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Innovative Fertiliser Based on Urea and Ammonium Nitrate Solution with Potassium Thiosulphate as a Crucial Factor in Shaping Plant Yield and Its Parameters

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Abstract: In the cultivation of crops in recent times, in addition to taking care of the balanced supply of nutrients to plants and the protection of soil resources, it is also important to take into account the non-productive factor by implementing production systems based on balanced fertilisation. The aim of this study was to demonstrate the effect of soil kind and the application of a new fertiliser based on a urea and ammonium nitrate solution with potassium thiosulphate (UAN-KTS) on the yielding and biometric characteristics of spring wheat, spring rape, and maize to determine the optimal N:K:S ratio. An increase in the soil kind increased the weight of 1000 spring rape seeds, the yield of maize fresh matter, a reduction in the height of spring wheat and maize plants, a reduction in the yield of spring wheat grains and straw, and the yield of the fresh and dry matter of spring rape straw. A higher nitrogen dose promoted the growth of spring rape at the later growing stage and maize and had a positive effect on the yield of spring wheat grains and straw, spring rape seeds and straw, and the above-ground parts of maize. The application of potassium fertilisers caused a significant increase in the spring rape plant height, an increase in the yield of spring wheat grains and straw and spring rape seeds and straw, the above-ground parts of maize, a reduction in the plant height at the beginning of the spring wheat growing period, and a reduction in the weight of 1000 spring rape seeds (only on the soil with rich quality). The fertiliser with the $N{:}K_2{:}S_2$ ratio had a particularly favourable effect on the yielding of spring wheat. In the cultivation of maize, the same effect was most often obtained under the influence of fertiliser in the ratio of $N{:}K_1{:}S_1$ on the weaker soil fertilised at the same time as a higher dose of nitrogen (N 1) and $N{:}K_2{:}S_2$ (in other cases). In the case of spring rape, generally, fertiliser with $N{:}K_1{:}S_1$ was the strongest, although, in some objects, a higher yield was achieved under the influence of $N{:}K_2{:}S_2$. The existence of statistically confirmed correlations (expressed as the percentage of the variability observed) between the soil kind and the fertilisers applied and the yielding and biometric characteristics of the plants were observed.

Keywords: soil kind; UAN-KTS; plants; yield; biometric characteristics

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Citation: Wyszkowski, M.; Brodowska, M.S.; Karsznia, M. Innovative Fertiliser Based on Urea and Ammonium Nitrate Solution with Potassium Thiosulphate as a Crucial Factor in Shaping Plant Yield and Its Parameters. *Agronomy* **2024**, *14*, 802. https://doi.org/10.3390/agronomy14040802

Received: 27 February 2024
Revised: 1 April 2024
Accepted: 10 April 2024
Published: 12 April 2024

1. Introduction

Plant yielding is largely determined by the soil abundance of assimilable nutrients. Under intensive farming, the natural soil abundance in nutrients is insufficient and fails to meet the nutritional needs of crops. Therefore, it is necessary to replenish the nutrients contained in the soil through fertilisation, primarily mineral fertilisation [1], and to protect the soil against the absorption of contaminants [2,3].

The response of crops to mineral fertilisation shows considerable variation depending on the species [4]. Particularly significant changes are observed for nitrogen fertilisation, followed by potassium fertilisation [5,6]. Many factors determine the optimal dose of both nitrogen and potassium, inter alia the species and cultivar, the length of the growing period, the pattern of meteorological conditions, and the soil abundance in nutrients and other soil properties [4,7,8]. Pollution, especially of the air and soil, can have a significant impact [9,10]. As the fertiliser doses increase, the fertilisation efficiency decreases significantly [11]. It is therefore becoming important to determine the dose in such a way as to simultaneously secure the fertiliser needs of plants and to take into account the economic aspect of the use of fertilisers [12]. It is also important (particularly with regard to nitrogen fertilisers) to apply them at the appropriate growing stage in an easily absorbable form so that the plants can quickly take them up and use them [12,13]. A high yield of crops can then be expected. Such fertilisers include a urea–ammonium nitrate (UAN) solution [14,15]. The urea–ammonium nitrate solution contains a rapid-acting nitrate form, a slower-acting ammonium form, and a slowly (or even very slowly) acting amide form of nitrogen [13].

For these reasons, it is characterised by both rapid and long-lasting action, thus providing a constant supply of nitrogen during the plant growing season. The presence of three nitrogen forms safeguards plants against nitrogen content fluctuations in the soil environment [16]. An advantage of UAN is its liquid form, which makes the fertilisation and nitrogen availability to plants independent of the soil moisture content and precipitation, which is of particular importance during periods of drought [17,18]. The fertiliser migration into the root zone of plants increases the efficiency of nitrogen uptake by plants [19]. It is therefore recommended that the full UAN dose should be adapted to the cultivation of individual plant species to ensure the adequate availability of nutrients at critical growing stages [13]. Potassium or phosphorus fertilisers are usually applied pre-sowing. It is therefore important that they are taken up by plants throughout the growing period, particularly during the so-called critical phases.

Optimal potassium fertilisation has a positive effect on crop yield and increases the food and technological value of the crop. One of the most important quality characteristics that depend on the potassium nutrition of the plant is the protein, starch, and fat content. Potassium fertilisation determines the resistance of plants to many abiotic and biotic stresses [20]. Adequate potassium fertilisation improves plants' resistance to periodic water shortages, which have often been the limiting factor in recent yields. It enables plants to survive periods of drought by preventing wilting or withering, which is linked to the element's effect on water control. Potassium facilitates water uptake by influencing better plant rooting. It also promotes a more efficient use of water, for example, by regulating transpiration [21,22]. Balanced potassium fertilisation increases plant resistance to low temperatures and frost through its effect on nitrogen and carbohydrate metabolism. This is because it increases the sugar content of the tissues and also increases the osmotic pressure of the cell sap. This helps to lower the freezing point of the sap [23].

Optimal sulphur fertilisation significantly influences the uptake and utilisation of nitrogen from mineral fertilisers and its incorporation into proteins, reducing the accumulation of non-protein forms of nitrogen in the plant. An important function of sulphur in plants is the formation of disulphide groups, which are found in both proteins and other compounds with important functions in metabolism, such as coenzyme A and ferredoxin. Coenzyme A controls oxidoreductive processes, and photosynthesis acts as a specific carrier and is involved in fatty acid synthesis and fat metabolism [24]. Sulphur fertilisation influences the efficiency of photosynthesis and induces the plant's resistance system against fungal diseases. This is because sulphur is essential for the synthesis of lignins, and its deficiency weakens the mechanical tissues of plants. This is particularly dangerous with excess nitrogen, as the proportion of low-molecular-weight nitrogen compounds—amino acids and amides—increases in the leaf cells, leading to an increase in plant infection by pathogens, for which they are an ideal food source [25,26].

In the cultivation of crops in recent times, in addition to taking care of the balanced supply of nutrients to plants and the protection of soil resources, it is also important to take into account the non-productive factor by implementing production systems based on balanced fertilisation while minimizing the negative impact of fertilisation on the environment [27].

Fertiliser manufacturers are striving to put into production new fertilisers whose components can be increasingly efficiently used by plants. For this reason, an innovative study was conducted into increasing the efficiency of fertilisation with nitrogen in the form of a urea and ammonium nitrate solution with potassium thiosulphate (UAN-KTS) as a source of nitrogen, potassium, and sulphur for the test plant species. The aim of this study was to demonstrate the relationships between the nitrogen supply to different plant species (spring wheat, spring rape, and maize) and their yielding and biometric characteristics and to determine the optimal N:K:S ratio as a factor determining the effect of nitrogen in order to obtain high yields of the test plant species. This study was conducted on two soils differing in potassium content and other properties.

2. Materials and Methods

2.1. Methodological Assumptions

The three-pot experiments with three plant species were conducted in a greenhouse at the University of Warmia in Mazury in Olsztyn (North-Eastern Poland) on two soils of different quality. The soil properties are provided in Table 1.

Table 1. Some properties of soils.

Parameter	Soil 1	Soil 2
Granulometric composition	Sand	Loamy sand
Sand > 0.05 mm (%)	91.9	77.6
Silt 0.002–0.05 mm (%)	7.4	19.9
Clay < 0.002 mm (%)	0.7	2.5
pH value in 1 M KCl dm^{-3}	6.17	5.73
Total nitrogen (g kg^{-1} DM)	0.672	1.120
Available phosphorus (mg P kg^{-1} DM)	14.83	22.16
Available potassium (mg K kg^{-1} DM)	102.0	145.0
Sulphur (mg S-SO_4 kg^{-1} DM)	18.97	15.92

DM—dry matter.

The test crops included spring wheat (*Triticum aestivum* L.) of the Harenda cultivar, spring rape (*Brassica napus* L. var. *napus*) of the Lumen cultivar, and maize (*Zea mays* L.) of the Kadryl cultivar. The experiment involved the following variable factors for each of the test crops: soil kind (2 levels: Soil 1—less abundant in potassium and Soil 2—more abundant in potassium), the urea and ammonium nitrate solution with potassium thiosulphate (UAN-KTS) new fertiliser dose (2 levels: N 1—a higher nitrogen dose, optimal for a particular plant species, and N 2—a nitrogen dose lower by 25%), the N:K:S ratio (4 levels: N—with no potassium and sulphur fertilisation, N:K_1:S_1—a restricted ratio, N:K_2:S_2—an optimal ratio, N:K_3:S_3—an extended ratio). The doses of fertilisers applied in the pot experiment are presented in Table 2.

Nitrogen, potassium, and sulphur were applied to 9 kg of soil in the form of a new fertiliser UAN-KTS. A new liquid fertiliser made from UAN (total N—32%, including N-NH_4—8%, N-NO_3—8%, and N-NH_2—16%) and KTS (K_2O—25%, total sulphur—17%) was used for this experiment. The used UAN is a commercial fertiliser produced and sold on a large scale by Grupa Azoty Zakłady Azotowe "Puławy" S.A. company (Poland), and KTS came from the flue gas desulphurisation from the sulphuric acid installation. The innovation of the fertiliser used is not only its composition (nitrogen and potassium thiosulphate with strong antiseptic properties) but also its innovative production technology based on a closed cycle using a by-product of flue gas desulphurisation. UAN-KTS was produced in small quantities required for the model (vegetation) experiment. The mixture of UAN and KTS was used in a pot experiment (model) with different N:K:S ratios adapted to the nutrient requirements of the test plants. Each of the fertiliser objects uses the appropriate proportions of UAN-KTS to apply fertiliser doses according to the experimental scheme shown in Table 2. After determining the optimal proportions in the UAN-KTS fertiliser for individual crops and additional trials, it is planned to use UAN-KTS for full-scale production.

Table 2. Fertilisers doses (mg kg^{-1} of soil).

N:K:S	N:K:S Ratio	Series with N 1 Dose				Series with N 2 Dose			
		N	P_2O_5	K_2O	S	N	P_2O_5	K_2O	S
Spring wheat (*Triticum aestivum* L.)									
N	1:0:0	140	60	0	0	105	60	0	0
$N:K_1:S_1$	1:0.5:0.3	140	60	70	42	105	60	53	31.5
$N:K_2:S_2$	1:0.7:0.5	140	60	98	70	105	60	74	52.5
$N:K_3:S_3$	1:0.9:0.6	140	60	126	84	105	60	95	63
Spring rape (*Brassica napus* L. var. *napus*)									
N	1:0:0	160	80	0	0	120	80	0	0
$N:K_1:S_1$	1:0.5:0.3	160	80	80	54	120	80	60	36
$N:K_2:S_2$	1:0.7:0.5	160	80	112	80	120	80	84	60
$N:K_3:S_3$	1:0.9:0.6	160	80	144	108	120	80	108	72
Maize (*Zea mays* L.)									
N:K:S	1:0:0	160	80	0	0	120	80	0	0
$N:K_1:S_1$	1:0.8:0.5	160	80	128	80	120	80	96	60
$N:K_2:S_2$	1:1.1:0.7	160	80	176	112	120	80	132	84
$N:K_3:S_3$	1:1.4:1	160	80	224	160	120	80	168	120

SuperFosDar 40 (P_2O_5—41.2%, CaO—13.1%), on the other hand, is a commercial phosphorus fertiliser applied separately as a phosphorus source in our experiment. In addition, a micronutrient containing Zn–$ZnSO_4 \cdot 7H_2O$; Cu–$CuSO_4 \cdot 5H_2O$; B–H_3BO_3; Mo–$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$; and Mn–$MnSO_4 \cdot H_2O$ was applied. Mineral fertilisation was applied before the plant sowing and during the growing period. The first and second doses of the UAN-KTS were diluted with distilled water prior to being added to the soil. The new fertiliser-based UAN-KTS was applied at the following times: spring wheat—60% pre-sowing and 40% at the tillering stage (BBCH 23); spring rape—50% pre-sowing and 50% before the rosette stage (BBCH 15); maize—50% pre-sowing and 50% at the 4–6 unfolded leaf stage (BBCH 15). The weighed amounts of phosphorus fertilisers and the liquid micronutrient nutrient were applied pre-sowing directly into the soil.

The innovation of the potassium tiosulphate used in the research is primarily a process innovation. An important advantage of producing fertilisers in liquid form is the environmental aspect, namely the reduction of the negative environmental impact of tower concentration and granulation, which is the final stage in the production of granulated fertilisers. In addition, the production of liquid fertilisers allows the treatment of wastewater, solutions, and exhaust gases from industrial production, including fertilisers and concentrates from wastewater treatment plants, which is very important in meeting the requirements of various environmental programmes, e.g., the European Green Deal. Potassium tiosulphate solution, which is used in the production of multi-component liquid fertilisers for pots, has been obtained as a result of an innovative technology using waste gases containing small amounts of sulphur oxides from the sulphuric acid plant. In the first stage, potassium sulphate (IV) technology was developed as a result of the absorption of sulphur dioxide from sulphuric acid production. As a result of the technology used, the emission of sulphur dioxide and nitrogen oxides to the atmosphere was reduced by approximately 90%, which has a measurable effect on the emission of greenhouse gases to the atmosphere, improves air quality, and is part of the principles of the closed cycle economy. In the second stage, potassium tiosulphate was produced from the potassium sulphate (IV) and sulphur from the Claus process. The innovative technology used in this stage makes it possible to obtain a product of very high purity and, above all, high stability to UV radiation. A 50% potassium thiosulphate solution produced at this stage can be used as an independent liquid potassium sulphur fertiliser, as well as a raw material for the production of multi-component liquid fertilisers.

The Harenda spring wheat variety is a medium-early variety that is also suitable for late autumn drilling. It has a high yield potential, and its yield exceeds that of the reference varieties. It is suitable for acid soils with low soil requirements. It is a medium-sized plant with very good lodging resistance. Harenda's grains are characterised by a high 1000 kernel weight, correct orientation, and high bulk density. It also shows very good resistance to fungal diseases, especially powdery mildew, brown rust, stem base diseases, *Fusarium* ear blight, and husk and leaf septoria [28].

Spring rape of the Lumen variety is characterised by early sowing, depending on weather conditions, and a high initial development rate, high yield, very high oil content and yield. The plants are of medium height and have a high resistance to lodging. The variety is characterised by its high tolerance to diseases (sclerotia rot, crucifer black), medium flowering and ripening [29].

The Kadryl maize variety (FAO 270–280) is characterised by its high adaptability, which means that it produces stable yields under different environmental conditions. This maize is mainly grown for highly digestible silage and as a feedstock for biogas plants. It can also be grown for grain. Kadryl has medium soil requirements and good early vigour. It is a very tall plant (295 cm) with strong foliage and produces very high yields. It is characterised by high quality and resistance to nodular head, root lodging, and leaf spot. Kadryl maize is also highly adaptable and guarantees yield stability in different environments. It also grows well on poorer soils and tolerates periodic water shortages [30].

On April 12, the sowing was carried out according to the principles of particular agricultural crop species cultivation. The number of plants in the pots was determined by the crop species and amounted to spring wheat—15 plants, spring rape—8 plants, and maize—8 plants. The emerging diseases and pests were controlled during the growing period using classic plant protection products according to the recommendations of the Institute of Plant Protection—National Research Institute in Poznań (Central Poland): spring wheat—twice with Topsin M (active substance: thiophanate-methyl) against powdery mildew; spring rape—with Mospilan (active substance: acetamiprid) against aphids and with Topsin M against powdery mildew; maize—with Mospilan against aphids. During the plant growing period, the soil moisture content in the pots (60% of maximum water capacity), adjusted to the plant requirements, was maintained at a constant level. The plants were watered to a constant weight with distilled water. The experiment was carried out in three replications. The climatic conditions during the experiments were within the following ranges (monthly averages): air humidity—67% (April), 64% (May), 63% (June), 75% (July), insolation—260.9 h (April), 368.5 h (May), 292.3 h (June), 255.3 h (July) and air temperature—11.6 °C (April), 16.5 °C (May), 17.8 °C (June), 20.3 °C (July). Figure 1 shows spring wheat, rape, and maize during the growing season. Spring wheat was harvested at the full maturity stage (BBCH 89—July 20), spring rape at the processing maturity stage (BBCH 85—July 18), and maize at the tasseling stage (BBCH 59—June 21).

2.2. Laboratory and Statistical Analysis Methods

Before setting up the pot experiment, the following basic parameters were determined in order to characterise the soils: the granulometric composition—by the laser method [31], the pH value in 1 mol KCl—by the potentiometric method [32], total N—by a modified Kjeldahl method [33], the contents of available phosphorus [34] and potassium [35] by the Egner–Riehm method, and sulphur—by the nephelometric method according to the Bardsley and Lancaster's formula [36]. Immediately after the crop harvest, the pot experiment determined the following: the yield of grains and straw, the weight of 1000 grains (spring wheat), the yield of seeds and straw, the weight of 1000 seeds (spring rape), and the weight of the above-ground parts of maize. The plant dry matter yield was determined by the gravimetric method with oven-drying. During the plant growing period, their height was determined by measuring each plant at the following growing stages: spring wheat—three-leaf unfolded (BBCH 13), stem elongation (BBCH 30), flowering (BBCH 61), and full maturity (BBCH 89) stages, spring rape—three-leaf unfolded (BBCH 13), formation of side shoots (BBCH 23), flowering (BBCH 65), and processing maturity (BBCH 85) stages, maize—three-leaf unfolded (BBCH 13), at the beginning of stem development (BBCH 30), the stem development (third–fourth node) (BBCH 34), and the tassel emergence (BBCH 59) stages. The results obtained from the pot experiment were statistically verified using the ANOVA module (for factorial designs), Tukey's HSD (honestly significant difference) test and the principal component analysis (PCA) module, and by calculating the percentage of the variability observed using the η2 coefficient. Statistical computations were performed using the STATISTICA program [37].

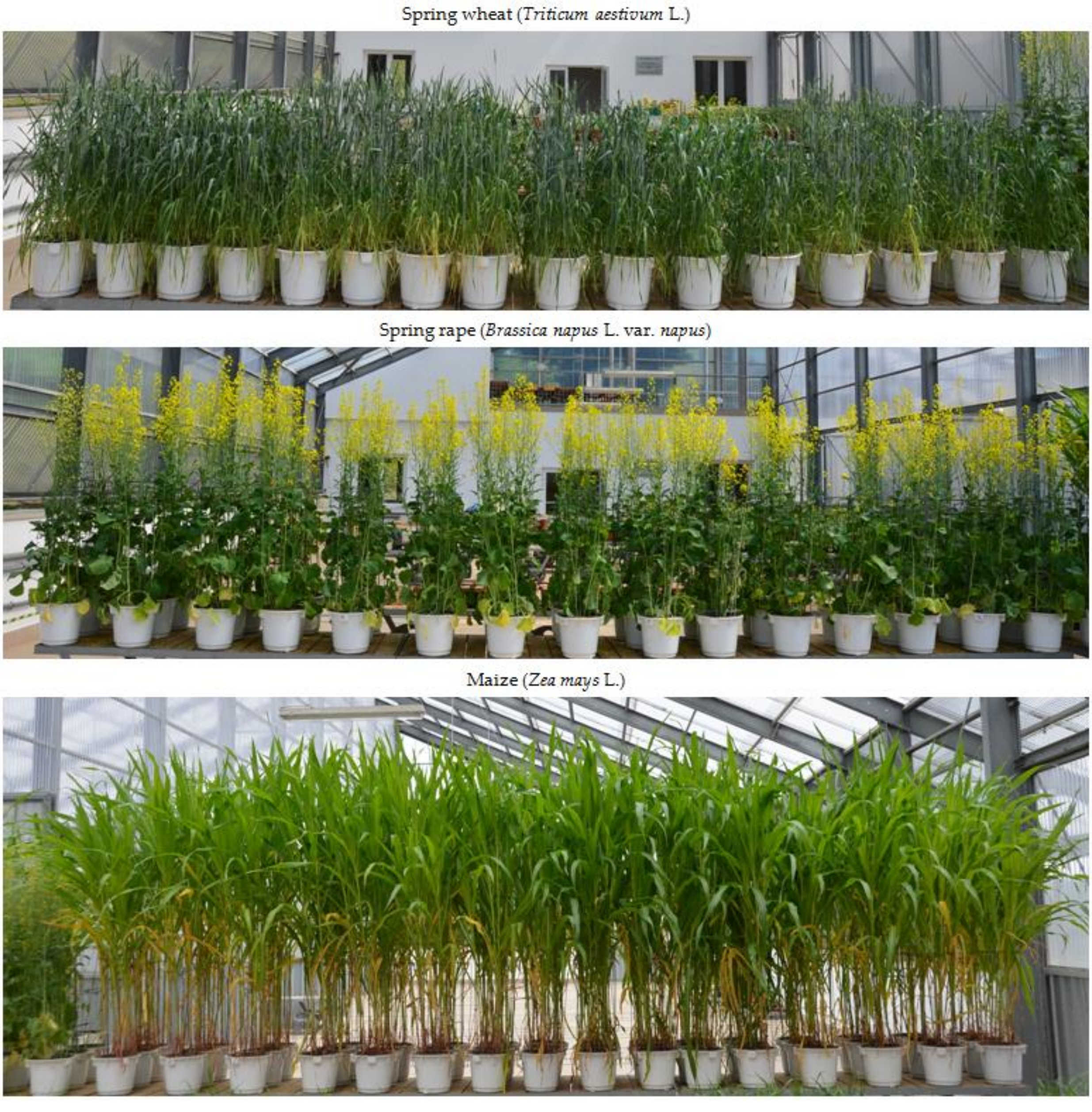

Figure 1. Spring wheat (*Triticum aestivum* L.), spring rape (*Brassica napus* L. var. *napus*), and maize (*Zea mays* L.) during the growing season.

3. Results

3.1. Plant Height

The height of plants during the growing season was determined by the soil kind, the nitrogen dose, and the N:K:S ratio in the fertilisers.

3.1.1. Spring Wheat

The soil kind had a significant effect on the spring wheat plant height at all growing stages (Figure 2). An increase in the soil kind had no positive effect on wheat plant height (it was lower by 18%, 19%, 10%, and 5%, respectively, than on the poorer soil). Therefore, the impact of this factor decreased markedly as the growing season progressed.

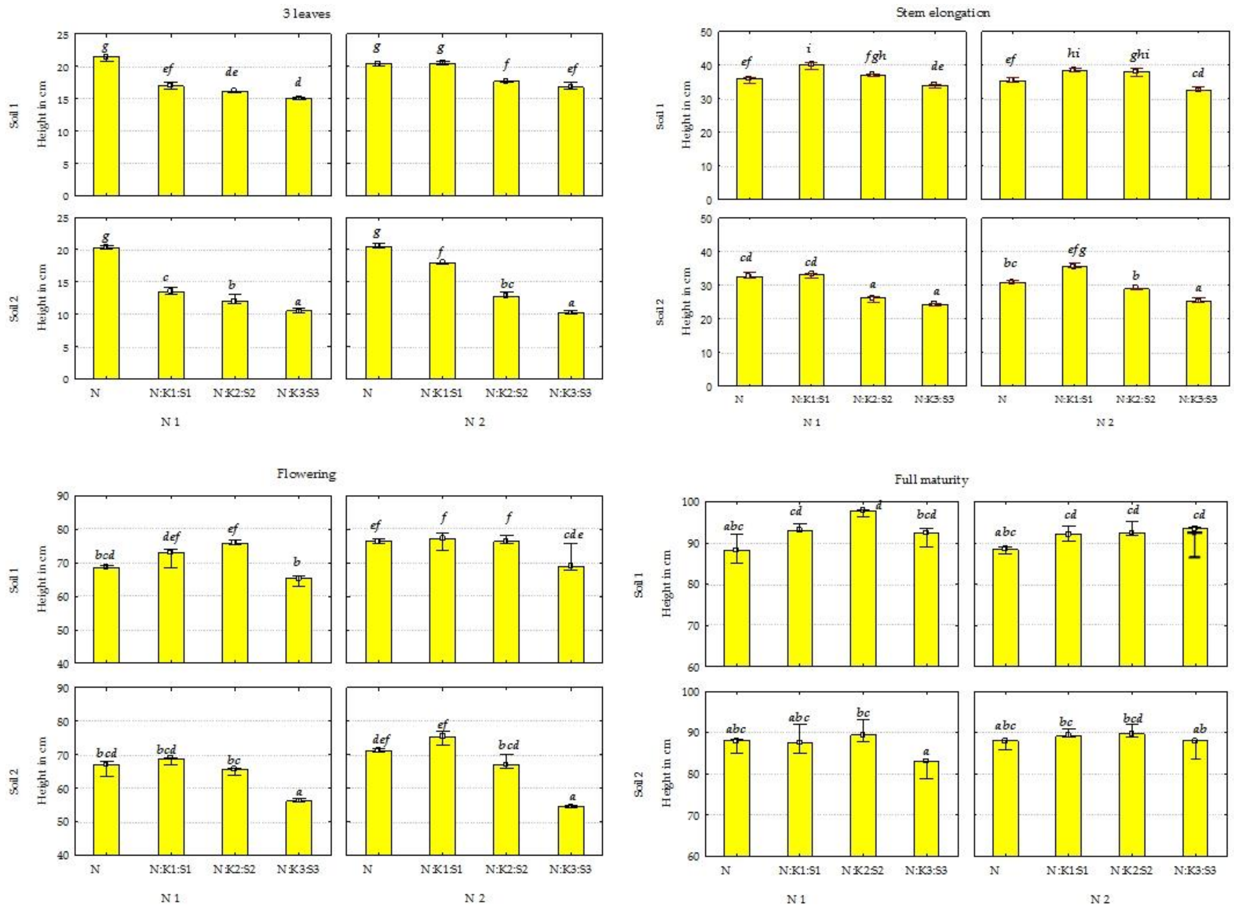

Figure 2. Effect of fertilisation and soil kind on spring wheat (*Triticum aestivum* L.) height in phases: 3 leaves and stem elongation, flowering, and full maturity in cm (averages and standard deviations on the vertical bars). Different letters (homogeneous groups from Tukey's HSD test) above the bars indicate significant differences between the research objects at $p \leq 0.01$; $n = 720$.

The nitrogen dose had a significantly weaker effect on the spring wheat plant height compared to the effect of soil kind. Its significant influence on the shaping of the tested parameter values was only noted at the three-leaf unfolded stage and the flowering stage. A decrease in the nitrogen dose had a positive effect by increasing the spring wheat plant height by an average of 9% on both soils at the three-leaf unfolded stage and by an average of 5% on the richer soil as well as by an average of 7% on the poorer soil at the flowering stage.

The impact of potassium fertilisation on plant height was significant at all spring wheat growing stages. The potassium and sulphur fertilisation limited the spring wheat plant height at the three-leaf unfolded stage more pronounced on the richer soil. On the other hand, at the stem elongation stage, a positive effect of the fertiliser with the NK_1:S_1 ratio on the spring wheat plant height was observed (except for the treatment fertilised with the higher nitrogen dose in the richer soil). A significant increase in the plant height (by 10–11%) was also noted for the treatment with the fertiliser with the N:K_2:S_2 ratio in a series with the higher nitrogen dose in the poorer soil.

3.1.2. Spring Rape

An increase in the soil kind had a significant effect on the spring rape plant height at most growing stages, with the strongest effect at the three-leaf unfolded stage (Figure 3). The processing maturity stage was an exception.

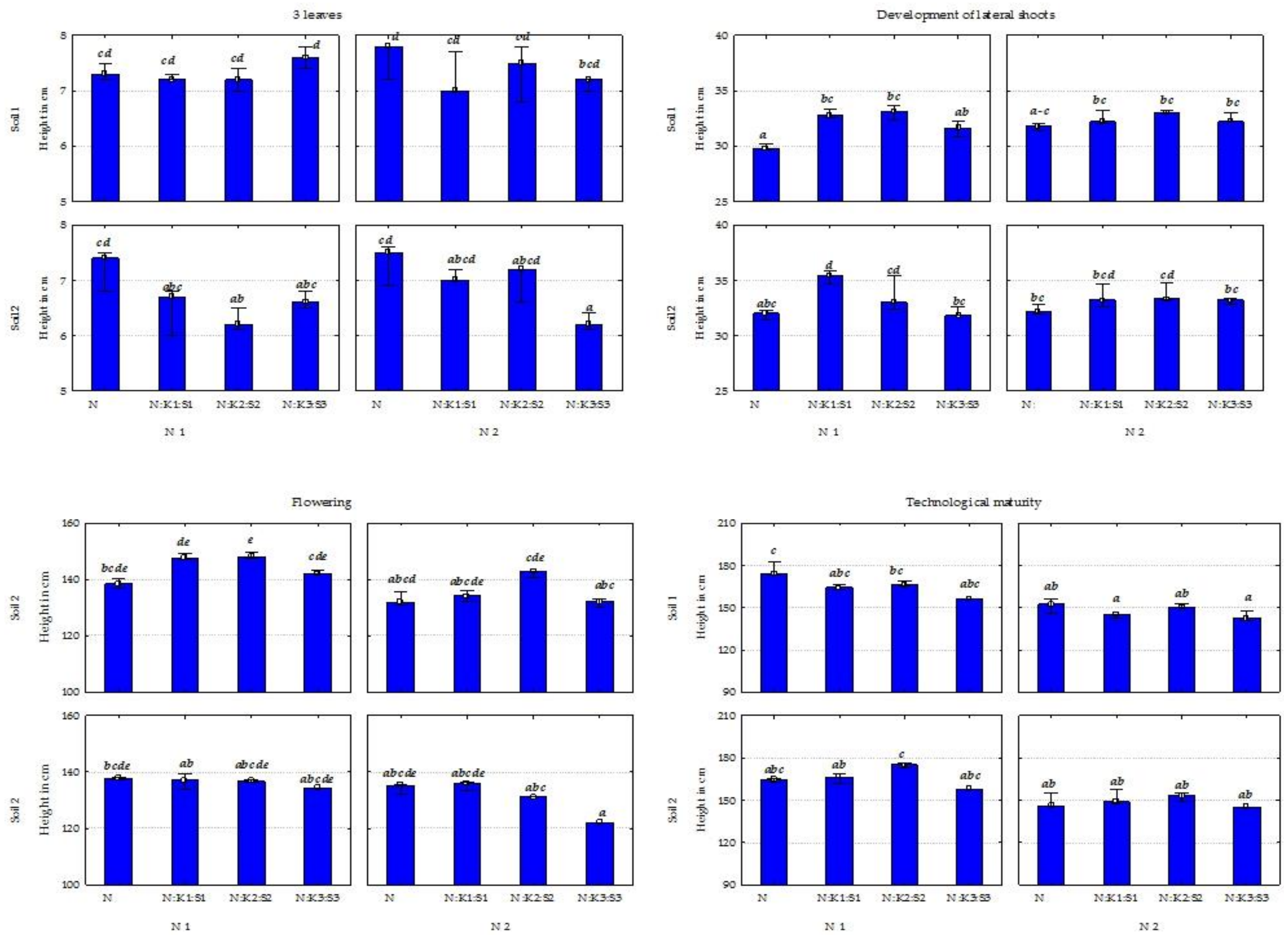

Figure 3. Effect of fertilisation and soil kind on spring rape (*Brassica napus* L. var. *napus*) height in phases: 3 leaves, development of lateral shoots, flowering, and technological maturity in cm (averages and standard deviations on the vertical bars). Different letters (homogeneous groups from Tukey's HSD test) above the bars indicate significant differences between the research objects at $p \leq 0.01$; $n = 384$.

In the stages, in the three-leaf unfolded stage and flowering stage, there was a decrease, and at the formation of the side shoots stage, there was an increase in the heights of the plants.

The nitrogen dose had no significant impact on the height of spring rape at the three-leaf unfolded or the formation of side shoot stages. A lower nitrogen dose inhibited the spring rape growth at the subsequent growing stages, thus reducing the plant height by 5–6% at the flowering stage and by 10–11% at the technological stage. No significant differences were noted for the spring rape plant height under the influence of a nitrogen dose between the test soils.

The impact of potassium fertilisation on spring rape plant height was greater at the two initial growing stages than at the final stages and was, in general, favourable while being insignificant at the flowering stage. It was rather negative at the three-leaf unfolded stage, especially in the second soil, in which it accounted for a maximum of 13–15%. The fertiliser with the N:K_1:S_1 ratio had the most positive effect on spring rape growth at the formation of the side shoots stage in the series with a higher nitrogen dose in both soils. At the processing maturity stage, the effect of potassium fertilisation was less clear and the greatest on the treatments with a higher nitrogen dose in both soils.

3.1.3. Maize

The height of maize plants during the growing period was significantly determined by the experimental factors (Figure 4).

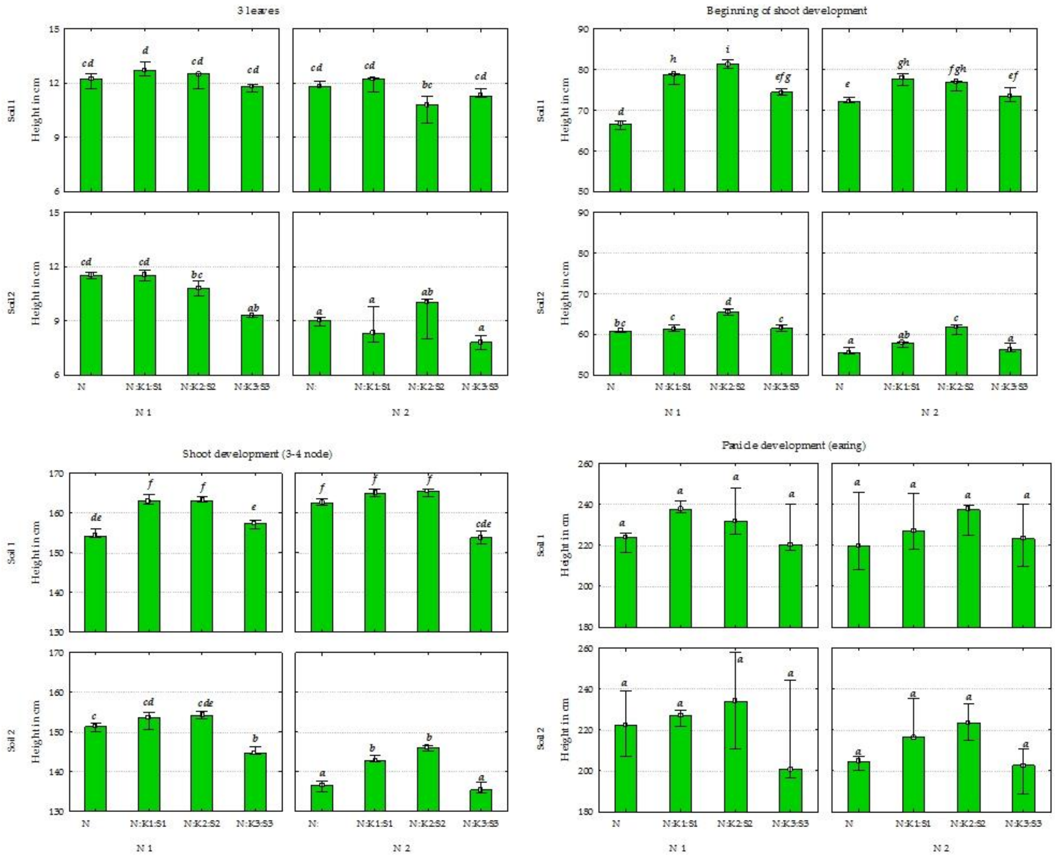

Figure 4. Effect of fertilisation and soil kind on maize (*Zea mays* L.) height in phases: 3 leaves, at beginning of shoot development, shoot development (3–4 node), and panicle development (earing) in cm (averages and standard deviations on the vertical bars). Different letters (homogeneous groups from Tukey's HSD test) above the bars indicate significant differences between the research objects at $p \leq 0.01$; $n = 384$.

The soil kind had a significant effect on the spring wheat plant height at all growing stages except for the tasseling stage. At the beginning of the maize growing period, at the three-leaf unfolded stage, and at the beginning of stem development, the heights of the plants in the poorer soil were, on average, 11.8 and 75.0 cm, while in the soil more abundant in this nutrient, it was lower by 18% and 20%, respectively. At the later growing stages, in the first of the soils under comparison, maize reached a height of 160.6 cm at the third–fourth node and 229.3 cm at the crop harvest at the tassel development stage. In the second soil, its height was lower by 9% and 5%, respectively.

The nitrogen dose had a weaker effect on the maize plant height than the soil kind. A lower nitrogen dose had a negative effect on the plant height, but at the beginning of the growing stage, the difference was 12%, as compared to a higher nitrogen dose. The impact of nitrogen was greater on the soil with higher quality. It should also be mentioned that after performing the statistical calculations, at the moment of crop harvesting, the effect of nitrogen on the maize plant height proved to be insignificant.

The effect of potassium fertilisation at the maize plant height was, in general, favourable, with its greatest impact noted on the poorer soil in synergy with a higher nitrogen dose and the soil with higher quality in synergy with a lower nitrogen dose. At the three-leaf unfolded, third–fourth node, and the tasseling stages, the plants were the highest in the poorer soil after the application of the fertiliser with the $N:K_1:S_1$ ratio and a higher nitrogen dose and at all growing stages in the soil with higher quality fertilised with the potassium fertiliser with the $N:K_2:S_2$ ratio and a lower nitrogen dose. The changes in the plant height were, however, relatively small, as they usually did not exceed 10%. The exception was the beginning of stem development where the $N:K_2:S_2$ ratio resulted in a 22% increase in the height for the poorer soil and fertilised with a higher nitrogen dose.

3.2. Crop Yield

3.2.1. Spring Wheat Yield

An increase in the soil kind had no positive effect on the yield of the fresh and dry matter of spring wheat grains (Table 3). Similar dependencies were shown in the case of the fresh and dry mass of wheat straw. In the soil with higher quality, the yield of the fresh and dry matter of the spring wheat straw was lower by up to 26–27% than in the poorer soil. A decrease in the nitrogen dose had a negative effect on the yield of spring wheat grains and straw. The impact of nitrogen was stronger on the poorer soil. A lower nitrogen dose resulted in a reduction in the yield of the fresh and dry matter of spring wheat grains by 19% and 16%, respectively, of straw by 24% and 19% on the poorer soil, while of grains by 9% and 11%, and of straw by 10% and 11% on the soil with higher quality as compared to a higher dose of this fertiliser.

Table 3. Effect of fertilisation and soil kind on spring wheat (*Triticum aestivum* L.) yield (g pot^{-1}).

N:K:S (C)	**Soil Kind (A)**						**Nitrogen Dose (B)**		
	Soil 1			**Soil 2**					
	Nitrogen Dose (B)								
	N 1	**N 2**	**Average**	**N 1**	**N 2**	**Average**	**N 1**	**N 2**	**Average**
Spring wheat grain fresh matter (FM) yield									
N	43.33	39.30	41.32	38.35	36.54	37.45	40.84	37.92	39.38
$N:K_1:S_1$	51.03	41.43	46.23	43.82	40.71	42.27	47.43	41.07	44.25
$N:K_2:S_2$	54.64	44.81	49.73	47.46	44.56	46.01	51.05	44.69	47.87
$N:K_3:S_3$	55.54	39.85	47.70	42.79	34.75	38.77	49.17	37.30	43.23
Average	51.14	41.35	46.24	43.11	39.14	41.12	47.12	40.24	43.68
$LSD_{0.01}$	A—3.44, B—3.44, C—4.87, A × B—n.s., A × C—n.s., B × C—n.s., A × B × C—n.s.								
Spring wheat grain dry matter (DM)yield									
N	39.56	35.85	37.71	35.02	33.36	34.19	37.29	34.61	35.95
$N:K_1:S_1$	45.80	37.74	41.77	40.32	37.14	38.73	43.06	37.44	40.25
$N:K_2:S_2$	46.52	40.74	43.63	43.41	40.34	41.88	44.97	40.54	42.75
$N:K_3:S_3$	46.84	36.10	41.47	39.09	30.12	34.61	42.97	33.11	38.04
Average	44.68	37.61	41.14	39.46	35.24	37.35	42.07	36.42	39.25
$LSD_{0.01}$	A—2.98, B—2.98, C—4.21, A × B—n.s., A × C—n.s., B × C—n.s., A × B × C—n.s.								
Spring wheat straw fresh matter (FM) yield									

Table 3. *Cont.*

N:K:S (C)	Soil Kind (A)						Nitrogen Dose (B)		
	Soil 1			Soil 2					
	Nitrogen Dose (B)								
	N 1	**N 2**	**Average**	**N 1**	**N 2**	**Average**	**N 1**	**N 2**	**Average**
N	74.83	55.25	65.04	52.36	45.61	48.99	63.60	50.43	57.01
$N:K_1:S_1$	79.94	66.31	73.13	56.55	51.06	53.81	68.25	58.69	63.47
$N:K_2:S_2$	88.85	66.44	77.65	60.72	53.45	57.09	74.79	59.95	67.37
$N:K_3:S_3$	81.74	59.21	70.48	50.61	49.22	49.92	66.18	54.22	60.20
Average	81.34	61.80	71.57	55.06	49.84	52.45	68.20	55.82	62.01
$LSD_{0.01}$	A—2.15, B—2.15, C—3.04, A × B—3.04, A × C—n.s., B × C—n.s., A × B × C—n.s.								
	Spring wheat straw dry matter (DM) yield								
N	58.53	45.45	51.99	42.15	36.66	39.41	50.34	41.06	45.70
$N:K_1:S_1$	60.38	54.15	57.27	46.26	40.77	43.52	53.32	47.46	50.39
$N:K_2:S_2$	66.49	53.20	59.85	48.63	42.23	45.43	57.56	47.72	52.64
$N:K_3:S_3$	60.55	47.32	53.94	39.03	36.47	37.75	49.79	41.90	45.84
Average	61.49	50.03	55.76	44.02	39.03	41.53	52.75	44.53	48.64
$LSD_{0.01}$	A—1.95, B—1.95, C—2.76, A × B—2.76, A × C—n.s., B × C—n.s., A × B × C—n.s.								

n.s.—non-significant.

The effect of the fertiliser with the $N:K_2:S_2$ ratio on the yield of the fresh and dry matter of spring wheat grains and straw was the most significant in the series with a lower nitrogen dose in both soils and on treatments with a higher nitrogen dose in the soil with a higher quality. As a result of this fertiliser's effect, it amounted to 14%, 22%, and 24%, respectively, for the yield of the fresh and dry matter of grains and to 20%, 17%, and 17% for wheat spring straw. However, in the series with a higher nitrogen dose in the poorer soil, the best effects were achieved under the influence of the fertiliser with the $N:K_3:S_3$ ratio, which resulted in a 28% increase in the yield of the fresh (and an 18% increase in the yield of dry) matter of spring wheat grains as compared to the control treatments. In the soil with higher quality, the effect of the fertiliser with the $N:K_2:S_2$ ratio on the yield of the dry matter of spring wheat straw was similar in both series with the nitrogen and was at a level of 15%.

3.2.2. Spring Rape Yield

The effect of soil kind on the yield of the fresh and dry matter of spring rape seeds was small and insignificant (Table 4). In the soil with higher quality, a slightly lower yield of the fresh and dry matter of spring rape straw was obtained. A decrease in the nitrogen dose had no positive effect on the yield of spring rape seeds and straw, particularly in the soil with less quality. A higher nitrogen dose resulted in an increase in the yield of fresh matter of spring rape seeds by 29%, of straw by 23% in the poorer soil (and by 16% and 9%, respectively, in the soil with higher quality) in potassium, in the yield of the dry matter of seeds by 19% and 14%, respectively, and of straw by 25% and 20%, respectively, as compared to a lower dose of this fertiliser.

The effect of fertilisers with different N:K:S ratios on the yield of the fresh and dry matter of spring rape seeds on both soils was greater in the series with a higher nitrogen dose rather than a lower dose. After the application of the fertiliser with the $N:K_2:S_2$ ratio into the soil, the highest yield of the dry matter of wheat rape seeds in both soils and the yield of the fresh matter of spring rape seeds was higher in the soil with a higher quality (it was higher by 90%, 33%, and 27%, respectively, than the control treatments). The fertiliser with the $N:K_3:S_3$ ratio had a similar effect on the yield of the fresh matter of spring rape seeds on the poorer soil and resulted in a 90% increase in the yield of the fresh matter of this crop's seeds.

Table 4. Effect of fertilisation and soil kind on spring rape (*Brassica napus* L. var. *napus*) yield (g pot^{-1}).

N:K:S (C)	Soil Kind (A)						Nitrogen Dose (B)		
	Soil 1			Soil 2					
	Nitrogen Dose (B)								
	N 1	N 2	Average	N 1	N 2	Average	N 1	N 2	Average
Spring rape seed fresh matter yield									
N	25.65	30.44	28.05	33.11	32.80	32.96	29.38	31.62	30.50
$N:K_1:S_1$	45.04	34.29	39.67	40.37	33.08	36.73	42.71	33.69	38.20
$N:K_2:S_2$	45.08	30.38	37.73	41.89	33.97	37.93	43.49	32.18	37.83
$N:K_3:S_3$	48.64	32.13	40.39	38.94	33.69	36.32	43.79	32.91	38.35
Average	41.10	31.81	36.46	38.58	33.39	35.98	39.84	32.60	36.22
$LSD_{0.01}$	A—n.s., B—4.15, C—5.87, A × B—n.s., A × C—n.s., B × C—n.s., A × B × C—n.s.								
Spring rape seed dry matter yield									
N	15.72	18.83	17.28	20.56	21.44	21.00	18.14	20.14	19.14
$N:K_1:S_1$	28.75	23.65	26.20	24.84	22.31	23.58	26.80	22.98	24.89
$N:K_2:S_2$	29.79	23.84	26.82	27.27	21.35	24.31	28.53	22.60	25.56
$N:K_3:S_3$	29.43	20.85	25.14	25.61	21.04	23.33	27.52	20.95	24.23
Average	25.92	21.79	23.86	24.57	21.54	23.05	25.25	21.66	23.46
$LSD_{0.01}$	A—n.s., B—2.41, C—3.41, A × B—n.s., A × C—n.s., B × C—4.83, A × B × C—n.s.								
Spring rape straw fresh matter yield									
N	267.00	217.07	242.04	226.90	221.45	224.18	246.95	219.26	233.11
$N:K_1:S_1$	272.84	220.52	246.68	232.07	226.90	229.49	252.46	223.71	238.08
$N:K_2:S_2$	273.27	231.63	252.45	253.24	218.85	236.05	263.26	225.24	244.25
$N:K_3:S_3$	270.96	214.55	242.76	251.41	214.23	232.82	261.19	214.39	237.79
Average	271.02	220.94	245.98	240.91	220.36	230.63	255.96	220.65	238.31
$LSD_{0.01}$	A—7.22, B—7.22, C—10.22, A × B—n.s., A × C—n.s., B × C—14.45, A × B × C—n.s.								
Spring rape straw dry matter yield									
N	105.60	80.98	93.29	88.44	82.05	85.25	97.02	81.52	89.27
$N:K_1:S_1$	112.39	86.32	99.36	103.75	81.25	92.50	108.07	83.79	95.93
$N:K_2:S_2$	106.36	93.26	99.81	103.01	77.76	90.39	104.69	85.51	95.10
$N:K_3:S_3$	96.74	77.61	87.18	97.85	86.87	92.36	97.30	82.24	89.77
Average	105.27	84.54	94.91	98.26	81.98	90.12	101.77	83.26	92.52
$LSD_{0.01}$	A—3.90, B—3.90, C—5.52, A × B—n.s., A × C—7.80, B × C—n.s., A × B × C—11.04								

n.s.—non-significant.

The fertiliser with the $N:K_2:S_2$ ratio had the most positive effect on the yield of spring rape straw but only in the series with a lower nitrogen dose in the soil with less quality (fresh and dry matter) and on treatments with a higher nitrogen dose in the soil with higher quality (fresh matter). On the above-mentioned treatments, the increase in the yield of the fresh matter of straw on both soils ranged from 7% to 12%, and in the dry matter of spring rape, it amounted to 15%, as compared to the control treatments. Moreover, there was a 17% increase in the yield of the dry matter of spring rape in the series with a higher nitrogen dose after the application of the fertiliser with the $N:K_1:S_1$ ratio in the soil with higher quality. The effect of fertilisers with different N:K:S ratios on the yield of straw was clearly smaller than that on the yield of spring rape seeds.

3.2.3. Maize Yield

An increase in the soil kind had a positive effect on the fresh matter of the above-ground parts of maize (Table 5). The difference in the yield of this plant's fresh matter on both soils was significant (10%). Its impact on the yield of dry matter of the above-ground parts of maize was insignificant.

Table 5. Effect of fertilisation and soil kind on maize (*Zea mays* L.) above-ground parts yield (g pot^{-1}).

N:K:S (C)	Soil Kind (A)						Nitrogen Dose (B)		
	Soil 1			Soil 2					
	Nitrogen Dose (B)								
	N 1	N 2	Average	N 1	N 2	Average	N 1	N 2	Average
Maize above-ground parts fresh matter yield									
N	881.2	768.5	824.9	868.4	830.5	849.5	874.8	799.5	837.2
$N:K_1:S_1$	1014.4	785.3	899.9	959.7	956.5	958.1	987.1	870.9	929.0
$N:K_2:S_2$	990.8	808.3	899.6	1030.4	975.3	1002.9	1010.6	891.8	951.2
$N:K_3:S_3$	814.7	714.3	764.5	882.6	966.8	924.7	848.7	840.6	844.6
Average	925.3	769.1	847.2	935.3	932.3	933.8	930.3	850.7	890.5
$LSD_{0.01}$	A—28.5, B—28.5, C—40.4, A × B—40.4, A × C—57.1, B × C—57.1, A × B × C—n.s.								
Maize above-ground parts dry matter yield									
N	164.2	131.7	148.0	141.1	122.0	131.6	152.7	126.9	139.8
$N:K_1:S_1$	187.3	137.3	162.3	148.2	145.0	146.6	167.8	141.2	154.5
$N:K_2:S_2$	187.4	138.9	163.2	152.5	154.2	153.4	170.0	146.6	158.3
$N:K_3:S_3$	145.9	103.7	124.8	125.6	159.0	142.3	135.8	131.4	133.6
Average	171.2	127.9	149.6	141.9	145.1	143.5	156.5	136.5	146.5
$LSD_{0.01}$	A—n.s., B—12.0, C—17.0, A × B—17.0, A × C—n.s., B × C—n.s., A × B × C—n.s.								

n.s.—non-significant.

A decrease in the nitrogen dose had a negative effect on maize yielding. A lower nitrogen dose reduced the yield of the fresh and dry matter of the above-ground parts of maize by 9% and 13%, respectively, compared to a higher dose of this fertiliser. The impact of nitrogen was greater on the soil with less quality.

The effect of fertilisers with different N:K:S ratios on the yield of the fresh matter of the above-ground parts of maize in both soils and on the soil of maize dry matter in the poorer soil was stronger in the series with a higher nitrogen dose. Inverse relationships were noted for the soil with a higher kind, and the yield of the dry matter of the above-ground parts of maize. In the soil with less quality and in the series with a higher nitrogen dose, the greatest increase (14–15%) in the yield of the fresh and dry matter of the above-ground parts of maize was demonstrated after the application of the fertiliser with the $N:K_1:S_1$ ratio into the soil. In the soil with higher quality, the optimal level of fertilisation ($N:K_2:S_2$) increased the yield of the fresh matter of the above-ground parts of maize in the series with a higher and a lower nitrogen dose by 19% and 17%, respectively, and the yield of its dry matter by 8% and 26%, respectively, compared to the control treatments.

3.3. The Weight of 1000 Grains (Seeds) of the Crops

3.3.1. Spring Wheat

None of the factors tested (soil kind, nitrogen dose, or fertilisers with different N:K:S ratios) had a significant effect on the weight of 1000 grains of spring wheat (Table 6). However, an increase in the weight of 1000 spring wheat grains was noted after the application of the fertiliser with the $N:K_1:S_1$ ratio in the soil in all of the series of this study. The increase in the weight of 1000 spring wheat grains under the influence of this fertiliser as compared to the control treatments was 12% (the soil with less quality, the series with N 1, the soil with higher quality, and the series with N 2); however, it was not statistically proven.

Table 6. Effect of fertilisation and soil kind on spring wheat (*Triticum aestivum* L.) weight of 1000 grains and spring rape (*Brassica napus* L. var. *napus*) weight of 1000 seeds (g).

N:K:S (C)	Soil Kind (A)						Nitrogen Dose (B)		
	Soil 1			Soil 2					
	Nitrogen Dose (B)								
	N 1	N 2	Average	N 1	N 2	Average	N 1	N 2	Average
Spring wheat weight of 1000 grains									
N	45.27	44.13	44.70	44.13	44.60	44.37	44.70	44.37	44.53
$N:K_1:S_1$	50.53	47.13	48.83	46.73	50.07	48.40	48.63	48.60	48.62
$N:K_2:S_2$	48.80	47.27	48.04	47.60	47.80	47.70	48.20	47.54	47.87
$N:K_3:S_3$	47.53	46.33	46.93	46.13	48.00	47.07	46.83	47.17	47.00
Average	48.03	46.22	47.12	46.15	47.62	46.88	47.09	46.92	47.00
$LSD_{0.01}$	A—n.s., B—n.s., C—n.s., A × B—n.s., A × C—n.s., B × C—n.s., A × B × C—n.s.								
Spring rape weight of 1000 seeds									
N	4.550	4.793	4.672	5.783	5.313	5.548	5.167	5.053	5.110
$N:K_1:S_1$	4.588	4.964	4.776	4.933	4.604	4.769	4.761	4.784	4.772
$N:K_2:S_2$	4.665	3.681	4.173	4.742	4.574	4.658	4.704	4.128	4.416
$N:K_3:S_3$	5.203	4.880	5.042	4.562	4.547	4.555	4.883	4.714	4.798
Average	4.752	4.580	4.666	5.005	4.760	4.882	4.878	4.670	4.774
$LSD_{0.01}$	A—0.353, B—n.s., C—0.500, A × B—n.s., A × C—n.s., B × C—n.s., A × B × C—n.s.								

n.s.—non-significant.

3.3.2. Spring Rape

Of all the tested factors, only the soil kind and fertilisers with different N:K:S ratios had a significant effect on the weight of 1000 spring rape seeds (Table 6). Both the nitrogen doses and the interaction of factors had no significant effect on the weight of 1000 test plant seeds. A negative impact of all fertilisers with an expanding N:K:S ratio on the weight of 1000 spring rape seeds on the soil with a greater kind was noted.

3.4. PCA Analysis and the Percentage of Variability Observed

3.4.1. Spring Wheat

The conducted PCA analysis (Figure 5) shows the existence of significant relationships between the plant parameters tested (the height at the three-leaf unfolded, stem elongation, flowering and the full maturity stages, the yield of the fresh and dry matter of grains and straw, and the weight of 1000 grains). The first group of properties (the yield of the dry and fresh matter of wheat straw, the plant height at the stem elongation and full maturity stages, and the weight of 1000 grains) determined 47.29% and the second group (the yield of the fresh and dry matter of wheat grains and the plant height at the three-leaf unfolded and the flowering stages) determined 24.80% of the total correlation of the data set. The vectors of plant height at the stem elongation stage and the yield of the fresh matter of grains (the longest vectors) had the greatest and the weight of 1000 grains (the shortest vectors) had the smallest significance in the variability proportion. The strongest positive correlation was demonstrated between the yield of the fresh matter and the yield of the dry matter of grains, between the yield of the fresh matter and the yield of the dry matter of spring wheat straw, and between the plant height at the stem elongation stage and the plant height at the flowering stage.

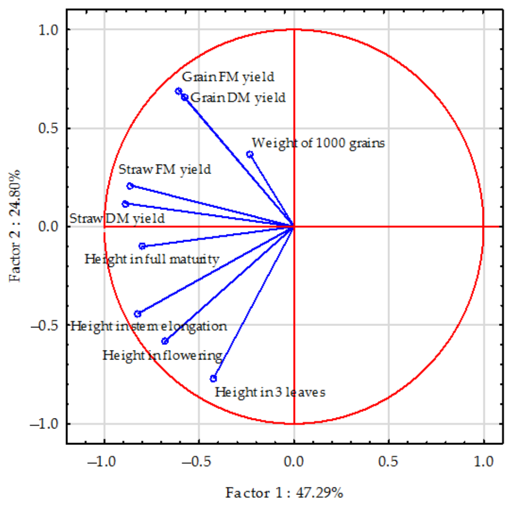

Figure 5. Relations between yield and biometric features of spring wheat (*Triticum aestivum* L.) calculated with PCA method. Vectors represent parameters (height in phases: 3 leaves, stem elongation, flowering, and full maturity; grain fresh matter and dry matter yield; straw fresh matter and dry matter yield; and weight of 1000 grains) as PCA results.

An analysis of the cumulative effect of the tested factors, expressed as the percentage of the variability observed using the ANOVA method, indicates that the soil kind had the greatest effect on the plant height at the stem elongation stage (51.7%) and the full maturity stage (34.0%) and the yield of the fresh (55.3%) and dry matter of spring wheat straw (59.6%) (Figure 6). The appropriate N:K:S ratios in the fertilisers had the strongest effect on the plant height at the three-leaf unfolded stage (61.0%) and the flowering stage (43.3%) and on the weight of 1000 grains of spring wheat (18.8%). However, the nitrogen dose contributed the most to the establishment of the yield of the fresh (21.2%) and dry matter of grains (20.1%) of this crop at an appropriate level. The N:K:S ratios in the fertilisers also had a significant effect on the plant height at the stem elongation stage (34.8%) and the full maturity stage (25.8%) and on the yield of fresh (13.7%) and dry matter of grains (13.7%), and the nitrogen doses had a significant effect on the yield on fresh (23.2%) and dry matter of spring wheat straw (19.9%).

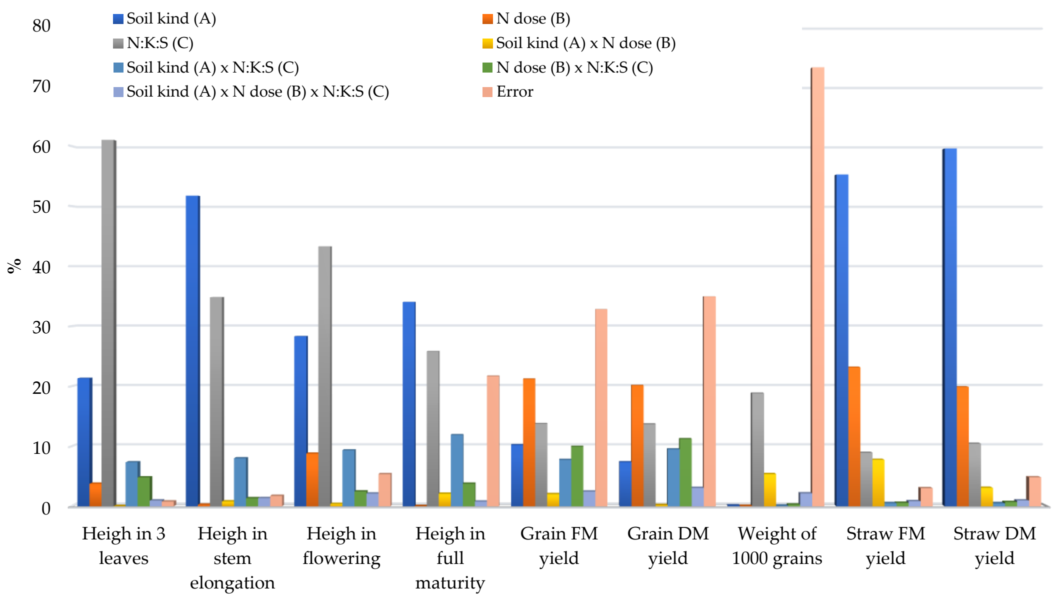

Figure 6. Relatively effect of factors on yield and biometric features of spring wheat—*Triticum aestivum* L. (in per cent).

3.4.2. Spring Rape

The PCA analysis (Figure 7) determined that parameters such as the yields of the fresh and dry matter of spring rape seeds and straw, the height of plants at the flowering and processing maturity stages, the weight of 1000 seeds accounted for 43.45%, and the plant height at the three-leaf unfolded and the formation of side shoots stages accounted for 19.66% of the total correlation of the data set. Most vectors were characterised by a considerable length, which indicates a similar impact, with the vector representing the plant height at the flowering stage being the longest and the vector for the weight of 1000 seeds being decidedly the shortest. The strongest positive correlations were demonstrated between the yield of the fresh matter and the yield of the dry matter of grains, between the yield of the fresh matter of straw and the yield of the dry matter of straw, and between the plant height at the flowering stage and the plant height at the spring rape processing maturity stage.

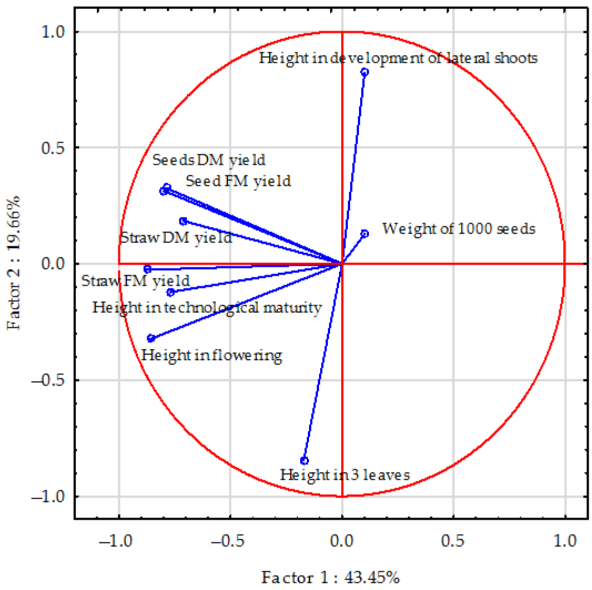

Figure 7. Relations between yield and biometric features of spring rape (*Brassica napus* L. var. *napus*) calculated with PCA method. Vectors represent parameters (height in phases: 3 leaves, development of lateral shoots, flowering, and technological maturity; seed fresh matter and dry matter yield; straw fresh matter and dry matter yield; and weight of 1000 seeds) as PCA results.

After calculating the percentage of the variability observed, expressing the effect of the tested factors on spring rape in the statistical form, it was found that the soil kind had a decisive effect on the plant height at the three-leaf unfolded stage (33.5%) and the flowering stage (22.2%) (Figure 8). The optimal N:K:S ratios in the fertilisers affected the plant height at the formation of side shoots stage the most (43.6%), the yield of the dry matter of seeds (28.3%), and the weight of 1000 spring rape seeds (32.9%). A nitrogen dose had the strongest effect on the plant height at the processing maturity stage (45.7%) and on the yield of the fresh (58.6%) and dry matter of seeds (62.9%). Moreover, a significant effect of the N:K:S ratios in the fertilisers on the plant height at the three-leaf unfolded stage (15.0%) and the processing maturity stage (15.0%), and on the yield of the fresh matter of spring rape seeds (17.6%), was also demonstrated.

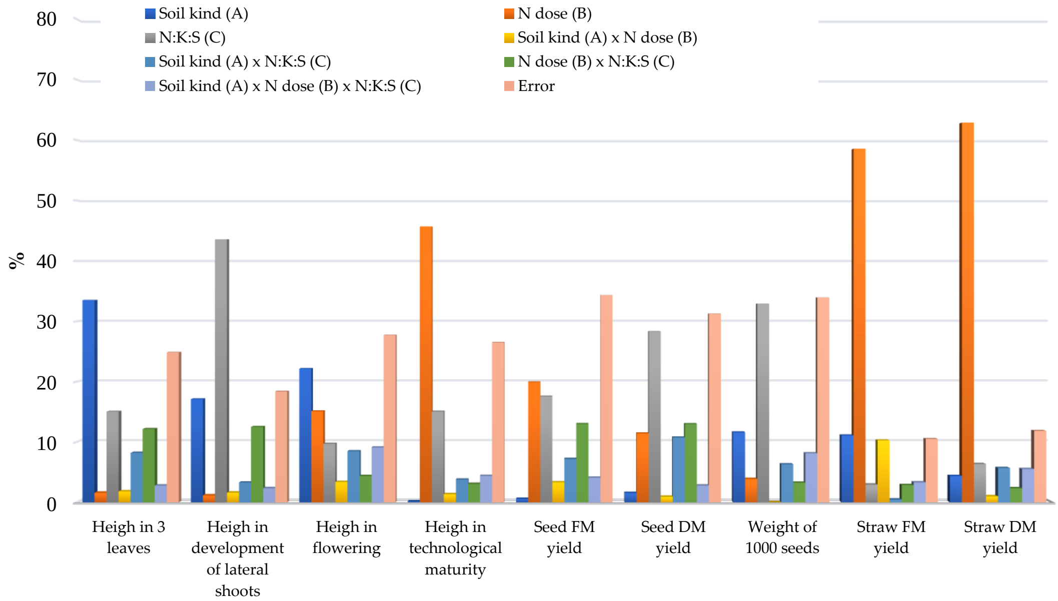

Figure 8. Relatively effect of factors on yield and biometric features of rape—*Brassica napus* L. var. *napus* (in per cent).

3.4.3. Maize

The PCA analyses (Figure 9) showed that the plant height parameters at the three-leaf unfolded, the beginning of stem development, the third–fourth node stage, and the tassel development stage were found in the first group and accounted for 52.98%, while the yield of the fresh and dry matter of the above-ground parts was found in the second group and accounted for 29.60%, of the correlations of the data set. The similar length of most vectors corresponds to a similar impact, and only the vector representing the plant height at the final growing stage was shorter. The strongest positive correlations were demonstrated between the plant height at the three initial growing stages (three-leaf unfolded, at the beginning of stem development, third–fourth node), and a weaker correlation was demonstrated between the yield of the fresh matter and the yield of the dry matter of the above-ground parts of maize.

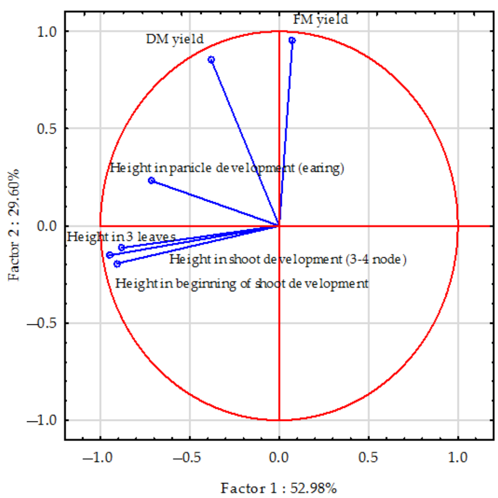

Figure 9. Relations between yield and biometric features of maize (*Zea mays* L.) calculated with PCA method. Vectors represent parameters (height in phases: 3 leaves, at beginning of shoot development, shoot development (3–4 node), panicle development (earing), above-ground parts fresh matter and dry matter yield) as PCA results.

Of all the tested factors, the soil quality had the greatest effect on the plant height at the following stages: three-leaf unfolded (48.5%), the beginning of stem development (80.0%), and third–fourth node (63.6%) (Figure 10). The optimal N:K:S ratios in the fertilisers had the strongest effect on the plant height at the tassel development stage (19.6%) and the yield of the fresh (26.1%) and dry matter of the above-ground parts of maize (17.2%). The nitrogen dose had a strong effect on the yield of the fresh (16.4%) and dry matter of the above-ground parts of maize (16.7%) and on the plant height at the beginning of the growing stage (21.2%). A rather significant effect of the soil kind was noted in potassium on the plant height at the tassel development stage (12.8%) and the yield of the fresh matter of the above-ground parts of maize (19.4%) and the N:K:S ratios in the fertilisers on the plant height at the stem development stage—third–fourth node (15.7%).

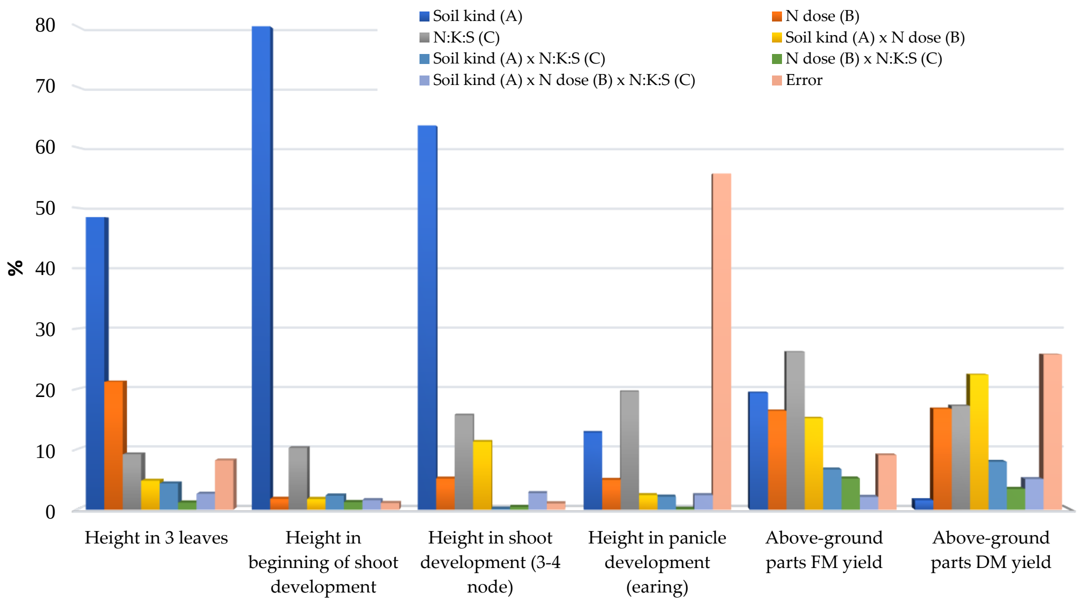

Figure 10. Relatively effect of factors on yield and biometric features of maize—*Zea mays* L. (in per cent).

4. Discussion

Mineral fertilisation is the basic factor that affects yield volume and quality [38]. Its application is essential to achieve high yields, which is extremely important in light of the global food deficit. It is also important for the yields achieved to be of good or very good quality. Fertilisation with basic nutrients, particularly nitrogen, has a strong effect on both the volume and the quality of yields. In order to achieve good quality yields, fertilisers should be applied at the appropriate ratios adjusted to the nutritional needs of individual plant species at their appropriate growing stages. The nitrogen-to-potassium ratios are of particular importance [39]. Potassium and nitrogen are among the three basic macroelements that are essential for proper plant growth and development [40]. Nitrogen has the strongest effect on the plant growth rate and the yield volume. However, excessively high doses of nitrogen fertilisers can inhibit the uptake of potassium and other elements, which consequently can adversely affect the yield and, in particular, the quality of agricultural products [39].

Potassium is a critical nutrient for plant growth [40,41]. According to Dawson et al. [41], it is essential for cereals and other crop species to flower properly and obtain adequate straw stiffness and, consequently, high-quality yields. It also has a favourable effect on plants' resistance to pests and diseases. Potassium is involved in many physiological processes occurring in plants, e.g., in enzyme activation, photosynthesis, protein and starch synthesis, and the transport of water and nutrients [42,43].

At the initial growing stages, the effect of nitrogen fertilisation on plants is generally more noticeable than the effect of fertilising with other nutrients [44]. It is determined, however, by the fertiliser form and the crop species [38]. This was confirmed in the authors' own study in which a higher nitrogen dose had a favourable effect on the growth of maize and spring rape, particularly at the later growing stages. The impact of fertilisation, including nitrogen fertilisation, is determined by the crop cultivation location, i.e., the soil quality and water availability [45]. This was reflected in the authors' own study in which the soil type had an effect on both the crop yielding and other tested parameters.

In a study by Bielski [46], nitrogen fertilisation had a favourable effect on the yield of winter triticale and the components of its structure (the weight of 1000 grains, number of ears per m^2). The years of the study also had a significant effect. In a study by Ferrise et al. [47], the yielding of wheat and the weight of 1000 grains were determined by the nitrogen fertiliser dose and the date of fertiliser application. The weight of 1000 grains ranged from 44.2 to 57.3 g. Similar results were obtained in the authors' own studies. However, excessively high nitrogen doses may inhibit both the yield and the weight of 1000 grains [46,48]. These relationships are also confirmed by Alderfasi and Refay [49], who obtained an increase in the yield of wheat up to 200 kg K_2O ha^{-1}, yet higher potassium doses no longer had a significant effect.

In general, potassium is taken up by plants earlier than nitrogen and phosphorus, and its uptake increases faster than dry matter production. It is likely that potassium accumulates at the beginning of plant growth and is then transported to other organs [40]. Aown et al. [50] demonstrated that adequate potassium availability for plants is particularly important at the critical growth stages (shooting, flower initiation, and ripening), as it increases plant tolerance to drought and contributes favourably to the plant growth and plumpness of the grain. This was reflected in the obtained results of the authors' own studies. A favourable effect of potassium fertilisation in the cultivation of maize was demonstrated by Niu et al. [51], who obtained an increase in the yield of over 20%. According to Zhang et al. [52], the increase in the maize yield under the influence of potassium fertilisation can be much greater (up to 60%). The increase in the wheat grain yield is usually lower by half. The positive impact of potassium fertilisation on growth and development as well as the yielding of rape was noted by Li et al. [18]. However, potassium fertilisation usually has a weaker effect than nitrogen fertilisation on the yielding of crops [42].

The antagonism between nitrogen and potassium plays a very important role in the fertilisation and uptake of the elements by plants and, consequently, in crop yields. Therefore, the dose of nitrogen cannot be increased too much, as this will limit the availability of nitrogen to plants [53]. As a result, plant yield will decrease. The antagonistic effect of potassium on nitrogen uptake is also sometimes found, but most often it affects the NH_4^+ ion. The NH_4^+ ion in turn has an antagonistic effect on potassium. In turn, there may be an opposite relationship with the NO_3^- ion because potassium is also an antagonist in relation to magnesium, which is also not indifferent to growth, development, and, as a consequence, crop yield [54]. However, too low of potassium fertilisation can also limit the uptake of many macro- and microelements by plants because the right ratio between potassium, calcium, magnesium, and sodium determines the correct water management of plants [55]. Correct ratios between fertiliser components (balancing their negative interactions) are therefore essential for high crop yields. In our own research, in most cases, the highest yield was obtained with a higher (optimum) nitrogen dose at the $N:K_2:S_2$ ratio.

Antagonism between ammonium (NH_4^+) and nitrate (NO_3^-) is observed in some plants [56]. Under conditions of excess NH_4^+, NO_3^- may be less transported to the aerial parts of plants, limiting their biomass. Yang et al. [56] found such dependencies in the early stages of wheat growth. For most species, fertilisers had the greatest effect on the growth and development of plants in which the $NH_4^+:NO_3^-$ ratio was 50:50 [57]. The application of the higher nitrogen dose probably caused physiological stress at the beginning of spring wheat vegetation in our own research. The spring wheat height in the object with a higher nitrogen (N 1) dose was lower than the plant height in other objects. Spring wheat is a more sensitive crop to stress factors than spring rape or maize.

In the authors' own study, potassium and sulphur fertilisation increased the yield of spring wheat grains and straw, spring rape seeds and straw, and the above-ground parts of maize. It should be noted, however, that the application of potassium fertilisers caused a significant reduction in the plant height at the beginning of the spring wheat growing period and a reduction in the weight of 1000 spring rape seeds (only on the soil with higher quality).

5. Conclusions

A higher nitrogen dose promoted the growth of spring rape at the later growing stage and of maize and had a positive effect on the yield of spring wheat grains and straw, spring rape seeds and straw, and the above-ground parts of maize.

The application of potassium fertilisers caused a significant increase in spring rape plant height, an increase in the yield of spring wheat grains and straw, spring rape seeds and straw, and the above-ground parts of maize, and a reduction in the plant height at the beginning of the spring wheat growing period and the weight of 1000 spring rape seeds (only on the soil with rich quality). The fertiliser with the $N:K_2:S_2$ ratio had a particularly favourable effect on the yielding of spring wheat. In the cultivation of maize, the same effect was most often obtained under the influence of fertiliser with the ratio of $N:K_1:S_1$ on the weaker soil fertilised at the same time as a higher dose of nitrogen (N 1) and $N:K_2:S_2$ (in other cases). In the case of spring rape, generally, fertiliser with the $N:K_1:S_1$ ratio was the strongest, although, in some objects, a higher yield was achieved under the influence of $N:K_2:S_2$.

The existence of statistically confirmed correlations (expressed as the percentage of the variability observed) between the soil kind and the fertilisers applied and the yielding and biometric characteristics of the plants were observed.

Author Contributions: Conceptualization, M.S.B., M.W. and M.K.; methodology, M.S.B., M.W. and M.K.; investigation, M.W.; analysis, M.S.B. and M.W.; visualization, M.W.; writing—review and editing, M.W. and M.S.B.; supervision, M.W., M.S.B. and M.K.; M.S.B., corresponding author. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded as a part of the National Centre for Research and Development project No POIR.01.02.00-00-0061/17. This paper was co-financed by the University of Warmia and Mazury in Olsztyn, Faculty of Agriculture and Forestry, Department of Agricultural and Environmental Chemistry (grant No. 30.610.004-110).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: We acknowledge the staff of the Department of Environmental Chemistry of UWM Olsztyn for their assistance in carrying out the experimental work in the vegetation greenhouse.

Conflicts of Interest: Author Monika Karsznia was employed by the company Grupa Azoty Zakłady Azotowe "Puławy" S.A., Technology and development Division. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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