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Assessing the Efficiency of Different Nitrogen Fertilization Levels on Sorghum Yield and Quality Characteristics

Dimitrios Bartzialis, Kyriakos D. Giannoulis *, Ippolitos Gintsioudis and Nicholaos G. Danalatos

Laboratory of Agronomy and Applied Crop Physiology, Department of Agriculture Crop Production and Rural Environment, University of Thessaly, Fytokoy Str., 38446 Volos, Greece; dbartz@uth.gr (D.B.); igints@uth.gr (I.G.); danal@uth.gr (N.G.D.)

* Correspondence: kgiannoulis@uth.gr; Tel.: +30-24-2109-3129

Abstract: Sorghum is a *Poaceae* family plant that produces a lot of hay. A field experiment was carried out at the University of Thessaly's experimental farm to investigate the hay yield and quality characteristics of six different sorghum varieties (V1: Buffalo grain, V2: Elite, V3: Big Kahuna, V4: 25K1009, V5: 4264, and V6: 5D61) under different nitrogen fertilization levels (N_1: 0, N_2: 80, N_3: 160, and N_4: 240 kg ha^{-1}, using urinary ammonia 40-0-0). Pea for silage production was established in the same field prior to sorghum cultivation. Hay yield was found to differ significantly between the tested varieties and was also influenced by nitrogen fertilizer. Nitrogen fertilization has a statistically significant effect on sorghum production, with a higher nitrogen supply contributing to a higher protein content in the sorghum yield. Other hay quality indicators, such as ash, NDF, and ADF, demonstrated differences between the different varieties and nitrogen fertilizer levels. According to the study, the variety that had stable output was "Elite", which had good quality attributes and could be used as an alternative to feed production before sorghum development.

Keywords: sorghum; fertilization; hay; yield; protein; ADF; NDF

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1. Introduction

Sorghum is a C4 plant typical to tropical–subtropical areas and belongs to *Poaceae* family [1]. Its drought and salinity resistance makes it an important ecological crop [2,3]. Sweet sorghum, forage sorghum, grain sorghum, and sorghum for biomass or bioenergy are the four primary categories based on end-use preferences. *Sorghum* species are becoming increasingly popular, particularly as fodder crops, especially in semi-arid, tropical countries because of its capacity to thrive in high temperatures and dry conditions where no other crops can be cultivated [4]. Sweet, forage, and grain sorghum are the most significant in terms of animal nutrition; however, genotype and phenotype diversity must be acknowledged [5]. When compared to corn, sorghum has a high adaptability, a high water use efficiency (WUE), and a low fertilizer demand [6,7].

Sorghum bicolor (L.) is a valuable annual feed crop with excellent yields. Even if global sorghum production is now stagnant, the future of sorghum production is dependent on producers' capacity to breed suitable silage types. A general precondition for excellent yields is to meet plant requirements as efficiently as possible during the growth season. This suggests good nutrient absorption as well as the production and usage of essential chemicals in the optimal ratio and levels for plant growth [8].

Furthermore, soil fertility decrease has been documented in recent decades as a result of agricultural intensification and land overexploitation. In addition, there has been an increase in cultivation costs, year by year, with the price of the fossil fuels and the price of the fertilizers increasing dramatically. Since the last decade, higher amounts of fertilizers, particularly nitrogen fertilizers, are used to increase agricultural yield. Nitrogen is a nutrient that aids crop growth and has been touted around the world for its ability to boost yields in various crops [9,10].

Even if it is reported that sorghum has a low fertilizer demand [6,7], the economic optimum N rate varies according to the tested genotype (variety) as well as the price of sorghum hay and the cost of N fertilizer. Nitrogen absorption and crude protein concentration rise as N fertilizer rates rise, whereas nitrogen utilization efficiency and N recovery fall as N fertilizer rates rise [11]. Proper application of nitrogen mineral fertilizers can play a crucial role in enhancing the agro-ecological and soil conditions for sorghum cultivation, leading to higher crop potential and increased animal feed outputs per unit area. Nitrogen is a key nutrient for plant growth and development, and its availability in the soil is often a limiting factor for crop productivity. By providing sorghum crops with adequate nitrogen fertilizers, farmers can promote healthy growth and maximize yields.

However, it is important to note that the optimal application rate of nitrogen fertilizers will depend on a variety of factors, including soil type, climate, and crop management practices. Overuse of nitrogen fertilizers can lead to negative environmental impacts, such as soil degradation and water pollution. Therefore, it is important to carefully consider the specific needs of the crop and the local environment when determining the appropriate fertilizer application rates.

Overall, the proper application of nitrogen mineral fertilizers can be an effective strategy for enhancing sorghum productivity and improving the nutritional quality of sorghum biomass for animal feed. However, it is important to approach fertilizer use in a responsible and sustainable manner to minimize negative environmental impacts.

According to reports, sorghum cultivation is recommended for silage production in drought situations [12], and there are novel silage-producing varieties that might completely replace maize silage without reducing dairy cow milk yields [13,14]. Animal feed is becoming more popular, especially in locations with limited precipitation during the sorghum-growing season and due to rising nitrogen fertilizer prices (silages).

Discovering a sorghum variety that might provide higher quality animal feed as well as deciphering the amount of nitrogen fertilizer that would aid in enhancing its qualitative attributes were the goals of this study.

2. Materials and Methods

2.1. Experimental Site and Design

The research conducted in 2019 and 2020 aimed to investigate the impact of different varieties and nitrogen fertilization levels on crop growth and yield in a typical Mediterranean soil-climatic environment. The study was carried out in Central Greece, specifically in East Thessaly, Velestino, Magnesia, at coordinates 39°23′55′′ N and 22°45′11′′ E (Figure 1).

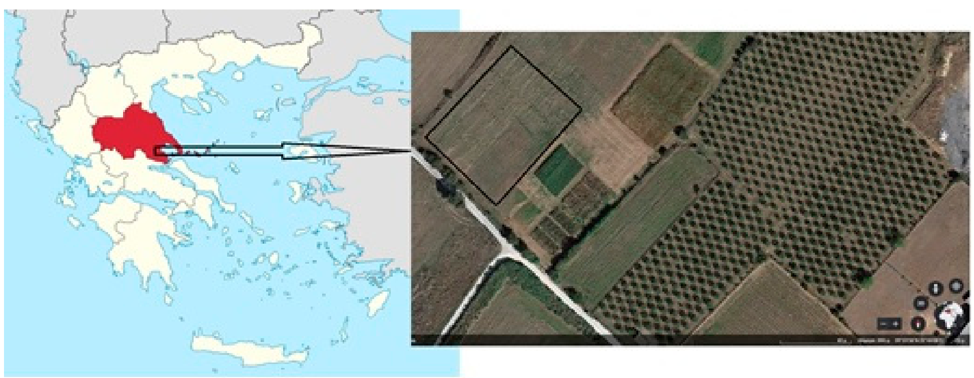

Figure 1. Experimental site.

To achieve the research objectives, a factorial split-plot design was utilized, with three replicates (blocks) and twenty-four plots per replication. The main factor was the different varieties used in the experiment, including Buffalo grain (V1), Elite (V2), Big Kahuna (V3), 25K1009 (V4), 4264 (V5), and 5D61 (V6). On the other hand, the sub-factor was the different nitrogen fertilization levels, which included N1: 0, N2: 80, N3: 160, and N4: 240 kg ha^{-1}, using urinary ammonia 40-0-0.

Each plot in the experiment occupied an area of 42 m^2, with dimensions of 6 m width and 7 m length. The use of a factorial split-plot design with multiple replicates and plots per replication helped to ensure the accuracy and reliability of the research findings. Overall, the study aimed to provide valuable insights into the impact of different varieties and nitrogen fertilization levels on crop growth and yield in a Mediterranean soil-climatic environment.

2.2. Soil Characteristics

The soil of the experimental field is classified as *Calcixerollic xerochrept* [15], and it is characterized as particularly fertile (organic matter of 2.91% at a depth of 0–30 cm and 1.86% at 30–60 cm). It is a clayey soil with an alkaline nature (pH 7.63 and 7.9 at 0–30 and 30–60 cm depth, respectively). The average C/N ratio was 8.81 for both depths (8.78 at 0–30 cm and 8.85 at 30–60 cm), and the cation exchange capacity ranged between 6.78 (0–30 cm) and 7.68 (30–60 cm).

2.3. Experimental Management

The sorghum crops were sown on 5 June 2019 and 3 June 2020, with a plant distance of 50 cm between lines for the first three varieties (Buffalo grain, Elite, and Big Kahuna) and 75 cm for the remaining three varieties (25K1009, 4264, and 5D61). The plant distance on the line was 8 cm for all varieties, based on their individual characteristics and the recommended procedure of their respective companies.

Before the sorghum crops were sown, the field had previously been used to grow pea for silage purposes. The pea was harvested on 29 May 2019 and 25 May 2020.

The final harvest of the sorghum crops took place on 25 October 2019 and 30 October 2020. To minimize the border effect, plants from an inner plot with a surface area of 1 m^2 were cut 10 cm above ground level. The plants were then weighed immediately, and a sub-sample was taken for further laboratory measurements. The sub-sample was air-dried at a temperature of $\leq$60 °C to ensure accurate measurements. Overall, the study aimed to investigate the impact of different varieties and nitrogen fertilization levels on sorghum growth and yield in a Mediterranean soil-climatic environment.

2.4. Yield Quality Characteristics Measures

After the sorghum plants were harvested and air-dried at a temperature of $\leq$60 °C, the dry samples were chopped and grounded for laboratory analysis. The analysis included determining the ash, protein, neutral detergent fiber (NDF), and acid detergent fiber (ADF) using near-infrared reflectance (NIR) spectroscopy technique with the DA 7250 NIR analyzer from Perten Instruments in Hägersten, Sweden.

NDF and ADF are plant quality characteristics that are related to the age and growth stage of the crop. The NDF and ADF values estimate the feed content of lignin, cellulose, hemicelluloses, and insoluble minerals. These values are important in determining the nutritional value and quality of the sorghum crop, particularly for animal feed purposes.

Overall, the laboratory analysis aimed to provide valuable insights into the chemical composition of the sorghum crop and its potential use as a feed source for animals. The use of NIR spectroscopy technique with the DA 7250 NIR analyzer from Perten Instruments in Hägersten, Sweden, helped to ensure accurate and reliable measurements.

2.5. Meteorological Data and Statistical Analysis

An automated meteorological station was installed near the experimental field to collect comprehensive weather data.

The research region is known for its Mediterranean climate, which is characterized by warm summers and mild winters. Throughout the summer months, the average recorded air temperature ranged between 25.8 °C in 2019 and 26.1 °C in 2020, which is almost similar to the 30-year average air temperature (as depicted in Figure 2). Interestingly, there was a significant drop in temperature during autumn months, with temperatures plummeting by 4 °C during both experimental years.

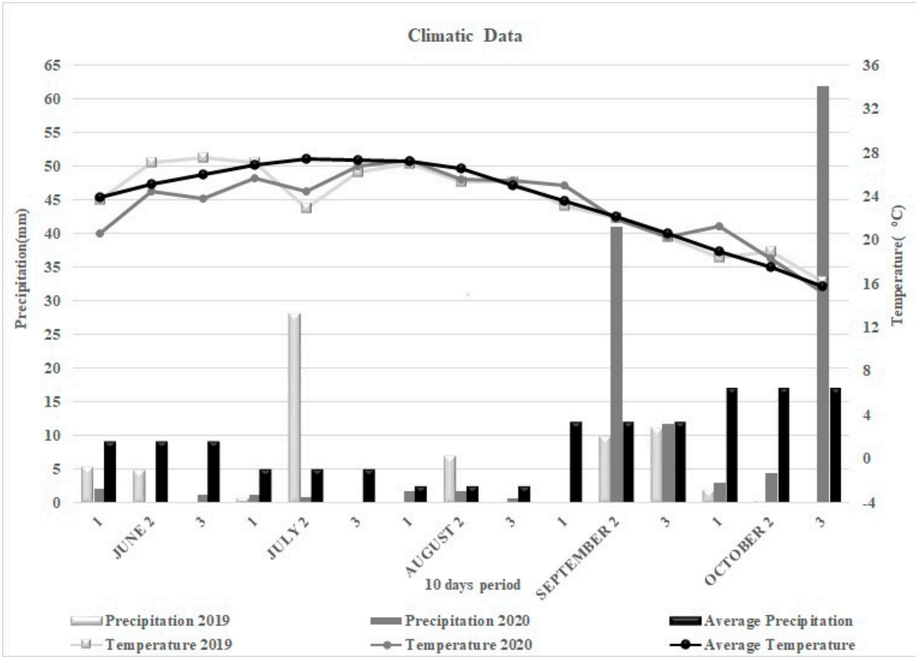

Figure 2. Average ten days air temperature-precipitation of the study site in 2019–2020, and average air temperature-precipitation of the last 30 years.

Precipitation is another important climatic factor that has a significant impact on crop growth and yield. On average, the area receives about 50 mm of rainfall during the summer months. This was also observed in 2019 where the recorded precipitation was 46 mm (as shown in Figure 2). However, the summer of 2020 was characterized by a lack of rainfall, with precipitation not exceeding 10 mm. As a result, it could be considered as a dry summer.

Moreover, the summer months in both experimental years were not ideal for irrigated crops. This is because the recorded rainfall, even in 2019, was not distributed evenly. In fact, 60% of the rainfall occurred during the second ten days of July (as depicted in Figure 2). This uneven distribution of rainfall can have a negative impact on crop growth and yield as it may lead to water stress and affect the overall productivity of crops.

Finally, the collected data was subjected to an analysis of variance (ANOVA) within the sample timings for all measured and derived variables using the statistical package GenStat (7th Edition). The $LSD_{0.05}$ test criterion was used to evaluate the differences between means of the main and/or interaction effects [16]. This statistical analysis allowed for a rigorous examination of the data and ensured that any observed differences between the tested variables were statistically significant and not due to chance.

3. Results

3.1. Sorghum Yield

The study found significant differences in harvested yield among the tested sorghum varieties. The variety 4264 had the highest dry biomass yield of 18.84 t ha^{-1} in the second year of cultivation (2020). The Elite variety had the most stable production, with yields of 14.69 and 14.84 t ha^{-1} in both years. The 2020 cultivation year was generally more productive for most varieties, except for 25K1009, which had lower yields that year (Table 1).

Table 1. Produced dry yield in 2019 and 2020 of the tested varieties (Buffalo Grain, Elite, Big Kahuna, 25K1009, 4264, and 5D61) affected by the different N-fertilization levels (0, 80, 160, and 240 kg N ha^{-1}).

		Dry Weight t ha^{-1} 2019	Dry Weight t ha^{-1} 2020
Varieties	**Buffalo Grain**	9.07	11.42
	Elite	14.69	14.84
	Big Kahuna	11.53	14.06
	25K1009	16.15	13.24
	4264	10.96	18.84
	5D61	10.56	13.76
	$LSD_{0.05}$	***1.991***	***1.526***
Nitrogen (kg ha^{-1})	**0**	10.81	12.41
	80	11.82	14.42
	160	12.01	14.9
	240	13.98	15.71
	$LSD_{0.05}$	***1.275***	***1.612***
Interaction		***ns***	***ns***
CV (%)		***15.5***	***19.4***

LSD: Least significant difference, ns: non-significant, CV: coefficient of variance.

It is worth noting that the sorghum crop was sown after pea harvest for silage purposes as the next crop in rotation. This suggests that the crop rotation strategy may have played a role in the sorghum yield outcomes. Overall, the study provides valuable insights into the performance of different sorghum varieties under specific cultivation conditions, which can inform future crop management decisions.

Regarding the effect of nitrogen fertilization, there are statistically significant differences, with the higher nitrogen supply contributing to the maximum sorghum yield (Table 1).

The results indicate that the use of crop rotation techniques can significantly increase sorghum yield by approximately 2 tons per hectare, as shown in Table 1. Additionally, the data suggests that while the highest supply of nitrogen fertilization may produce a greater quantity of biomass in the second year of cultivation, this difference is not statistically significant when compared to the supply with 160 kg per hectare. This lack of statistical difference is likely due to the positive effect of pea cultivation as a previous crop. Finally, the study did not find any statistically significant differences in the interaction between the tested varieties and nitrogen fertilization. These findings suggest that crop rotation can be a useful technique for increasing sorghum yield and careful management of nitrogen fertilization levels can also be beneficial.

3.2. Biomass Quality Characteristics

The study found no statistically significant differences in protein content between the tested sorghum varieties in both years of cultivation (as shown in Table 2). The protein content ranged between 5.1 and 6.5 percent, depending on the specific variety. However, higher levels of nitrogen fertilization led to dry biomass with a higher protein content. Specifically, the control treatments had statistically lower protein content in both years of cultivation, while the biomass produced with higher nitrogen dosages (160 and 240 kg ha^{-1}) had statistically higher protein content (as shown in Table 2). Among the different nitrogen treatments, the 160 kg ha^{-1} dosage resulted in the highest protein content, while the control treatment had the lowest protein content. These findings suggest that the use of nitrogen fertilization can have a significant impact on the protein content of sorghum biomass, while the choice of sorghum variety may have a lesser effect.

Table 2. Protein, ash, NDF, and ADF (%) content of the produced yield in 2019 and 2020 of the tested varieties (Buffalo Grain, Elite, Big Kahuna, 25K1009, 4264, and 5D61) affected by the different N-fertilization levels (0, 80, 160, and 240 kg N ha^{-1}).

		Protein		Ash		NDF		ADF	
		2019	2020	2019	2020	2019	2020	2019	2020
Varieties	**Buffalo Grain**	6.54	6.16	4.84	6.58	52.71	44.70	31.33	39.27
	Elite	5.16	5.11	4.4	5.76	54.00	45.63	32.36	40.09
	Big Kahuna	5.38	5.23	5.06	7.01	57.96	47.47	34.73	42.21
	25K1009	5.63	5.25	4.85	4.78	56.46	47.66	34.02	40.19
	4264	5.45	5.86	4.84	5.17	57.69	47.43	35.18	40.24
	5D61	5.00	5.53	5.55	5.01	58.93	45.69	35.78	40.09
	$LSD_{0.05}$	***ns***	***ns***	***0.249***	***0.604***	***2.992***	***1.033***	***2.196***	***ns***
Nitrogen (kg ha^{-1})	**0**	3.71	4.69	4.56	5.98	55.71	46.75	33.48	40.38
	80	5.12	5.55	4.99	5.67	56.43	46.31	33.80	39.86
	160	6.92	5.76	5.29	5.60	57.46	46.40	34.92	40.03
	240	6.36	6.10	5.2	5.63	57.10	46.27	34.47	41.12
	$LSD_{0.05}$	***0.789***	***0.599***	***0.239***	***ns***	***1.222***	***ns***	***0.829***	***ns***
Interaction		***ns***	***ns***	***ns***	***ns***	***ns***	***ns***	***ns***	***ns***
CV (%)		***21.1***	***18.7***	***11.9***	***17.3***	***4.3***	***3.9***	***5.2***	***6.1***

LSD: Least significant difference, ns: non-significant, CV: coefficient of variance.

The study also investigated the amount of ash in the animal feed. The results showed statistically significant differences between the sorghum varieties and the levels of nitrogen fertilization used (as shown in Table 2). The "25K1009" variety had a similar ash content in both years of cultivation, while the "Big Kahuna" variety had a larger variation in ash content between the two years. Regarding nitrogen fertilization levels, it was found that the ash content varied more for the control and the first nitrogen level, while the higher levels appeared to be more stable in terms of ash content. These findings suggest that both the choice of sorghum variety and the level of nitrogen fertilization can affect the ash content of sorghum biomass, which is an important consideration for animal feed.

The study also evaluated the cell wall components, i.e., ADF and NDF, which are important quality characteristics for forages and are related to crop age and growth stage. The results showed that the NDF and ADF indexes were lower in the first two sorghum varieties, "Buffalo grain" and "Elite", in both years of cultivation (as shown in Table 2). The "Buffalo grain" variety had significantly lower values than all the others except for "Elite", which had significantly lower values than "Big Kahuna", "4264", and "5D61". In terms of nitrogen fertilization levels (as shown in Table 2), statistically significant differences were only observed in 2020 where increasing nitrogen doses led to increased NDF and ADF indexes. These findings suggest that the choice of sorghum variety can have a significant impact on the NDF and ADF indexes of sorghum biomass, while the effect of nitrogen fertilization may depend on the specific year of cultivation.

4. Discussion

Crop rotation with legumes is reported to help improve soil structure [17] and retain more moisture in the soil at greater depths [18]. As a result, it appears that the above technique adds to production optimization once again and coincides with past research.

Sorghum hay yield appears to be a genetic feature, which is also influenced by nitrogen fertilization. The "Elite" variety had the most stable production.

Nitrogen fertilization statistically significant affect sorghum yield, with higher nitrogen supply contributing to maximum sorghum yield. The higher nitrogen supply contributes to the highest sorghum production, which is in line with prior research that has shown that increasing nitrogen rate leads to enhanced yield [19–24].

However, a noteworthy conclusion is that crop rotation increases sorghum output by roughly 2 tons per hectare on average (Table 1), which is consistent with literature [25–27] as a soil improvement approach.

In comparison to previous studies [11,28–30], sorghum dry biomass production was not expected to be satisfactory. This was due to the fact that sorghum cultivation settled in the field in June when the prevailing climatic conditions were not ideal for its early stages of development (Figure 2). Nevertheless, some of the tested varieties' dry biomass yields were quite high (for example, varieties 4264 and Elite), surpassing sorghum hay yields reported in the literature under lower nitrogen treatment regimens [31–33].

The other hay quality parameters, such as ash, NDF, and ADF, revealed variances among the studied varieties and nitrogen fertilizer levels. In many countries, a scarcity of livestock feed, especially fodder, has become a major limiting factor in the long-term management of the livestock business [34]. Crop yields in marginal lands are likely to be lower. Crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), and ash content are all essential markers of nutritional value. ADF refers to the forage's cell walls, which are made up of cellulose and lignin. The ability of an animal to digest the feed is measured by these statistics. As ADF increases, forage digestibility usually decreases. Many of the calculated figures on the forage reports are based on ADF data.

There were not found statistically significant differences in protein content between the tested varieties, which is in line with literature where it is reported that there were no significant differences among the genotypes [35].

In conclusion, the study found that while sorghum yield may be determined by genetics, the protein content of the biomass is primarily affected by the dosage of nitrogen fertilization. Specifically, higher doses of nitrogen fertilization were found to produce dry biomass with higher protein content, while the control group with no fertilization had the lowest protein content. These findings are consistent with previous research [36] and suggest that careful management of nitrogen fertilization can be an effective way to optimize the nutritional quality of sorghum biomass for animal feed production.

The study found that the ash concentration in the sorghum biomass was lower than what had been reported in a previous study [37]. This difference could be attributed to the varying soil and climatic conditions in the regions where the sorghum was grown as well as to the differences in the growth stages at the time of harvest. These results highlight the importance of considering the specific growth conditions and harvest time when analyzing the nutritional composition of sorghum biomass. Further research is needed to better understand the factors that affect the ash concentration in sorghum and to develop strategies for optimizing the nutritional quality of this important feed crop. It is important to note that the stage of growth at the time of harvest can significantly impact the ash content of sorghum biomass. Previous research has shown that the ash content tends to decrease as the plant matures [38], with lower levels observed in more mature plants. This highlights the importance of carefully timing the harvest of sorghum crops in order to optimize their nutritional quality. By understanding the relationship between plant maturity and ash content, farmers and feed producers can develop strategies for achieving the desired nutritional profile in sorghum biomass for animal feed. Further research is needed to explore the factors that influence the ash content of sorghum at different growth stages and to develop best practices for optimizing its nutritional value.

The cell wall components, i.e., ADF and NDF, are important quality characteristics for forages and are related to crop age and growth stage. According to literature [39], most cereal hay has an ADF ranging from 36 to 42 percent. The whole cell wall is represented by the NDF value, which includes both the ADF and hemicellulose portions. The measures of the above indexes are similar to previous studies where they are reported to be 48.3–55.4% for NDF and 21.7–37.0% for ADF [32,40,41].

In summary, the study found that the Elite variety of sorghum has a high yield of high-quality hay, especially when grown following a pea crop. This technique can provide an alternative to traditional animal feed production and may be particularly beneficial to farmers looking to diversify their operations or reduce their environmental impact. By carefully selecting the right sorghum varieties and employing appropriate crop rotation techniques, farmers can optimize their production of high-quality sorghum hay while also promoting the long-term health and productivity of their land.

5. Conclusions

Sorghum hay yield is a complex trait that is influenced by both genetic and environmental factors. While genetic traits play a significant role in determining the yield of sorghum hay, the application of nitrogen fertilizers can also have a significant impact on the yield. Certain varieties, such as the "Elite" variety, are known for their stable production and can be relied upon to produce consistent yields.

In addition to selecting the right variety, farmers can also increase the yield of sorghum hay by employing crop rotation techniques. By cultivating peas before sorghum, farmers can create a more favorable environment for sorghum growth and increase the yield of the second crop.

As for nitrogen fertilization, it has been shown to have a statistically significant impact on the yield of sorghum hay. In general, higher nitrogen supply has been found to contribute to the maximum sorghum yield. However, the ideal nitrogen fertilization dose may vary depending on the specific crop rotation technique employed. When pea cultivation precedes sorghum cultivation, the maximum nitrogen fertilization dose appears to be between 160 and 180 kg per hectare. By carefully managing nitrogen fertilization and selecting the right crop rotation techniques, farmers can maximize their sorghum hay yield and achieve more profitable harvests.

While sorghum yield is largely determined by genetic factors, nitrogen fertilization can have a significant impact on the protein content of the resulting hay. In fact, higher doses of nitrogen have been found to produce dry biomass with higher protein content. However, other hay quality parameters, such as ash, NDF, and ADF, can vary depending on the specific variety of sorghum and the level of nitrogen fertilization applied.

The study also found that certain sorghum cultivars, such as the Elite variety, are particularly well-suited for producing high-quality hay. In particular, when peas are grown before sorghum cultivation, the yield of high-quality hay can be significantly increased. This could provide an attractive alternative to the production of animal feed as high-quality sorghum hay can be used to supplement the diets of livestock and other animals.

Overall, by carefully selecting the right sorghum cultivars and employing appropriate crop rotation techniques, farmers can maximize their yield of high-quality sorghum hay. By doing so, they can improve the profitability of their operations and meet the growing demand for high-quality animal feed and other agricultural products.

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