D × M	ns				ns	ns	ns				ns	ns

Note: Different letters indicate that the difference between the treatments reached a significant level of $p < 0.05$; * indicates a significant difference at $p < 0.05$, ** indicates significance $p < 0.01$, *** indicates a significant difference at $p < 0.001$, and ns indicates no significant difference.

3.6. Comprehensive Evaluation

Random forest analysis identified indicators with significant contributions to dry matter yield and forage grading index as evaluation indices (Figure 6). Accordingly, six indicators—dry matter yield, economic benefit, total digestible nutrients, forage grading index, food equivalent unit, and starch content—were selected for comprehensive evaluation to identify the optimal planting density and mowing regime. Radar chart-based comprehensive evaluation revealed clear differences among treatments across the evaluation indicators (Figure 7). The comprehensive evaluation function value (Y) of each treatment was ranked as follows: NMD₉ was ranked highest (0.917), followed by NMD₁₁ (0.915), NMD₇ (0.866), NMD₅ (0.861), MD₁₁ (0.848), MD₉ (0.838), MD₅ (0.795), and MD₇ (0.791). Thus, the overall performance ranking of the forage sweet sorghum under different planting densities and mowing regimes was as follows: NMD₉ > NMD₁₁ > NMD₇ > NMD₅ > MD₁₁ > MD₉ > MD₅ > MD₇.

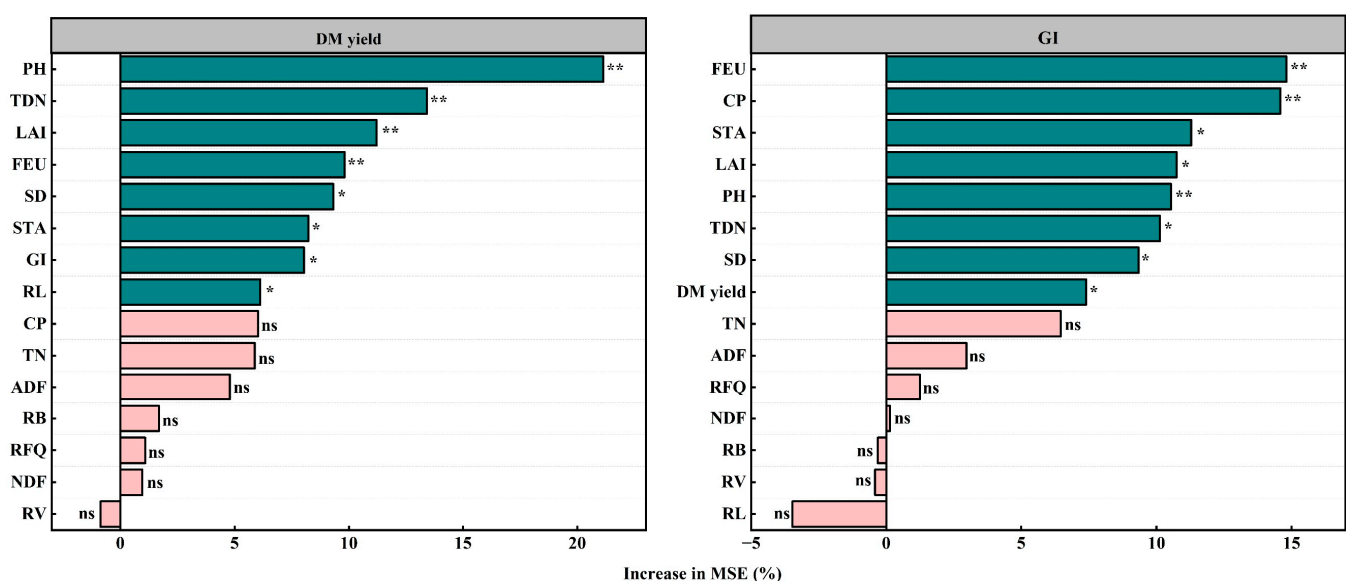


Figure 6. Relative importance of variables affecting dry matter yield and forage grading index based on random forest analysis. * indicates a significant difference at $p < 0.05$, ** indicates significance $p < 0.01$, ns indicates no significance. Note: DM yield, PH, SD, TDNs, LAI, FEU, STA, GI, RL, CP, TN, ADF, RB, RFQ, NDF, RV represent dry matter yield, plant height, stem diameter, total digestible nutrients, leaf area index, food equivalent, starch content, feed grading index, root length, crude protein content, tiller number, acid detergent fiber content, root biomass, relative feed value, neutral detergent fiber content, root volume, respectively.

Structural equation modeling (SEM) was used to parse the influence pathways of planting density and mowing on dry matter yield and forage quality (Figure 7). The model showed a good fit with a GFI of 0.937. Mowing had significant negative direct effects on plant height, stem diameter, and LAI (standardized path coefficients of -0.996 , -0.965 , and -0.961 , respectively), whereas planting density only had a significant negative effect on stem diameter (coefficient of -0.204). Plant height had a significant positive effect on dry matter yield (coefficient of 4.313).

Importantly, mowing had a very strong negative direct effect on dry matter yield (coefficient of -4.211), independent of its negative effects on agronomic traits. The model explained 85.0% to 99.6% of the variance in endogenous variables, with 94.9% of the variance in dry matter yield explained. The strong negative direct effect of mowing was the dominant factor reducing yield, while planting density had no significant direct effect on yield. Regarding GI, mowing had no significant direct effect but indirectly and substantially

improved GI by reducing stem diameter. These results indicate that mowing significantly suppresses plant morphogenesis and greatly reduces dry matter yield but at the same time indirectly improves forage quality by reducing stem diameter, reflecting a trade-off between yield and quality.

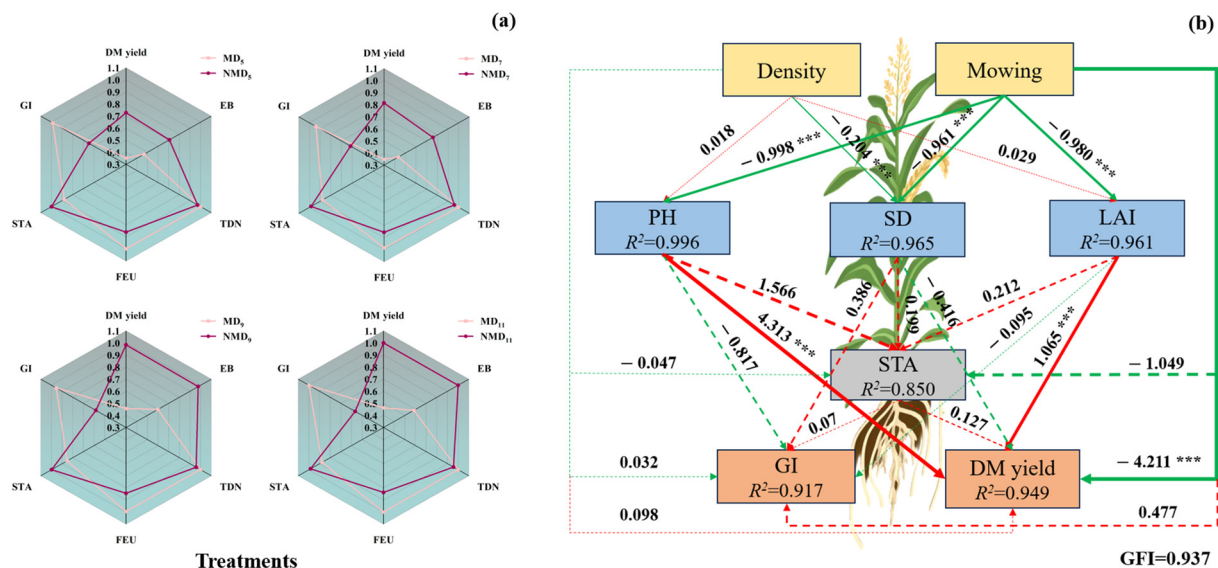


Figure 7. Identification of optimal planting density and mowing regime based on radar chart comprehensive evaluation (a). Structural equation model (SEM) analysis of dry matter yield and forage grading index of forage sweet sorghum under different treatments (b). Note: DM yield, dry matter yield; EB, economic benefit; FEU, food equivalent unit; STA, starch content; GI, forage grading index; TDNs, total digestible nutrients. Red lines indicate positive relationships, and green lines negative relationships. Solid and dashed lines indicate significant and non-significant effects, respectively. *** indicates a significant difference at $p < 0.001$. GFI, goodness-of-fit index.

4. Discussion

4.1. Effects on Dry Matter Yield and Distribution of Forage Sweet Sorghum

In resource-limited cropping environments, such as semiarid regions, the effect of planting density on crop yield typically follows a parabolic trend [17]. Too low a density fails to efficiently utilize resources such as water, fertilizer, light, and heat; too high a density intensifies competition among individuals for light, water, and nutrients, resulting in slender stems, reduced leaf proportion, increased lodging risk, and a stable or even declining population yield. Only within an appropriate range can the canopy leaf area index be rapidly established, improving light capture efficiency and thereby promoting dry matter accumulation per unit area [18]. Some studies have found that in semiarid regions, increasing maize density from 80,000 to 100,000 plants·ha⁻¹ significantly increases dry matter yield, but further increasing to 120,000 plants·ha⁻¹ leads to yield reduction, indicating that beyond a threshold, intensified resource competition reduces yield [19]. In the present study, dry matter yield increased with increasing density in both 2023 and 2024. The highest yield was achieved at 90,000 plants·ha⁻¹ in 2023 and at 110,000 plants·ha⁻¹ in 2024, but there were no significant differences among the three higher densities (70,000, 90,000, and 110,000 plants·ha⁻¹) in either year (Figure 4). This phenomenon is essentially a compensatory transcendence of population photosynthetic efficiency to individual photosynthetic efficiency. With an increase in density, the number of individual plants per unit area increased, the leaf area index (LAI) increased significantly, and the surface coverage increased, which intercepted more photosynthetically active radiation (PAR) at the population scale and provided sufficient material basis for dry matter accumulation [20].

Furthermore, mowing significantly affected dry matter yield and allocation. Some studies have shown that excessive mowing inevitably shortens the crop growth cycle, reduces aboveground biomass and dry matter yield, and may affect crop survival [21]. In the present study, the two-year results consistently showed that non-mowing resulted in a significantly higher dry matter yield than mowing; within the mowing treatment, the yield from the first cutting was significantly higher than from the regrowth (Figure 4). This phenomenon may be attributed to two main factors. First, plants not subjected to mowing stress photosynthesize continuously throughout the growing season, enabling stable utilization of natural resources, such as light and temperature, to accumulate more photosynthates [22]. Second, under mowing stress, plants allocate more resources to aboveground regrowth, reducing the energy and material available for root development and resulting in restricted root growth (Figure 3), which in turn reduces dry matter accumulation [23]. For example, a study on forage species such as *Poa pratensis*, *Trifolium repens*, and *Vicia villosa* in a semiarid region found that mowing with a stubble height of 3 cm reduced root length by 51.85%, 47.04%, and 39.80%, respectively. Regarding dry matter allocation, the mowing treatment exhibited two-phase characteristics. The reason may be that under non-mowing, plants experience a complete growth cycle; although leaves may senesce partially in the late stage, the absence of aboveground removal stress allows for longer functional leaf longevity and a higher leaf biomass proportion [24]. Under mowing, however, the limited regrowth period forces plants to allocate limited photosynthates preferentially to stems to rapidly restore plant height and competitive advantage, resulting in an increased stem proportion and a decreased leaf proportion.

4.2. Effects on Forage Quality of Forage Sweet Sorghum

The forage quality of sweet sorghum is regulated by agronomic management practices, with planting density and mowing regime influencing plant morphogenesis, canopy structure, and root development, thereby affecting quality. Density influences the competitive patterns for light, water, and nutrients at the population level, thereby affecting individual plant morphology and population photosynthetic efficiency. The present study found that as density increased from D_5 to D_{11} , there were no significant differences in crude protein, starch, or ADF contents in either year. This may be because sweet sorghum is a compact plant type and has strong density tolerance, such that the population's capacity for nitrogen uptake and assimilation is not substantially inhibited by density competition, while the partitioning pattern of photosynthates remains relatively stable within this density range [25]. However, NDF content responded differently to density. The two-year results show that NDF content increased significantly with an increasing density, with the lowest value observed at 50,000 plants·ha⁻¹ (Figure 5). The reason may be that the stem is significantly thinner at a high density (Figure 2), and stem diameter is closely related to NDF content. The relative proportion of structural components, such as vascular bundles and mechanical tissues, in fine stems is usually higher than that in coarse stems. In addition, an increase in density intensified the competition for resources among individuals, prompting plants to put more assimilates into the construction of supporting structures, such as stems, further increasing the content of fiber components. These results are consistent with findings from a study on cotton in arid regions [26]. Notably, once density exceeded 70,000 plants·ha⁻¹, NDF content no longer showed significant differences, suggesting a threshold effect of density on NDF: the deterioration of the within-canopy light environment tends to saturate, and fiber deposition no longer increases linearly with density.

Mowing alters plant regrowth patterns, canopy structure, and root function by removing aboveground parts. In the present study, crude protein content was significantly higher under mowing than under non-mowing in both years. Clipping broke the apical dominance

of the plant and significantly promoted the occurrence of tillers, resulting in a significant increase in the proportion of young tissues in the population (Figure 2). However, there was less structural carbohydrate deposition in the cell wall of young leaves and tillers, and the proportion of cytoplasmic nitrogen-containing components was relatively high, thereby increasing the average crude protein concentration at the population scale [27]. In contrast, starch content showed the opposite pattern. The likely reason is that starch is a storage carbohydrate; when plants are not subjected to mowing stress, they complete a full growth cycle, and photosynthates can be fully transported and stored in stems and grains [28]. Mowing interrupts this accumulation process, forcing plants to prioritize the use of limited photosynthates for regrowing new leaves and branches rather than starch reserves. Moreover, reduced root biomass after mowing may weaken the capacity for carbohydrate storage. NDF and ADF contents directly affect forage digestibility and live-stock intake. Some studies have found that early mowing of alfalfa not only results in a lower yield but also lower NDF and ADF contents and increased CP concentration and digestibility [29]. In the present study, compared with mowing, non-mowing significantly reduced NDF and ADF contents. The reason for this difference may be that after mowing, sweet sorghum plants grow and tiller rapidly, and the new stem and leaf growth requires substantial cellulose and hemicellulose to build cell walls, leading to increased NDF and ADF contents.

5. Conclusions

For the rainfed sweet sorghum in semiarid areas, the treatment involving a planting density of 90,000 plants·ha⁻¹ with no mowing had the best comprehensive performance (comprehensive score $Y = 0.917$). Taking the Loess Plateau variety ‘Hunnigreen’ as the research case, compared with the treatment involving 50,000 plants·ha⁻¹ (two-year average), the dry matter yield increased by 27.6% and the net profit increased by 42.3%. Under all planting densities, the yield and economic benefits of the no-cutting treatment were continuously better than those of the cutting treatment. At the mechanism level, the structural equation model (goodness of fit (GFI) = 0.937) confirmed an obvious yield–quality trade-off effect: mowing significantly reduced dry matter yield by inhibiting plant height, stem diameter and root development (with a direct path coefficient of -4.211 , which could explain 94.9% of the variation). Mowing can optimize the distribution ratio of leaf–stem by reducing the stem diameter and indirectly improve the feeding grade index. The comprehensive analysis framework (integrated structural equation model, random forest and radar chart evaluation) constructed in this study can provide a methodological reference for the agronomic trade-off analysis of drought-tolerant feed crops in resource-limited environments. However, the effects of planting density and mowing measures on the yield of the forage sweet sorghum were limited by annual precipitation fluctuations and annual distribution patterns, which still need to be further verified by multi-year and multi-point experiments. In addition, the current optimization scheme should not be applied directly without conditions. Localized cultivation experiments still need to be carried out when introducing new varieties to match the appropriate density and mowing system, so as to further tap the yield and economic potential.

Author Contributions: Conceptualization, Y.L. and X.Y.; investigation, Z.L. and C.J.; data curation, R.T. and Z.L.; writing—original draft preparation, R.T. and Y.L.; writing—review and editing, Y.L. and X.Y.; visualization, R.T.; supervision, Y.L.; project administration, X.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by the Horizontal Project (GSAU-JSFW-2025-139) and the National Key Research and Development Program of China (Grant No. 2024YFD1301105),

and the Central Government Guidance Fund for Local Science and Technology Development Projects (Grant No. ZYYD2025QY07, 24ZYQA049).

Data Availability Statement: The datasets generated and analyzed during the present study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors thank all colleagues who participated in field sampling and laboratory measurement for their valuable support.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

LAI	Leaf area index
NDF	Neutral detergent fiber
ADF	Acid detergent fiber
RFQ	Linear dichroism
GI	The forage grading index
RFV	Relative feed value
TDNs	Total digestible nutrients
FEU	Food equivalent unit
EB	Economic benefit
STA	Starch content

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