

Article

Nitrogen Fertilization and Its Effect on Silage Maize Quality in the Context of Sustainable Fertilization Practices

Wojciech Kozera ¹, Joanna Lemanowicz ^{2,*}, Weronika Dudzińska ¹ and Tomasz Knapowski ¹

¹ Department of Biogeochemistry, Soil Science and Irrigation and Drainage, Faculty of Agriculture and Biotechnology, Bydgoszcz University of Science and Technology, Bernardyńska 6 St., 85-029 Bydgoszcz, Poland; wojciech.kozera@pbs.edu.pl (W.K.); werdud000@pbs.edu.pl (W.D.); tomasz.knapowski@pbs.edu.pl (T.K.)

² Division of Biochemistry, Faculty of Medicine, Bydgoszcz University of Science and Technology, Bernardyńska 6 St., 85-029 Bydgoszcz, Poland

* Correspondence: joanna.lemanowicz@pbs.edu.pl

Abstract

Sustainable agriculture, particularly efficient nitrogen management, is essential for maintaining soil fertility, improving crop quality, and reducing the environmental footprint of agricultural production. This study evaluated the effects of reduced soil-applied nitrogen and foliar application of the nitrogen–sulfur fertilizer Nitron-S on the quality of silage maize (*Zea mays* L.). A field experiment was conducted using a single-factor design with four fertilization treatments differing in nitrogen supply and foliar fertilization intensity. The silage maize cultivar Farmmortiz was grown under uniform manure application (30 t ha^{−1}) applied in autumn. The control treatment received the full soil-applied nitrogen rate, whereas experimental treatments received 50% of the conventional nitrogen dose supplemented with foliar Nitron-S at doses of 20, 40, and 60 dm³ ha^{−1}, applied twice during the growing season. After harvest, plant yield and selected quality parameters were determined, including dry matter, crude protein, sugars, starch, ash, neutral detergent fiber (NDF), acid detergent lignin (ADL), ammonia fraction, and organic matter digestibility (VOS). Fertilization treatments significantly affected most quality traits. The highest Nitron-S rate increased starch concentration (up to approximately 30% under N4) but also elevated ADL content (by about 25%) and slightly reduced VOS (only by about 1–3%). Partial replacement of soil-applied nitrogen with foliar nitrogen–sulfur fertilization improved the nutritional quality of maize silage and reduced nitrogen input. This approach may contribute to more sustainable maize production.

Keywords: silage maize; yield; dry matter; crude protein; sugars; ash; fiber fractions; ammonia fraction; organic matter digestibility; foliar fertilization



Academic Editor: Teodor Rusu

Received: 15 June 2026

Revised: 16 July 2026

Accepted: 20 July 2026

Published: 27 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Silage maize is one of the most important forage crops in both intensive and sustainable agricultural systems, playing a central role in dairy and beef cattle nutrition worldwide [1,2]. As a major component of total mixed ration (TMR) diets, it provides substantial amounts of energy and structural fiber, directly influencing dry matter intake, milk yield, and animal performance [3]. Its widespread use is also attributed to its high biomass productivity. Maize produces relatively stable yields across diverse environmental and agronomic conditions, making it one of the most efficient crops in terms of output per unit area [4]. The quality of maize silage, determined by its chemical composition,

digestibility, and fermentation characteristics, is a key factor affecting livestock productivity. High-quality silage enhances nutrient utilization and contributes to improved production parameters, including dry matter intake, milk yield, and milk quality [2]. Maize silage quality is determined by key nutritional parameters, including dry matter, crude protein, water-soluble sugars, ash, fiber fractions (NDF and ADF), ammonia nitrogen, and organic matter digestibility. These parameters directly affect fermentation quality, nutrient availability, feed intake, and animal performance [5]. High-quality silage is characterized by an optimal dry matter content, high crude protein concentration and digestibility, adequate water-soluble sugar content, lower fiber fractions, and low ammonia nitrogen levels, all of which improve its feeding value for ruminants [6]. Therefore, optimizing agronomic practices that influence silage quality, particularly fertilization management, remains an important research priority in modern sustainable agriculture.

Sustainable nitrogen (N) management is a key component of modern precision agriculture, aiming to improve nitrogen use efficiency (NUE) while minimizing environmental impacts. Excessive or poorly synchronized nitrogen application contributes to N_2O emissions, nitrate leaching, and water eutrophication, highlighting the need for more efficient fertilization strategies [7]. Increasing attention is being given to site-specific nutrient management, which accounts for the spatial and temporal variability of crop nitrogen demand. This approach is supported by remote sensing technologies, crop growth models, and advanced monitoring systems [8]. In addition, stabilized and organic fertilizers can better synchronize nitrogen release with plant uptake, thereby reducing nutrient losses and improving fertilizer efficiency [9]. Simultaneously, the integration of advanced crop monitoring technologies, including nitrogen sensors, unmanned aerial vehicles (UAVs), and decision support systems (DSS), enables real-time adjustment of fertilizer application to crop nutrient demand. Such an approach enhances nutrient use efficiency and supports the sustainable intensification of agricultural production [10].

Nitrogen fertilization is one of the primary factors determining maize productivity, as nitrogen plays a crucial role in protein synthesis, chlorophyll formation, and photosynthetic activity. Maize is highly sensitive to nitrogen availability, and deficiency can restrict growth, reduce leaf area development, and decrease biomass yield [11,12]. Consequently, nitrogen is considered a major yield-forming factor in silage maize production [11]. The effectiveness of nitrogen fertilization depends not only on the application rate but also on the fertilizer form and timing of application [13]. Optimizing these factors can improve nitrogen uptake efficiency while reducing environmental losses, which is particularly important in modern agricultural systems [14]. Compared with conventional soil fertilization, foliar application provides a rapid and efficient method for supplying nutrients, particularly during periods of increased demand or limited root uptake. It can enhance nutrient use efficiency (NUE) while reducing nutrient losses. However, its effectiveness depends on nutrient form, leaf surface characteristics, plant developmental stage, and environmental conditions during and after application [15,16]. Nutrients applied to leaves are absorbed mainly through the cuticle and stomata, allowing their rapid transport into leaf tissues and metabolically active organs. This pathway bypasses soil-related limitations, including nutrient fixation, immobilization, and leaching. Foliar nitrogen application combined with sulfur can further improve nitrogen use efficiency, as sulfur promotes nitrogen assimilation and the synthesis of nitrogen-containing compounds [17]. Nitrogen supply also affects the nutritional quality of silage maize. Increased nitrogen doses generally enhance crude protein content; however, their effects on other quality traits, such as dry matter concentration and fiber digestibility, are often variable. Excessive nitrogen fertilization may reduce fiber digestibility and adversely affect silage fermentation characteristics despite increasing protein levels [18]. In contrast, balanced nitrogen management can improve the energy value of forage and

enhance nutrient concentration, contributing to greater livestock production efficiency [19]. Therefore, sustainable fertilization strategies should aim to optimize both biomass yield and silage quality.

To date, research aimed at identifying an optimal balance between silage maize yield and forage quality under reduced nitrogen fertilization remains limited. In particular, there is a lack of evidence regarding the potential to reduce soil-applied nitrogen inputs through the use of foliar fertilization. Within the framework of sustainable agriculture, a comprehensive evaluation of this approach is warranted, considering both its agronomic performance and environmental implications, while accounting for the specific characteristics of local agroecological conditions. We hypothesized that reducing soil-applied nitrogen (N) fertilization could be offset by foliar N application, thereby maintaining the yield and quality of silage maize while improving nitrogen use efficiency. The aim of this study was to evaluate the effects of different soil and foliar nitrogen fertilization strategies on the yield and quality of silage maize (*Zea mays* L.) cultivar ‘Farmmortiz’ and to assess whether soil-applied nitrogen rates could be reduced without compromising crop performance.

2. Materials and Methods

2.1. Study Site

The field experiment was conducted in the village of Wielkie Radowiska (53°13' N, 19°01' E), located in the Dębowa Łąka municipality, Wąbrzeźno County, Kuyavian–Pomeranian Voivodeship, Poland (Figure 1). The research was carried out over two growing seasons, from 2024 to 2025.

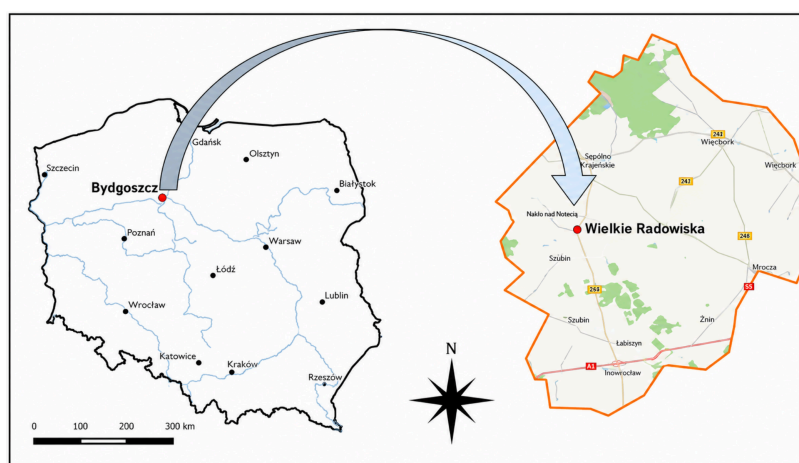


Figure 1. Location of the field experiment.

According to the agricultural–climatic regionalization of Poland, the Dębowa Łąka municipality is situated within the Masurian agricultural–climatic region. The local climate is classified as temperate, warm, and transitional, influenced by the moderate effects of the Baltic Sea. It is characterized by relatively short and mild summers and longer, cooler winters compared with many other regions of the country. The mean annual precipitation is approximately 550 mm, while the growing season lasts between 220 and 225 days. Average air temperatures are approximately −2 °C in January and 18 °C in July, resulting in a mean annual temperature of about 8 °C (Figure 2).

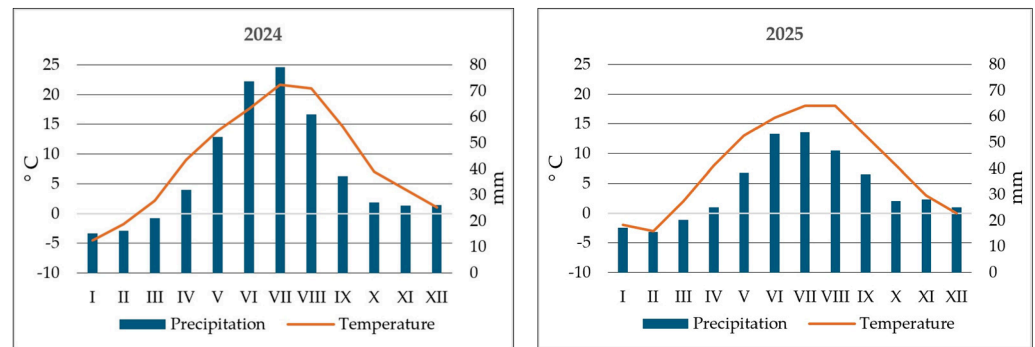


Figure 2. Hydrothermal conditions in the study area during the 2024–2025 growing seasons.

2.2. Materials

The experimental material consisted of fresh biomass of the silage maize cultivar ‘Farmoritz’. Farmoritz is a medium-early to medium-late maize hybrid (FAO maturity group approximately 240–260) characterized by broad adaptability and versatile utilization. The cultivar is distinguished by its high and stable productivity for grain, silage, and biogas production. It exhibits strong early vigor, good tolerance to adverse environmental conditions, including temporary drought and low spring temperatures, and a pronounced stay-green effect, allowing plants to maintain physiological activity for an extended period. The hybrid produces flex-type ears, enabling partial compensation for environmental stress or reduced plant density. In addition, it demonstrates good disease resistance and relatively low soil requirements, contributing to stable performance under diverse growing conditions. The field experiment was established on a medium-textured soil classified as quality class IVa and belonging to the very good rye complex. According to the classification of the IUSS Working Group WRB, the soil was identified as a Haplic Luvisol (Cutanic) with a near-neutral pH [20]. The soil contained moderate levels of available phosphorus ($58 \text{ mg P kg}^{-1} \text{ soil}$), potassium ($134 \text{ mg K kg}^{-1} \text{ soil}$), and magnesium ($65 \text{ mg Mg kg}^{-1} \text{ soil}$). The concentration of sulfate sulfur (S-SO_4^{2-}) was $16.4 \text{ mg SO}_4^{2-} \text{ kg}^{-1} \text{ soil}$, indicating a low sulfur status according to established agronomic criteria [21]. Winter wheat served as the preceding crop in both years of the study. A single-factor field experiment was conducted using a randomized complete block design (RCBD) according to the treatment scheme presented in Table 1. The experiment included four fertilization treatments, each with a plot area of 20 m^2 , arranged in three field replications.

Table 1. Scheme of experience.

Experimental Plot	Fertilizer Form	Dose	NITRON-S I Dose	NITRON-S II Dose
N1	CAN fertilizer	80 kg N ha^{-1}	-	-
N2	CAN fertilizer	40 kg N ha^{-1}	$10 \text{ dm}^3 \text{ ha}^{-1}$	$10 \text{ dm}^3 \text{ ha}^{-1}$
N3	CAN fertilizer	40 kg N ha^{-1}	$20 \text{ dm}^3 \text{ ha}^{-1}$	$20 \text{ dm}^3 \text{ ha}^{-1}$
N4	CAN fertilizer	40 kg N ha^{-1}	$30 \text{ dm}^3 \text{ ha}^{-1}$	$30 \text{ dm}^3 \text{ ha}^{-1}$

CAN—Calcium Ammonium Nitrate; I dose—the application rate applied on June 7; II dose—the application rate applied on June 22.

In early spring, farmyard manure was applied uniformly across the entire experimental area at a rate of 30 t ha^{-1} and subsequently incorporated into the soil by ploughing. Cattle manure was obtained from a dairy farm where cattle were kept in a bedding system. It was assumed that this application rate supplied 146 kg N , $82 \text{ kg P}_2\text{O}_5$, $182 \text{ kg K}_2\text{O}$, 100 kg CaO , 55 kg MgO , 22 kg S , and approximately 2.88 t of organic carbon per hectare. In addition, the manure supplied the following micronutrients: 16.2 kg Fe , 9.0 kg Mn , 2.64 kg

Zn, 0.54 kg Cu, 0.24 kg B, and 22.2 g Mo per hectare. Prior to sowing, all plots received a basal application of 15 kg N ha⁻¹ in the form of the multi-component fertilizer Polifoska 6 (NPK 6–20–30), followed by soil harrowing. Identical agronomic practices and plant protection measures, consistent with standard maize cultivation recommendations, were implemented across all experimental treatments. The foliar fertilizer Nitron-S was applied in two equal doses. The first application was performed at the six-leaf stage (BBCH 16)—the plants reached the six-leaf stage 35 days after emergence, while the second was carried out 14 days later. The chemical composition of the foliar fertilizer Nitron-S was as follows: total nitrogen (N)—25% (*w/w*), including nitrate nitrogen (N-NO₃)—3.4% (*w/w*), ammonium nitrogen (N-NH₄)—5.0% (*w/w*), and amide nitrogen (N-NH₂)—16.0% (*w/w*). The sulfur (S) content was 68 g L⁻¹. The applied fertilizer rates were diluted in 300 L of water per hectare. Foliar spraying was carried out in the afternoon under calm weather conditions. The spray droplet diameter was 300 µm. The first application was performed on June 7, and the second on June 22. Nitron-S was developed through a collaborative initiative involving Bydgoszcz University of Science and Technology, the Biostyma company (Zasutowo, Poland), and Micromix (London, UK). Nitron-S is a highly effective nitrogen–sulfur foliar fertilizer intended for use throughout the growing season. It contains stabilized nitrogen (300–320 g dm⁻³) in nitrate, amide, and ammonium forms, as well as sulfur (60–70 g dm⁻³ expressed as SO₃). Sulfur plays an important role in improving nitrogen metabolism within plants, thereby contributing to increased yield and enhanced crop quality [22]. Calcium ammonium nitrate (CAN; 27% N) was applied manually, whereas Nitron-S was sprayed foliarly using a backpack sprayer (Stihl, Waiblingen, Germany).

Maize seeds were sown during the third decade of April and the first decade of May at a seeding rate of 30 kg ha⁻¹, with a row spacing of 70 cm. Harvesting was performed at the full wax maturity stage of the grain on 11 September and 15 September in the respective years of the study. Samples of fresh biomass were collected from each experimental plot for subsequent laboratory analyses.

2.3. Methods

Following harvest, fresh biomass yield was determined for each plot. The collected plant material was subsequently analyzed for dry matter content using the oven-drying method; crude protein content using the Kjeldahl method, with total nitrogen converted to crude protein [23]; ash content by incineration in a muffle furnace at 550 °C [24]; carbohydrate and starch concentrations using near-infrared spectroscopy (NIRS) calibrated against reference samples [25]; neutral detergent fiber (NDF) according to the detergent extraction method of Van Soest [26]; acid detergent lignin (ADL) using the detergent and acid extraction procedure of Van Soest [27]; and organic matter digestibility (VOS) by NIRS calibrated with reference samples [25].

The values of the analyzed parameters were additionally expressed as percentage change (relative change) relative to the control treatment (N1) [28]:

$$RCh = \left(\frac{P_0}{C_0} - 1 \right) \times 100 \quad (1)$$

where P_0 is the content of the tested parameters in the control (N1); C_0 is the content of the tested parameters (N2–N4).

2.4. Statistics

Statistical analyses were performed using STATISTICA 13 software (StatSoft Polska, Kraków, Poland). To evaluate the effects of nitrogen fertilization treatments on the analyzed parameters of silage maize, a one-way analysis of variance (ANOVA) was conducted using

a randomized complete block design. Results are presented as means $\pm$ standard deviation (SD). When significant treatment effects were detected, differences among means were assessed using Tukey's post hoc multiple comparison test. Statistical significance was determined at $p < 0.05$.

3. Results and Discussion

3.1. The Fresh Biomass Yield

The fresh biomass yield of maize intended for silage production was significantly ($p < 0.05$) affected by nitrogen (N) application doses, showing a clear increase with increasing N doses (N1–N4). This trend was observed in both years of the study (Figure 3). The lowest yield was obtained under the lowest N rate (N1), whereas the highest yield was recorded following the application of N4, reaching 56.09 t ha^{-1} in 2024 and 55.20 t ha^{-1} in 2025. These results indicate a strong maize response to increasing N doses, suggesting that further optimization of N supply may be required to achieve maximum yield potential under the tested conditions [29].

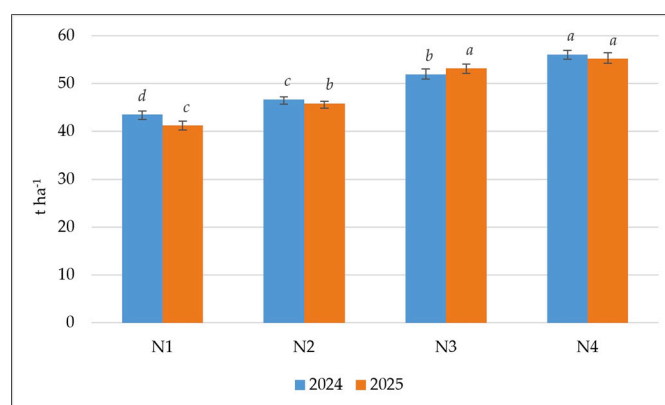


Figure 3. The fresh biomass yield of maize intended for silage [t ha^{-1}] in the study years (2024–2025). Different small letters indicate a compare on between the fertilization variants (N1–N4) at $p < 0.05$; N1–N4—doses nitrogen.

The response of maize to N fertilization has been extensively documented in the literature, as N is a key factor determining plant growth, chlorophyll synthesis, and crop productivity [30]. A comparison of yields obtained in 2024 and 2025 revealed only minor differences between growing seasons. Fresh biomass yields were slightly higher in 2024 than in 2025, particularly at higher N application doses, which may be attributed to more favorable thermal and precipitation conditions (Figure 2). Environmental factors are known to influence maize response to N fertilization and modify the efficiency of nitrogen use under field conditions [9]. During the 2024 growing season, air temperatures gradually increased from spring until July, when the highest values (approximately $24\text{--}25^\circ\text{C}$) were recorded, followed by a gradual decline. Simultaneously, cumulative precipitation during the critical summer months (June–August) remained relatively high, with a peak of approximately $70\text{--}75 \text{ mm}$ in July, creating favorable conditions for intensive maize growth and development. In contrast, hydrothermal conditions in 2025 were less favorable for maize cultivation. Summer temperatures were considerably lower, reaching a maximum of only $16\text{--}18^\circ\text{C}$, which may have reduced plant growth rates and metabolic activity. Although precipitation was distributed more evenly throughout the growing season, its temporal pattern did not fully coincide with the period of greatest water demand by maize. Furthermore, the absence of a distinct precipitation peak during the summer months may have limited the crop's yield potential. Consequently, the hydrothermal conditions pre-

vailing in 2024 should be considered more favorable for silage maize production. These conditions may also have contributed to more favorable development of plant quality and structural traits, resulting from improved growth conditions, enhanced metabolic activity, and more efficient nutrient utilization. Similar year-to-year relationships were reported by Jarecki et al. [31], who demonstrated that meteorological conditions strongly influenced both maize yield and N use efficiency. Foliar fertilization may have further supported N utilization and improved yield quality parameters, which is consistent with previous findings indicating that foliar application of micronutrients and N in various forms enhances nutrient use efficiency and may increase yield by approximately $0.2\text{--}1.5\text{ t ha}^{-1}$ [31]. However, the magnitude of this effect depends on the applied rate and environmental conditions, and under optimal mineral fertilization its contribution may be reduced or statistically insignificant [32]. The obtained results indicate that increasing N fertilization intensity was the main factor influencing maize yield. Foliar fertilization had a complementary effect by improving selected yield-related traits and supporting maize performance under the tested environmental conditions.

3.2. Dry Matter and Ash Content of Maize Intended for Silage

The dry matter content of maize intended for silage production was significantly influenced by both N application doses and foliar fertilization treatments (Table 2). The lowest dry matter content in 2024 and 2025 was recorded in treatment N1 (soil fertilization only, 80 kg N ha^{-1}), reaching 333.7 and 332.2 g kg^{-1} , respectively. Significantly ($p < 0.05$) higher values were obtained in treatments where soil fertilization was combined with foliar application (N2–N4). Increasing the rate of the NITRON-S fertilizer from 20 to $60\text{ dm}^3\text{ ha}^{-1}$ resulted in a significant increase in maize dry matter content compared with treatment N2, amounting to 3.6 and 4.4% in 2024 and 4.4 and 4.0% in 2025, respectively. However, differences between treatments N3 and N4 were not statistically significant. Dry matter production increased with increasing N doses, indicating a positive response of maize biomass to N availability. However, at higher application levels, further fertilization did not result in additional biomass accumulation. Only minor differences were observed between the two experimental years, indicating a high stability of this parameter despite varying weather conditions. Slightly higher values recorded in 2024 for the higher N treatments (N3–N4) may be attributed to more favorable moisture and temperature conditions during the plant maturation period. The obtained results confirm that balanced N fertilization, applied both to the soil and foliarly, enhances dry matter accumulation in maize plants. This effect is associated with improved photosynthetic efficiency and more effective nutrient utilization [33,34]. Similarly, Bai et al. [13] reported a positive response of maize to N fertilization; however, the highest dry matter accumulation was achieved at optimal rather than maximum N doses.

Table 2. Dry matter content and ash content [g kg^{-1}] in maize dry matter for silage in the study years (2024–2025).

Experimental Plot	Dry Matter		Ash	
	2024	2025	2024	2025
N1	$333.7\text{ c} \pm 5.54$	$332.2\text{ c} \pm 6.25$	$24.26\text{ bc} \pm 0.75$	$22.16\text{ d} \pm 0.86$
N2	$359.7\text{ b} \pm 5.11$	$357.4\text{ b} \pm 4.01$	$23.59\text{ c} \pm 0.96$	$23.09\text{ c} \pm 1.29$
N3	$372.7\text{ a} \pm 4.08$	$373.2\text{ a} \pm 0.51$	$24.94\text{ b} \pm 1.02$	$24.11\text{ b} \pm 0.93$
N4	$375.4\text{ a} \pm 5.31$	$371.8\text{ a} \pm 3.16$	$27.14\text{ a} \pm 1.05$	$26.99\text{ a} \pm 1.01$

Different small letters indicate a compare on between the fertilization variants (N1–N4) at $p < 0.05$; $\pm$ Standard Deviation.

The present study also demonstrated significant ($p < 0.05$) differences in ash content of maize dry matter depending on N application rate. In 2024, the lowest ash content was recorded in treatment N2 (23.59 g kg⁻¹), whereas the highest value was observed in N4 (27.14 g kg⁻¹). In 2025, the lowest ash content was found in N1 (22.16 g kg⁻¹), while the highest value was again recorded in N4 (26.99 g kg⁻¹). Overall, an increasing trend in ash content was observed with increasing N doses, particularly within the N2–N4 range (Table 2). This finding confirms a consistent and repeatable pattern of mineral nutrient accumulation in maize plants under more intensive N fertilization. The observed increase in ash content may be attributed to enhanced uptake and translocation of macronutrients under improved N supply, as nitrogen stimulates root system activity and plant metabolism. Consequently, greater concentrations of mineral nutrients are accumulated in plant tissues, leading indirectly to increased ash content in biomass [35,36]. Ash content in plants is considered an indicator of the total concentration of mineral elements (e.g., K, Ca, Mg, P, and Fe) and reflects the degree of their accumulation, which depends on both environmental conditions and fertilization practices [37]. The relatively small differences observed between years suggest that the effect of N fertilization on ash content was stronger than the influence of variable environmental conditions. From a silage quality perspective, crude ash content in maize dry matter is also important because it may affect silage pH and, consequently, the fermentation process.

The Relative Change (*RCh*) index for dry matter content, calculated in relation to treatment N1, indicated a clear effect of foliar fertilization in both years of the study (Figure 4). The highest *RCh* values were recorded for treatment N3, whereas a further increase in the fertilizer rate (N4) did not result in any substantial improvement, showing either stabilization or a slight decline in relative values. This finding confirms the occurrence of a saturation effect [38]. The application of foliar fertilization (NITRON-S) increased dry matter content by approximately 8–12% compared with N1, with the most favorable response observed for treatment N3. Similar results were reported by Lu et al. [34], who found that dry matter content was highest following the application of 180 kg N ha⁻¹, reaching a value 28.4% greater than that of the control treatment. However, further increases in N doses reduced biomass production efficiency. A substantially greater response was observed for crude ash content (Figure 4). In 2024, ash content in treatment N2 was 2.76% lower than in N1, whereas in treatment N4 it increased by nearly 12%. In 2025, differences among treatments were even more pronounced, with ash content in N4 exceeding that of N1 by almost 22%. These results suggest that more intensive foliar fertilization promoted the accumulation of mineral nutrients in plant tissues, likely due to improved uptake and translocation of both macro- and micronutrients. Comparable relationships were reported by Wang et al. [39], who demonstrated that enhanced N metabolism contributes to greater biomass production and increased mineral nutrient accumulation in maize plants.

3.3. Conventional Nutritional Components of Maize Intended for Silage

3.3.1. Content of the Ammonium Fraction and Crude Protein

The ammonium fraction (NH₄⁺) in plants, including maize, represents a direct nitrogen source for the rapid synthesis of amino acids, primarily glutamine and glutamate. This is a key step in nitrogen assimilation, determining the synthesis of nitrogen compounds essential for plant growth [40,41]. The NH₄⁺ content was significantly ($p < 0.05$) influenced by both soil nitrogen application doses and foliar fertilization (Table 3). The lowest values of this fraction were recorded in treatment N1 (9.23 g kg⁻¹), whereas significantly ($p < 0.05$) higher values were observed in treatments N2–N4, reaching 10.48–12.33 g kg⁻¹. The highest values were obtained in treatments N3 and N4; however, no statistically significant differences were found between these two treatments. The results were highly

stable across both years (2024–2025), confirming the reproducibility of plant responses to nitrogen fertilization. The increase in the ammonium fraction with increasing nitrogen supply can be attributed to greater NH_4^+ availability and its accumulation in plant tissues. At higher N doses, a stabilization of this parameter was also observed, which may be related to limitations in nitrogen uptake and metabolic conversion. Similar relationships were reported by Dawar et al. [14], who demonstrated that ammonium content and NH_3 emission in maize are strongly dependent on nitrogen rate and fertilizer form. Increasing nitrogen availability led to higher levels of these parameters, simultaneously affecting nitrogen use efficiency (NUE).

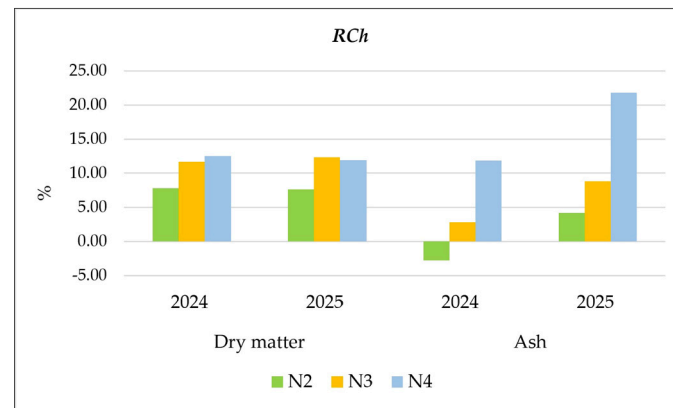


Figure 4. Relative changes (*RCh*, %) in dry matter and ash content of maize silage biomass under different nitrogen fertilization treatments (N2, N3, and N4) during two consecutive study years (2024–2025). The *RCh* values represent the percentage change in relation to the control treatment (N1).

Table 3. Content of the ammonium fraction (NH_4^+) and crude protein [g kg^{-1}] in maize dry matter for silage during the study years (2024–2025).

Experimental Plot	Ammoniacal Nitrogen Fraction		Crude Protein	
	2024	2025	2024	2025
N1	9.23 c $\pm$ 0.009	9.20 c $\pm$ 0.008	71.08 c $\pm$ 0.21	69.82 bc $\pm$ 0.68
N2	10.48 b $\pm$ 0.011	10.41 b $\pm$ 0.009	85.77 a $\pm$ 0.68	83.99 a $\pm$ 0.82
N3	11.95 a $\pm$ 0.008	11.92 a $\pm$ 0.009	73.12 b $\pm$ 1.52	71.36 b $\pm$ 1.08
N4	12.33 a $\pm$ 0.010	12.01 a $\pm$ 0.011	69.52 d $\pm$ 0.96	70.72 b $\pm$ 1.12

Different small letters indicate a compare on between the fertilization variants (N1–N4) at $p < 0.05$; $\pm$ Standard Deviation.

A significant effect of N doses and foliar application on crude protein content in maize dry matter was also observed (Table 3). The lowest crude protein content was recorded in treatment N1 in both years (71.08 and 69.82 g kg^{-1}). A significant ($p < 0.05$) increase in this parameter, compared with N1, was observed in treatment N2 in both 2024 and 2025, by 20.7% and 20.3%, respectively. Further increases in N doses (N3 and N4) resulted in a decrease in crude protein content. Similar trends were reported by Liu et al. [42], who showed that increasing N doses enhanced crude protein content up to an optimum level, beyond which further increases led to stabilization or a decline. Crude protein content represents total nitrogen content converted into a protein equivalent and includes both true proteins and non-protein nitrogen compounds [43]. It is a variable trait, typically ranging from approximately 7% to 16% of dry matter, and is strongly influenced by cultivar, environmental conditions, and nitrogen fertilization level [44]. Wang et al. [39] demonstrated that nitrogen fertilization significantly enhances protein synthesis in maize through the activation of nitrogen metabolism enzymes; however, this

effect is nonlinear and depends on the applied N dose. The response to Nitron-S may be attributed to the complementary roles of nitrogen and sulfur in plant metabolism. Sulfur supplied with the foliar fertilizer supports cysteine and glutathione biosynthesis, thereby enhancing nitrogen assimilation and improving nitrogen use efficiency. This occurs because glutathione maintains cellular redox homeostasis and regulates the activity of enzymes involved in sulfate reduction and nitrogen metabolism, facilitating the incorporation of inorganic nitrogen into amino acids and proteins [45,46].

The *RCh* index revealed a stronger response of the ammonium nitrogen (NH_4^+) fraction than of crude protein to foliar fertilization with NITRON-S (Figure 5). The NH_4^+ content increased consistently with increasing fertilizer doses, rising from approximately 13% in treatment N2 to more than 33% in treatment N4 in 2024 and to approximately 31% in 2025. This pattern indicates enhanced accumulation of mineral nitrogen forms in plant tissues. Similar relationships have been reported in studies on nitrogen metabolism in maize, demonstrating that increased nitrogen availability intensifies nitrogen uptake and redistribution within the plant, leading to higher concentrations of mineral nitrogen forms and enhanced activity of nitrogen transformation processes [47]. A different response pattern was observed for crude protein content. The greatest increase in crude protein concentration, reaching approximately 20% in both years, was recorded in treatment N2. However, higher N doses reduced this effect, and in treatment N4 a decline in crude protein content was observed in 2024. These findings indicate a nonlinear response of maize to nitrogen fertilization and suggest a possible shift in plant metabolism toward the accumulation of mineral nitrogen forms under conditions of excessive nitrogen supply. Such a response may reflect a reduced efficiency of nitrogen assimilation into organic compounds, resulting in greater retention of inorganic nitrogen within plant tissues.

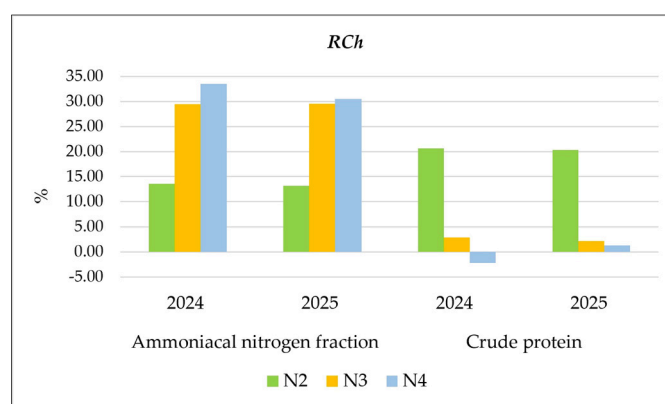


Figure 5. Relative changes (*RCh*, %) in ammonium nitrogen fraction and crude protein content of maize silage biomass under different nitrogen fertilization treatments (N2, N3, and N4) during two consecutive study years (2024–2025). The *RCh* values represent the percentage change in relation to the control treatment (N1).

3.3.2. Content of the Carbohydrate and Starch

Carbohydrates content in maize intended for silage showed a clear positive response to increasing nitrogen fertilization in both years of the study (2024–2025). The lowest carbohydrates concentrations were recorded under the lowest nitrogen rate (N1), reaching 4.88 and 3.88 g kg⁻¹, respectively, whereas the highest values were observed under the highest N fertilization level (N4), reaching 20.75 and 21.11 g kg⁻¹, respectively (Table 4). At the same time, very similar values between years indicate a stable plant response to this factor. Carbohydrates, primarily in the form of sucrose, glucose, and fructose, play a key role as products of photosynthesis as well as transport and regulatory compounds. They govern plant growth and development by controlling carbon allocation among different

organs [48]. This pattern of changes is consistent with studies reporting that N fertilization significantly increases the content of soluble carbohydrates (sucrose, glucose, and fructose) in maize [49–51]. The application of N intensifies photosynthetic activity, carbohydrate metabolism, and the activity of enzymes involved in carbohydrates synthesis, leading to greater accumulation of these compounds in plant tissues during crop development. Soluble carbohydrates in maize represent a key substrate for lactic acid fermentation. Their increased concentration improves silage quality by enhancing lactic acid production and promoting faster pH stabilization during ensiling [52].

Table 4. Content of the carbohydrate and starch [g kg^{-1}] in maize dry matter for silage during the study years (2024–2025).

Experimental Plot	Carbohydrates		Starch	
	2024	2025	2024	2025
N1	4.88 d $\pm$ 0.52	3.88 d $\pm$ 0.66	298.7 c $\pm$ 3.17	281.6 d $\pm$ 4.22
N2	12.36 c $\pm$ 0.85	11.23 c $\pm$ 0.82	305.3 c $\pm$ 3.58	304.7 c $\pm$ 3.58
N3	17.30 b $\pm$ 0.76	17.12 b $\pm$ 0.89	334.1 b $\pm$ 4.08	329.1 b $\pm$ 4.06
N4	20.75 a $\pm$ 1.08	21.11 a $\pm$ 0.93	371.9 a $\pm$ 3.83	366.5 a $\pm$ 4.12

Different small letters indicate a compare on between the fertilization variants (N1–N4) at $p < 0.05$; $\pm$ Standard Deviation.

The results presented in Table 4 indicate a significant effect of varying N application doses on starch content. A clear linear increase in starch content was observed with increasing N doses from N1 to N4. In both years of the study, the lowest statistically significant ($p < 0.05$) starch content was recorded in treatment N1 (298.7 and 281.6 g kg^{-1}), whereas the highest values were found in treatment N4 (371.9 and 366.5 g kg^{-1} , respectively). These results demonstrate a highly consistent response of maize to increasing N supply across both experimental seasons. The increase in starch content in maize dry matter with higher N doses can be attributed to the stimulation of photosynthesis and the activity of enzymes involved in carbohydrate metabolism.

This enhances assimilate transport to the kernels and intensifies the grain-filling process. High nitrogen fertilization also promotes the activity of key starch biosynthesis enzymes (including ADP-glucose pyrophosphorylase (AGPase) and granule-bound starch synthase (GBSS)), leading to greater accumulation of storage polysaccharides in the maize endosperm and more efficient kernel filling [49,52,53]. Starch represents the primary storage form of carbohydrates, serving as a key reserve energy source. It is also a fundamental energetic component of feed and food, particularly in dairy cattle nutrition [54]. Although the N4 treatment increased starch concentration, its nutritional advantage may have been offset by the concurrent increase in ADL and NDF. Lignin forms cross-links with structural polysaccharides within the cell wall, restricting microbial access to cellulose and hemicellulose and thereby reducing NDF degradability in the rumen. Consequently, increased starch concentration does not necessarily improve the overall digestibility of maize silage when accompanied by greater lignification [55].

Figure 6 presents *RCh* in carbohydrates and starch content compared with treatment N1, depending on increasing N application rates (N2–N4). A clear dose-dependent relationship was observed, with a gradual increase in *RCh* values for both analyzed fractions as N fertilization levels increased. In the case of carbohydrates, a strong and consistent increase in *RCh* was recorded, particularly under the highest N rate (N4), where values reached approximately 320% in 2024 and over 400% in 2025. This indicates a substantial stimulation of soluble sugar accumulation with increasing nitrogen supply, with an even stronger response observed in 2025 [56,57]. For starch, *RCh* values were considerably lower, ranging from small to moderate increases (up to approximately 30% under N4). Nevertheless, a

positive trend was also observed with increasing N doses, suggesting a beneficial, albeit much weaker, effect of nitrogen fertilization on starch accumulation. The pronounced differences among treatments observed in this study are most likely associated with improved nitrogen use efficiency resulting from partial foliar application rather than exclusive soil fertilization. This aligns with the concept of sustainable fertilization strategies aimed at enhancing nutrient use efficiency (NUE) and reducing nitrogen losses to the environment. Foliar-applied nitrogen acts rapidly and directly supports the photosynthetic apparatus, which may enhance photosynthetic intensity and assimilate production. Consequently, an increase in dry matter content was observed, indicating improved crop maturation and a greater proportion of carbohydrate-rich fractions, thereby confirming the potential of sustainable fertilization strategies for improving yield quality [58,59].

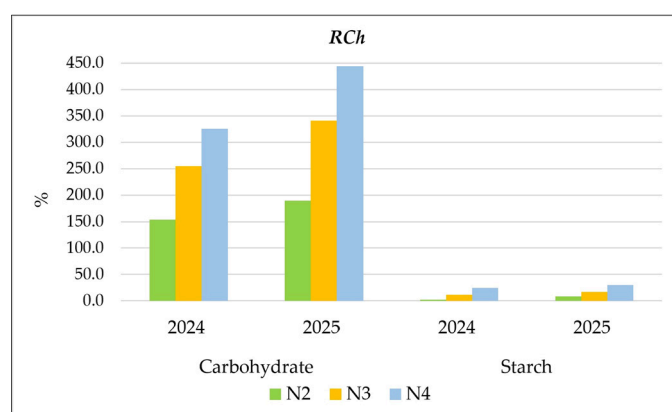


Figure 6. Relative changes (*RCh*, %) in carbohydrate and starch content of maize silage biomass under different nitrogen fertilization treatments (N2, N3, and N4) during two consecutive study years (2024–2025). The *RCh* values represent the percentage change in relation to the control treatment (N1).

3.4. Fiber Components and Digestibility of Maize Silage

3.4.1. Content of the Crude Fiber and Neutral Detergent Fiber

Table 5 presents the crude fiber content of maize as affected by the applied fertilization treatments. In both years of the study, a statistically significant ($p < 0.05$) decrease in crude fiber content was observed with increasing nitrogen application rates. The highest crude fiber content was recorded in treatment N1 (234.9 and 232.1 g kg^{−1} in 2024 and 2025, respectively), whereas the lowest values were found in treatment N4 (199.8 and 195.6 g kg^{−1}, respectively). These results indicate a consistent decline in crude fiber content with increasing N fertilization intensity. Differences between years were relatively small, suggesting that the effect of N fertilization was more pronounced than the variability in weather conditions between growing seasons. Feng et al. [49] reported that N fertilization affects the dynamics of carbohydrate deposition and cell wall component formation through changes in enzyme activity and assimilate partitioning, which may indirectly influence crude fiber content. In maize, crude fiber content is primarily associated with structural cell wall polysaccharides, including cellulose, hemicellulose, and, to some extent, lignin, and is therefore considered an approximate indicator of structural cell wall constituents [56]. Increasing N fertilization alters carbon and nitrogen (C/N) metabolism in maize, directing a greater proportion of assimilates toward protein and starch synthesis. This process occurs at the expense of the relative contribution of cell wall structures, leading to a reduction in constituents associated with crude fiber content [57].

Table 5. Content of the crude fiber and neutral detergent fiber (NDF) [g kg^{-1}] in maize dry matter for silage during the study years (2024–2025).

Experimental Plot	Crude Fiber		NDF	
	2024	2025	2024	2025
N1	234.9 a $\pm$ 4.17	232.1 a $\pm$ 3.35	404.1 c $\pm$ 6.17	403.2 d $\pm$ 4.86
N2	224.9 b $\pm$ 3.59	215.8 b $\pm$ 4.02	411.8 b $\pm$ 6.05	410.3 b $\pm$ 5.53
N3	206.2 c $\pm$ 3.86	198.7 c $\pm$ 3.12	416.3 b $\pm$ 5.52	415.2 a $\pm$ 6.12
N4	199.8 d $\pm$ 2.11	195.6 c $\pm$ 2.89	421.5 a $\pm$ 7.46	416.8 a $\pm$ 4.47

Different small letters indicate a compare on between the fertilization variants (N1–N4) at $p < 0.05$; $\pm$ Standard Deviation.

Statistical analysis of the obtained results demonstrated that increasing nitrogen fertilization levels promoted a gradual increase in NDF content in maize during both years of the study (Table 5). The highest NDF content was recorded in treatment N4 (421.5 and 416.8 g kg^{-1} in 2024 and 2025, respectively), whereas the lowest values were observed in treatment N1 (404.1 and 403.2 g kg^{-1} , respectively). These findings suggest that a more intensive nitrogen supply may have stimulated the development of structural tissues and increased the proportion of cell wall components in plant dry matter. The observed increase may be related to enhanced cellulose and hemicellulose synthesis under higher nitrogen rates. Additionally, greater vegetative biomass production may contribute to increased NDF content. In maize and maize silage, NDF content (neutral detergent fiber) comprises the structural components of the cell wall, including cellulose, hemicellulose, and lignin. Consequently, NDF content is considered a key indicator of fiber concentration and plant maturity, strongly influencing the nutritional value of forage [14]. NDF content affects digestibility and ruminal fermentation dynamics, as a higher proportion of structural fiber fractions reduces energy availability and may limit feed intake by ruminants [58]. Nitrogen fertilization may indirectly influence NDF content in maize by modifying plant growth rates and the proportion of structural constituents, thereby affecting silage quality and its energy value [59]. Similar relationships were reported by Ferreira et al. [60], who demonstrated that agronomic management practices significantly modify cell wall structure and the composition of NDF fractions in silage maize, thereby influencing forage nutritional value and digestibility.

Figure 7 presents the *RCh* values of crude fiber content and NDF content relative to treatment N1. In the case of crude fiber content, a clear decrease compared with the control treatment (N1) was observed across all fertilization variants. In 2024, the reduction ranged from approximately -4% in N2 to around -15% in N4. An even greater decrease was recorded in 2025, particularly in the higher fertilization treatments (N3 and N4), where values reached approximately -15 to -16% . These results indicate that intensification of nitrogen fertilization, especially when combined with foliar application, reduced the proportion of crude fiber content in the plant material. An opposite trend was observed for NDF content. All fertilization treatments resulted in an increase in NDF content relative to N1. In 2024, the increase ranged from approximately 2% (N2) to over 4% (N4). A similar pattern was observed in 2025, although with slightly lower variation, as values increased by approximately 2% to 3.5% . The greatest increase in NDF content was recorded under the highest nitrogen fertilization level (N4). The obtained results suggest that increasing nitrogen application rates altered the fiber composition of maize, reducing crude fiber content while simultaneously increasing NDF content. These trends are consistent with the literature, which indicates that nitrogen fertilization can significantly influence the chemical composition of plant biomass and cell wall structure [61,62].

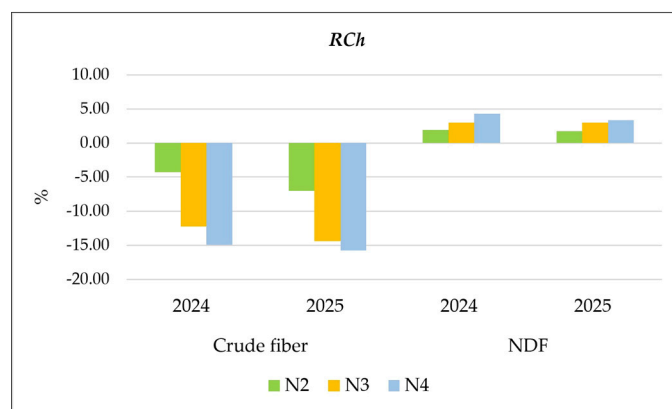


Figure 7. Relative changes (*RCh*, %) in crude fiber and NDF (neutral detergent fiber) content of maize silage biomass under different nitrogen fertilization treatments (N2, N3, and N4) during two consecutive study years (2024–2025). The *RCh* values represent the percentage change in relation to the control treatment (N1).

3.4.2. Content of the Lignin and Organic Matter Digestibility

Lignin content (ADL) in maize showed a clear increasing trend with rising N fertilization doses. In both 2024 and 2025, the significantly ($p < 0.05$) lowest ADL values were recorded in treatment N1, amounting to 16.40 and 15.71 g kg⁻¹, respectively (Table 6). The highest values were observed in treatments N3 and N4, where ADL content remained at a comparable level, with no statistically significant differences between these treatments in either year. According to Podkowska [63], the effect of nitrogen fertilization on the composition of plant fiber fractions, including lignin content, is indirect in nature. The observed relationships may be explained by enhanced formation of secondary cell walls and increased synthesis of phenolic compounds responsible for lignification of vascular and mechanical tissues. Higher lignin content in maize silage negatively affects nutritional value by limiting fiber degradation in the rumen. This reduces the digestibility of structural feed fractions and lowers the energy availability for ruminants. Similar relationships regarding changes in fiber digestibility and the proportion of lignified cell wall structures in silage maize were reported by Ferreira et al. [57]. Increased lignin content limits fiber degradation in the rumen and reduces the digestibility of structural feed fractions, thereby decreasing the energy value of forage for ruminants [55]. This effect results from the formation of lignin–carbohydrate complexes, which restrict the accessibility of cell wall carbohydrates to microbial enzymes and reduce the degradation of cellulose and hemicellulose, ultimately lowering fiber digestibility and energy availability [64]. The organic matter digestibility (VOS) value of maize was significantly ($p < 0.05$) influenced by the applied nitrogen fertilization (Table 6). In both years of the study, the highest VOS values were recorded in treatment N2 (759.2 and 751.2 g kg⁻¹ in 2024 and 2025, respectively), whereas the lowest values were observed in treatment N1 (739.8 and 729.9 g kg⁻¹, respectively). These differences were statistically significant and amounted to 2.6 and 2.9%, respectively. Further increases in N application (N3 and N4) led to a decrease in VOS values compared with treatment N2, which was statistically confirmed in 2024. This trend may be attributed to increased tissue lignification and a higher proportion of structural fiber fractions in plants subjected to intensive N fertilization. Moderate N fertilization promotes the development of photosynthetically active tissues and increases the proportion of more digestible cellular components, whereas excessive N doses may enhance lignin deposition and reduce fiber degradability in the digestive tract of ruminants. Similar relationships between N fertilization, cell wall lignification, and organic matter digestibility in silage maize have been reported by Ferreira et al. [57], Khan et al. [65], and Hlisnikovský et al. [66].

Table 6. Content of the lignin (ADL) and organic matter digestibility (VOS) [g kg^{-1}] in maize for silage during the study years (2024–2025).

Experimental Plot	ADL		VOS	
	2024	2025	2024	2025
N1	16.40 c $\pm$ 0.86	15.71 c $\pm$ 0.75	739.8 c $\pm$ 7.46	729.9 b $\pm$ 8.84
N2	18.57 b $\pm$ 0.44	18.43 b $\pm$ 0.62	759.2 a $\pm$ 8.12	751.2 a $\pm$ 7.34
N3	19.54 a $\pm$ 0.56	19.99 a $\pm$ 0.79	750.0 b $\pm$ 8.36	748.8 a $\pm$ 7.61
N4	19.89 a $\pm$ 1.06	19.76 a $\pm$ 0.87	749.5 b $\pm$ 7.26	745.5 a $\pm$ 6.46

Different small letters indicate a compare on between the fertilization variants (N1–N4) at $p < 0.05$; $\pm$ Standard Deviation.

For the ADL fraction, a clear increase in its content was observed with increasing N fertilization levels. In 2024, the *RCh* value increased from approximately 13% for N2 to over 21% for N4 (Figure 8). An even stronger effect was recorded in 2025, when ADL increased by approximately 17% for N2 and by more than 25% for treatments N3 and N4. The greatest changes were observed at higher N doses, indicating a significant effect of intensive fertilization, including foliar application, on the increased proportion of lignin in plant biomass. In the case of organic matter digestibility (VOS), the observed changes were considerably smaller. In 2024, a slight increase in *RCh* values relative to N1 was recorded, ranging from approximately 1% to 3%. In 2025, a similar trend was observed; however, differences among fertilization treatments were small and more uniform. These results suggest that N fertilization had a limited effect on VOS compared with the strong response observed for ADL. Previous studies on maize indicate that N fertilization may modify cell wall composition, including ADL content, and influence organic matter digestibility. In maize, changes in ADL levels and fiber structure have been shown to be closely associated with biomass degradability and digestibility, thereby affecting forage nutritional value [67,68]. Moreover, in silage maize and forage biomass, cell wall chemical parameters, particularly lignin (ADL) content, remain important indicators of organic matter and fiber digestibility. Studies on maize have shown associations between ADL, NDF content, and in vitro digestibility parameters (IVDMD and IVNDFD). Higher lignification may reduce fiber degradability, thereby decreasing the nutritional value of maize biomass [69].

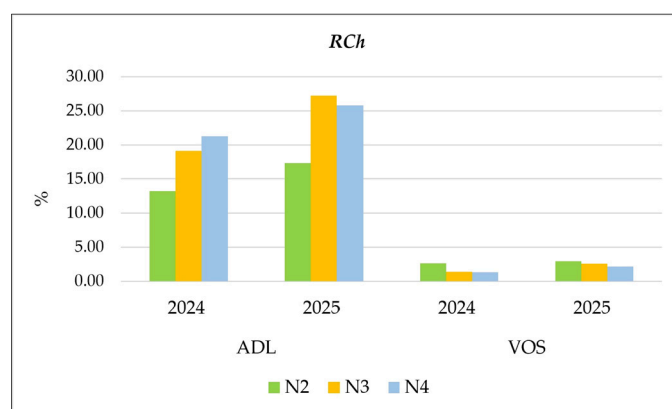


Figure 8. Relative changes (*RCh*, %) in lignin (ADL) and organic matter digestibility (VOS) content of maize silage biomass under different nitrogen fertilization treatments (N2, N3, and N4) during two consecutive study years (2024–2025). The *RCh* values represent the percentage change in relation to the control treatment (N1).

4. Conclusions

Differentiated nitrogen fertilization significantly influenced the quality of silage maize by modifying dry matter and starch contents, fiber fractions (NDF and ADL), organic

matter digestibility (VOS), and ammonium fraction. The most favorable balance between forage quality and nitrogen use efficiency was achieved with moderate foliar applications of NITRON-S (20–40 L ha^{−1}) combined with reduced soil-applied nitrogen. This fertilization strategy maintained silage quality while reducing mineral nitrogen inputs. In contrast, the highest nitrogen rate increased lignin content and the ammonium fraction while reducing organic matter digestibility, indicating that excessive nitrogen supply does not further improve silage quality. These results support applications of optimized nitrogen management strategies to enhance nutrient use efficiency and promote more sustainable forage production. The study was conducted at a single location over two growing seasons using one maize cultivar; therefore, further multilocation and long-term studies involving different cultivars, soil types, and climatic conditions are required to validate the broader applicability of the proposed fertilization strategy.

Author Contributions: Conceptualization, W.K.; methodology, W.K. and W.D.; software, W.K. and J.L.; formal analysis, W.D. and W.K.; investigation, W.K., J.L. and W.D.; data curation, W.K.; writing—preparation J.L., W.K. and T.K.; writing—review and editing, W.K., J.L. and T.K.; visualization, J.L.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Bydgoszcz University of Science and Technology under Grant BN-WRiB 1/2022 and BN-WRiB 2/2022.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

References

1. Khan, N.A.; Yu, P.; Ali, M.; Cone, J.W.; Hendriks, W.H. Nutritive value of maize silage in relation to dairy cow performance and milk quality. *J. Sci. Food Agric.* **2015**, *95*, 238–252. [[CrossRef](#)] [[PubMed](#)]
2. Serva, L. A comparative evaluation of maize silage quality under diverse pre-ensiling strategies. *PLoS ONE* **2024**, *19*, e0308627. [[CrossRef](#)] [[PubMed](#)]
3. Serva, L.; Andrighetto, I.; Segato, S.; Marchesini, G.; Chinello, M.; Magrin, L. Assessment of maize silage quality under different pre-ensiling conditions. *Data* **2023**, *8*, 117. [[CrossRef](#)]
4. Özata, E.; Yıldırım, G.H.; Alaca, B. Multi-year evaluation of silage yield, quality, and stability of maize (*Zea mays* L.) genotypes in the central Black Sea region of Türkiye. *Sci. Rep.* **2026**, *16*, 18037. [[CrossRef](#)] [[PubMed](#)]
5. Vuma, M.; Ratsaka, M.M.; Tjelele, J.T.; Langa, T.; Nkosi, B.D.; Malebana, I.M.M. effects of protein supplementation and microbial inoculation on fermentation quality, aerobic stability, and in vitro digestibility of maize silage. *Fermentation* **2026**, *12*, 155. [[CrossRef](#)]
6. Zhang, X.; Liang, X.; Zhang, Y. Advancements in the research and application of whole-plant maize silage for feeding purposes. *Animals* **2025**, *15*, 1922. [[CrossRef](#)] [[PubMed](#)]
7. Karn, R.; Rabia, M.H.; Lewis, K.; Siebecker, M.G.; Guo, W. Principles and application of nitrogen management in precision agriculture: A review. *Adv. Agron.* **2025**, *191*, 47–109. [[CrossRef](#)]
8. Li, Y.; Miao, Y.; Zhang, J.; Cammarano, D.; Li, S.; Liu, X.; Tian, Y.; Zhu, Y.; Cao, W.; Cao, Q. Improving estimation of winter wheat nitrogen status using random forest by integrating multi-source data across different agro-ecological zones. *Front. Plant Sci.* **2022**, *13*, 890892. [[CrossRef](#)] [[PubMed](#)]
9. Jiang, Y.; Li, H.; Ma, W.; Yu, W.; Chen, J.; Gao, Y.; Qi, G.; Yin, M.; Kang, Y.; Ma, Y.; et al. A meta-analysis of the effects of nitrogen fertilizer application on maize (*Zea mays* L.) yield in Northwest China. *Front. Plant Sci.* **2025**, *15*, 1485237. [[CrossRef](#)] [[PubMed](#)]
10. Setiyono, T. Precise positioning in nitrogen fertility sensing in maize (*Zea mays* L.). *Sensors* **2024**, *24*, 5322. [[CrossRef](#)] [[PubMed](#)]
11. Han, X.; Xiao, X.; Zhang, J.; Shao, M.; Jie, Y.; Xing, H. Effects of nitrogen fertilizer and planting density on growth, nutrient characteristics, and chlorophyll fluorescence in silage maize. *Agronomy* **2024**, *14*, 1352. [[CrossRef](#)]
12. Zhang, Y.; Zhang, X.; Wang, X.; Zhao, F.; Xu, Y.; Yang, H.; Zhang, W. integrated moderate stay-green hybrids and optimal nitrogen management improving maize productivity and grain nitrogen uptake. *Agronomy* **2025**, *15*, 853. [[CrossRef](#)]

13. Bai, J.; Tian, W.-C.; Giu, Z.-J.; Wei, X.-Y.; Xue, X.-R.; Huang, G.-J.; Wang, Y.-L.; Yang, Z.-P. Effects of different nitrogen types and levels on the yield and forage quality of silage maize in saline-alkali soil. *J. Plant Nutr. Fertil.* **2024**, *30*, 1683–1693. [\[CrossRef\]](#)
14. Dawar, K.; Dawar, A.; Tariq, M.; Mian, I.A.; Muhammad, A.; Farid, L.; Khan, S.; Khan, K.; Shah Fahad, S.; Danish, S.; et al. Enhancing nitrogen use efficiency and yield of maize (*Zea mays* L.) through Ammonia volatilization mitigation and nitrogen management approaches. *BMC Plant Biol.* **2024**, *24*, 74. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Januszkiewicz, R.; Kulczycki, G.; Samoraj, M. Foliar fertilization of crop plants in polish agriculture. *Agriculture* **2023**, *13*, 1715. [\[CrossRef\]](#)
16. de Castro, S.A.Q.; Schjoerring, J.K. Chapter Three—Foliar nitrogen and phosphorus fertilization. *Adv. Agron.* **2024**, *187*, 109–169. [\[CrossRef\]](#)
17. Agyin-Birikorang, S.; Boubakry, C.; Kadyampakeni, D.M.; Adu-Gyamfi, R.; Chambers, R.A.; Tindjina, I.; Fuseni, A.-R.A. Synergism of sulfur availability and agronomic nitrogen use efficiency. *Agron. J.* **2024**, *116*, 753–764. [\[CrossRef\]](#)
18. Neumann, M.; Dochwat, A.; Horst, E.H.; Vigne, G.L.D.; Mendes, M.C. Production of maize for silage under increasing levels of nitrogen fertilization in cover. *Appl. Res. Agrotechnol.* **2017**, *2*, 61–70. [\[CrossRef\]](#)
19. Nogalska, A.; Borsuk-Stanulewicz, M.; Nogalski, Z. The effect of meat and bone meal on yield and herbage quality in silage maize. *Appl. Sci.* **2025**, *15*, 117. [\[CrossRef\]](#)
20. IUSS Working Group WRB. *World Reference Base for Soil Resources 2014; Update 2015*; World Soil Resources Reports No. 106; FAO: Rome, Italy, 2015.
21. Lipiński, W.; Terelak, H.; Motowicka-Terelak, T. Suggestion for limiting values of sulphate sulphur content in mineral soils for fertilization advisory needs. *Soil Sci. Annu.* **2003**, *54*, 79–84.
22. De Souza Junior, J.C.; Monteiro, F.A. Sulfur improvements in growth, nutrient use efficiency, and photosynthesis depend on ammonium–nitrate nutrition in *Megathyrus maximus*. *Front. Plant Sci.* **2026**, *17*, 1828558. [\[CrossRef\]](#) [\[PubMed\]](#)
23. PN-EN ISO 5983-1:2009; Animal Feeding Stuffs—Determination of Nitrogen Content and Calculation of Crude Protein Content—Part 1: Kjeldahl Method. ISO: Geneva, Switzerland, 2009.
24. PN-EN ISO 5984:2005; Animal Feeding Stuffs—Determination of Crude Ash. ISO: Geneva, Switzerland, 2005.
25. PN-EN ISO 12099:2017-02; Animal Feeding Stuffs, Cereals and Milled Cereal Products—Guidelines for the Application of Near Infrared Spectrometry. ISO: Geneva, Switzerland, 2005.
26. PN-EN ISO 16472:2007; Animal Feeding Stuffs—Determination of Amylase-Treated Neutral Detergent Fibre Content (aNDF) and Acid Detergent Fibre Content (ADF). ISO: Geneva, Switzerland, 2005.
27. PN-EN ISO 13906:2009; Animal Feeding Stuffs—Determination of Acid Detergent Lignin (ADL) Content. ISO: Geneva, Switzerland, 2005.
28. Chaer, G.; Fernandes, M.; Myrold, D.; Bottomley, P. Comparative resistance and resilience of soil microbial communities and enzyme activities in adjacent native forest and agricultural soils. *Microb. Ecol.* **2009**, *58*, 414–424. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Birhan, D.A.; Sharma, A.K.; Katoch, K.; Singh, R.; Singh, S.; Sharma, L.K. Systematic review of maize nitrogen rates, yield, nitrate leaching, and their variability. *Agron. J.* **2025**, *117*, e70244. [\[CrossRef\]](#)
30. Ssemugenze, B.; Ocwa, A.; Kuunya, R.; Gumisiriya, C.; Bojtor, C.; Nagy, J.; Széles, A.; Illés, Á. Enhancing maize production through timely nutrient supply: The role of foliar fertiliser application. *Agronomy* **2025**, *15*, 176. [\[CrossRef\]](#)
31. Jarecki, W.; Borza, I.M.; Rosan, C.A.; Domuța, C.G.; Vicas, S.I. The effect of foliar micronutrient fertilization on yield and nutritional quality of maize grain. *Agronomy* **2025**, *15*, 1859. [\[CrossRef\]](#)
32. Jakab, P.; Zoltán, G.; Festő, D.; Komarek, L. Investigation of foliar fertilization in maize production. *Adv. Res. Life Sci.* **2017**, *1*, 1–6. [\[CrossRef\]](#)
33. Guo, X.; Li, G.; Ding, X.; Zhang, J.; Ren, B.; Liu, P.; Zhang, S.; Zhao, B. Response of leaf senescence, photosynthetic characteristics, and yield of summer maize to controlled-release urea-based application depth. *Agronomy* **2022**, *12*, 687. [\[CrossRef\]](#)
34. Lu, Y.; Ma, R.; Gao, W.; You, Y.; Jiang, C.; Zhang, Z.; Kamran, M.; Yang, X. Optimizing the nitrogen application rate and planting density to improve dry matter yield, water productivity and N-use efficiency of forage maize in a rainfed region. *Agric. Water Manag.* **2024**, *305*, 109125. [\[CrossRef\]](#)
35. Wyszowski, M.; Wyszowska, J.; Kordala, N.; Borowik, A. Effects of coal and sewage sludge ashes on macronutrient content in maize (*Zea mays* L.) grown on soil contaminated with eco-diesel oil. *Materials* **2022**, *15*, 525. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Wyszowski, M.; Brodowska, M.S.; Kordala, N. Trace element contents in maize following the application of organic materials to reduce the potential adverse effects of nitrogen. *Materials* **2022**, *16*, 215. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Puri, L.; Hu, Y.; Naterer, G. Critical review of the role of ash content and composition in biomass pyrolysis. *Front. Fuels* **2024**, *2*, 1378361. [\[CrossRef\]](#)
38. Zhang, T.; Liu, J.; Zhang, H.; Lian, A.; Gao, F.; Zhang, Z.; Guo, Z. The impact of fertilizer type on dry matter, nitrogen partitioning, and yield of spring maize with film-side sowing. *Agronomy* **2023**, *13*, 2999. [\[CrossRef\]](#)
39. Wang, H.; Zhang, X.; Zhang, G.; Fang, Y.; Hou, H.; Lei, K.; Ma, Y. Regulation of density and fertilization on crude protein synthesis in forage maize in a semiarid rain-fed area. *Agriculture* **2023**, *13*, 715. [\[CrossRef\]](#)

40. Asibi, A.E.; Chai, Q.; Coulter, J.A. Mechanisms of nitrogen use in maize. *Agronomy* **2019**, *9*, 775. [[CrossRef](#)]
41. Fortunato, S.; Nigro, D.; Lasorella, C.; Marcotuli, I.; Gadaleta, A.; de Pinto, M.C. The Role of glutamine synthetase (GS) and glutamate synthase (GOGAT) in the improvement of nitrogen use efficiency in cereals. *Biomolecules* **2023**, *13*, 1771. [[CrossRef](#)] [[PubMed](#)]
42. Liu, X.; Zhang, L.; Yu, Y.; Qian, C.; Li, C.; Wei, S.; Li, C.; Gu, W. Nitrogen and chemical control management improve yield and quality in high-density planting of maize by promoting root-bleeding sap and nutrient absorption. *Front. Plant Sci.* **2022**, *13*, 754232. [[CrossRef](#)] [[PubMed](#)]
43. Alhotan, R.A.; Pesti, G.M.; Billard, L. The linear relationship between true protein and nitrogen contents of feed and food ingredients: Calculating true protein from a new conversion factor. *Cogent. Food Agric.* **2024**, *10*, 2428821. [[CrossRef](#)]
44. Drochioiu, G.; Mihalcea, E.; Lagobo, J.; Ciobanu, C.I. Rapid tryptophan assay as a screening procedure for quality protein maize. *Molecules* **2024**, *29*, 4341. [[CrossRef](#)] [[PubMed](#)]
45. Bouranis, D.L.; Chorianopoulou, S.N. Foliar application of sulfur-containing compounds—Pros and cons. *Plants* **2023**, *12*, 3794. [[CrossRef](#)] [[PubMed](#)]
46. Narayan, O.P.; Kumar, P.; Yadav, B.; Dua, M.; Johri, A.K. Sulfur nutrition and its role in plant growth and development. *Plant Signal. Behav.* **2023**, *18*, 2030082. [[CrossRef](#)] [[PubMed](#)]
47. Fan, P.; Ming, B.; Evers, J.B.; Li, Y.; Li, S.; Xie, R.; Anten, N.P.R. Nitrogen availability determines the vertical patterns of accumulation, partitioning, and reallocation of dry matter and nitrogen in maize. *Field Crops Res.* **2023**, *297*, 108927. [[CrossRef](#)]
48. Amoah, J.N.; Keitel, C.; Kaiser, B.N. Nitrogen deficiency impacts growth and modulates carbon metabolism in maize. *Planta* **2025**, *262*, 94. [[CrossRef](#)] [[PubMed](#)]
49. Feng, W.; Xue, W.; Zhao, Z.; Shi, Z.; Wang, W.; Bai, Y.; Wang, H.; Qiu, P.; Xue, J.; Chen, B. Nitrogen fertilizer application rate affects the dynamic metabolism of nitrogen and carbohydrates in kernels of waxy maize. *Front. Plant Sci.* **2024**, *15*, 1416397. [[CrossRef](#)] [[PubMed](#)]
50. Amoah, J.N.; Keitel, C.; Kaiser, B.N. Supplemental nitrogen induces robust physiological and molecular adaptations by enhancing carbon metabolism in maize. *Protoplasma* **2026**, *263*, 403–420. [[CrossRef](#)] [[PubMed](#)]
51. Liu, H.; Wang, Y.; Liu, L.; Wei, B.; Wang, X.; Xiao, Q.; Li, Y.; Ajayo, B.S.; Huang, Y. Pleiotropic ZmICE1 is an important transcriptional regulator of maize endosperm starch biosynthesis. *Front. Plant Sci.* **2022**, *13*, 895763. [[CrossRef](#)] [[PubMed](#)]
52. Yue, K.; Li, L.; Xie, J.; Liu, Y.; Xie, J.; Anwar, S.; Fudjoe, S.K. Nitrogen Supply affects yield and grain filling of maize by regulating starch metabolizing enzyme activities and endogenous hormone contents. *Front. Plant Sci.* **2022**, *12*, 798119. [[CrossRef](#)] [[PubMed](#)]
53. Apriyanto, A.; Compart, J.; Fettke, J. A review of starch, a unique biopolymer—Structure, metabolism and in planta modifications. *Plant Sci.* **2022**, *318*, 111223. [[CrossRef](#)] [[PubMed](#)]
54. Kung, L.; Shaver, R.D.; Grant, R.J.; Schmidt, R.J. Silage review: Interpretation of chemical, microbial, and organoleptic components of silages. *J. Dairy Sci.* **2018**, *101*, 4020–4033. [[CrossRef](#)] [[PubMed](#)]
55. Vanhevel, Y.; De Moor, A.; Muylle, H.; Vanholme, R.; Boerjan, W. Breeding for improved digestibility and processing of lignocellulosic biomass in *Zea mays*. *Front. Plant Sci.* **2024**, *15*, 1419796. [[CrossRef](#)] [[PubMed](#)]
56. Syamsu, J.A.; Purwanti, S.; Yamin, A.A.; Amal, I.; Samsudin, A.A. Evaluating physical and chemical quality of corn kernel as poultry feed ingredient in the procurement of feed mill raw material. *Int. J. Agric. Biosci.* **2025**, *14*, 683–692. [[CrossRef](#)]
57. Ferreira, G.; Teets, C.L.; Kingori, A.M.; Ondiek, J.O. Effect of drought stress on neutral detergent fiber degradation kinetics of corn for silage. *JDS Commun.* **2023**, *4*, 196–201. [[CrossRef](#)] [[PubMed](#)]
58. Jančík, F.; Kubelková, P.; Loučka, R.; Jambor, V.; Kumprechtová, D.; Homolka, P.; Koukolová, V.; Tyrolová, Y.; Výborná, A. Shredlage processing affects the digestibility of maize silage. *Agronomy* **2022**, *12*, 1164. [[CrossRef](#)]
59. Ma, R.; Jiang, C.; Shou, N.; Gao, W.; Yang, X. An optimized nitrogen application rate and basal topdressing ratio improves yield, quality, and water- and n-use efficiencies for forage maize (*Zea mays* L.). *Agronomy* **2023**, *13*, 181. [[CrossRef](#)]
60. Ferreira, G.; Thomas, S.E.; Teets, C.L.; Corl, B.A. Intrinsic and extrinsic factors affecting neutral detergent fiber (NDF) digestibility of vegetative tissues in corn for silage. *Agriculture* **2023**, *13*, 1485. [[CrossRef](#)]
61. Brunšek, R.; Butorac, J.; Augustinović, Z.; Pospíšil, M. Effect of nitrogen on the properties of flax (*Linum usitatissimum* L.) plants and fibres. *Polymers* **2022**, *14*, 558. [[CrossRef](#)] [[PubMed](#)]
62. Okukenu, O.A.; Adekale, A.O.; Olajide, A.A.; Onifade, O.S.; Jolaosho, A.O. Chemical composition of two maize varieties at different levels of green manure application. *Agric. Trop. Subtrop.* **2022**, *55*, 30–39. [[CrossRef](#)]
63. Podkówka, Z. Jakość kiszzonek z kukurydzy w zależności od warunków uprawy i technologii zakiszczania. *Zesz. Nauk. IZ* **2004**, *1*, 45–58.
64. Vieira, D.J.C.; Grigoletto, N.T.S.; Poletti, G.; Chesini, R.G.; Diepersloot, E.C.; Takiya, C.S.; Ferraretto, L.F.; Rennó, F.P. Impact of decreasing undigested neutral detergent fiber concentration in corn silage-based diets for dairy cows: Nutrient digestibility, ruminal fermentation, feeding behavior, and performance. *J. Dairy Sci.* **2025**, *108*, 8462–8475. [[CrossRef](#)] [[PubMed](#)]

65. Khan, N.A.; Khan, N.; Tang, S.; Tan, Z. Optimizing corn silage quality during hot summer conditions of the tropics: Investigating the effect of additives on in-silo fermentation characteristics, nutrient profiles, digestibility and post-ensiling stability. *Front. Plant Sci.* **2023**, *14*, 1305999. [[CrossRef](#)] [[PubMed](#)]
66. Hlisnikovský, L.; Menšík, L.; Roman, M.; Iqbal, J.; Zemanová, V.; Kincl, D.; Nerušil, P. The Effect of organic and mineral fertilizers on silage maize biomass yield and quality across different soil–climate conditions in the Czech Republic. *Plants* **2026**, *15*, 1231. [[CrossRef](#)] [[PubMed](#)]
67. He, Y.; Mouthier, T.M.B.; Kabel, M.A.; Dijkstra, J.; Hendriks, W.H.; Struik, P.C.; Cone, J.W. Lignin composition is more important than content for maize stem cell wall degradation. *J. Sci. Food Agric.* **2018**, *98*, 384–390. [[CrossRef](#)] [[PubMed](#)]
68. Šidlauskaitė, G.; Kadžiulienė, Ž. The Effect of inorganic nitrogen fertilizers on the quality of forage composed of various species of legumes in the northern part of a temperate climate zone. *Plants* **2023**, *12*, 3676. [[CrossRef](#)] [[PubMed](#)]
69. Li, K.; Yang, X.; Liu, X.-G.; Hu, X.-J.; Wu, Y.-J.; Wang, Q.; Ma, F.-Q.; Li, S.-Q.; Wang, H.-W.; Liu, Z.-F.; et al. QTL analysis of the developmental changes in cell wall components and forage digestibility in maize (*Zea mays* L.). *J. Integr. Agric.* **2022**, *21*, 3501–3513. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.