AГРАРЕН УНИВЕРСИТЕТ
ПЛОВДИВ

FACULTY OF AGRONOMY

DEPARTMENT OF CROP SCIENCE

GEORGI STOYANOV STOYANOV

STUDY ON THE POSSIBILITIES OF USING MATHEMATICAL MODELS FOR YIELD MANAGEMENT OF MAIZE (*ZEA MAYS* L.) GROWN FOR DIFFERENT PURPOSES

AUTHOR'S ABSTRACT

of a dissertation

for the acquisition of the educational and scientific degree **"Doctor"**

Professional field: **6.1. Crop Science**

Scientific specialty: **Forage Production and Grassland Management**

Scientific Supervisors:

Assoc. Prof. Dr. Atanas Sevov

Assoc. Prof. Dr. Velika Kuneva

Plovdiv, 2025

The dissertation consists of **175 pages**, including **29 figures** and **36 tables**. The list of references comprises **191 sources**, of which **24 are in Cyrillic** and the remaining **167 in Latin script**.

The defense of the dissertation will take place on at , during an open session of the academic jury appointed by Order **RD /** , issued by the Rector of the Agricultural University – Plovdiv.

Academic Jury:

1. Prof. Dr. Hristofor Kirchev Kirchev
2. Prof. Dr. Hristina Georgieva Yancheva
3. Prof. Dr. Boryana Georgieva Chuгкова
4. Prof. Dr. Tatyana Ivanova Bozhanska
5. Assoc. Prof. Dr. Katya Spasova Uzundzhalieva

Internal reserve member: Prof. Dr. Vanya Atanasova Delibaltova
External reserve member: Assoc. Prof. Dr. Stanislav Kostov Stamatov

The materials related to the defense (the dissertation and the reviews) are available to interested parties on the website of the Agricultural University – Plovdiv.

Table of Contents

1. Introduction

Climate change in recent years has become a serious and often unpredictable factor, significantly contributing to increasingly frequent and prolonged droughts. Faced with the challenge of producing more food from ever-decreasing agricultural land while simultaneously maintaining and even improving the quality of agricultural production it is necessary to structure a sustainable, efficient, and adaptive farming system by implementing scientifically grounded approaches to mitigate the adverse effects of environmental factors.

Among the most promising approaches in support of farmers is mathematical modeling, which enables forecasting of crop development, resource management, and yield estimation. CART models (Classification and Regression Trees) are a modern analytical tool that allows for the analysis of dynamic processes in agricultural production, as well as assessment of the impact of various management strategies on yields and efficiency.

Maize, as the most important cereal forage crop in the worldacco unting for more than half of the cultivated area under forage crops and nearly three-quarters of total grain production—is a suitable crop for the development of such models. Achieving high and sustainable maize yields, however, would not be possible without balanced plant nutrition. The use of chemical fertilizers significantly increases yields but also brings numerous environmental risks, such as soil pollution, acidification, salinization, etc.

Therefore, increasing attention is being paid to balanced and precise fertilization, tailored to the specifics of each crop, its varietal and hybrid characteristics, developmental stages (phenophases), and the applied agrotechnical practices. In this context, foliar fertilization is gaining increasing importance as an effective supplement to soil fertilization. It provides an opportunity for rapid and targeted nutrient supply, particularly during periods of stress, extreme temperatures, or moisture deficiency.

2. Aim and Objectives of the Research

The aim of this dissertation is to develop mathematical (analytical) models for five maize hybrids with different FAO numbers and various genetic origins (generations), in two directions—for silage and for grain production.

To achieve this aim, the following objectives were set:

1. To study the productive potential of the crop in its two main production directions - silage and grain.
2. To develop and analyze models reflecting the impact of foliar products on yield.
3. To model yield as a function of structural yield components.
4. Based on models describing the influence of meteorological conditions and applied foliar products, to determine optimal ranges of variation and potential quality parameter reductions.
5. To compare the results of the applied methods and models, and to assess their predictive performance against actual data.
6. To conduct statistical analysis using the **CART** method for selecting adequate models.
7. To perform error diagnostics, as well as analysis and evaluation of the developed models.

3. Materials and Methods

3.1. Field Trial Methodology

The field experiment was conducted during the period 2022–2024 at the Academic Technological Complex (ATC) of Trakia University, Stara Zagora, on typical meadow-cinnamon soil under irrigated conditions.

The trial followed the split-plot method (Shanin, 1977), with four replications and a plot size of 15 m².

Experimental Factors:

- Factor A – Maize Hybrids
  - A1 – DKC 4416
  - A2 – LG 31.390
  - A3 – PREMEO
  - A4 – PIONEER P9889
  - A5 – KNEZHA-461
- Factor B – Foliar Fertilization Products
  - B1 – Control (no foliar fertilization)
  - B2 – Treatment with Aminosol + Lebosol B + Lebosol Zn, Nutriplant 36
  - B3 – Treatment with Kinsidro Grow, N-Lock
- Factor C – Meteorological Conditions by Harvest Year
  - C1 – 2022
  - C2 – 2023
  - C3 – 2024

Scheme of the field experiment: 5 maize hybrids × 3 foliar fertilization variants – 15 treatment combinations.

The field experiment was conducted under irrigated conditions. Irrigation was carried out using a drip irrigation system with built-in emitters spaced at 0.15 m, with an irrigation norm of 30 ml, triggered when soil moisture dropped below 75–80% of field capacity (FC) in the 0–50 cm soil layer.

Fertilization during the growing season, using organic and inorganic foliar fertilizers, was applied at the recommended doses for each product. Under the first fertilization technology (Var. 2), the following doses were applied: Aminosol (2.0 l/ha), Lebozol B (2.0 L/ha), Lebosol Zn (1.0 l/ha), and Nutriplant 36 (10.0 l/ha). Under the second technology (Var. 3), the applied doses were: Kinsidro Grow (150 g/ha, in granular form) and N-Lock (2.50 l/ha).

The experiment included the following maize hybrids: "DKC4416" – representative of the FieldShield hybrids from Bayer; "LG 31.390" – hybrid from the Hydraneo technology of Limagrain; "PREMEO" - Artesian hybrid technology representative from Syngenta; "PIONEER P9889" – hybrid from Pioneer, part of the Optimum® AQUAmax® product line, selected for drought tolerance; and "Knezha-461" – a representative of Bulgarian hybrid selection.

Sowing was carried out within the optimal agrotechnical window for the region using a mechanical single-row precision seeder, at a depth of 5–6 cm, with a sowing rate of 8000 plants/da and a row spacing of 0.70 m.During the study period, soil samples were collected to determine soil reaction, as well as humus content and available forms of N, P, and K in the 0–30 cm and 30–70 cm soil layers.

During the growing season, several important biological indicators were recorded. The main phenological phases of maize hybrid development were tracked. Biometric plant indicators were recorded (plant height, number of leaves per plant), as well as structural grain yield components (cob length, number of rows per cob, number of kernels per row, 1000-kernel weight) and productivity indicators (grain yield, green biomass yield).

3.2. Mathematical processing of the obtained results

The mathematical and statistical analysis of the experimental data included two-factor analysis of variance (ANOVA), correlation analysis, regression analysis, and factor analysis. One of the most modern data mining models for statistical modeling and data analysis Classification and Regression Trees (CART) was applied. The software products used were: MS Excel and SPSS 26.0.

An assessment was made of the energy and protein content of the forages used for feeding ruminant and non-ruminant animals.

3.3. Soil and Climatic Characteristics

The field experiment was conducted at the Academic Technological Complex (ATC) of Trakia University, located in the city of Stara Zagora. The soil at the experimental site is typical meadow-cinnamon soil, with a well-developed humus horizon (0–45 cm). The humus content characterizes the soil as moderately supplied. In the 0–30 cm soil layer, humus content ranges from 3.07% to 3.28%, while in the 30–70 cm horizon it is between 3.17% and 3.18%. The soil reaction ranges from neutral to slightly acidic. The mineral nitrogen content is moderate, and analyses of ammonium and nitrate nitrogen levels indicate favorable conditions for nitrification.

The soil is low to moderately supplied with available phosphorus, but has good potassium availability.

The climate in the region is transitional-continental, characterized by mild winters and relatively hot summers. Precipitation is relatively evenly distributed across the seasons. The coordinates of the experimental field are 42°23'05.71" N latitude and 25°38'47.3" E longitude.

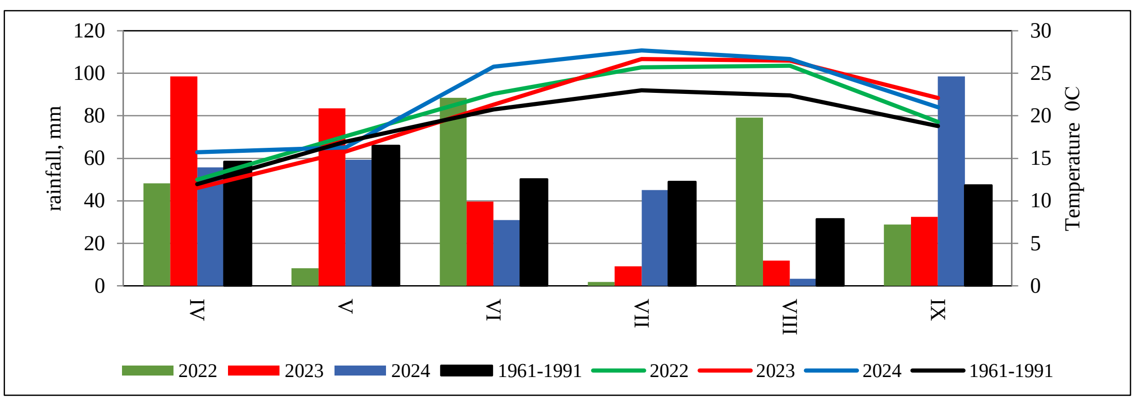

Figure 1. Climatic diagram of the region of Stara Zagora during the maize vegetation period, 2022–2024

Figure 1 presents the dynamics of the average daily temperature values, as well as the amount and distribution of precipitation by months for the maize vegetation period. During the years of the field study, significant differences were recorded in terms of the measured average daily temperatures by month compared to the multi-year period (1961–1991). In the months of June, July, and August, positive deviations from the temperature norm were observed.

norm. These differences are characteristic for all three years of the field trial. On average for the study period, the average daily temperatures were higher by 12.1% (June), 16.1% (July), and 17.9% (August).

The total precipitation for the study period averaged 274.5 mm compared to a normal of 302.3 mm, i.e., 9.2% less than the measured norm. In 2022, the lowest amount of precipitation was recorded—254.9 mm, which is 15.7% below the norm for the respective period. The precipitation total in July 2022 was only 1.8 mm compared to the norm of 49.0 mm. During the next two experimental years, the amount of precipitation was again below the norm throughout the entire vegetation period. In 2023, the total was 275.5 mm, and in 2024, it was 293.0 mm, which corresponded to decreases of 8.9% and 3.1%, respectively.

4. Results and Discussion

4.1. Phenological Development

The main phenological phases in maize development are: emergence, third leaf, tasseling, silking, silk browning, milk stage, dough stage, and full maturity. The vegetation period in the first year lasted from 118 to 127 days, averaging 123 days. In 2023, the duration varied between 116 and 126 days. The third year was characterized by the shortest vegetation period—an average of 117.4 days.

4.2. Biometric Indicators of the Plants

4.2.1. Plant Height of Maize

Over the three years of the study, the parameters of the structural elements of maize were determined under the influence of applied foliar fertilizers. Plant height is an indicator of the adaptability of a hybrid to intensive cultivation technologies.

Table 1. Analysis of variance for the effect of factors on plant height

Year.	Source of variation	Influence strength	Sum of Squares (SS)	df	Mean Square (MS)	F	P-value	F crit
2022	Hybrid (A)***	40 %	28973,36	4	7243,340	99,535	0,000	2,439
	Foliar fertilization products (B)***	36 %	24923,05	2	12461,527	171,241	0,000	3,063
	Interaction (A×B)***	10 %	6414,48	8	801,810	11,018	0,000	2,008
	Error	14 %	9824,2	135	72,772			
2023	Hybrid (A)***	10 %	3109,467	4	777,367	7,915	0,000	2,439
	Foliar fertilization products (B)***	22 %	6438,453	2	3219,227	32,776	0,000	3,063
	Interaction (A×B)***	23 %	6867,413	8	858,427	8,740	0,000	2,008
	Error	45 %	13259,500	135	98,219			
2024	Hybrid (A)***	48 %	7394,973	4	1848,743	48,044	0,000	2,439
	Foliar fertilization products (B)***	15 %	2363,773	2	1181,887	30,714	0,000	3,063
	Interaction (A×B) n.s.	4 %	572,427	8	71,553	1,859	0,071	2,008
	Error	33 %	5194,800	135	38,480			

***, **, * – significant at p≤0.001, p≤0.01, and p≤0.05, respectively; n.s. – not significant.

On average for the study period, there was a tendency for plant height to increase after foliar fertilization. The increase ranged from 8.3% (Knezha-461) to 119.7% (Premeo) after applying the foliar fertilizers Amino-sol + Lebozol B + Lebosol Zn, Nutriplant 36. Treatment with organic fertilizers Kinsidro Grow and N-Lock contributed to an increase of 1.8% in LG 31.390 compared to the unfertilized control.

Table 1 presents the results of the data analysis for the height indicator. The most significant influence on the variation of the trait was factor A “hybrid” with an effect of 48% (2024), followed by factor B “foliar fertilizer products” with 36% (2022).

4.2.2. Number of Leaves per Plant

The number of leaves varies by hybrid and foliar fertilization variant. Analyses show that the number of leaves during the first year was the lowest, which is explained by the growth rate of the hybrids under conditions of high temperatures and moisture deficit. In the second and third years, significantly higher values of the indicator were measured. On average for the study period, the hybrids Pioneer P9889 (13.7 leaves) and LG 31.390 (13.8 leaves) were the most responsive to fertilization with Aminosol + Lebosol B + Lebosol Zn, Nutriplant 36. They increased the value of the indicator by 13.7% and 12.2%, respectively, compared to the untreated variants. The effect was weaker in DKC 4416 – 7.5%, in Knezha-461 – 8.2%, and in Premeo – 9.8%. The increase in the number of leaves in variant 3 was 4.4% (DKC 4416), 5.2% (Knezha-461), 6.4% (Premeo), 9.8% (LG 31.390), and 12.0% (Pioneer P9889).

The results of the analysis of variance for the effect of the factors and their interaction on the indicator “number of leaves per plant” show that statistically significant differences were observed (Table 2). The most significant influence on the variation of the trait was factor A “hybrid” with 46% (2022), followed by factor B “foliar fertilization products” with 29% (2023).

Table 2. Analysis of variance for the effect of factors on the number of leaves per plant

Year.	Source of variation	Influence strength	Sum of Squares (SS)	df	Mean Square (MS)	F	P-value	F crit
2022	Hibrid (A) ***	46%	143,373	4	35,843	41,042	0,000	2,439
	Foliar fertilization products (B)***	16%	51,893	2	25,947	29,710	0,000	3,063
	Interaction (A×B)***	1%	4,707	8	0,588	0,674	0,714	2,008
	Error	37%	117,900	135	0,873			
2023	Hybrid (A)***	1 %	1,493	4	0,373	0,650	0,628	2,439
	Foliar fertilization products (B)***	29 %	33,333	2	16,667	29,032	0,000	3,063
	Interaction (A×B)***	4 %	4,267	8	0,533	0,929	0,495	2,008
	Error	66 %	77,500	135	0,574			
2024	Hybrid (A)***	6 %	7,107	4	1,777	2,338	0,058	2,439
	Foliar fertilization products (B)***	12 %	15,213	2	7,607	10,009	0,000	3,063
	Interaction (A×B) n.s.	1 %	1,053	8	0,132	0,173	0,994	2,008
	Error	81 %	102,600	135	0,760			

4.3. Structural Elements of Grain Yield

4.3.1. Ear Length

The elements that determine the productive potential of individual maize hybrids are the parameters of the ear of a single plant ar length, number of rows per ear, number of kernels per row, and kernel weight per ear.

Responsive to the foliar-applied fertilizers Aminosol + Lebosol B + Lebosol Zn, Nutriplant 36 are the hybrids Knezha-461, Premeo, LG 31.390, and DKC 4416. More responsive to the products Kinsidro Grow and N-Lock is Pioneer P9889. The observed increase in the indicator in variant 2 is within the range of 0.80 – 0.80–2.00 cm. The lowest increase was recorded in LG 31.390 (5.03%), followed by 8.14% (Knezha-461), 8.75% (Pioneer P9889), 8.97% (DKC 4416), and 12.82% (Premeo). In variant 3, an increase compared to variant 1 was recorded as follows: 2.53% in LG 31.390, 4.65% in Knezha-461, 7.69% in DKC 4416, 10.00% in Pioneer P9889, and 10.26% in Premeo.

Table 3. Analysis of variance for the effect of factors on ear length

Year.	Source of variation	Influence strength	Sum of Squares (SS)	df	Mean Square (MS)	F	P-value	F crit
2022	Hybrid (A)***	6%	7,107	4	1,777	2,338	0,058	2,439
	Foliar fertilization products (B)***	12%	15,213	2	7,607	10,009	0,000	3,063
	Interaction (A×B)***	1%	1,053	8	0,132	0,173	0,994	2,008
	Error	81%	102,600	135	0,760			
2023	Hybrid (A)***	1 %	1,493	4	0,373	0,650	0,628	2,439
	Foliar fertilization products (B)***	29 %	33,333	2	16,667	29,032	0,000	3,063
	Interaction (A×B)***	4 %	4,267	8	0,533	0,929	0,495	2,008
	Error	66 %	77,500	135	0,574			
2024	Hybrid (A)***	46 %	143,373	4	35,843	41,042	0,000	2,439
	Foliar fertilization products (B)***	16 %	51,893	2	25,947	29,710	0,000	3,063
	Interaction (A×B) n.s.	1 %	4,707	8	0,588	0,674	0,714	2,008
	Error	37 %	117,900	135	0,873			

The results of the analysis of variance for the effect of the factors and their interaction on the indicator "ear length" show that clear significant differences were observed, while the interaction between the two factors was statistically insignificant (Table 3).

4.3.2. Number of Rows per Ear

Throughout the three years of the study, there was a tendency for an increase in this indicator after foliar fertilization.

Table 4. Analysis of variance for the number of rows per ear

Year.	Source of variation	Influence strength	Sum of Squares (SS)	df	Mean Square (MS)	F	P-value	F crit
2022	Hibrid (A) ***	26 %	29,68	4	7,42	5,537	0,001	2,525
	Foliar fertilization products (B)***	2 %	2,59	2	1,29	0,965	0,387	3,150
	Interaction (A×B)***	3 %	4,08	8	0,51	0,381	0,927	2,097
	Error	69 %	80,40	60	1,34			
2023	Hybrid (A)***	6 %	11,520	4	2,880	1,125	0,353	2,525
	Foliar fertilization products (B)***	3 %	5,227	2	2,613	1,021	0,366	3,150
	Interaction (A×B)***	9 %	16,640	8	2,080	0,812	0,594	2,097
	Error	82 %	153,600	60	2,560			
2024	Hybrid (A)***	8 %	10,267	4	2,567	1,578	0,192	2,525
	Foliar fertilization products (B)***	13 %	16,027	2	8,013	4,926	0,010	3,150
	Interaction (A×B) n.s.	2 %	2,773	8	0,347	0,213	0,987	2,097
	Error	77 %	97,600	60	1,627			

On average over the three years of the field trial, the effect of the organic fertilizers Aminosol + Lebosol B + Lebosol Zn, Nutriplant 36 was highest in DKC 4416 (15.67). The hybrids LG 31.390, Pioneer P9889, and Premeo were more responsive to the combination of fertilizers Kinsidro Grow and N-Lock. The application of foliar fertilizers during the vegetation period contributed to an increase in the number of rows per ear, but within narrow limits (Table 4). The conducted analysis of variance for the effect of the factors hybrid, foliar fertilization products, and their interaction on the structural indicator "number of rows per ear" showed that the most significant influence on the variation of the trait was factor A "hybrid," with an influence of 26% in the first year, while factor B and the interaction of the two factors were expressed the least.

4.3.3. Number of Kernels per Row

Although genetically predetermined, the values of this indicator can vary under the influence of growing conditions. The number of kernels in the number of kernels per row varied during the study years. On average for the three-year period, the studies showed that the use of foliar fertilizers had a positive effect on the indicator "number of kernels per row" for all hybrids. The effect of fertilization that included the products Aminosol + Lebosol B + Lebosol Zn, Nutriplant 36 was highest in DKC 4416 (33.1%), LG 31.390 (16.1%), and Knezha-461 (11.1%). The hybrids most responsive to foliar fertilization with the products Kinsidro Grow and N-Lock were Pioneer P9889 (8.9%) and Premeo (15.2%).

The two-factor analysis of variance of the indicator "number of kernels per row" for the three study years showed that the differences obtained for both Factor A and Factor B were statistically significant (Table 5).

Table 5. Analysis of variance for the effect of factors on the indicator – number of kernels per row

Year.	Source of variation	Influence strength	Sum of Squares (SS)	df	Mean Square (MS)	F	P-value	F crit
2022	Hibrid (A) ***	21 %	336,167	4	84,042	4,505	0,003	2,525
	Foliar fertilization products (B)***	3 %	55,547	2	27,773	1,489	0,234	3,150
	Interaction (A×B)***	8 %	139,253	8	17,407	0,933	0,496	2,097
	Error	68 %	1119,200	60	18,653			
2023	Hybrid (A)***	30 %	842,187	4	210,547	9,173	0,000	2,525
	Foliar fertilization products (B)***	19 %	552,027	2	276,013	12,025	0,000	3,150
	Interaction (A×B)***	3 %	77,973	8	9,747	0,425	0,902	2,097
	Error	48 %	1377,200	60	22,953			
2024	Hybrid (A)***	25 %	423,547	4	105,887	6,693	0,000	2,525
	Foliar fertilization products (B)***	18 %	305,627	2	152,813	9,660	0,000	3,150
	Interaction (A×B) n.s.	1 %	9,173	8	1,147	0,072	1,000	2,097
	Error	56 %	949,200	60	15,820			

The two factors had a proven effect on the values of this indicator due to the lower F crit. compared to F, which did not exceed the P level in 2023 and 2024. During the experimental years, the interaction between the two factors was not statistically significant.

4.3.4. Thousand Kernel Weight

A consistent trend of increasing kernel weight after foliar treatment was recorded for all hybrids. After applying the first technology, the indicator showed the highest values in hybrids DKC 4416 (236.30 g), LG 31.390 (272.50 g), and Knezha-461 (216.90 g). The data show that after using Kinsidro Grow and N-Lock, the increase was in favor of hybrids Pioneer P9889 (240.20 g) and Premeo (248.40 g). On average for the period, under conditions without foliar fertilizer application, the thousand-kernel weight varied from 210.33 g (DKC 4416) to 246.41 g (LG 31.390). Foliar fertilizer application contributed to an increase in kernel weight, to varying degrees. The effect was most pronounced in DKC 4416 (28.53%), followed by

Premeo (24.69%). The results were obtained after treatment with the products Aminosol + Lebosol B + Lebosol Zn, Nutriplant 36. The increase in Pioneer P9889 (9.92%), LG 31.390 (11.32%), and Knezha-461 (14.62%) was again recorded after the application of the same foliar fertilization products.

The analysis of variance conducted to assess the effect of the factors hybrid, foliar fertilization products, and their interaction on the structural indicator “thousand kernel weight” is presented in Table 6. The table reflects the results of the data analysis for the experimental years. The most significant influence on the variation of the trait was factor B “foliar fertilization products,” with an influence of 58% during the first and second years, while factor A “hybrid” had an influence of 54% in the third year (2024). The interaction between the two factors was expressed to a lesser extent during the study period.

Table 6. Analysis of variance for the effect on thousand kernel weight

Year.	Source of variation	Influence strength	Sum of Squares (SS)	df	Mean Square (MS)	F	P-value	F crit
2022	Hybrid (A)***	23%	8384,048	4	2096,012	572,046	0,000	2,525
	Foliar fertilization products (B)***	58%	21149,421	2	10574,710	2886,062	0,000	3,150
	Interaction (A×B)***	18%	6452,570	8	806,571	220,130	0,000	2,097
	Error	1%	219,844	60	3,664062			
2023	Hybrid (A)***	25%	10084,051	4	2521,013	1722,945	0,000	2,525
	Foliar fertilization products (B)***	58%	23940,082	2	11970,041	8180,728	0,000	3,150
	Interaction (A×B)***	17%	6920,183	8	865,023	591,186	0,000	2,097
	Error	0%	87,792	60	1,463			
2024	Hybrid (A)***	54%	27399,520	4	6849,880	4362,055	0,000	2,525
	Foliar fertilization products (B)***	41%	21048,087	2	10524,043	6701,789	0,000	3,150
	Interaction (A×B) n.s.	5%	2428,580	8	303,572	193,317	0,000	2,097
	Error	0%	94,220	60	1,570			
***, **, * – significant at p≤0.001, p≤0.01, and p≤0.05, respectively; n.s. – not significant.								

4.4. Productive Indicators

4.4.1. Green Mass Yield (for Silage Production)

The experimental results for green mass yield show an increase in values after the application of foliar fertilization products. For the studied hybrids, an increase was recorded during all three years of the field experiment.

During the study period, LG 31.390 stood out as the most responsive to foliar-applied fertilizers. The application of the organic fertilizers Aminosol + Lebosol B + Lebosol Zn and Nutriplant 36 contributed to an increase in productivity by 49.6%, while treatment with the products Kinsidro Grow and N-Lock resulted in an increase of 48.2%. For the other hybrids, productivity increased by 35.2% (Premeo), 37.8% (Knezha-461), 41.1% (Pioneer P9889), and

43.4% (Pioneer P9889) after applying Aminosol + Lebosol B + Lebosol Zn and Nutriplant 36. The increase was 26.4%, 29.8%, 38.6%, and 38.8% for Knezha-461, Premeo, DKC 4416, and Pioneer P9889, respectively.

The two-factor analysis of variance showed a strong statistical influence on the indicator “silage (green mass) yield,” both from the hybrids and from the foliar fertilization products (Table 7). The interaction between the two factors for the three experimental years was also mathematically proven.

The analysis shows that for both factors, the F value was greater than F crit. during all three years, which confirms the significant effect of these factors on the studied indicator. The most significant influence on the variation of the trait was exerted by factor B “foliar fertilization products,” with an influence of 98% in 2023, while factor A and the interaction between the two factors were expressed to a lesser extent.

Table 7. Two-factor analysis of variance for silage (green mass) yield

Year.	Source of variation	Influence strength	Sum of Squares (SS)	df	Mean Square (MS)	F	P-value	F crit
2022	Hybrid (A)***	43 %	21684082	4	5421020,489	10916,753	0,000	2,579
	Foliar fertilization products (B)***	49 %	24698024,4	2	12349012,194	24868,217	0,000	3,204
	Interaction (A×B)***	8 %	4148490,52	8	518561,315	1044,269	0,000	2,152
	Error	0 %	22346,0149	45	496,578			
2023	Hybrid (A)***	1 %	308308,83	4	77077,207	178,793	0,000	2,579
	Foliar fertilization products (B)***	98 %	101901326,04	2	50950663,020	118188,458	0,000	3,204
	Interaction (A×B)***	1 %	1036329,88	8	129541,235	300,492	0,000	2,152
	Error	0 %	19399,35	45	431,097			
2024	Hybrid (A)***	1 %	1336249,6	4	334062,397	428,687	0,000	2,579
	Foliar fertilization products (B)***	97 %	102521846,0	2	51260922,983	65780,798	0,000	3,204
	Interaction (A×B) n.s.	2 %	2059138,3	8	257392,283	330,300	0,000	2,152
	Error	0 %	35067,1	45	779,269			

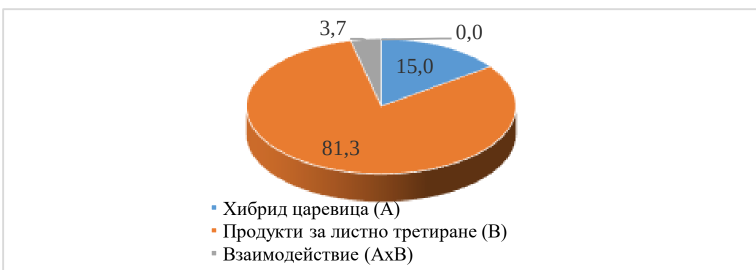

Figure 2. Percentage contribution of the studied factors over a three-year period on the formed green mass yield

Figure 2 shows the percentage contribution of the studied factors to the formation of green mass yield. On average for the study period, it can be seen that the greatest influence was exerted by the factor foliar fertilization products (81.3%). The influence of the hybrid factor was 15.0%, while the interaction accounted for only 3.7%.

4.4.2. Grain Yield, kg/ha

Regarding grain yield, during the three years of the field experiment, an increase in the productivity of maize hybrids under the influence of foliar fertilization was established. The results show an increase in yield in the treated variants for all five hybrids, but at different rates. Grain yield values varied across the years, depending on climatic conditions—temperature, precipitation, relative humidity, and others.

Table 8. Two-factor analysis of variance for grain yield

Year.	Source of variation	Influence strength	Sum of Squares (SS)	df	Mean Square (MS)	F	P-value	F crit
2022	Hybrid (A)***	21	22506638	4	5626660	571,463	0,000	2,579
	Foliar fertilization products (B)***	66	69415272	2	34707636	3525,028	0,000	3,204
	Interaction (A×B)***	13	13250123	8	1656265	168,216	0,000	2,152
	Error	0	443073	45	9846,06			
2023	Hybrid (A)***	15	12340354	4	3085089	111,139	0,000	2,579
	Foliar fertilization products (B)***	68	57344842	2	28672421	1032,915	0,000	3,204
	Interaction (A×B)***	16	13269301	8	1658663	59,753	0,000	2,152
	Error	1	1249143	45	27758,74			
2024	Hybrid (A)***	10	7599029	4	1899757	313,219	0,000	2,579
	Foliar fertilization products (B)***	83	61585633	2	30792817	5076,903	0,000	3,204
	Interaction (A×B) n.s.	6	4493057	8	561632	92,598	0,000	2,152
	Error	1	272937,4	45	6065			

The productivity of maize hybrids without additional foliar fertilization ranged from 9652.93 kg/ha (DKC 4416) to 11,284.23 kg/ha (Knezha-461). Yields were 15.5% higher after treatment with Kinsidro Grow and the nitrogen stabilizer N-Lock, and 23.6% higher after the application of the foliar fertilizer complex Aminosol + Lebosol B + Lebosol Zn, Nutriplant 36. The increase in productivity for variant 2 was 9.7% (Knezha-461), 22.8% (LG 31.390), 24.4% (DKC 4416), 31.0% and 31.8% (Pioneer P9889 and Premeo, respectively). The increase in yields under the influence of the organic fertilizer Kinsidro Grow and the nitrogen stabilizer N-Lock ranged from 6.1% to 24.0%. By hybrid, the increase was as follows: 6.1% for Knezha-461, 10.8% for LG 31.390, 18.2% for Premeo, 19.4% for DKC 4416, and 24.0% for Pioneer P9889, averaged over the three-year study period.

The two-factor analysis of variance showed a strong statistical influence on grain yield from both the studied hybrids and the foliar fertilization products. The interaction between the two factors was also mathematically proven for the three years (Table 8). The most significant influence on the variation of the trait was exerted by factor B "foliar fertilization products," with an influence of 83% in 2024, while factor A and the interaction (A×B) were expressed to a lesser extent.

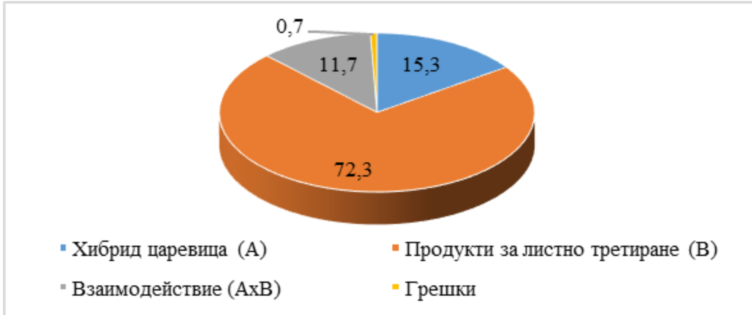

Figure 3. Percentage contribution of the studied factors over a three-year research period

Figure 3 shows the share of the factors influencing the formation of grain yield. The greatest influence was exerted by the tested foliar fertilization products, at 72.3%. The share of the hybrids was 15.3%, and a weaker effect was observed for the interaction between the two factors 11.7%.

4.5. Chemical Analyses

4.5.1. Qualitative Analysis of Green Biomass

The results of the chemical analysis of the five studied maize hybrids are presented by years, with the data recalculated to 100 % dry matter (DM). The data show the effect of foliar fertilization on the content of crude protein, crude fat, crude fiber, ash, and nitrogen-free extract substances (NFE) (Table 9). The content of the studied quality parameters varied by treatment, hybrid, and year. For the study period, the data show that the applied foliar fertilizers contributed to an increase in crude protein content in the green mass by 15.2% in Premeo (variant 2), 12.7% in Knezha-461 (variant 3), 12.4% in Pioneer P9889 (variant 2), 7.5% in LG 31.390 (variant 2), and 5.6% in DKC 4416 (variant 2). Regarding crude fat content, a weak influence of foliar fertilizer application was established. Higher crude fiber content leads to a decrease in forage digestibility and nutritional value. The results show fluctuations in crude fiber values by years and treatments. The content of nitrogen-free extract substances was relatively stable in both common wheat varieties.

Table 9. Chemical composition of green biomass, average for the period 2022–2024 (g/kg DM)

Maize Hybrid	Variant	CP	CF	CFb	Ash	NFE
DKC 4416	1. Control	99,60	13,83	139,03	58,13	664,33
	2. AS, B, Zn, N36	105,17	12,20	141,50	59,63	656,03
	3. N-Lock, KG	104,37	12,30	145,67	66,03	645,83
LG 31.390	1. Control	94,07	12,00	147,77	59,17	660,77
	2. AS, B, Zn, N36	101,10	10,57	152,10	63,73	650,20
	3. N-Lock, KG	100,77	12,27	140,40	55,87	668,63
Premeo	1. Control	91,70	13,43	150,60	54,83	665,03
	2. AS, B, Zn, N36	105,63	13,13	152,77	54,17	651,10
	3. N-Lock, KG	104,33	10,60	163,70	68,80	630,87
Pioneer P9889	1. Control	93,87	9,97	140,00	53,97	674,17
	2. AS, B, Zn, N36	105,47	8,67	151,07	58,73	649,97
	3. N-Lock, KG	103,77	11,97	149,87	66,33	641,97
Knezha-461	1. Control	99,03	14,10	176,97	62,13	624,10
	2. AS, B, Zn, N36	111,17	14,87	145,33	58,50	645,77
	3. N-Lock, KG	111,63	11,27	161,73	63,67	628,23

4.5.2. Qualitative Analysis of Grain

The quality indicators of grain are genetically determined, but they are also influenced by the applied agronomic practices, climatic factors during the vegetation period, and the specific agro-ecological conditions of the region where the crop is grown.

On average for the study period, the established increase in crude protein content across the five hybrids was 13.6% in variant 2 and 12.4% in variant 3. By hybrid, the analysis showed that LG 31.390 was the most responsive to foliar fertilization. An increase in crude protein levels was recorded in variant 2 by 24.9% and in variant 3 by 29.5%. For the other hybrids, the increase in variant 2 was 5.9% (Knezha-461), 7.1% (Premeo), 11.0% (Pioneer P9889), and 19.0% (DKC 4416). In variant 3, the increase was 4.5% (Knezha-461), 6.8% (Premeo), 7.9% (DKC 4416), and 13.3% (Pioneer P9889).

Table 10. Chemical composition of maize grain, average for the period 2022–2024 (g/kg DM)

Maize Hybrid	Variant	CP	CF	CFb	Ash	NFE
DKC 4416	1. Control	67,73	36,30	22,77	9,03	864,17
	2. AS, B, Zn, N36	80,60	37,57	18,77	14,23	852,17
	3. N-Lock, KG	73,10	38,53	21,30	13,10	853,97
LG 31.390	1. Control	63,93	40,60	24,80	15,43	855,23
	2. AS, B, Zn, N36	79,87	37,60	22,90	17,67	841,97
	3. N-Lock, KG	82,77	37,27	23,70	19,10	837,17
Premeo	1. Control	80,00	33,67	23,17	10,17	853,00
	2. AS, B, Zn, N36	85,67	28,67	21,43	16,30	847,93
	3. N-Lock, KG	85,43	37,03	27,07	17,60	832,87
Pioneer P9889	1. Control	73,80	35,50	23,10	17,83	849,77
	2. AS, B, Zn, N36	81,90	34,93	22,93	12,80	847,43
	3. N-Lock, KG	83,63	37,40	25,43	17,90	835,63
Knezha-461	1. Control	97,73	44,37	23,63	8,76	819,23
	2. AS, B, Zn, N36	103,53	40,87	25,97	8,80	815,40
	3. N-Lock, KG	102,17	36,40	28,43	5,27	819,30

4.5.3. Energy and Protein Nutritional Value of Feeds

Energy in feed is a key indicator of its nutritional value. The energy requirements of animals largely determine their overall feed needs. The energy content of feeds is evaluated based on their ability to meet the animals' energy demands. Energy plays a primary role in animal nutrition.

For different animal species, the evaluation of energy content in feed varies. The most accurate, but also the most difficult, is the assessment of net energy. It is calculated when determining the energy value of feeds for ruminants and horses, using different measurement units. For ruminants, feed units for milk (FUM) and feed units for growth (FUG) are used. FUM is applied for lactating females (cows, buffaloes, sheep, goats), while FUG is used for growing and fattening ruminants.

Table 11. Energy and protein nutritional value of maize – whole plant for ruminant animals (per 1 kg DM), for the period 2022–2024

Maize Hybrid	Variant	2022				2023				2024				2022-2024			
		FUM	FUG	DCP	DPT	FUM	FUG	DCP	DPT	FUM	FUG	DCP	DPT	FUM	FUG	DCP	DPT
DKC 4416	1. Control	1,16	1,22	89,05	-52,54	1,05	1,08	95,03	-23,64	1,10	1,13	90,67	-38,08	1,10	1,14	91,58	-38,09
	2. AS, B, Zn, N36	1,15	1,20	89,58	-49,69	1,05	1,07	94,40	-24,77	1,10	1,13	92,83	-32,09	1,10	1,13	92,27	-35,52
	3. N-Lock, KG	1,11	1,16	87,32	-47,35	1,06	1,09	93,07	-27,21	1,10	1,13	92,30	-34,72	1,09	1,13	90,90	-36,43
LG 31.390	1. Control	1,12	1,17	89,38	-47,19	1,07	1,10	90,32	-37,89	1,07	1,10	91,93	-34,07	1,09	1,12	90,54	-39,72
	2. AS, B, Zn, N36	1,11	1,16	90,18	-43,20	1,09	1,13	90,94	-37,25	1,07	1,10	92,10	-32,22	1,09	1,13	91,07	-37,56
	3. N-Lock, KG	1,15	1,20	91,60	-46,11	1,08	1,11	89,26	-39,23	1,10	1,14	90,06	-41,62	1,11	1,15	90,31	-42,32
Premeo	1. Control	1,16	1,22	91,15	-47,92	1,06	1,09	86,05	-46,93	1,11	1,14	93,10	-33,33	1,11	1,15	90,10	-42,73
	2. AS, B, Zn, N36	1,16	1,21	92,93	-44,95	1,05	1,07	92,53	-30,30	1,11	1,14	90,71	-39,33	1,11	1,14	92,06	-38,19
	3. N-Lock, KG	1,09	1,13	91,13	-39,13	1,05	1,08	90,27	-32,41	1,07	1,09	92,31	-34,03	1,07	1,10	91,24	-35,19
Pioneer P9889	1. Control	1,15	1,20	91,60	-46,11	1,08	1,11	88,94	-43,20	1,11	1,15	91,88	-40,37	1,11	1,15	90,81	-43,23
	2. AS, B, Zn, N36	1,16	1,21	92,93	-44,95	1,06	1,09	92,29	-33,64	1,14	1,18	90,52	-47,11	1,12	1,16	91,91	-41,90
	3. N-Lock, KG	1,14	1,19	92,46	-41,62	1,05	1,08	90,11	-33,83	1,11	1,15	90,70	-41,37	1,10	1,14	91,09	-38,94
Knezha-461	1. Control	1,14	1,19	92,46	-39,62	1,06	1,08	89,92	-34,76	1,08	1,10	94,64	-26,16	1,09	1,12	92,34	-33,51
	2. AS, B, Zn, N36	1,14	1,19	95,38	-34,49	1,05	1,07	91,63	-30,12	1,10	1,13	93,74	-29,69	1,10	1,13	93,58	-31,43
	3. N-Lock, KG	1,11	1,14	93,19	-35,75	1,05	1,06	92,31	-30,08	1,07	1,10	88,94	-41,67	1,08	1,10	91,48	-35,83

Table 12. Energy and protein nutritional value of maize grain for ruminant animals (per 1 kg DM), for the period 2022–2024

Maize hybrids	Variant	2022				2023				2024				2022-2024			
		FUM	FUG	DCP	DPT	FUM	FUG	DCP	DPT	FUM	FUG	DCP	DPT	FUM	FUG	DCP	DPT
DKC 4416	1. Control	1,58	1,79	114,25	-93,81	1,57	1,79	109,96	-97,41	1,59	1,8	112,69	-92,08	1,58	1,79	112,30	-94,43
	2. AS, B, Zn, N36	1,58	1,79	120,44	-85,58	1,55	1,76	119,84	-86,29	1,59	1,81	112,21	-92,64	1,57	1,79	117,50	-88,17
	3. N-Lock, KG	1,57	1,77	118,39	-86,28	1,56	1,78	110,1	-97,64	1,59	1,81	113,53	-89,6	1,57	1,79	114,01	-91,17
LG 31.390	1. Control	1,57	1,77	115,85	-90,49	1,57	1,79	103,85	-99,62	1,59	1,8	112,1	-92,11	1,58	1,79	110,60	-94,07
	2. AS, B, Zn, N36	1,56	1,77	116,38	-88,96	1,53	1,73	121,5	-80,82	1,59	1,81	108,77	-94,85	1,56	1,77	115,55	-88,21
	3. N-Lock, KG	1,55	1,75	121,78	-82,56	1,52	1,72	119,74	-82,59	1,59	1,8	111,98	-91,93	1,55	1,76	117,83	-85,69
Premeo	1. Control	1,57	1,78	120,39	-86,2	1,54	1,75	121,9	-86,55	1,58	1,79	110,81	-93,54	1,56	1,77	117,70	-88,76
	2. AS, B, Zn, N36	1,57	1,77	120,56	-85,04	1,49	1,68	125,66	-81,4	1,58	1,79	114,24	-91,18	1,55	1,75	120,15	-85,87
	3. N-Lock, KG	1,56	1,76	120,41	-85,65	1,52	1,72	121,45	-80,15	1,57	1,77	115,43	-87,71	1,55	1,75	119,10	-84,50
Pioneer P9889	1. Control	1,54	1,75	121,68	-83,96	1,56	1,77	112,47	-90,67	1,58	1,79	108,24	-96,99	1,56	1,77	114,13	-90,54
	2. AS, B, Zn, N36	1,55	1,75	124,54	-81,18	1,55	1,76	119,22	-87,22	1,58	1,79	110,88	-93,52	1,56	1,77	118,21	-87,31
	3. N-Lock, KG	1,55	1,75	123,39	-82,95	1,53	1,73	121,64	-77,97	1,58	1,8	109,79	-95,13	1,55	1,76	118,27	-85,35
Knezha-461	1. Control	1,54	1,73	132,64	-70,13	1,56	1,77	121,88	-79,28	1,58	1,79	118,11	-82,77	1,56	1,76	124,21	-77,39
	2. AS, B, Zn, N36	1,54	1,73	132,46	-69,14	1,54	1,74	126,9	-78,24	1,57	1,78	118,12	-84,32	1,55	1,75	125,83	-77,23
	3. N-Lock, KG	1,54	1,72	136,17	-67,22	1,5	1,7	126,37	-80,48	1,57	1,77	121,95	-79,28	1,54	1,73	128,16	-75,66

Table 13. Energy and protein nutritional value of maize grain for pigs (per 1 kg DM), for the period 2022–2024

Maize hybrids	Variant	2022		2023		2024		2022-2024	
		GE	DE	GE	DE	GE	DE	GE	DE
DKC 4416	1. Control	16,20	16,04	16,02	15,90	16,27	16,10	16,16	16,01
	2. AS, B, Zn, N36	16,35	16,15	16,09	15,91	16,28	16,11	16,24	16,06
	3. N-Lock, KG	16,20	16,00	15,93	15,81	16,36	16,17	16,16	15,99
LG 31.390	1. Control	16,11	15,93	15,92	15,81	16,26	16,09	16,10	15,94
	2. AS, B, Zn, N36	16,08	15,90	15,92	15,72	16,24	16,09	16,08	15,90
	3. N-Lock, KG	16,13	15,92	15,79	15,61	16,25	16,08	16,06	15,87
Premeo	1. Control	16,29	16,09	16,00	15,83	16,15	15,99	16,15	15,97
	2. AS, B, Zn, N36	16,26	16,06	15,57	15,39	16,22	16,05	16,02	15,83
	3. N-Lock, KG	16,15	15,96	15,88	15,67	16,14	15,95	16,06	15,86
Pioneer P9889	1. Control	16,03	15,83	15,99	15,83	16,07	15,93	16,03	15,86
	2. AS, B, Zn, N36	16,17	15,96	16,06	15,89	16,16	16,00	16,13	15,95
	3. N-Lock, KG	16,09	15,88	15,95	15,73	16,16	16,01	16,07	15,87
Knezha-461	1. Control	16,26	15,98	16,30	16,07	16,34	16,10	16,30	16,05
	2. AS, B, Zn, N36	16,26	15,97	16,10	15,88	16,25	16,04	16,20	15,96
	3. N-Lock, KG	16,34	16,03	15,73	15,54	16,38	16,15	16,15	15,91

Table 14. Energy and protein nutritional value of maize grain for poultry (per 1 kg DM), for the period 2022–2024

Maize hybrids	Variant	2022		2023		2024		2022-2024	
		GE	DE	GE	DE	GE	DE	GE	DE
DKC 4416	1. Control	16,31	15,95	16,15	15,84	16,40	16,04	16,29	15,94
	2. AS, B, Zn, N36	16,48	16,05	16,23	15,80	16,41	16,06	16,37	15,97
	3. N-Lock, KG	16,33	15,91	16,06	15,75	16,49	16,12	16,29	15,93
LG 31.390	1. Control	16,22	15,84	16,05	15,78	16,38	16,03	16,22	15,88
	2. AS, B, Zn, N36	16,20	15,80	16,06	15,60	16,37	16,05	16,21	15,82
	3. N-Lock, KG	16,26	15,80	15,94	15,49	16,37	16,02	16,19	15,77
Premeo	1. Control	16,42	15,99	16,14	15,71	16,26	15,93	16,27	15,88
	2. AS, B, Zn, N36	16,39	15,95	15,71	15,22	16,35	15,98	16,15	15,72
	3. N-Lock, KG	16,27	15,84	16,02	15,55	16,25	15,86	16,18	15,75
Pioneer P9889	1. Control	16,16	15,71	16,13	15,77	16,19	15,88	16,16	15,79
	2. AS, B, Zn, N36	16,31	15,83	16,2	15,78	16,28	15,94	16,26	15,85
	3. N-Lock, KG	16,21	15,75	16,09	15,61	16,28	15,95	16,19	15,77
Knezha-461	1. Control	16,40	15,82	16,44	15,97	16,47	16,00	16,44	15,93
	2. AS, B, Zn, N36	16,39	15,81	16,24	15,73	16,38	15,95	16,34	15,83
	3. N-Lock, KG	16,46	15,85	15,87	15,38	16,51	16,08	16,28	15,77

On average for the study period, the results indicate an extremely weak effect of foliar fertilizers applied during the vegetation period of maize hybrids. The variation of NEL (Net Energy for Lactation) is within the range of 1.07 – 1.12 per 1 kg DM when feeding ruminants with silage (Tables 11 and 12), while for grain it is in the range of 1.54 – 1.58 per 1 kg DM.

In forages, four types of energy are determined: gross, digestible, metabolizable, and net energy. Gross energy (GE) is the total amount of energy released during the complete combustion of the feed in an oxygen environment in a bomb calorimeter. Digestible energy (DE) is obtained by subtracting from gross energy the energy of the indigestible nutrients excreted in the feces. Metabolizable energy (ME) is the so-called physiologically useful energy.

Tables 13 and 14 present the calculated values for the content of digestible and metabolizable energy for pigs and poultry in 1 kg of dry matter. The application of different foliar fertilizers had no significant effect on the studied parameters. The results for DE range from 16.03 to 16.30 MJ/kg DM. Metabolizable energy for pigs also varied within narrow limits – 15.86 to 16.06 MJ/kg DM. An analysis of the results for poultry again showed no significant differences in the content of digestible and metabolizable energy. The DE values for poultry were within 16.15 – 16.44 MJ/kg DM, on average for the period. Metabolizable energy ranged from 15.72 to 15.97 MJ/kg DM.

5. Statistical Analyses and Models

In this dissertation, statistical methods are applied to assess the effect of foliar products on yield, as well as to construct appropriate models based on structural and chemical indicators.

5.1. Correlation Analysis

Correlation relationships of biometric and productive indicators
The evaluation of the tested variants was carried out by comparing the following indicators determining maize quality: x_1 – plant height, x_2 – number of leaves, x_3 – ear length, x_4 – number of rows per ear, x_5 – number of kernels per row, x_6 – 1000-kernel weight, x_7 – green mass yield, x_8 – grain yield.

A correlation analysis was performed to establish the presence of statistically significant correlations between the studied indicators.

The correlation coefficients expressing the relationships between the studied indicators are presented in the correlation matrix (Table 15). Positive correlations were established between the structural elements determining the productivity of the studied hybrids. High positive r values (r = 0.953) were observed between "1000-kernel weight" and "green mass yield".

A strong positive correlation was found between the indicators "number of leaves" and "plant height" (r = 0.866); "ear length" and "1000-kernel weight" (r = 0.806), "green mass yield" (r = 0.830); as well as between "number of kernels per row" and "1000-kernel weight", and "grain yield" with coefficients of r = 0.815 and r = 0.866, respectively. A strong negative correlation was observed between "ear length" and "number of rows per ear" (r = -0.977).

The correlation relationships between "number of leaves" and the other indicators under consideration were mathematically insignificant.

Table 15. Correlation Matrix

Indicators	Plant height	Number of leaves	Ear length	Number of rows per ear	Number of kernels per row	1000-kernel weight	Green mass yield	Grain yield
Plant height	1							
Number of leaves	0,866*	1						
Ear length	-0,321	-0,352	1					
Number of rows per ear	0,198	0,304	-0,977**	1				
Number of kernels per row	0,405	0,469	0,621	-0,678	1			
1000-kernel weight	-0,110	0,124	0,806*	-0,743	0,815*	1		
Green mass yield	-0,363	-0,116	0,830*	-0,761	0,687	0,953**	1	
Grain yield	0,478	0,500	0,596	-0,603	0,866*	0,758	0,537	1

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

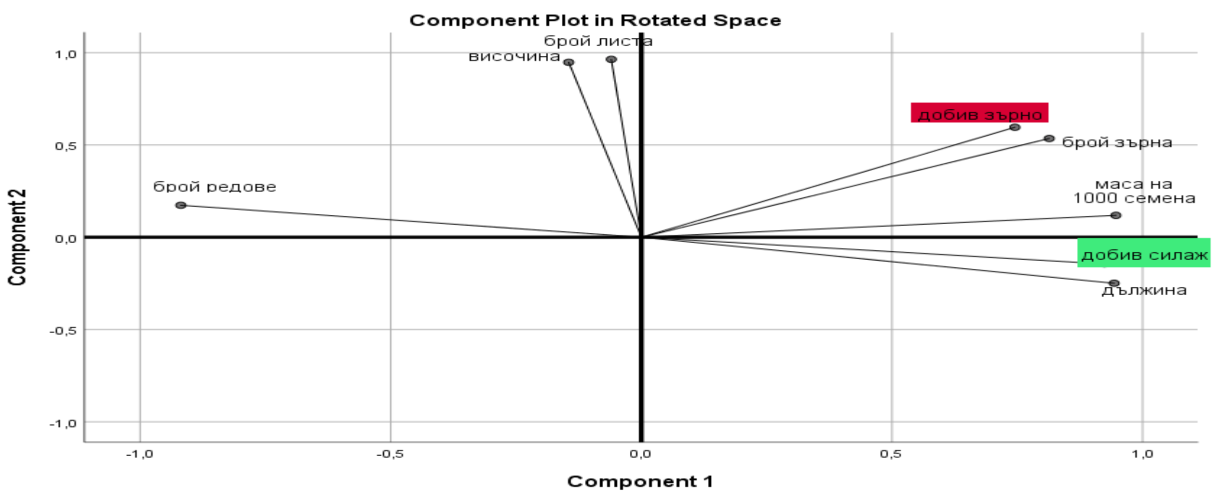

Figure 4. Principal Component Analysis (PCA) of the Quantitative Traits in Maize

Visually, the relationship between grain yield and silage yield with the other quantitative traits is clearly expressed through the positioning of their vectors in the plane (Figure 4).

Correlation Relationships Between Chemical Indicators of Grain in Maize Hybrids

The evaluation of the tested variants was performed by comparing the following chemical indicators determining the quality of maize: CP (Crude Protein), CF (Crude Fat), CFib (Crude Fiber), Ash, and NFE (Nitrogen-Free Extracts).

The correlation analysis of the chemical indicators for grain yield revealed a positive relationship between CP and CFib (r = 0.839).

A strong negative correlation was observed between the indicators NFE and CP, as well as CFib, with correlation coefficients r = -0.957 and r = -0.925, respectively (Table 34).

The correlation dependencies between CF and Ash with the other considered indicators were found to be statistically insignificant.

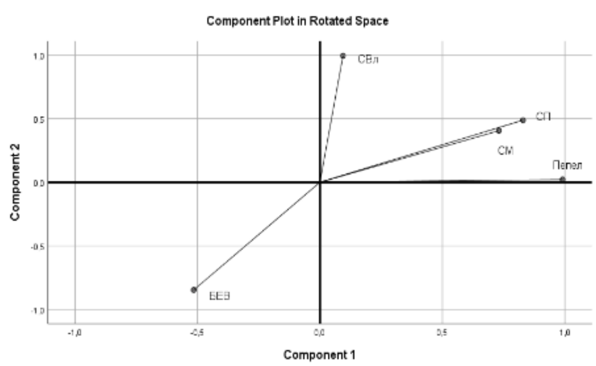

Figure 4. Principal Component Analysis (PCA) of the Chemical Indicators in Maize

5.2. Regression Models for the Effect of Foliar Fertilizers on the Productivity of Maize Hybrids

Regression models were developed to evaluate the influence of foliar fertilizers on silage yield for each experimental year and as an average over the study period (**Figures 5–8**). These models illustrate the relationship between the applied foliar treatments and the silage productivity of different maize hybrids, allowing assessment of the strength and direction of the effect.

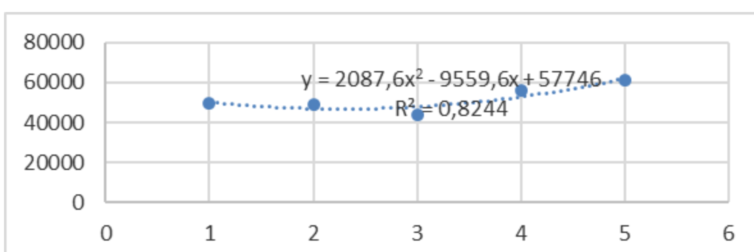

Figure 5. Regression model between foliar fertilizers and silage yield, 2022

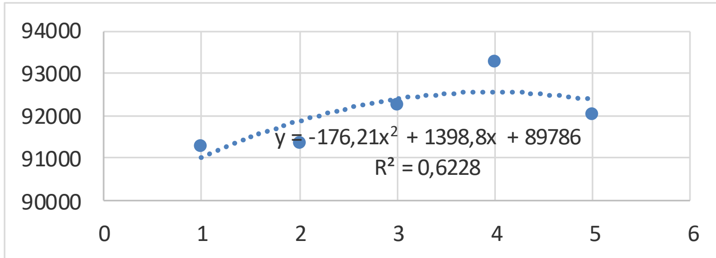

Figure 6. Regression model between foliar fertilizers and silage yield, 2023

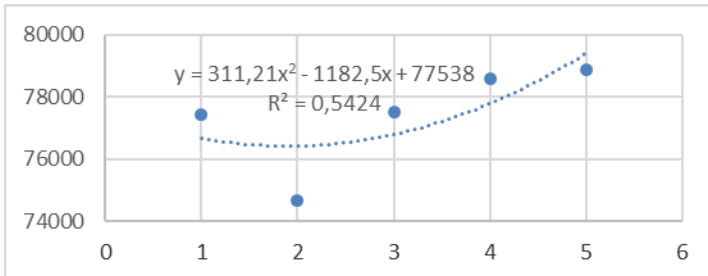

Figure 7. Regression model between foliar fertilizers and silage yield, 2024

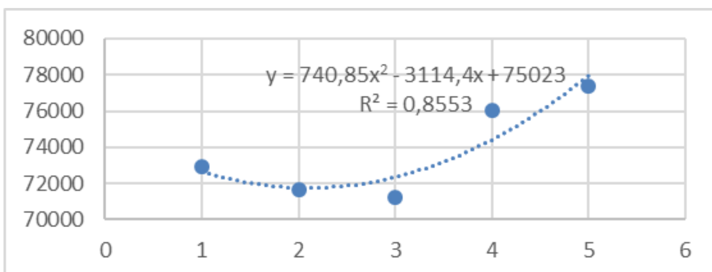

Figure 8. Regression model between foliar fertilizers and silage yield, average for 2022–2024

The correlation coefficient squared – R^2 (R Square) is referred to as the coefficient of determination. It indicates what percentage of the variability of the dependent variable is explained by the independent variable. In this case, $R^2 = 0.8553$, meaning that 86% of the variation in grain yield is determined by the foliar fertilization products. Based on this value, the polynomial regression model of the second degree can be considered adequate.

Regression models were developed to evaluate the influence of foliar fertilizers on grain yield for each experimental year, as well as for the average of the three-year period (Figures 9–12).

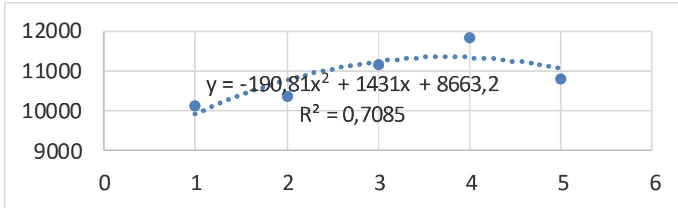

Figure 9. Polynomial regression model describing the relationship between foliar fertilizers and grain yield in 2022.

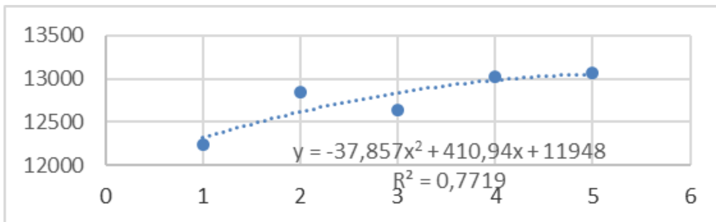

Figure 10. Regression model between foliar fertilizers and grain yield for 2023

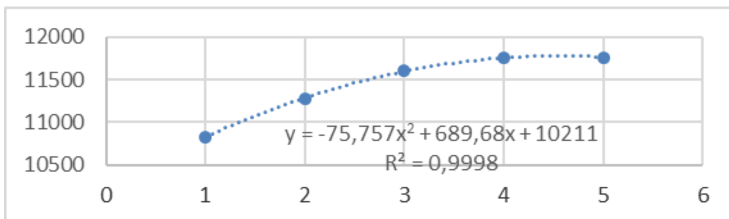

Figure 11. Regression model between foliar fertilizers and grain yield for 2024

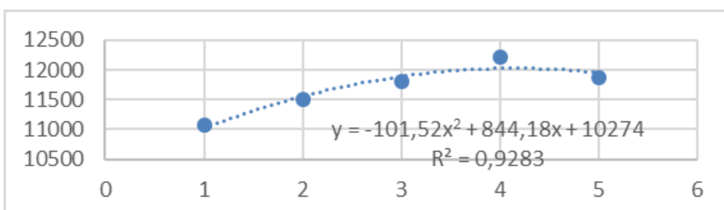

Figure 12. Regression model between foliar fertilizers and grain yield, average for 2022–2024

5.3. Cluster Analysis

To identify the similarity and proximity among the five studied hybrids, a hierarchical cluster analysis was applied. The $D(x,y)=\sqrt{\sum_{i=1}^{n}(x_i-y_i)^2}$ was used as a measure of similarity. To avoid discrepancies in the dimensions of the examined indicators, the data were standardized in advance.

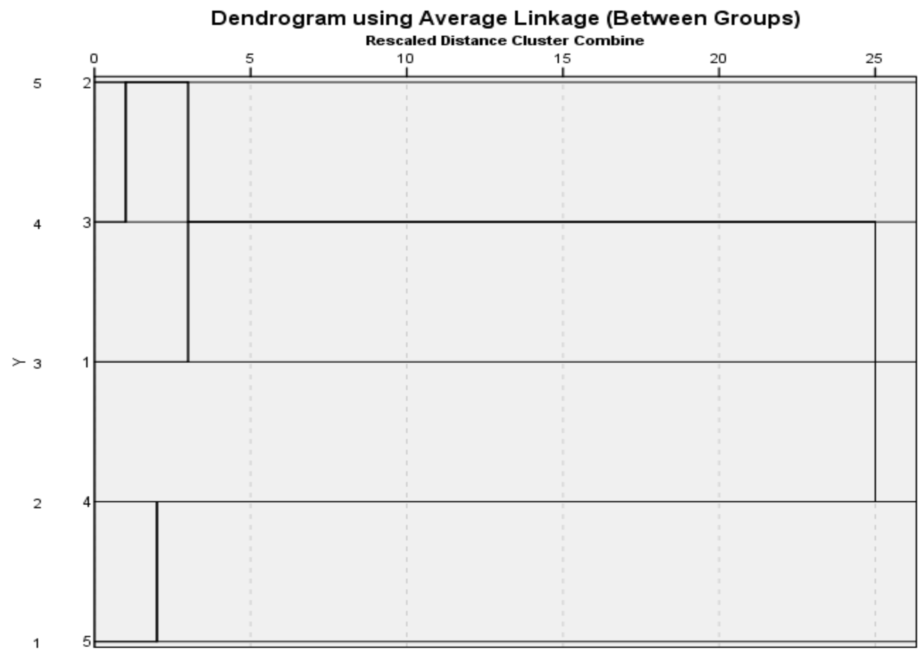

Figure 13. Dendrogram Based on Average Between-Group Distances

The clustering results are graphically presented through a dendrogram, which illustrates the sequence of merging the objects and the formation of clusters. The data were processed using the statistical software SPSS 26.0.

Based on the cluster analysis of the tested hybrids, two clusters were formed (Fig. 13). The first cluster includes three hybrids. Comparing the Euclidean distances between them shows that there is practically no difference among them. Hybrids **1 –** DKC 4416, 2 – LG 31.390, and 3 – Premeo in this cluster are similar in terms of content of NFE (nitrogen-free extract), ash, crude fat, grain yield, number of leaves, cob length, and number of rows per cob**.**

The second cluster includes hybrids 4 – Pioneer and 5 – Knezha-461. Within this cluster, they are homogeneous in terms of number of kernels per row, ash content, and silage yield**.**

By applying hierarchical cluster analysis based on 13 studied indicators, the genotypes were evaluated and grouped into two clusters with different levels of similarity. The grouping includes samples with similar agronomic characteristics. This classification improves the objectivity of the evaluation.

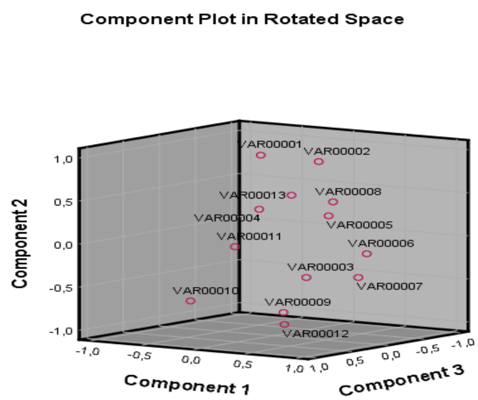

Figure 14. Visualization of the studied indicators in the factor plane

5.4. The CART Method for Processing and Analyzing Real Empirical Data in Crop Production

Modern agricultural science requires increasingly accurate and precise research methods to enable an in-depth analysis of the relationships between studied traits and indicators. Biological objects, for which data are most often collected in crop production experiments, exist within a specific life cycle. By applying one of the most advanced data mining models for statistical modeling and data analysis—Classification and Regression Trees (CART)—it is possible to uncover complex patterns and interactions within the dataset.

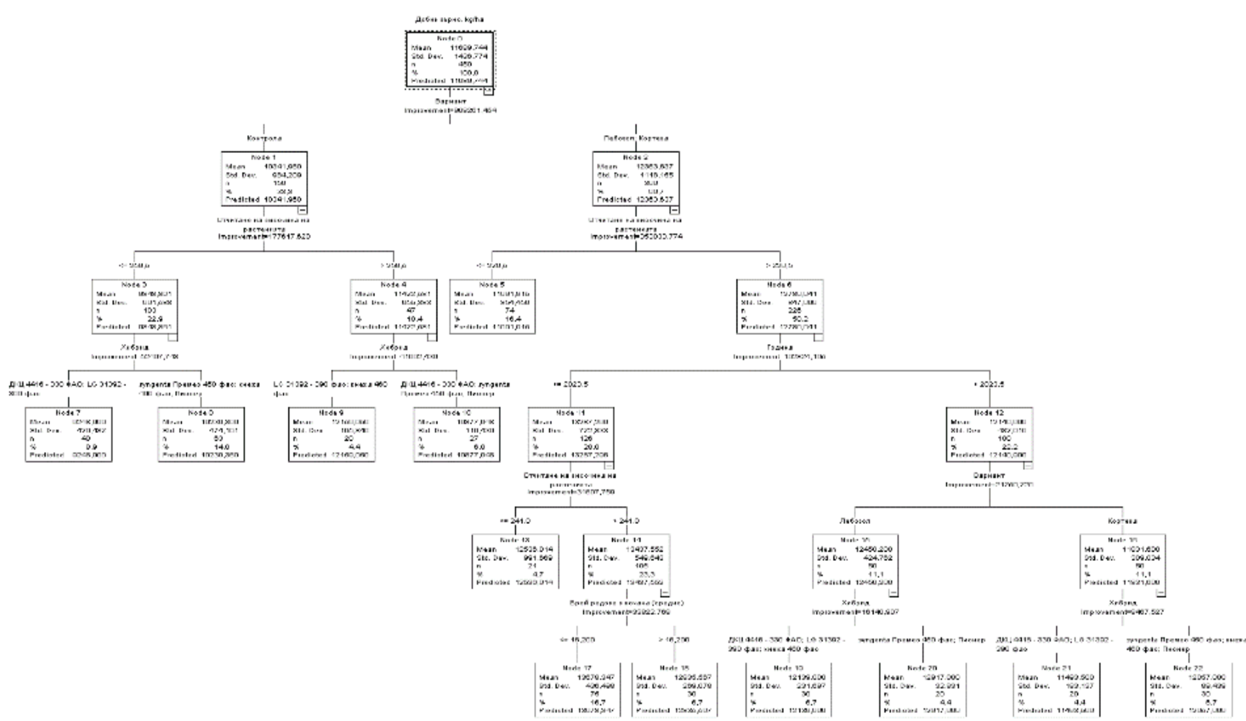

Figure 15. Decision Tree for the Variable "Grain Yield" Based on the CART Model

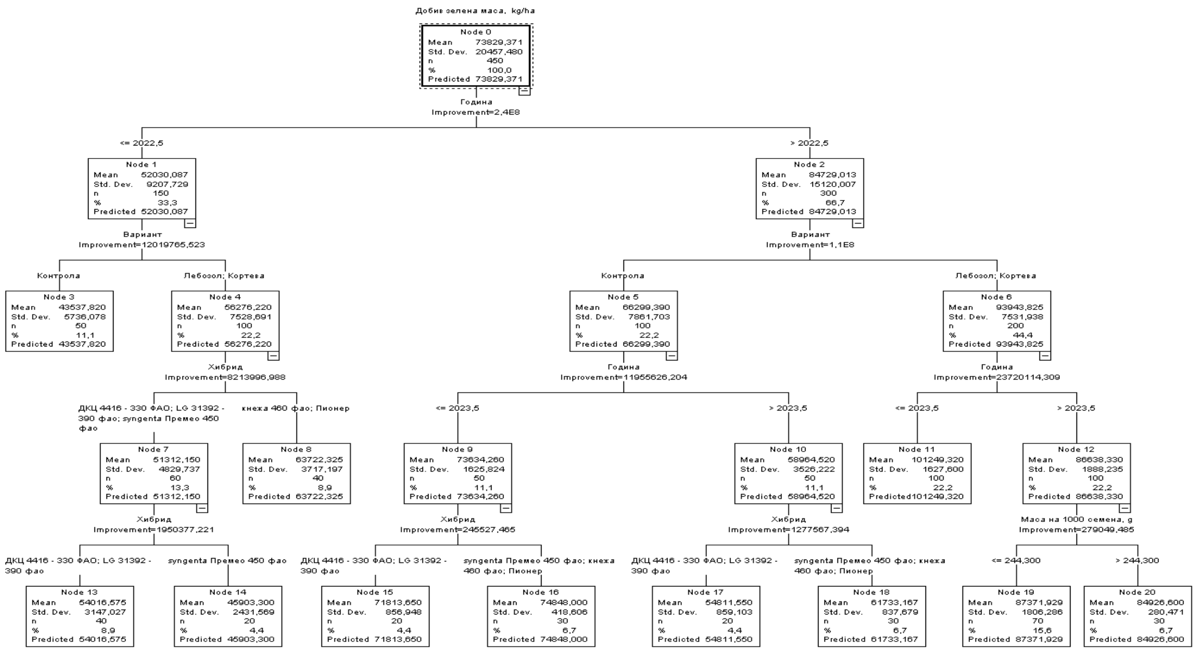

Figure 16. Decision Tree for the Variable "Green Mass Yield" Based on the CART Model

The objective and one of the main tasks of this dissertation was to develop and analyze models for maize based on linear traits using the method of Classification and Regression Trees (CART).

The CART method was applied to the dependent variable *"grain yield"* and 22 exterior traits of ordinal type (Figure 15). Control parameters were set for the tree, with a minimum number of cases in a terminal node of 20. The resulting tree had a depth of 5, with 21 nodes, of which 6 were terminal.

The CART method was also applied to the dependent variable *"green mass yield"* and 20 exterior traits of ordinal type. Control parameters were set for the tree, with a minimum number of cases in a terminal node of 20. The resulting tree had a depth of 4, with 21 nodes, of which 8 were terminal (Figure 16).

Conclusion

A significant part of the obtained results has been published in three scientific papers. Additionally, three reports were presented – one at an international forum and two at national forums.

The dissertation includes the application and analysis of a wide range of statistical methods and models for yield management depending on different foliar treatments.

The main contribution, from the perspective of mathematical modeling and its practical application in agriculture, is the use of real experimental data to construct and validate models that can predict crop performance and optimize production practices.

Crop production was modeled using **a** data mining model with machine learning of the CART type**.**

6. Conclusions

Based on the results obtained from the field trials, chemical analyses, and statistical evaluations, the following conclusions can be drawn:

1. Under the conditions of Stara Zagora, the average duration of the vegetation period was established for five maize hybrids belonging to the early and medium-early FAO maturity groups. The hybrid DKC 4416 was the earliest maturing, with a duration of 116.3 days, while the hybrid Knezha-461 recorded the longest vegetation period of 124.7 days.
2. The application of multicomponent and single-component foliar fertilizers (Aminosol + Lebosol B + Lebosol Zn, Nutriplant 36) contributed to an increase in plant height and the number of leaves per plant. Plant height increased by 8.3% (Knezha-461) up to 119.7% (Premeo) compared to the control. Hybrids LG 31.390 and Pioneer P9889 increased the number of leaves by 12.2% and 13.7%, respectively, compared to the control variants, after applying Aminosol + Lebosol B + Lebosol Zn, Nutriplant 36. The increase in these indicators was less pronounced after the application of Kinsidro Grow and N-Lock.
3. A positive trend was observed in increasing the values of cob length and number of rows per cob after foliar treatment. Hybrids Knezha-461 and Premeo formed longer cobs under the influence of the combined treatment with Aminosol + Lebosol B + Lebosol Zn, Nutriplant 36.
4. The application of foliar fertilizers had a positive effect on the number of kernels per row in all hybrids. The effect of fertilization with Aminosol + Lebosol B + Lebosol Zn, Nutriplant 36 was highest in DKC 4416 (+33.1%). The hybrid most responsive to foliar fertilization with Kinsidro Grow and N-Lock was Premeo (+15.2%).
5. An increase in the weight of 1000 grains was recorded after applying foliar fertilizers during the vegetation period. The strongest effect was observed in DKC 4416 (+28.53%), followed by Premeo (+24.69%), after treatment with Aminosol + Lebosol B + Lebosol Zn, Nutriplant 36. Increases of 9.92% (Pioneer P9889), 11.32% (LG 31.390), and 14.62% (Knezha-461) were also recorded after applying the same foliar fertilizer products.
6. The formation of green biomass in the five hybrids is strongly influenced by foliar fertilization. On average for the study period, the application of Aminosol + Lebosol B + Lebosol Zn and Nutriplant 36 increased yields by 41.4% compared to the control. The use of the organic fertilizer Kinsidro Grow and the nitrogen stabilizer N-Lock contributed to an increase of 36.4% in the studied hybrids.
7. A positive trend was observed in grain yield for all five maize hybrids tested. Yields were 15.5% higher after treatment with Kinsidro Grow and N-Lock, and 23.6% higher after the application of the foliar fertilizer complex Aminosol + Lebosol B + Lebosol Zn and Nutriplant 36.

8. A two-factor ANOVA was conducted to determine the influence of factors on maize productivity. On average for the study period, the greatest influence was exerted by the factor foliar fertilizer products, accounting for 81.3% of the variation in green biomass yield and 72.3% in grain yield. The influence of the hybrid factor was 15.0% for green biomass and 15.3% for grain yield.
9. Foliar fertilization increased the crude protein content in green biomass. The content increased by 15.2% compared to the control in Premeo (105.63 g/kg DM) after treatment with Aminosol + Lebosol B + Lebosol Zn and Nutriplant 36. Foliar application with Kinsidro Grow and N-Lock raised crude protein levels from 4.8% (DKC 4416) to 13.8% (Premeo).
10. Foliar treatment also increased crude protein content in grain in all studied hybrids by 4.5% to 19.0% compared to the control. The highest increase was observed in DKC 4416 and Pioneer P9889.
11. The influence of foliar fertilization on the energy and protein nutritional value of the feed was minimal. The variation of NEL (Net Energy for Lactation) ranged from 1.06 to 1.11 per kg DM in silage for ruminants and from 1.54 to 1.58 per kg DM in grain. Digestible energy values for poultry were in the range of 16.15–16.44 MJ/kg DM, on average for the period, while metabolizable energy varied from 15.72 to 15.97 MJ/kg DM.
12. A strong correlation was established between the indicators "number of leaves" and "plant height" (r = 0.866); "cob length" and "1000-kernel weight" (r = 0.806), "green biomass yield" (r = 0.830); "number of kernels per row" and "1000-kernel weight", "grain yield" with coefficients of r = 0.815 and r = 0.866, respectively.
13. The developed regression models for determining the degree of influence of foliar fertilizers are adequate and exhibit high values of the coefficient of determination (R^2 = 0.8553 for silage yield and R^2 = 0.9283 for grain yield).
14. A hierarchical cluster analysis established the formation of two clusters. The first cluster includes hybrids DKC 4416, LG 31.390, and Premeo, which are similar in terms of NFE content, ash, DM, grain yield, number of leaves, cob length, and number of kernel rows. The second cluster groups the hybrids Pioneer and Knezha-461, which are similar in number of kernels per row, ash content, and silage yield.
15. Decision trees were constructed for the variable "green biomass yield" and for the variable "grain yield" using the CART model.

Based on the conclusions, the following scientific-theoretical and scientific-applied contributions can be formulated:

7. Scientific-Theoretical Contributions

1. For the first time under the agro-ecological conditions of the Stara Zagora region, specific patterns of growth, development, and vegetation duration have been identified for five maize hybrids from the group of early and medium-early FAO hybrids.

2. The quantitative influence of the factors “foliar fertilization” and “hybrid” on grain and silage yield has been established. The two-factor analysis of variance demonstrates that the greatest effect is exerted by foliar fertilization (72.3% for grain yield and 81.3% for silage yield), surpassing the influence of the genotypic factor.
3. Strong positive correlations have been proven between key structural yield components and productivity indicators — for example, between number of leaves and plant height ($r = 0.866$), as well as between cob length, 1000-kernel weight, and grain yield.
4. Regression models have been developed ($R^2 = 0.8553$ for green biomass and $R^2 = 0.9283$ for grain yield), and, based on the application of a data mining model with machine learning of the CART type, the possibility of predicting the effect of foliar fertilizers has been demonstrated.
5. Through the use of hierarchical cluster analysis, the studied hybrids were grouped based on their productivity and chemical composition, which provides the opportunity for targeted utilization in production.

8. Scientific-Applied Contributions

1. The positive effect of foliar fertilizers on silage yield (up to 49.6%) and grain yield (up to 31.8%) has been proven. The best combination has been identified, namely Aminosol + Lebosol B + Lebosol Zn and Nutriplant 36.
2. Hybrids with the highest responsiveness to foliar fertilization (Premeo, Pioneer P9889, DKC 4416) have been determined, making them suitable for intensive production.
3. Based on the obtained results, specific combinations of foliar fertilizers have been proposed for optimizing technological parameters in maize cultivation, aimed at increasing crude protein content in green biomass and grain.
4. A scientifically grounded technology for foliar fertilization of maize has been developed, applicable under the conditions of Southeastern Bulgaria, supported by statistically validated results.
5. A practical foundation has been established for precision management of fertilization in maize, including the possibility of adapting the model for different hybrids and production goals (biomass, grain, etc.).

List of Publications Related to the Dissertation

1. **Stoyanov, G., & Kuneva, V. (2024).** Mathematical approach for assessing the impact of foliar nutrition on the main indicators in maize hybrids. *Scientific Papers. Series A. Agronomy*, 67(1).
2. **Stoyanov, G. (2025).** Influence of foliar fertilization on biomass yield of new corn hybrids (*Zea mays L.*). Scientific Papers of the Union of Scientists in Bulgaria – Plovdiv, Series B. Natural Sciences and Humanities. Vol. XXVI, 151-156.
3. **Stoyanov, G., & Sevov, A. (2025).** Influence of foliar fertilization on grain yield of new corn hybrids (*Zea mays L.*). Scientific Papers of the Union of Scientists in Bulgaria – Plovdiv, Series B. Natural Sciences and Humanities. Vol. XXVI, 157-160.

Studying the possibilities of using mathematical models to manage the yield of maize (Zea mays L.) grown in different directions
Summary of PhD Thesis

Georgi Stoyanov

The object of the study is 5 corn hybrids, with different FAO and different origins, in two directions - for silage and for grain. The aim of the dissertation work is to develop analytical models with the studied hybrids, which were grown during the period 2022-2024. The hybrids DKC 4416, LG 31.390, PREMEO, PIONEER P9889 and KNEZHA-461, on which foliar fertilization products were tested, were included in the study. The field experience was conducted under irrigated conditions. Foliar fertilization, with organic and inorganic foliar fertilizers, was carried out according to two technologies - in the first technology, fertilization was carried out with Aminosol (2.0 l/ha), Lebozol B (2.0 l/ha), Lebosol Zn (1.0 l/ha) and Nutriplant 36 (10.0 l/ha). In the second technology, Kinsidro Grow (150 g/ha) and N-Lock (2.50 l/ha) foliar fertilizers were used. Phenological observations and biometric measurements of the structural elements of corn hybrids were carried out. Two-factor analysis of variance showed the degree of influence of hybrid and foliar products on plant height, number of leaves per plant, cob length, number of rows per cob, number of kernels per row, grain weight per cob and green mass and grain productivity. The parameters of the energy and protein nutritional value of the forages were calculated. Correlational dependences were established between biometric, chemical and productive indicators for the five corn hybrids studied. Regression models have been developed to determine the degree of influence of foliar fertilizers on yield of green mass and grain yield. Through the application of hierarchical cluster analysis, based on 13 studied indicators, the genotypes were evaluated and grouped into two clusters with different proximity. A decision tree was constructed for the variable "green mass yield" and a decision tree was constructed for the variable "grain yield" using the CART model.