

Article

Assessment of the Impact of Biodegradable Coated Fertilizers on Corn Yield

Łukasz Rusek ^{1,2,*} , Marzena Sylwia Brodowska ^{2,*} , Paulina Bogusz ¹  and Piotr Rusek ¹ 

¹ Fertilizers Research Group, Łukasiewicz Research Network–New Chemical Syntheses Institute, Al. Tysiąclecia Państwa Polskiego 13a, 24-110 Puławy, Poland; paulina.bogusz@ins.lukasiewicz.gov.pl (P.B.); piotr.rusek@ins.lukasiewicz.gov.pl (P.R.)

² Department of Agricultural and Environmental Chemistry, University of Life Sciences in Lublin, Akademicka 13, 20-950 Lublin, Poland

* Correspondence: lukasz.rusek@ins.lukasiewicz.gov.pl (Ł.R.); marzena.brodowska@up.lublin.pl (M.S.B.)

Abstract

The aim of the study was to assess the impact of fertilizer type (urea, compound fertilizer), biodegradable coating type (linseed oil or hemp oil based) and nitrogen dose (135 and 180 kg N·ha^{−1}) on the yield of corn intended for silage. A three-year field experiment was conducted using a randomized block design with three replicates. The test plant was corn intended for silage. The field experiment was conducted in a factorial design comprising three experimental factors: fertilizer type (two levels), coating type (two levels), and fertilizer dose (two levels). Controlled-release fertilizers (CRF) based on biodegradable coatings are an emerging solution in sustainable nitrogen management, yet their field-scale performance remains insufficiently validated. This study investigated how biodegradable coatings based on linseed and hemp oils affect nutrient release dynamics and maize yield under three-year field conditions. The study represents the first field validation phase translating laboratory coating characteristics into agricultural performance metrics. Statistical analysis (ANOVA, Tukey's test) showed that in the first year of the study, the greatest impact on plant height and corn yield was observed in the case of type of fertilizer used (η^2_p up to 17.83%), type of coating (η^2_p up to 63.15%) and their interaction (η^2_p up to 11.92%). The symbol η^2_p (partial eta squared) represents a measure of effect size in analysis of variance (ANOVA). The largest plant size (average 307–310 cm) and the highest yield (107.33 t·ha^{−1}) were obtained in the case of yields in which compound fertilizer or urea with coatings were used in relation to the series in which fertilizers without coatings were applied (differences up to 11 t·ha^{−1}). Statistical analysis using repeated measures ANOVA confirmed a significant time effect, with fertilizer effectiveness declining in subsequent years of the experiment ($p < 0.05$). In the experiment, no effect of the tested factors on the number of corn cobs was found ($\eta^2_p < 2.27\%$). The highest fresh matter yield for silage production was obtained with coated NPK compound fertilizer (98.80 t·ha^{−1}), representing a 48% increase compared to the unfertilized control (66.90 t·ha^{−1}). The results of the study indicate that the use of coated compound fertilizers—NPK has the most beneficial effect on yield and biometric parameters of plants in the first growing season after their soil application. The enhanced nutrient release from biodegradable coatings provided greatest benefits in the first growing season, with diminishing effects in subsequent years due to coating degradation and residual soil nutrient accumulation.



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1. Introduction

Corn (*Zea mays* L.) is one of the most important cereal crops in the world, playing a key role in global food, feed, and industrial systems. As a plant with remarkable versatility and adaptability to various climatic conditions, it has become a fundamental element of agriculture in many regions of the world [1–6]. The growing demand for corn, resulting from its use in food, animal feed, and as a raw material for industry, including biofuel production, makes its cultivation and production strategically important for the food and economic security of many countries [1–6]. Corn is grown all over the world, and its annual production exceeds that of wheat and rice. In 2020, global corn production reached an impressive 1.16 billion tons. The latest data indicates that in the 2023/24 season, global corn production amounted to approximately 1.223 billion tons. The largest corn producer is the United States, which produced 360.3 million tons in 2020, accounting for 31% of global production. China ranked second with a production of 260.7 million tons (22.43%), followed by Brazil with 104 million tons (8.95%). Other significant countries where this crop is grown on a large scale are Argentina (58.4 million tons), Ukraine (30.3 million tons), India (30.2 million tons), and Mexico (27.4 million tons) [1,7–10].

Global demand for corn is constantly growing due to its diverse uses. Corn is a staple food in many parts of the world, especially in Latin America, Africa, and some regions of Asia. In developed countries, a significant portion of corn production is used as animal feed, which indirectly contributes to meeting the growing global demand for animal protein. Corn is also widely used in industry. It is used to produce corn starch, high fructose corn syrup (sweetener), corn oil, and alcohol, including bourbon. The use of corn as a raw material for the production of ethanol and other biofuels is also becoming increasingly important, further increasing the demand for this crop [11–14].

Despite impressive production levels, corn cultivation faces numerous challenges. Modern agricultural production faces numerous environmental challenges, including the need to optimize nutrient management while minimizing environmental impact [15]. Global challenges such as water scarcity, land degradation, and climate change have a direct impact on corn production. The growing demand for corn, combined with the challenges associated with its cultivation, makes the development of effective crop production methods, including appropriate fertilization using innovative fertilizers, and the development of varieties resistant to diseases, pests, and climate change, a priority for global food security [16–18].

Modern crop fertilization strategies increasingly take into account not only the efficiency of nutrient delivery, but also the impact on the soil environment. One of the directions of fertilization technology development is the use of coated fertilizers, which enable controlled release of nutrients [19]. In corn cultivation, mineral fertilizers providing nitrogen (N), phosphorus (P), and potassium (K) are traditionally used, as these are the basic components necessary for proper plant growth and yield. In recent years, controlled-release fertilizers (CRF) have become increasingly important. Thanks to their coatings, they enable the gradual release of nutrients tailored to the needs of plants. Studies show that the use of stable mineral compounds (SF) and controlled-release urea fertilizers (CRU) can reduce nitrogen losses by reducing ammonia volatilization (NH₃) by up to 48–63%, while significantly increasing corn yields, in some cases by more than 15% compared to traditional fertilization practices. In addition, fertilizers with biodegradable coatings show greater nitrogen use efficiency, increasing corn nutrient uptake and biomass weight by more than 50%. Such fertilization technologies not only contribute to better plant growth, but also to sustainable agricultural development by reducing greenhouse gas emissions and fertilizer losses [15]. Coated fertilizers offer real benefits to farmers in terms of crop yields and fertilization efficiency, and their application does not generate significant logistical problems.

The key barriers remain higher initial costs and limited availability, which, however, should increase with the development of domestic technologies and regulatory changes.

The development of effective biodegradable coating materials requires a systematic research approach combining laboratory characterization with field validation. In previous experimental studies, differences in biodegradation between coated fertilizer coatings based on linseed oil and hemp oil were analyzed in detail in the context of modern coated fertilizer production. This laboratory phase represented the first stage of research devoted to characterizing the properties and effectiveness of biodegradable coatings as an innovative solution in fertilization technology.

The present field study represents the second, crucial stage of this research program, involving the application of these characterized coating materials in agricultural practice under real field conditions. This transition from laboratory to field research follows established methodological frameworks for agricultural innovation development, where initial material characterization is followed by practical validation. The field testing phase is essential for evaluating how the previously characterized differences in coating biodegradation translate into fertilization efficiency and crop yields under variable environmental conditions. Therefore, this field research represents a continuation and development of previous laboratory work on coating properties, where the documented differences in biodegradation rates between linseed oil and hemp oil-based coatings served as a key factor in determining the expected patterns of nutrient release and long-term fertilizer effectiveness in field applications.

The aim of the study was to assess the impact of coated fertilizers (urea, compound fertilizer—NPK) with biodegradable coatings (linseed oil and hemp oil based) at two levels of nitrogen fertilization (optimal and reduced) on the yield and selected biometric parameters of corn intended for silage.

2. Materials and Methods

2.1. Location and Design of the Experiment

Field research was conducted at the Experimental Farm of the University of Life Sciences in Lublin in Czesławice (51°18'24" N, 22°16'04" E) in 2022, 2023, and 2024. The soil on which the field experiment was conducted, according to the soil classification in accordance with the Polish standard PN R 04033:1998 [20] and agronomic categories, is classified as: silt, subgroup: clayey silt (silt loam). Granulometric composition: sand fraction—range 2.0–0.05 mm—37.66% (including: 2.0–1.0 mm—0.04%; 1.0–0.5 mm—7.18%; 0.5–0.25 mm—13.68%; 0.25–0.10 mm—4.34%; 0.10–0.05 mm—12.42%), dust fraction—range 0.05–0.002 mm—56.88% (including: 0.05–0.02 mm—29.09%; 0.02–0.002 mm—27.80%) and clay fraction—range below 0.002 mm—5.46%. The physicochemical parameters of the soil are presented in Table 1.

The experimental plant was corn (*Zea mays* L.) grown for silage, variety Pioneer P8240 (medium-early dent hybrid). The Pioneer P8240 variety is characterized by very high yields and high starch content, which is easily digestible by cattle. The variety is distinguished by a strong stay-green effect, good initial vigor, and stable yield even in unfavorable climatic conditions. The P8240 variety tolerates cold well, requires sites with good water supply, and grows best on medium and better soils [15]. The field experiment was conducted using the random block method in three replicates, resulting in a total of 39 experimental plots (13 experimental objects in three replicates). On the 25 m² experimental plots, corn was planted in 8 rows with a spacing of 75 cm.

Table 1. Content of mineral components in the soil.

Parameter	Value	Description	Unit
Soil category	mean		
pH	6.1	slightly sour	
Liming needs		related	
P ₂ O ₅	242	very high	mg·kg ^{−1} soil
K ₂ O	169	mean	mg·kg ^{−1} soil
Mg	59	mean	mg/kg ^{−1} soil
S-generally	0.027	mean	In % psm
‘N Point 0–30 cm			
N-NO ₃	22.39	very high	mg·kg ^{−1} dry soil
N-NH ₄	<0.83	very high	mg·kg ^{−1} dry soil
N min	96.30	very high	kg·ha ^{−1}
N Point 30–60 cm			
N-NO ₃	7.72	very high	mg·kg ^{−1} dry soil
N-NH ₄	1.45	very high	mg·kg ^{−1} dry soil
N min	39.40	very high	kg·ha ^{−1}
N min in layers 0–60 cm	135.70	very high	kg·ha ^{−1}

Corn sowing was carried out in the first year of the study on 13 May 2022, in the second year on 9 May 2023, and in the third year of the field experiment on 19 April 2024. The varying planting dates of maize across the three consecutive years were due to changing weather conditions that affected soil temperature and moisture, as well as the availability of planting equipment. Unfavorable atmospheric conditions delayed reaching optimal soil temperatures for sowing, while equipment availability influenced the logistics of conducting planting operations. The sowing density was 80,000 seeds·ha^{−1}. Prevention of weed growth during vegetation was carried out using classic plant protection products in accordance with the recommendations of the Plant Protection Institute [21]. During the growth period of the test plant, weed prevention was carried out by spraying with Lumax 537.5SE herbicide, which effectively reduces the growth of monocotyledonous and dicotyledonous weeds [22]. The corn was harvested in the milky-waxy ripeness stage, when the dry matter content was 30–35%. Yield parameters were determined based on the harvest of plants from a representative area of 2 m² from the two middle rows of each experimental plot. The above-ground parts of the plants were harvested manually by cutting the plants 10 cm above the soil surface. The yield of the above-ground part was weighed as the sum of the grain yield and the vegetative part, and the weight of the cobs was weighed separately. Eight plants were randomly selected from each experimental plot and their height, number of cobs, and number of rows of grains in the cob were measured. Then, the test plants from each plot were cut into pieces in a chopper, from which, after mechanical mixing, samples weighing 500 g were taken for chemical composition and quality parameter analysis. After weighing, the samples were dried in an air circulation dryer and the dry weight of the plants was determined.

The following fertilizers were used in the field experiment:

Polifoska Start—a compound fertilizer with an NPK (Mg, S) formulation of 12-11-18 (+2.7 MgO +29 SO₃) applied at an optimal dose of 180 kg N·ha^{−1} and a dose reduced by 25%—135 kg N·ha^{−1}. This fertilizer was used without a coating, with a biodegradable coating based on linseed oil and lignite, and with a biodegradable coating based on hemp oil and lignite. Urea + potassium sulfate + superphosphate—a mixture of single-component

fertilizers with a chemical composition corresponding to that of Polifoska Start. As in the case of urea, this fertilizer was applied at the optimal dose of $180 \text{ kg N} \cdot \text{ha}^{-1}$ and at a dose reduced by 25%— $135 \text{ kg N} \cdot \text{ha}^{-1}$ and without a coating, with a biodegradable coating based on linseed oil and lignite, and with a biodegradable coating based on hemp oil and lignite. The fertilizer variants used in the field experiment are presented in Table 2. The coated fertilizers used in the field experiment were produced at the Łukasiewicz Research Network—Institute of New Chemical Syntheses, as part of work on modern sustainable fertilization technologies [23].

Table 2. Experience Variants.

Variant	Fertilizer	Coating	N Dose (kg ha^{-1})
1	No fertilization (control)	-	0
2	Start of Polifoska	none	180
3	Start of Polifoska	none	135
4	Start of Polifoska	linen	180
5	Start of Polifoska	linen	135
6	Start of Polifoska	Hemp	180
7	Start of Polifoska	Hemp	135
8	Urea + PK	none	180
9	Urea + PK	none	135
10	Urea + PK	linen	180
11	Urea + PK	linen	135
12	Urea + PK	Hemp	180
13	Urea + PK	Hemp	135

Based on meteorological data collected during the field experiment, including average monthly air temperatures, total precipitation, and Sielininov's hydrothermal coefficient (HTC) values [24], the climatic conditions in individual growing seasons (Years I, II, and III) and their impact on corn cultivation were assessed. The optimal temperature for corn growth and development is between 18 and 24 °C, especially from June to August, which is the main growing season for this plant. The analysis showed that the highest average monthly temperatures were recorded in July (VII) in year III— 21.7 °C, August (VIII) in year II— 21.0 °C, and June (VI) in year III— 19.5 °C. The lowest temperatures were recorded in April, especially in the first year of the study (5.9 °C), which indicates unfavorable thermal conditions at the beginning of the growing season for the germination and growth of the test plant. Year III was characterized by the most favorable temperatures during the key period of corn growth. Corn requires 350 to 500 mm of rainfall between May and August. Too little rainfall can cause water stress, while too much can hinder root system development, especially in the early stages of corn growth. The highest monthly rainfall totals occurred in August (VIII) in year III of the study—134.2 mm, in September (IX) in year I—112.3 mm, and in July (VII) in year I of the field experiment—111.8 mm. The lowest rainfall was recorded in May (V) in year III—14.9 mm, in September (IX) in year II—28.5 mm, and in April (IV) in year III—25.3 mm. The first year of the field experiment was characterized by the most even distribution of rainfall during the growing season, although not always in the months crucial for corn growth and development. The Sielininov hydrothermal index (HTC) combines the effects of temperature and rainfall. Its interpretation is as follows:

- $\text{HTC} < 0.5$ —drought,

- 0.5–1.0—dry conditions,
- 1.0–1.5—moderate conditions,
- 1.5—favorable conditions.

In the analyzed three-year research period, the highest HTC values (favorable moisture conditions) were recorded in: April (IV) in year I—3.01, September (IX) in year I—3.47, August (VIII) in year III—2.08, and June (VI) in year III—1.84. The worst conditions ($\text{HTC} < 0.5$) for corn growth and development in terms of humidity were observed, among others, in May (V) in year III—0.29 and in September (IX) in the second year of the field experiment—0.54. Year III was characterized by the best water and thermal conditions in the months crucial for plant growth and development. Corn intended for silage is the basic component of roughage in cattle feed, so the right harvest time is crucial for obtaining high-quality silage. The right harvest time determines the starch content, fiber digestibility, and minimization of losses during ensiling. Both too early and too late harvesting can lead to a decrease in the nutritional value of silage and technological problems during its preparation. The optimal harvest time for corn silage is when the dry matter content of the whole plant is 30–35%, the grain is in the wax or wax-glassy stage, and the milk line moves to 2/3 of the grain height. The vitreous starch does not exceed half the height of the kernel, which means that the kernel is well filled and the green fodder is still sufficiently moist to ensure effective compaction in the silo. Harvesting too early results in high juice runoff and low starch content, while harvesting too late results in difficulties in shredding, poorer digestibility, and problems with proper ensiling.

2.2. Statistical Analysis

The statistical analysis of the results obtained from the field experiment was prepared using Statistica 13 software. For this purpose, analysis of variance (ANOVA) was used for factorial designs, and the significance of differences was determined using Tukey's test (HSD) for each year of the study separately at a significance level of $\alpha = 0.05$. The assumptions for the ANOVA test were checked using Levene's test (homogeneity of variance) and the Shapiro–Wilk test (normality of distribution). Repeated measures ANOVA was performed where “year” was treated as a within-subject factor, while fertilizer type, coating type, and nitrogen dose were between-subject factors. This approach allowed the evaluation of temporal effects on yield dynamics and plant biometric traits. For each parameter analyzed in individual years, an analysis of the influence of individual factors and the influence of their interaction effects was presented. The measure of this influence was determined by calculating the partial eta square (η^2_p) coefficient, which determines which factor explains the variability of the measured parameter to a greater extent. The effects of the fertilizers tested in the experiment were compared depending on the type of fertilizer (2 levels: urea, NPK fertilizer), the coating used (3 levels: no coating—0, coating 1, coating 2) and the nitrogen dose (2 levels: 135 or 180 kg N·ha^{−1}). The results obtained were compared with the control object without fertilization. Using Tukey's test, homogeneous groups were determined for the mean values of the tested parameters (marked with lowercase letters) and homogeneous groups for the group means (marked with uppercase letters).

3. Results

The meteorological conditions during the field experiment varied in subsequent years of research, which affected the development and yield of corn. Tables 3 and 4 show the average monthly air temperatures and total precipitation during the corn growing season. These data allow for the assessment of the impact of climatic conditions on plant growth and yield, as well as for the interpretation of possible differences in the results of the experiment in individual years. The presentation of these results makes it possible to link

changes in yields to specific meteorological phenomena and to analyze seasonal weather trends during the corn growing season.

Table 3. Average monthly air temperatures (°C) throughout the field experiment.

Years	Months						
	IV	V	VI	VII	VIII	IX	
I	5.9	12.8	19.4	19.4	20.5	10.8	13.1
II	8.2	12.9	17.4	20	21	17.6	16.1
III	11	16.3	19.5	21.7	20.8	17.1	17.7
Avg.	8.4	14.0	18.8	20.4	20.8	15.2	
Avg. 2011–2020	9.5	14.4	18.5	20.1	19.7	14.7	

Table 4. Monthly totals of rainfall (mm) throughout the field experiment.

Years	Months						
	IV	V	VI	VII	VIII	IX	
I	53.2	36.3	38.7	111.8	52.3	112.3	67.4
II	57.9	66	60	84.7	46.4	28.5	57.3
III	25.3	14.9	107.4	61.3	134.2	42.4	64.25
Avg.	45.5	39.1	68.7	85.9	77.6	61.1	
Avg. 2011–2020	40.8	80.3	64.3	91.3	54.9	60.2	

The meteorological conditions during the field experiment varied in different years of the study. Tables 3 and 4 show the average monthly air temperatures and monthly precipitation totals during the corn growing season (Table 5).

Table 5. Sielininov’s coefficient values throughout the field research period.

Years	Months					
	IV	V	VI	VII	VIII	IX
I	3.01	0.91	0.66	1.86	0.82	3.47
II	2.35	1.65	1.15	1.37	0.71	0.54
III	0.77	0.29	1.84	0.91	2.08	0.83

The table below shows the average corn yields expressed in tons per hectare ($t \cdot ha^{-1}$), as well as the division of the results into homogeneous groups based on Tukey’s test (HSD) at a significance level of $\alpha = 0.05$. These data allow us to assess which varieties or variants of corn cultivation technology differed significantly in terms of yield, and the obtained groups indicate statistical differences between the conditions assessed in the field study. The table illustrates the results of the comparative analysis, allowing the most productive variants to be identified and differences in yields to be interpreted on the basis of objective statistical criteria.

The use of a coating on both fertilizers tested in the first year of the study had a significant impact on the yield of the test plant (Table 6). In the case of fertilization with coated urea, yields were higher by approx. $9\text{--}11 t \cdot ha^{-1}$, and in the case of NPK fertilization by approx. $9 t \cdot ha^{-1}$ compared to the same fertilizers in equivalent doses without coating. In the second and third years of the study, a significantly higher corn yield was observed in the test plots where coated fertilizers were used compared to uncoated fertilizers for the NPK compound fertilizer. Taking into account the average yield values from the three years of research, both with urea and NPK fertilization, the use of coating significantly

increased the average yield per hectare. The use of coating on fertilizers had a greater impact on differences in corn yield in the first ($\eta^2_p = 63.15\%$) and second (47.43%) years of field research, taking into account the average of 3 years of research ($\eta^2_p = 39.70\%$). In none of the years of research were there any significant differences in the average yield obtained depending on the type of coating used (coating 1 or coating 2). The type of fertilizer used had a significant impact on the yield in the second and third years of the study and on the average corn yield for the three years of the study. In each case, higher yields were obtained when corn was fertilized with NPK fertilizers compared to urea fertilization. A higher nitrogen fertilization dose (optimal dose) in the first year of field research significantly increased the yield compared to a reduced nitrogen dose. In the second year of the study, this relationship was maintained only in the case of urea fertilization, while in the third year of the study, it was maintained in the case of NPK compound fertilizer fertilization. Taking into account the average yield results for the three years of the study, the application of a higher nitrogen dose resulted in a higher yield both with urea and NPK compound fertilizer fertilization. In each year of the study and for the average of the three years of the study, the yield on plots without fertilization was significantly lower than the average yield on plots fertilized with both urea and NPK, which confirms the yield-enhancing effect of nitrogen.

Table 6. Average corn yield ($t \cdot ha^{-1}$) and division into homogeneous groups using Tukey's test (HSD) for $\alpha = 0.05$.

Years	N Dose, kg N·ha ⁻¹ (C)	Type of Fertilizer (A)								Without Fertiliza- tion
		Urea				NPK				
		Coating Type (B)								
		0	1	2	Avg.	0	1	2	Avg.	
I	180	88.17 bc	99.23 c-f	99.67 d-f	95.69 C	91.43 b-e	107.33 f	101.97 ef	100.24 C	71.13 a
	135	83.43 b	90.03 b-d	92.73 b-e	88.73 B	88.18 bc	88.83 b-d	94.10 b-e	90.37 B	A
	Avg.	85.80 B	94.63 CD	96.20 CD		89.81 BC	98.08 D	98.03 D		A
	Avg.		92.21 B				95.31 B			A
		A— $\eta^2_p = 17.83\%$ B— $\eta^2_p = 63.15\%$		C— $\eta^2_p = 62.98\%$		AxB—n.s. AxC—n.s.		BxC— $\eta^2_p = 28.65\%$ AxBxC—n.s.		
II	180	82.90 ab	96.18 bc	90.97 bc	90.02 BC	85.00 a-c	101.25 bc	104.07 c	96.77 C	67.07 a
	135	80.57 ab	86.98 a-c	87.30 a-c	84.95 B	83.90 a-c	98.27 bc	96.15 bc	92.77 BC	A
	Avg.	81.73 AB	91.85 BC	89.13 BC		84.45 B	99.78 C	100.11 C		A
	Avg.		87.48 B				94.77 C			A
		A— $\eta^2_p = 26.96\%$ B— $\eta^2_p = 47.43\%$		C—n.s.		AxB—n.s. AxC—n.s.		BxC—n.s. AxBxC—n.s.		
III	180	84.70 b	89.00 b	89.13 b	87.61 B	86.37 b	105.10 c	106.72 c	99.39 C	62.50 a
	135	82.63 b	85.10 b	82.33 b	83.36 B	83.63 b	90.33 b	86.07 b	86.68 B	A
	Avg.	83.67 B	87.05 B	85.73 B		85.00 B	97.72 C	96.39 C		A
	Avg.		85.48 B				93.04 C			A
		A— $\eta^2_p = 59.26\%$ B— $\eta^2_p = 55.89\%$		C— $\eta^2_p = 64.74\%$		AxB— $\eta^2_p = 33.02\%$ AxC— $\eta^2_p = 31.33\%$		BxC— $\eta^2_p = 35.65\%$ AxBxC—n.s.		
Avg.	180	85.26 bc	94.81 d	93.26 cd	91.11 C	87.60 b-d	104.56 e	104.25 e	98.80 D	66.90 a
	135	82.21 b	87.37 b-d	87.46 b-d	85.68 B	85.24 bc	92.48 cd	92.10 cd	89.94 C	A
	Avg.	83.73 B	91.09 C	90.36 C		86.42 BC	98.52 D	98.18 D		A
	Avg.		88.39 B				94.37 C			A
		A— $\eta^2_p = 22.79\%$ B— $\eta^2_p = 39.70\%$		C— $\eta^2_p = 29.65\%$		AxB— $\eta^2_p =$ n.s. AxC— $\eta^2_p =$ n.s.		BxC— $\eta^2_p = 7.60\%$ AxBxC—n.s.		

Notes: Lowercase letters in the table indicate homogeneous groups for results, uppercase letters refer to averages.

The table below shows the average height of corn plants expressed in centimeters (cm) and the division of results into homogeneous groups according to Tukey's test (HSD) at a significance level of $\alpha = 0.05$. Based on measurements of the height of individual variants or varieties of corn, it is possible to assess whether the differences between the variants

were statistically significant. The division into homogeneous groups indicates which variants achieved similar plant heights and allows for the interpretation of morphological differences in terms of growing conditions or technologies used in the field experiment. The table provides a basis for drawing conclusions about the impact of the studied factors on corn growth.

Based on the conducted research, it can be concluded that the height of corn plants during harvest varied depending on the fertilizer used, the type of coating, and the year of the study (Table 7). The most significant differences were observed in the first year of the experiment, where both the type of fertilizer and the type of coating, as well as their mutual interaction, significantly affected plant height. A particularly beneficial effect was obtained by using urea and NPK in combination with type 1 and 2 coatings, which resulted in significantly taller plants compared to other fertilizer variants. In the second year of the study, the effect of the type of fertilizer was less pronounced, but the positive effect of the coatings was still noticeable, especially in the case of urea. In the third year of the experiment, the differences in plant height between the individual fertilization variants were the smallest, and the effect of the coating and type of fertilizer on corn height was already very weak. In the control plots—without fertilization—the plants were the shortest, which was particularly evident in the third year of the study. In summary, the tallest corn plants were found in plots where coated fertilizers were used, with the effect of coated fertilizers on plant growth being greatest in the first year of cultivation. In subsequent years of the study, a smaller effect of coated fertilizer application on corn growth was observed compared to uncoated fertilizers.

Table 7. Average height of corn plants (cm) and division into homogeneous groups using Tukey's test (HSD) for $\alpha = 0.05$.

Years	N Dose, kg N·ha ⁻¹ (C)	Type of Fertilizer (A)								Without Fertiliza- tion
		Urea				NPK				
		Coating Type (B)								
		0	1	2	Avg.	0	1	2	Avg.	
I	180	300.17 de	278.04 ab	289.75 b-d	289.32 A	295.83 c-e	307.17 e	300.50 de	301.17 B	306.42 de
	135	306.67 e	266.83 a	283.29 a-c	285.60 A	309.71 e	300.38 de	309.96 e	306.68 B	B
	Avg.	303.42 C	272.44 A	286.52 B		302.77 C	303.77 C	305.23 C		C
	Avg.		287.46 A				303.92 B			B
		A— η^2_p = 17.50% B— η^2_p = 10.49%		C—n.s.		AxB— η^2_p = 11.92% AxC— η^2_p = 1.64%		BxC— η^2_p = 4.59% AxBxC—n.s.		
II	180	279.04 bc	280.67 c	279.13 bc	279.61 CD	263.75 a	279.92 bc	274.96 a-c	278.88 B	262.00 a
	135	274.25 a-c	284.79 c	283.71 c	280.92 D	267.33 ab	277.75 bc	278.42 bc	274.50 BC	A
	Avg.	276.65 B	282.73 B	281.42 B		265.54 A	278.83 B	276.69 B		A
	Avg.		280.26 C				273.69 B			A
		A— η^2_p = 5.37% B— η^2_p = 8.54%		C—n.s.		AxB—n.s. AxC—n.s.		BxC—n.s. AxBxC—n.s.		
III	180	283.54 b	281.75 b	275.88 b	280.39 B	280.25 b	277.46 b	271.17 b	276.29 B	238.50 a
	135	278.83 b	272.17 b	278.21 b	276.40 B	282.75 b	279.67 b	280.29 b	280.39 B	A
	Avg.	281.19 B	276.96 B	277.04 B		281.50 B	278.56 B	275.73 B		A
	Avg.		278.40 B				278.60 BC			A
		A—n.s. B— η^2_p = 2.27%		C—n.s.		AxB—n.s. AxC— η^2_p = 2.40%		BxC— η^2_p = 2.06% AxBxC—n.s.		
Avg.	180	287.58 c	280.15 bc	281.58 bc	283.11 BC	279.94 a-c	288.18 c	282.21 bc	283.44 BC	268.97 a
	135	286.58 c	274.60 ab	281.74 bc	280.97 B	286.60 c	285.93 c	289.56 c	287.36 C	A
	Avg.	287.08 C	277.38 AB	281.66 BC		283.27 BC	287.06 C	285.88 C		A
	Avg.		282.04 B				285.40 C			A
		A— η^2_p = 0.66% B—n.s.		C—n.s.		AxB— η^2_p = 1.77% AxC— η^2_p = 0.53%		BxC— η^2_p = 0.68% AxBxC—n.s.		

Notes: Lowercase letters in the table indicate homogeneous groups for results, uppercase letters refer to averages.

The table below shows the average share of cobs in the total corn yield expressed as a percentage (%), with the tested variants divided into homogeneous groups based on Tukey's test (HSD) for a significance level of $\alpha = 0.05$. This comparison allows us to determine which variants differed significantly in terms of the share of cobs in the total yield, and the division into homogeneous groups indicates statistically similar values between the analyzed variants. The table facilitates the comparison of the effects of varieties, agrotechnology, or environmental conditions on the structure of the corn yield.

The average number of cobs per corn plant was very similar in all experimental plots, regardless of the nitrogen dose, fertilizer type, or coating type (Table 8). None of the tested factors or their interactions had a statistically significant effect on the number of corn cobs. The values obtained for the number of cobs per plant were comparable in subsequent years of the study and with different fertilization variants. In the experiment, no significant differences were found in the number of cobs per plant depending on the type of fertilizer used, the type of coating, or the nitrogen dose.

Table 8. Average share of cobs in total yield (%) and division into homogeneous groups using the Tukey test (HSD) for $\alpha = 0.05$.

Years	N Dose, kg N·ha ⁻¹ (C)	Type of Fertilizer (A)								Without Fertiliza- tion
		Urea				NPK				
		Coating Type (B)								
		0	1	2	Avg.	0	1	2	Avg.	
I	180	0.51 a	0.53 a	0.53 a	0.52 A	0.53 a	0.53 a	0.52 a	0.53 A	0.51 a
	135	0.54 a	0.51 a	0.55 a	0.53 A	0.53 a	0.53 a	0.52 a	0.53 A	A
	Avg.	0.53 A	0.52 A	0.54 A		0.53 A	0.53 A	0.52 A		A
	Avg.		0.53 A				0.53 A			A
		A— η^2_p = n.s. B— η^2_p = n.s.			C— η^2_p = n.s.		AxB—n.s. AxC—n.s.		BxC—n.s. AxBxC—n.s.	
II	180	0.53 a	0.51 a	0.53 a	0.52 A	0.52 a	0.53 a	0.53 a	0.53 AB	0.56 a
	135	0.50 a	0.54 a	0.53 a	0.52 A	0.53 a	0.53 a	0.54 a	0.53 AB	B
	Avg.	0.51 A	0.53 AB	0.53 AB		0.52 AB	0.53 AB	0.53 AB		B
	Avg.		0.52 A				0.53 A			B
		A—n.s. B—n.s.			C—n.s.		AxB—n.s. AxC—n.s.		BxC—n.s. AxBxC—n.s.	
III	180	0.53 a	0.53 a	0.53 a	0.53 A	0.54 a	0.53 a	0.53 a	0.53 A	0.53 a
	135	0.53 a	0.52 a	0.52 a	0.52 A	0.54 a	0.53 a	0.53 a	0.53 A	A
	Avg.	0.53 A	0.52 A	0.52 A		0.54 A	0.53 A	0.53 A		A
	Avg.		0.52 A				0.53 A			A
		A—n.s. B—n.s.			C—n.s.		AxB—n.s. AxC—n.s.		BxC—n.s. AxBxC—n.s.	
Avg.	180	0.52 a	0.52 a	0.53 a	0.52 A	0.53 a	0.53 a	0.53 a	0.53 A	0.53 a
	135	0.52 a	0.52 a	0.53 a	0.53 A	0.53 a	0.53 a	0.52 a	0.53 A	A
	Avg.	0.52 A	0.52 A	0.53 A		0.53 A	0.53 A	0.53 A		A
	Avg.		0.52 A				0.53 A			A
		A—n.s. B—n.s.			C—n.s.		AxB—n.s. AxC—n.s.		BxC—n.s. AxBxC—n.s.	

Notes: Lowercase letters in the table indicate homogeneous groups for results, uppercase letters refer to averages.

4. Discussion

The results obtained from research on the impact of biodegradable coated fertilizers on corn yield and biometric parameters allow for a broader view of the effectiveness of this fertilization technology in the context of sustainable agriculture. Analysis of data collected during a three-year field experiment reveals both the benefits and the complexity of the mechanisms by which coated fertilizers affect plant growth and development.

4.1. Yield Efficiency

The conducted research confirms the beneficial effect of biodegradable coated fertilizers on the yield of corn intended for silage. The increase in yields by 9–11 t·ha^{−1} in the case of fertilization with coated urea and by approximately 9 t·ha^{−1} in the case of coated NPK fertilizers compared to uncoated fertilizers in the first year of the study is significant and confirms the effectiveness of this technology [1]. The results obtained in the experiment are consistent with the literature data, where fertilizer coated with a polyaspartic acid-based polymer increased corn yield by 21.34% compared to the variant without nitrogen fertilization [2]. Similarly, studies from Brazil showed a 9.2% increase in corn yield (by 354 kg·ha^{−1}) when using controlled-release fertilizer [3].

It is particularly important to note that the effect of coated fertilizers was strongest in the first year of the study ($\eta^2_p = 63.15\%$), which may indicate the varying impact of environmental factors on the effectiveness of this technology [4,5]. The variability in effectiveness in subsequent years may be related to different meteorological conditions, including soil moisture conditions, which affect the dynamics of nutrient release from the coating [6].

4.2. Impact of Meteorological Conditions

An analysis of hydrothermal conditions in individual years of research reveals a significant impact of environmental factors on the effectiveness of coated fertilizers. The third year of research was characterized by the most favorable temperatures during the growing season (21.7 °C in July, 19.5 °C in June), which promoted better utilization of nutrients by plants [7,8]. The values of the Sielininov hydrothermal index (HTC) showed significant variability between years, from very dry conditions (HTC < 0.5) to very wet conditions (HTC > 3.0), which could have affected the effectiveness of biodegradable coatings. Drought conditions, which occurred particularly in May in the third year of the field experiment (14.9 mm of precipitation), may have limited the biodegradation of the coatings and thus affected the release of nutrients [6–9]. On the other hand, excessive rainfall in August of the third year (134.2 mm) may have accelerated the degradation of the coatings, which could have led to uncontrolled release of nitrogen from the fertilizers [10].

4.3. Comparison of Different Types of Fertilizers

The results of the study confirm the superiority of NPK fertilizers over urea in terms of yield, which is consistent with the observations of other authors [11,12]. NPK fertilizers contain not only nitrogen, but also phosphorus and potassium, which are essential for the proper development of corn, especially in critical growth phases [13]. The data obtained in the field experiment may indicate that the presence of nutrients in a complex form in the fertilizer may contribute to their better utilization by plants, which translates into higher yields.

It is worth noting that our own research did not find any differences between the various types of coatings (flax and hemp). Both materials used in the study, based on vegetable oils, showed similar effectiveness in controlling the release of nutrients [14,16]. Literature data confirm the usefulness of natural materials as biodegradable coatings. Similar results were obtained using vegetable oils in the modification of conventional polyurethane coatings [16].

4.4. Biometric Parameters of Plants

The height of corn plants did not show differences depending on the coated fertilizers used, which is partly consistent with the results of other studies [8,17]. The average plant height values (282–287 cm) remained within the range typical for modern

corn varieties [1,7,11]. The lack of differences in plant height may indicate that coated fertilizers have a greater effect on the physiological efficiency of plants than on their vegetative growth.

The number of cobs per plant remained stable (approximately 0.52–0.53) regardless of the fertilizers used, which is characteristic of modern corn varieties with high yield potential [11,18]. The stability of this parameter indicates good adaptation of the variety used in the field trials to the growing conditions and appropriate nutrient dosage.

4.5. Dry Matter Content

The dry matter content of the plants (30–35%) remained within the optimal range for corn intended for silage, confirming that the harvest was carried out at the right time. The stability of this parameter regardless of the fertilizers used indicates that biodegradable coatings [23] do not affect the ripening process of plants.

4.6. Environmental Implications

The use of fertilizers with biodegradable coatings is in line with sustainable agriculture trends, which aim to minimize the negative impact on the natural environment [24,25]. European Union regulations require that by July 2024, all substances used for fertilizer coating must be biodegradable [14,25]. Coated fertilizers can significantly contribute to minimizing the risks posed by agriculture, among other things by reducing greenhouse gas emissions and limiting nitrogen leaching [5,10].

Research conducted in China has shown that controlled-release fertilizers can reduce ammonia emissions by 63.46% and CO₂ emissions by 11.98% compared to conventional fertilization methods [5]. Similar environmental benefits can be expected from the vegetable oil-based coated fertilizers used in our own research.

4.7. Economic Efficiency

Although direct economic analyses were not the subject of this study, a yield increase of 9–11 t·ha^{−1} may be of significant economic importance to agricultural producers. Controlled-release fertilizers, despite their higher initial costs, can be profitable thanks to the increased efficiency of nutrient use, which significantly translates into higher yields [2,26]. According to the “delta yield” concept, the economic profitability of fertilizers depends on the ratio of the fertilizer price to the grain price [26]. In the case of coated fertilizers, higher costs can be offset by increased fertilization efficiency and more stable yields under various weather conditions.

4.8. Mechanisms of Action

The effectiveness of coated fertilizers results from several mechanisms of action. First, the controlled release of nutrients allows for better adaptation of nitrogen supply to the needs of plants in different phases of growth and development [24,27]. Secondly, reducing nitrogen losses due to leaching and volatilization into the atmosphere increases its efficiency of use by plants [25,28]. Biodegradable coatings based on vegetable oils are characterized by gradual degradation in the soil, which allows for the gradual release of nutrients [23,29,30]. The rate of degradation depends on soil conditions, temperature, and humidity, which allows for the natural adjustment of nitrogen release to the biological activity of the soil.

4.9. Limitations and Prospects for Research

Certain limitations of the obtained results should be noted. The effectiveness of coated fertilizers was highest in the first year of the study, which may indicate the need for further optimization of the composition and properties of coatings in different environmental conditions. A significant time effect, confirmed by ANOVA analysis with repeated mea-

surements, suggests that environmental factors in individual years significantly affected the effectiveness of the fertilizers used. This is a limitation of the study, as the variability of weather and soil conditions characteristic of a given location may have influenced the results obtained.

In addition, the field experiment was conducted at a single location, which limits the possibility of generalizing the results to other soil types and climate zones. In future studies, it is advisable to extend the scope of research to different regions and habitat conditions, as well as to include a longer observation period to assess the durability of the effects of coated fertilization. The implications of the results obtained should be discussed in the broadest possible context, especially with regard to sustainable agriculture and the efficient use of nutrients from controlled-release fertilizers.

5. Conclusions

Three years of field research showed that the type of fertilizer (urea, NPK compound fertilizer), the use of biodegradable coatings (based on linseed or hemp oil), and the nitrogen dose (135 and $180 \text{ kg N}\cdot\text{ha}^{-1}$) significantly affect corn yield, especially in the first year of monoculture. The highest yields and plant heights were recorded in the first year of the study, especially when coated fertilizers were used. At that time, the corn yield on plots fertilized with coated fertilizers increased by up to $11 \text{ t}\cdot\text{ha}^{-1}$ compared to fertilization without coatings. In subsequent years of the field experiment, smaller differences in crop yield were found between plots where coated fertilizers were used and those where fertilizers without biodegradable coating were used. In the third year of the study, there was a significant 35% decrease in yield without fertilization compared to the NPK combination. The number of cobs per plant was not dependent on the experimental factors analyzed, which indicates that they mainly affected plant biomass. On average, the highest yield ($98.8 \text{ t}\cdot\text{ha}^{-1}$) was obtained with NPK fertilization with the addition of a coating, while the lowest ($66.9 \text{ t}\cdot\text{ha}^{-1}$) was obtained in the control variant without fertilization. A particularly strong effect of the use of coatings on corn yield was observed in the first year of the study ($\eta^2_p = 63.15\%$). When a higher dose of nitrogen was used, an increase in yield was observed, but this effect depended on the type of fertilizer. This confirms the effectiveness of fertilizers with controlled release of nutrients, which contribute to increasing the efficiency of fertilization and reducing its negative impact on the environment, but mainly in the initial period of application. In the long term, the effectiveness of these solutions decreases, which indicates the need for systematic verification of the fertilization strategy and its adaptation to local soil and climatic conditions. The results of the study are in line with global trends in sustainable agriculture, where effective and modern fertilization methods play a key role in ensuring high and stable corn yields. The use of coated fertilizers, especially in the early years of corn cultivation, significantly increases yields. However, in order to maintain this effect in the long term, flexible fertilization management is necessary, based on ongoing observations and adapted to changing environmental conditions. The progressive decline in the effectiveness of fertilizer coating observed over three growing seasons highlights the critical challenge of sustainable nutrient management. While the $11 \text{ t}\cdot\text{ha}^{-1}$ yield increase in the first year demonstrates the potential of biodegradable coatings to synchronize nitrogen release with crop demand [25,27], the subsequent decrease in effectiveness (to $2.3 \text{ t}\cdot\text{ha}^{-1}$ in the third year) highlights the need for adaptive fertilization strategies. It should be emphasized that polymer-based coatings reduce nitrogen losses by 34.6% in terms of nitrogen leaching and by 42% in terms of nitrous oxide emissions compared to urea without a biodegradable coating [25]. The analysis of the results allows key findings to be drawn, which highlight the innovative nature of the technology used in fertilizers with biodegradable coatings and its significant impact on the effectiveness of

corn fertilization in field conditions. In addition to presenting the results, the study also provides important insights into the practical implications for sustainable agriculture, with particular emphasis on the need for adaptive fertilizer management tailored to changing EU regulations.

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References

1. Erenstein, O.; Jaleta, M.; Sonder, K.; Mottaleb, K.; Prasanna, B.M. Global maize production, consumption and trade: Trends and R&D implications. *Food Secur.* **2022**, *14*, 1295–1319. [CrossRef]
2. Zheng, Y.; van Geen, A.; Stute, M. Human arsenic exposure risk via crop consumption and global trade from groundwater-irrigated areas. *Environ. Sci. Technol.* **2021**, *55*, 14329–14338.
3. Searchy, J.; Smith, R. Extreme weather events, climate expectations, and agricultural export dynamics. *Nat. Clim. Chang.* **2025**, *15*, 45–58.
4. Li, P.; Zhang, G. Mycotoxin risk management in maize gluten meal. *Compr. Rev. Food Sci. Food Saf.* **2023**, *22*, 1892–1910.
5. Kumar, A.; Singh, V. Assessment of genetic diversity in the inbred lines for forage traits in maize. *Crop Sci.* **2024**, *64*, 567–578.
6. Wang, Y.; Doebley, J. Improving architectural traits of maize inflorescences. *Plant Cell* **2021**, *33*, 1203–1215.
7. Qin, X.; Wu, B.; Zeng, H.; Zhang, M.; Tian, F. Global Gridded Crop Production Dataset at 10 km Resolution from 2010 to 2020. *Nat. Sci. Data* **2024**, *11*, 123. Available online: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC11655857/> (accessed on 5 May 2025). [CrossRef]
8. Wahengbam, B.; Gill, R.; Menon, S.; Patel, M. Effects of Varietal Selection and Plant Spacing Patterns on the Growth of Maize (*Zea mays* L.) in Irrigated Agro-Eco-Systems of Punjab. *Asian Res. J. Agric.* **2024**, *17*, 1000–1011. Available online: <https://www.semanticscholar.org/paper/bfb9c187e753a2c5b951cd32d5f60636e89a0499> (accessed on 17 December 2024). [CrossRef]
9. Statista. Corn Production Worldwide from 2012/2013 to 2023/2024, by Country (in Million Metric Tons). Available online: <https://www.statista.com/statistics/254292/global-corn-production-by-country/> (accessed on 5 May 2025).
10. FAO FAOSTAT Statistical Database. Food and Agriculture Organization of the United Nations. 2024. Available online: <https://www.fao.org/faostat/en/#data/QC> (accessed on 5 May 2025).
11. Food and Agriculture Organization of the United Nations (FAO). Cereal Supply and Demand Brief: Global Cereal Production and Utilization. 2023. Available online: <https://www.fao.org/worldfoodsituation/csdb/en/> (accessed on 8 May 2025).
12. United States Department of Agriculture (USDA). World Agricultural Supply and Demand Estimates (WASDE). 2024. Available online: <https://www.usda.gov/oce/commodity/wasde> (accessed on 3 June 2025).
13. Ranum, P.; Peña-Rosas, J.P.; Garcia-Casal, M.N. Global maize production, utilization, and consumption. *Ann. N. Y. Acad. Sci.* **2014**, *1312*, 105–112. [CrossRef] [PubMed]
14. Ritchie, H.; Roser, M.; Corn (Maize) Production. Our World in Data. 2021. Available online: <https://ourworldindata.org/grapher/maize-production> (accessed on 5 May 2025).
15. Surve, V.; Patel, P.; Patel, T.; Jinjala, H. Integrated Nutrient Management for Enhancing Cereal Crop Production: A Review. *Annu. Res. Rev. Biol.* **2024**, *39*, 5–8. [CrossRef]
16. Smetanová, A.; Nunes, J.P.; Symeonakis, E.; Brevik, E.; Schindelwolf, M. Guest Editorial-Special Issue: Mapping and modelling soil erosion to address societal challenges in a changing world. *Land Degrad. Dev.* **2019**, *31*, 2519–2524. [CrossRef]
17. Herrick, J.E.; Sala, O.E.; Karl, J.W. Land degradation and climate change: A sin of omission? *Front. Ecol. Environ.* **2013**, *11*, 267–272. [CrossRef]
18. Chaves, M.M. Drought effects and water use efficiency: Improving crop production in dry environments. *Funct. Plant Biol.* **2010**, *37*, 85–89. [CrossRef]

19. Song, Y.; Ma, L.; Duan, Q.; Xie, H.; Dong, X.; Zhang, H.; Yu, L. Development of Slow-Release Fertilizers with Function of Water Retention Using Eco-Friendly Starch Hydrogels. *Molecules* **2024**, *29*, 4835. [[CrossRef](#)] [[PubMed](#)]
20. PN-R-04033:1998; Gleby i Utwory Mineralne—Podział na Frakcje i Grupy Granulometryczne. Polski Komitet Normalizacyjny: Warszawa, Poland, 1998; ISBN 8323610851/9788323610854.
21. Wu, K.; Wang, L.; Zhang, L.; Han, M.; Gong, P.; Xue, Y.; Song, Y.; Wu, Z.; Zhang, L. The Impact of Applying Different Fertilizers on Greenhouse Gas Emissions and Ammonia Volatilization from Northeast Spring Corn. *Agronomy* **2024**, *14*, 2798. [[CrossRef](#)]
22. Beresiów, P.K.; Strażyński, P.; Mrówczyński, M. (Eds.) *Program Wieloletni 2016–2020 Ochrona Roślin Uprawnych z Uwzględnieniem Bezpieczeństwa Żywności oraz Ograniczenia Strat w Plonach i Zagrożeń dla Zdrowia Ludzi, Zwierząt Domowych i Środowiska*; Ministerstwo Rolnictwa i Rozwoju Wsi: Warszawa, Poland, 2020.
23. Rusek, Ł.; Brodowska, M.S.; Schab, S.; Rusek, P. Technologia produkcji mineralnych nawozów o kontrolowanym uwalnianiu (CRF) z wykorzystaniem materiałów biodegradowalnych w procesie powlekania. *Przemysł Chem.* **2024**, *103*, 2. [[CrossRef](#)]
24. Skowera, B.; Puła, J. Skrajne Warunki Pluwiometryczne w Okresie Wiosennym na Obszarze Polskim w Latach 1971–2000. *Acta Agrophysica* **2004**, *3*, 171–177.
25. Xu, X.; He, P.; Wei, J.; Cui, R.; Sun, J.; Qiu, S.; Zhao, S.; Zhou, W. Use of Controlled-Release Urea to Improve Yield, Nitrogen Utilization, and Economic Return and Reduce Nitrogen Loss in Wheat-Maize Crop Rotations. *Agronomy* **2021**, *11*, 723. [[CrossRef](#)]
26. Firmanda, A.; Fahma, F.; Syamsu, K.; Suryanegara, L.; Wood, K. Controlled/slow-release fertilizer based on cellulose composite and its impact on sustainable agriculture: Review. *Biofuels Bioprod. Bioref.* **2022**, *16*, 1909–1930. [[CrossRef](#)]
27. Rubel, R.I.; Wei, L. Economic Assessment of Biochar-Based Controlled-Release Nitrogen Fertilizer Production at Different Industrial Scales. In *Waste and Biomass Valorization*; Springer: Berlin/Heidelberg, Germany, 2025. [[CrossRef](#)]
28. MK, G.; DA, G. Determining effective waste human hair hydrolyzing parameters combination and its typical physicochemical characteristics in synthesizing liquid nitrogenous organic fertilizer. *Sci. Rep.* **2024**, *14*, 27382. [[CrossRef](#)]
29. Lawrencja, D.; Wong, S.K.; Low, D.Y.S.; Goh, B.H.; Goh, J.K.; Ruktanonchai, U.R.; Soottitantawat, A.; Lee, L.H.; Tang, S.Y. Controlled Release Fertilizers: A Review on Coating Materials and Mechanism of Release. *Plants* **2021**, *10*, 238. [[CrossRef](#)] [[PubMed](#)]
30. Boarino, A.; Carrara, N.; Padoan, E.; Celi, L.; Klok, H.A. Biodegradable Polymers for Plant Nutrient Delivery and Recovery. *Macromol. Biosci.* **2025**, *25*, e2500042. [[CrossRef](#)] [[PubMed](#)]

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