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Cultivation of Crops in Strip-Till Technology and Microgranulated Fertilisers Containing a Gelling Agent as a Farming Response to Climate Change

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Abstract: Climatic and soil conditions are changing in response to the increasing human impact. This requires the introduction of low-cost, low-emission, but effective technologies in the field cultivation of crops, in turn requiring and justifying research in this area. In laboratory tests and field studies, the production and environmental effects of strip-till and the application of microgranular fertilisers with a gelling component were determined (and, in particular, their use in combination as a plant cultivation technology). These effects were measured in terms of soil properties, the biomass production, and the yields of maize (*Zea mays* L.), spring barley (*Hordeum vulgare* L.), and winter rape (*Brassica napus* L.). Fertiliser microgranules with a gelling agent absorbed water in the amount of 118.6–124.7% of fertiliser mass and increased the volumetric moisture content of the soil in the layer in which they were applied (0–7.5 cm) by 3.0–3.9 percentage points compared to the soil moisture without fertiliser. Strip tillage with the application of fertilisers with a gelling agent significantly increased the amount of water in the soil during the sowing period for winter and spring plants and reduced the CO_2 emissions from the soil relative to the conventional tillage without microgranular fertiliser. The biomass of maize, spring barley, and winter rape before flowering, as well as the yields of these plants, were higher when cultivated using strip-till and fertilisers with gelling agents than when ploughed with a mouldboard plough without the use of microgranulated fertilisers. This technology also increased the number of microorganisms, including bacteria, actinobacteria, and filamentous fungi in the soil after harvesting compared to the unfertilised, ploughed soil. Strip tillage and microgranulated fertilisers containing a gelling agent can thus reduce the environmental pressure exerted by agriculture and reduce the risk of climate change, as well as being a way of adapting agriculture to climate change.

Keywords: strip tillage; starter fertiliser; soil moisture; CO_2 emission; microorganisms; plant productivity

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1. Introduction

There is a feedback loop between agriculture and the environment (including the climate). Agriculture is the source of over 10% of global greenhouse gas emissions and about half of non-CO_2 greenhouse gas emissions. Practices such as land use, soil cultivation, fertilisation, and livestock breeding are among the causes of climate change [1–3]. In recent decades, the concentration of greenhouse gases such as methane, carbon dioxide, and nitrogen oxides in the atmosphere has been increasing. There is an increase in air temperature of about 0.15–0.20 °C per decade. Weather anomalies, including extreme air temperatures

and precipitation, droughts, and floods, are occurring increasingly often [4]. Changes in the environment are changing the conditions and results of agricultural production. Increased atmospheric CO_2 concentrations and higher air temperatures can increase plant productivity [5]. However, the water and thermal stress, soil erosion [6,7], weed infestation, and activity of pathogens and pests that climate change brings reduce yields [8–10].

In the conditions of the environment being threatened by human activity, there is a preference for agroecological and agricultural practices that have lower risks of adverse impacts on the soil, water, and air [11,12]. Elements of conservation agriculture that allow sustainable development are of particular importance [13,14]. Protecting the soil against erosion, the degradation of organic matter, and excessive compaction, as well as increasing the biodiversity and biological activity and improving the water conditions and nutrient circulation are equally important; they are sometimes even more important for soil cultivation tasks than its immediate preparation for plant cultivation [15]. Currently, conventional tillage with soil inversion via a mouldboard plough is being reduced. There is an increasing use of non-inversion tillage, which leaves a large amount of plant residues on the soil surface, and mechanical cultivation is increasingly being abandoned entirely [16,17]. One method of conservation soil cultivation is strip-till. Soil is only loosened deeply in narrow strips and not inverted. At the same time, fertilisers can be applied and crop seeds sown in these strips. Between the strips of loosened soil and the rows of plants, the soil is left intact and covered with plant residues [18–20]. The water and thermal conditions in the rows—loosened strips and between the rows—uncultivated strips are different due to the different soil properties in these zones. In loosened strips, the soil has low density and compactness, allowing water to infiltrate quickly and warm up. The non-loosened inter-row is covered by plant residues, limiting the evaporation, and thus, keeping the soil moist and maintaining a lower temperature [21,22]. This method is especially recommended in dry climates and areas with deficits of precipitation for field crop production [23]. By limiting the aeration and water retention in the soil, ploughless soil cultivation systems (including strip-till) create favourable conditions for the accumulation of organic matter. However, a specific ploughless cultivation system must be used continuously for a relatively long time to stabilise the amount of organic matter in the soil, and especially, to increase it. Organic matter builds up mainly in the top layer, which increases not only the productivity of the soil, but also its resistance to degradation under the influence of agricultural treatments and environmental factors. The consequence of increasing the content and amount of organic carbon in the soil as a result of ploughless cultivation may be a reduction in CO_2 emissions into the atmosphere, but with a greater risk of N_2O emissions [24–26]. The presence of soil organic matter and mulch creates an aggregate structure, and soil aggregates are water-resistant and durable [27,28]. Therefore, ploughless and no-till soil cultivation reduce water and wind erosion [29–31]. An equally effective agrotechnical method of reducing surface runoff and soil erosion is strip-till [32,33]. The accumulation of organic matter and favourable physical and chemical soil properties that result from conservation agriculture (including conservation soil tillage) create ideal conditions for the presence and activity of soil organisms [34–36]. Soil fertility and health depend on the abundance of the microbial population in terms of the species diversity and population size of bacteria and fungi. The occurrence of these organisms in the soil is also conditioned via soil cultivation and fertilisation [37–39].

One of the goals of modern field crop production is to improve the efficiency of fertilisation and reduce its negative environmental impact, and this is achieved by using microgranulated starter fertilisers. Very small granules with a diameter of ~1 mm are applied in the immediate vicinity of the seeds during sowing. The microgranules, each with the same chemical composition, provide nutrients for the plant roots from germination. This increases the efficiency of fertilisation, allowing doses and the costs of fertiliser and its application all to be reduced. The environmental benefits result from reductions in the leaching of ingredients not taken up by plants, the fuel consumption (and thus lower CO_2 emissions), and the consumption of packaging. The efficiency of nutrient use by

plants is greater, which allows the dose of fertiliser to be reduced. This, in turn, reduces the energy consumption and greenhouse gas emissions [40]. Starter fertilisers, including as microgranules, are increasingly being used in the agrotechnology of crops such as maize [41], other cereals [42], sugar beet [43], winter rape [44], and vegetables [45].

Conservation agriculture practices, including ploughless soil cultivation methods and localised starter fertilisation, must be well-suited to the local conditions to provide the beneficial production and environmental effects hoped of them. This is because their incorrect use can negatively affect the soil properties and plant yields [46–48]. The ambiguity of results published in past scientific works, the changing habitat conditions of field plant production, and the technical and technological advances in soil cultivation and plant fertilisation all justify further scientific research in this area. The aim of the present study was to determine what impact strip-till and microgranulated fertilisers containing a gelling agent (and, in particular, their combined use) had on the soil properties and productivity of maize, spring barley, and winter rape. It was assumed that the positive results could be used in agricultural development strategies that reduce pressure on the environment, including the risk of deepening climate change.

2. Materials and Methods

2.1. Study Site

Tests and experiments were conducted for three years during 2020–2023. The industrial research and development work was carried out as part of the projects co-financed by the National Centre for Research and Development using European Union funds at the Research and Development Centre of Agro-Land Marek Różniak in Śmielin (53°09′04.0″ N; 17°29′10.7″ E; 93.8 m a.s.l.) in Kuyavia-Pomerania Voivodeship (Poland), which is located in a humid continental climate zone (Dfb) [49].

2.2. Laboratory and Field Tests

The laboratory tests, and then field tests, employed microgranulated fertilisers formulated as part of research project POIR.01.01.01-00-0348/20 (Figure 1). These fertilisers' chemical composition includes a gelling agent designed to keep water in the hydrated granules and in the soil in the immediate vicinity of the roots of young plants. The proper names and properties of fertilisers dedicated to various species and groups of crops are presented in Table 1. To assess how the gelling agent affected the properties of the fertilisers, fertilisers were produced that had the same chemical composition, minus the gelling agent.

Table 1. Properties of microgranulated fertilisers with gelling agent.

Parameter	Unit	Fertiliser		
		Cereals	Maize	Oilseed
Phosphorus (P_2O_5)	% m/m	12.3	12.6	12.3
Potassium (K_2O)	% m/m	8.4	8.5	8.5
Magnesium (MgO)	% m/m	6.0	5.6	6.0
Sulphur (SO_3)	% m/m	14.2	14.4	13.9
Zinc (Zn)	% m/m	1.03	1.17	1.06
Boron (B)	% m/m	0.023	0.019	0.130
Copper (Cu)	% m/m	0.19	0.12	0.11
Iron (Fe)	% m/m	0.53	0.54	0.48
Manganese (Mn)	% m/m	0.22	0.18	0.18
Molybdenum (Mo)	% m/m	0.005	0.005	0.012
Gelling agent	% m/m	24.0	25.0	27.0
Bulk density	g/cm^3	0.92	0.93	0.92
Share of microgranules of Ø 0.6–1.2 mm	%	93.0	92.0	93.0

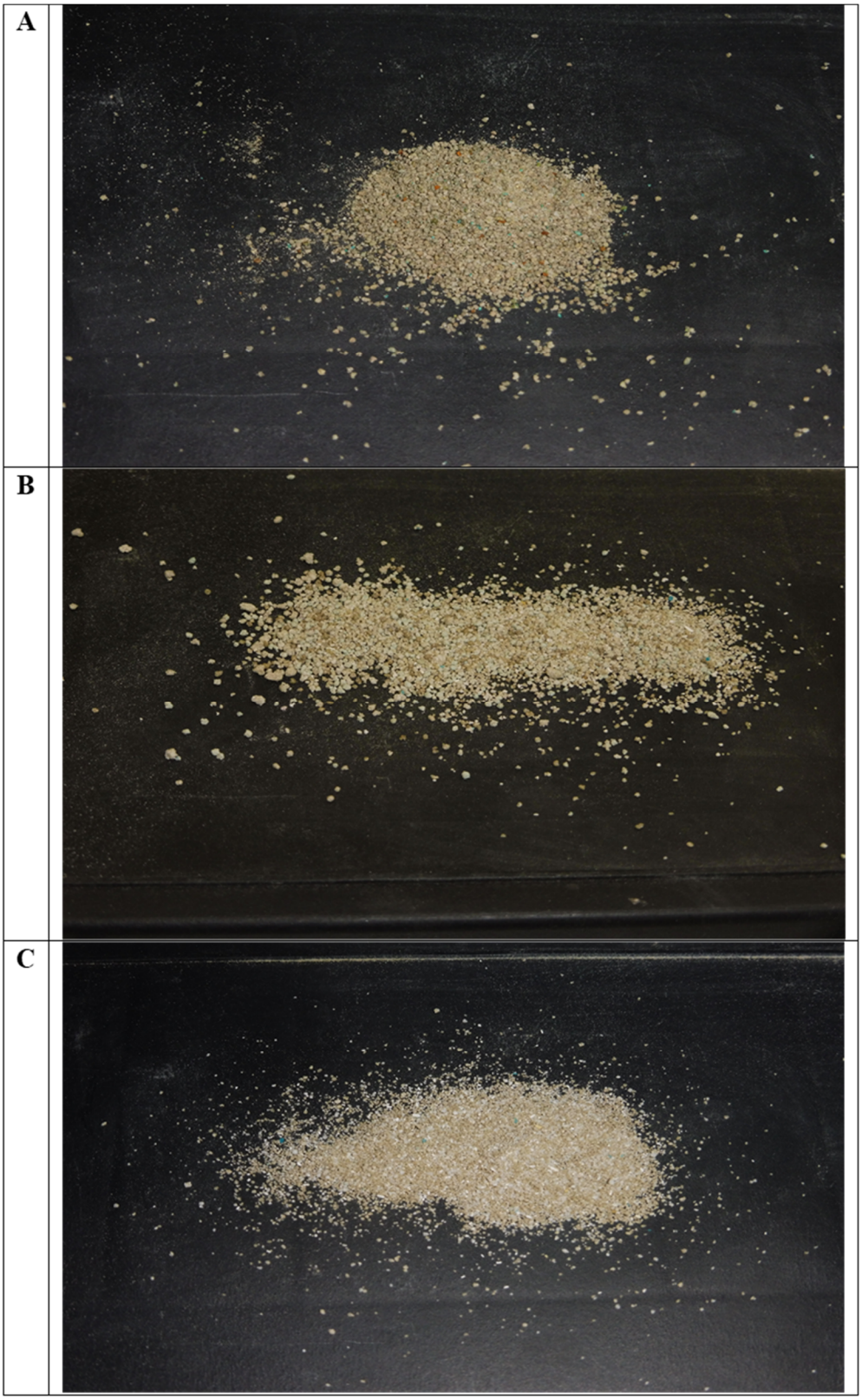

Figure 1. Microgranulated fertilisers with a gelling agent ((**A**)—Cereals, (**B**)—Maize, and (**C**)—Oilseeds).

The water absorption capacity of the fertilisers with the gelling agent was determined as the ratio of the mass of water absorbed and then retained by the granules for 1 h to the mass of the fertiliser sample. The assessment was performed five times, each time for a fertiliser sample of 100 g, in three consecutive series. The fertiliser samples were placed on

filter paper and then placed on a water-saturated 0.5-mm mesh. An analogous assessment of the water absorption capacity of the fertilisers was performed in soil. The microgranulate (five samples, 100 g each) was placed in 0.5 mm mesh bags, and then at a depth of 5 cm in a soil-filled 10 dm^3 pot with a moisture content equal to the full water capacity.

A fertiliser solubility test was also performed in the pot by placing the samples (1 g) on the surface of the water-saturated soil through which the moisture could rise via capillary action. The presence and condition of the microgranules were observed after 1, 2, 4, 6, 12, 24, 48, and 72 h.

Soil laboratory tests assessed the impact of fertilisers with the gelling agent on the soil moisture. Into 10 dm^3 pots was placed soil (sand 36.1%; silt 55.7%; clay 8.2%; content in 1 kg of soil: Corg 13.1 g; available phosphorus according to Egner–Riehm 89.6 mg P, potassium (Egner–Riehm) 183.1 mg K, magnesium (Schatschabel) 60.4 mg Mg, and $pH_{(KCl)}$ was 6.3, bulk density 1.5 g/cm^3, moisture 20% vol.) in four repetitions, and the tested fertilisers were placed in them at a depth of 5 cm. The experimental treatments being compared were the presence of the gelling agent in the fertiliser: fertiliser with a gelling agent, fertiliser without a gelling agent, and no fertiliser. The mass of fertiliser relative to the mass of soil in the pot corresponded to a dose of 30 kg/ha, assuming that in the field conditions, 30 kg of this fertiliser acts on a mass of soil of 3000 tonnes (area—10,000 m^2, arable layer thickness—0.2 m, and soil bulk density—1.5 t/m^3). The pots were placed in a plant growth chamber that controlled the environmental conditions (Biogenet, Józefów, Poland). Day/night was 16 h/8 h, temperature 20 °C/12 °C, and air humidity 60%. After 7 days of incubation, the moisture content of the 0–7.5-cm soil layer was determined using a FieldScout TDR 350 m (Spectrum Technologies, Inc., Thayer Ct. Aurora, IL, USA). A similar test was performed in the field conditions, in soil with the same texture as the soil in the pots, and the humidity at the time of the fertiliser application was 22.1% vol. The soil moisture was assessed after 10 days without rainfall.

After 4 weeks of incubation of the soil with fertilisers in the plant growth chamber, the occurrence of microorganisms was assessed in terms of the total bacteria, actinomycetes, and filamentous fungi, as well as the cellulolytic, amylolytic and proteolytic microorganisms. Ten soil samples of 100 g each were taken from each pot. The samples were thoroughly mixed and averaged. The number of individual groups of microorganisms was assessed in a laboratory soil sample that was shaken for 30 min after the addition of Ringer's solution. Microbiological inoculations were performed after preparing a series of ten-fold dilutions of soil solutions (10^{-1}–10^{-7}). Inoculations were performed on media appropriate to each group of microorganisms and according to generally used methods [50–52]: total bacteria—YPS with the addition of soil extract; actinomycetes—Pochon's medium with the addition of nystatin (100 $\mu g \cdot mL^{-1}$); filamentous fungi—Martin's medium with the addition of streptomycin (30 $\mu g \cdot mL^{-1}$); cellulolytic microorganisms—Congo red Agar with CMC-Na; amylolytic—medium with the addition of Difco starch (0.2%); and proteolytic—method according to Alef and Nannipieri [53]. The abundance of individual groups of microorganisms was expressed in cfu (colony-forming units)$\cdot g^{-1}$ of soil.

The influence that the tested fertilisers (in an amount corresponding to a dose of 30 kg/ha under the field conditions) had on the initial growth of maize, spring barley, and winter rapeseed was also determined in the plant growth chamber. The pots measuring 10 cm × 10 cm × 10 cm were filled with soil, the same as in the pot experiment assessing the effect of fertilisers on the soil moisture and on microorganisms. In each pot (five repetitions of each treatment), 12 grains of barley and rape seeds were placed, and in the pots with a diameter of 22 cm and a height of 20 cm, 12 maize grains were placed. The pots were placed in a chamber that regulated the environmental parameters: day/night was 16/8 h, air temperature 22 °C/12 °C (maize) or 20 °C/10 °C (barley, rapeseed), and air humidity 60%. The soil moisture was maintained in the range of 18–20% vol. After emergence, 10 plants were left in each pot. After three weeks of vegetation, the aboveground mass of the plants was determined and expressed in g/plant. The tests were repeated four times.

2.3. Field Experiments

In the years 2021–2023, a field experiment was carried out in which maize, spring barley, and winter rape were cultivated in succession. The meteorological conditions, long-term averages, and those occurring in the initial study period have been presented in the authors' earlier work—the experiment was also performed in this location (Śmielin) [54]. Moreover, in 2022, rainfall at the study site amounted to 528.0 mm, being the highest in February at 128.6 mm and September at 56.0 mm, and the lowest in March, at only 0.2 mm. The average air temperature was 9.4 °C. The warmest was August at 21.5 °C. During the 2022/2023 winter rapeseed growing season, the total rainfall was 503.6 mm. The most rainfall occurred in June 2023, with 89.9 mm. May 2023 (17.6 mm) and November 2022 (20.4 mm) were very dry. The warmest month was July 2023, at 19.2 °C, and the coldest was December 2022, at 0.25 °C. The field experiment was located on the soils classified as Cambisols according to the World Reference Base for Soil Resources [55]. The granulometric composition of the soil is: sand (2.0–0.05 mm) 39.6%, silt (0.05–0.002 mm) 53.3%, and clay (<0.002 mm) 7.1%. One kilogram of the soil contained Corg 12.8 g; available phosphorus according to Egner–Riehm 117.0 mg P; potassium (Egner–Riehm) 203.5 mg K; and magnesium (Schatschabel) 55.7 mg Mg, and $pH_{(KCl)}$ was 6.8.

The experiment compared the impact of the soil cultivation method and the application of microgranulated fertilisers on the soil water conditions, CO_2 emissions from the soil, the occurrence of microorganisms in the soil, and plant productivity. The experimental treatments were plant cultivation technologies with the differences in the soil tillage and application of microgranulated fertilisers: strip-till with the application of a fertiliser with a gelling agent (strip-till/with agent), strip-till with the application of a fertiliser without a gelling agent (strip-till/without agent), strip-till without the application of a microgranulated fertiliser (strip-till/no fertiliser), conventional tillage, and ploughing the soil without a microgranulated fertiliser (ploughing/no fertiliser). The experiment was planned in a randomised block design, in four repetitions, with plot sizes enabling the use of agricultural machines, i.e., 12 m × 200 m. The plough technology for soil cultivation involved: a Maschio Gaspardo s4 plough, Horsch Tiger 6 AS tilling set, Amazone ZG-TS 8200 pre-sowing fertiliser spreader, Horsch Pronto 4DC + MiniDrill grain and rapeseed seeder, and maize seeder Monosem NG PLUS 4 with a microgranulate applicator. Strip-till technology performs soil cultivation, basic fertilisation, sowing seeds of each crop species, and the application of the microgranulated fertiliser all using a single pass of one multifunctional Mzuri Pro-Til 4T machine adapted to the local conditions as part of the POIR.01.01.01-00-0910/17 project (Figure 2).

Basic fertilisation of N, P_2O_5, and K_2O for corn, spring barley, and winter rapeseed was recommended in appropriate amounts (in kg/ha) on all plots, based on soil fertility: 120, 60, 120; 100, 50, 80; and 160, 70, 120. In maize cultivation, the full dose of phosphorus, potassium, and nitrogen in maize cultivation was applied immediately before sowing for plough tillage or at the time of sowing for strip-till. In the period immediately before sowing, 60% of the nitrogen dose was also applied in the cultivation of spring barley and 20% of nitrogen in the cultivation of winter rapeseed. At the time of sowing, the microgranulated fertiliser was applied to the plots of the first two experimental treatments (strip-till/yes and strip-till/no) at a dose of 30 kg/ha into a loosened strip of soil to a depth of about 5 cm. Maize cv. Kokuna was sown on 23 April 2021, spring barley cv. Ismena on 4 April 2022, and winter rapeseed cv. Momento 23 August 2022. The remaining agrotechnical treatments were conducted on crops in accordance with the principles of integrated agricultural production. Seeds were harvested at full maturity (spring barley and winter rapeseed) and at a 32% water content in grain for maize. Yields were expressed after conversion, taking into account a water content of 15% for maize and spring barley, and 8% for winter rapeseed.

Figure 2. A multifunctional machine for strip soil tillage, fertilisation, sowing, and application of microgranules.

At the time of plant sowing (two days after sowing), the water content in the soil was determined. Its amount in the top 20 cm layer over an area of 1 ha (W) was calculated according to Formula (1):

$$W = \frac{F\ h\ VWC\ BD}{100,000} \left[\frac{t}{ha}\right] \quad (1)$$

where F is the area of 10,000 m^2; h is the soil layer thickness of 0.2 m; VWC is the volumetric water content (soil moisture), %; and BD is the bulk density of water equal to 1000 $kg \cdot m^{-3}$.

CO_2 emissions from soil to the atmosphere were assessed immediately (up to 48 h) after basic pre-sowing soil tillage, i.e., spring loosening and levelling tillage for the maize and spring barley cultivation, and after ploughing and levelling the field for the winter rapeseed cultivation. Subsequent measurements were made immediately after sowing (next day), 10 days after sowing, and 20 days after sowing. Soil respiration was measured using an automatic ACE system (ADC BioScientific Ltd., Hoddesdon, UK).

In the phase of intensive biomass growth, before the plants flowered, the mass of their aboveground parts was determined, and in the period from maturity until harvesting, the mass of grain and seeds was determined. After harvesting, the soil samples were taken from the 0–20-cm layer for microbiological analyses. The abundance of microorganisms was assessed in the same way as in the soil samples from the laboratory pots.

2.4. Analysis of Results

The laboratory test, field test, and field experiment results were analysed mathematically and statistically. The normality of the distribution of values of the parameters measured in the factor tests was assessed. The assumption of the normal distribution was verified using the Shapiro–Wilk test, assuming the null hypothesis H0 that the variables were normally distributed. Normally distributed data were subjected to ANOVA analysis according to the model appropriate for single-factor experiments. The statistical significance of the influence of the experimental treatments was assessed via the F test. Meanwhile, the significance of the differences between the mean values of the individual characteristics determined under the influence of the individual experimental treatments was assessed via Tukey's post-hoc test at $p < 0.05$. The coefficient of variation (CV) was calculated for the result of water absorption via fertiliser microgranules as a quotient of the standard deviation value and the arithmetic mean. Mathematical and statistical analyses were performed using the Microsoft Excel 2016 [56] and Statistica, version 12 [57] software packages.

3. Results

3.1. Laboratory and Field Tests

The mass of water absorbed by the granules placed on paper ranged from 122.2% of the mass of the Oilseed fertiliser to 124.7% of the Cereals fertiliser. The coefficient of variation in these results was 3.8–5.1% (Table 2). The water absorption of the microgranules placed in wet soil was 1.8–6.1 percentage points lower than in the tests on paper and the CV was 0.2–2.2% higher. The microgranules of fertilisers with a gelling agent remained on wet soil for about 60–70 h, while those without a gelling additive had dissolved completely within about 5–6 h (Figure 3).

Table 2. Water absorption (% m/m) of microgranulated fertilisers with gelling agent.

Test	Series	Fertiliser		
		Cereals	**Maize**	**Oilseed**
Laboratory	I	131.2	126.9	125.3
	II	120.6	119.4	121.7
	III	122.4	121.2	119.7
	average	124.7	122.5	122.2
	coefficient of variation	5.1	3.9	3.8
Soil	I	125.6	130.0	122.2
	II	116.3	116.4	119.8
	III	113.9	115.7	116.0
	average	118.6	120.7	119.3
	coefficient of variation	5.6	6.1	4.0

The soil in the laboratory pots to which microgranular fertilisers with the gelling agent were applied had higher moisture than soil with fertiliser without the gelling agent and soil without fertiliser (Table 3). Seven days after the application of fertilisers with the gelling agent, the moisture of the 0–7.5-cm soil layer was 2.7–3.7 percentage points higher than the soil moisture for fertiliser without the gelling agent and 3.0–3.9 percentage points higher than the soil moisture without fertiliser. The effect of microgranulated fertilisers on the soil moisture in the field conditions was similar to that in the laboratory. Ten rainless days after the application of fertilisers, the only soil moisture that did not differ significantly from that of the soil with fertiliser without the gelling agent and that of the unfertilised soil was that to which the Oilseed fertiliser with the gelling agent had been applied.

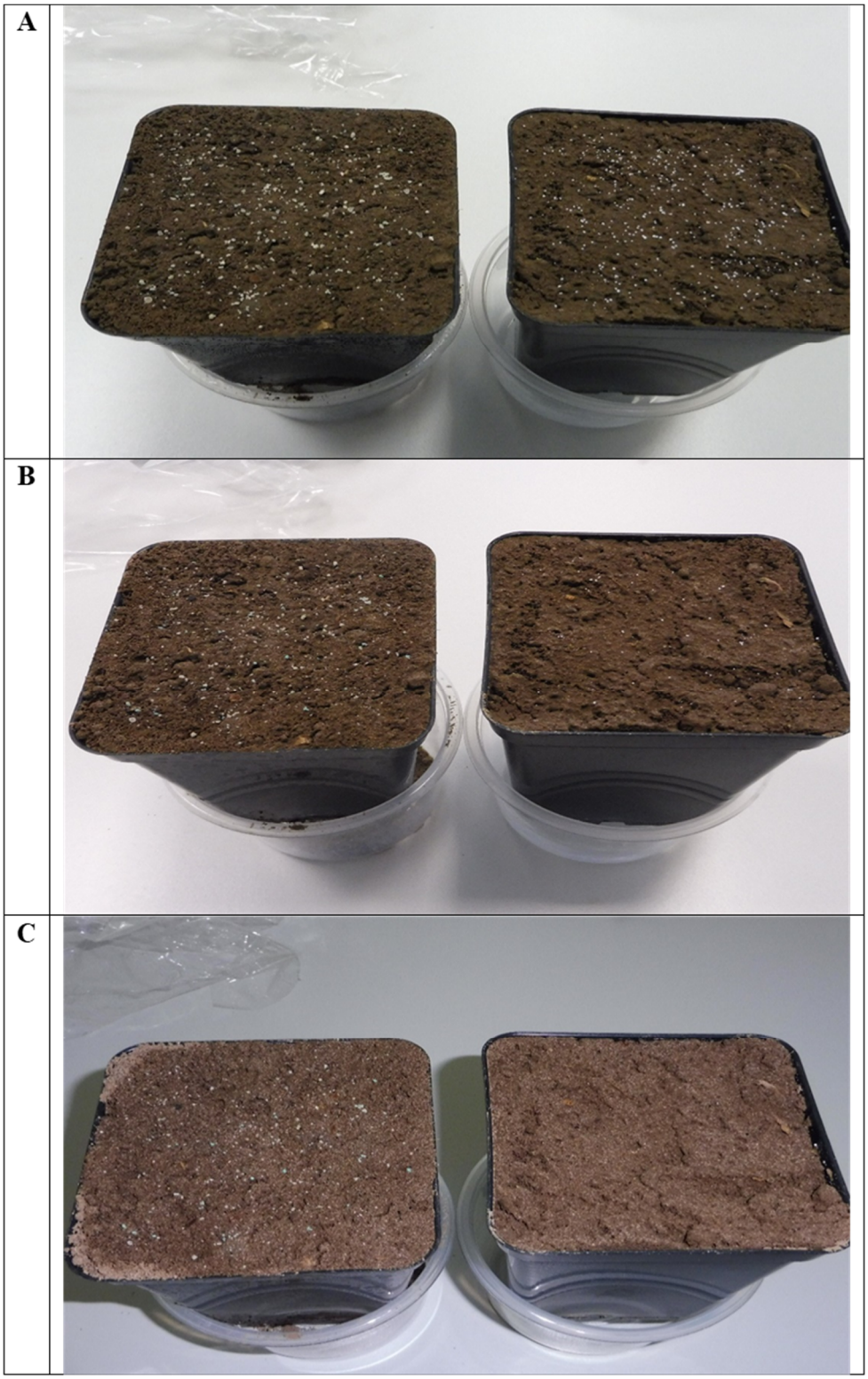

Figure 3. Solubility of Cereal fertiliser microgranules with gelling agent on moist soil ((**A**)—immediately after application, (**B**)—4 h after application, and (**C**)—6 h after application); left, fertiliser with gelling agent; right, without gelling agent.

Table 3. Soil moisture (% vol.) in the soil layer to which microgranulated fertilisers were applied.

Test	Gelling Agent in Fertiliser	Fertiliser		
		Cereals	Maize	Oilseed
Laboratory	with agent	13.8 a *	14.3 a	14.4 a
	without agent	11.1 b	10.8 b	10.7 b
	no fertiliser	10.8 b	10.9 b	10.5 b
Field	with agent	14.6 a	11.9 a	9.5 a
	without agent	12.2 b	10.0 b	9.0 a
	no fertiliser	12.3 b	10.2 b	9.3 a

*—the letters being the same in the laboratory column as in the field test column for a given fertiliser indicates a lack of statistically significant differences.

In the laboratory tests, microgranulated fertilisers both with and without the gelling agent significantly increased the population of bacteria, actinobacteria, and filamentous fungi compared to the unfertilised soil. Under the influence of the Oilseed fertiliser with the gelling agent, the abundance of fungi in the soil was significantly higher than after applying the same fertiliser without the gelling agent (Table 4). Under the influence of fertilisers with a gelling agent, the abundance of cellulolytic, amylolytic, and proteolytic microorganisms in the soil increased compared to the unfertilised soil. Compared to the fertiliser without the gelling agent, the Cereal fertiliser with the gelling agent significantly increased the abundance of proteolytic microorganisms, the Oilseed fertiliser increased the abundance of cellulolytic and amylolytic microorganisms, and the Maize fertiliser increased all three groups of microorganisms.

Table 4. Abundance of microorganisms after 4 weeks of soil incubation with microgranulated fertilisers with gelling agent.

Microorganisms	Unit	Gelling Agent in Fertiliser	Fertiliser		
			Cereals	Maize	Oilseed
Total bacteria	cfu × 10^6	with agent	13.4 a *	12.9 a	13.3 a
		without agent	13.1 a	12.9 a	13.1 a
		no fertiliser	11.4 b	11.4 b	11.4 b
Actinobacteria	cfu × 10^5	with agent	33.6 a	33.9 a	33.4 a
		without agent	33.7 a	33.5 a	33.3 a
		no fertiliser	30.5 b	30.5 b	30.5 b
Filamentous fungi	cfu × 10^4	with agent	39.4 a	38.9 a	39.4 a
		without agent	38.6 a	38.1 a	38.4 b
		no fertiliser	36.3 b	36.3 b	36.3 c
Cellulolytic microorganisms	cfu × 10^5	with agent	17.2 a	17.0 a	16.9 a
		without agent	16.7 a	16.4 b	16.2 b
		no fertiliser	15.5 b	15.5 c	15.5 c
Amylolytic microorganisms	cfu × 10^5	with agent	5.9 a	5.9 a	6.0 a
		without agent	5.6 ab	5.5 b	5.5 b
		no fertiliser	5.4 b	5.4 b	5.4 b
Proteolytic microorganisms	cfu × 10^5	with agent	10.1 a	9.8 a	9.5 a
		without agent	9.4 b	9.2 b	9.5 a
		no fertiliser	7.8 c	7.8 c	7.8 b

*—the letters being the same in the laboratory column as in the field test column for a given group of microorganisms indicates a lack of statistically significant differences.

Every microgranulated fertiliser with the gelling agent significantly increased the mass of the above-ground part of three-week-old plants compared to the unfertilised plants (Figure 4). At the same time, the mass of spring barley and winter rapeseed plants under

the influence of fertilisers with the gelling agent was significantly higher than the mass of plants fertilised with appropriate fertilizers lacking a gelling agent.

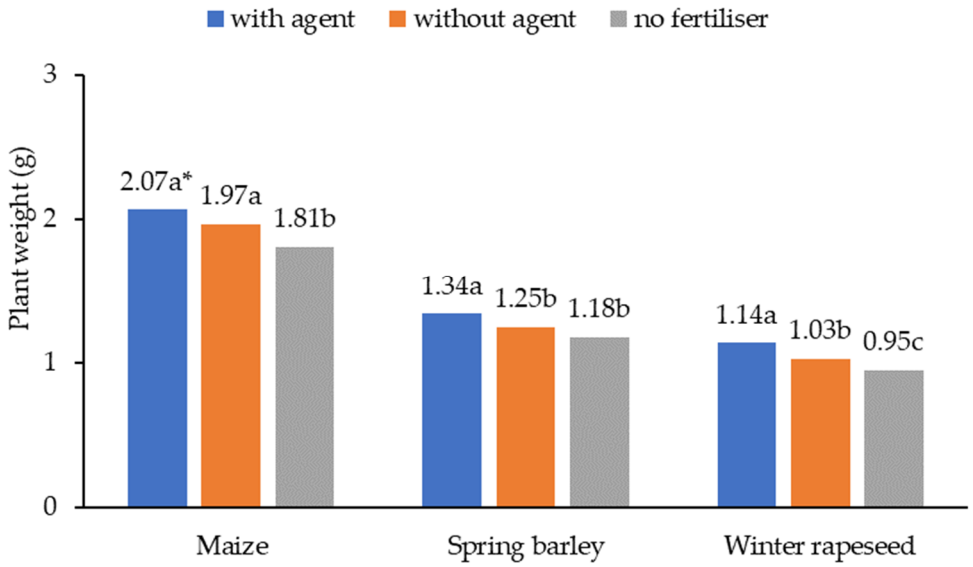

Figure 4. Plant seedling weight by presence of gelling agent in microgranulated fertiliser (with agent, without agent); *—the letters being the same in columns of results for a given crop indicates a lack of statistically significant differences.

3.2. Field Experiment

Plant cultivation technology, including varied soil tillage methods and the application of microgranulated fertilisers, significantly modified the soil water resources available to plants from the beginning of their vegetation period (Figure 5). After sowing the maize, the water content in the upper soil layer, i.e., 0–20 cm, was highest in the strip-till plots, regardless of whether microgranulated fertilisers were applied. Such plots contained about 100 m^3/ha more water than those tilled conventionally with a plough. Strip-till combined with fertilisation and the sowing of spring barley and winter rape performed in a single pass of a machine resulted in soil water resources also being significantly higher than after ploughing. None of the microgranulated fertilisers with a gelling agent increased the water resources in the soil to a significantly greater extent than did the fertilisers without the gelling agent. However, the water resources in the soil in plots where fertilisers with a gelling agent were used in the cultivation of maize, spring barley, and winter rapeseed was, respectively, 5.9 m^3/ha, 10.2 m^3/ha, and 12.6 m^3/ha higher than after the application of fertilisers without the additive.

The CO_2 emission from the soil was highest in the first measurement period, immediately after intensive ploughing, and in the second measurement period, after tillage with simultaneous sowing via strip-till technology. In the first measurement period, the differences in CO_2 emissions from the soil between plots was associated only with the differences in the soil tillage method and uncontrolled environmental factors. In this period, there was no possible impact of microgranulated fertilisers because the date of measurement preceded the fertiliser application (Table 5). At each subsequent measurement date, regardless of the application of microgranulated fertilisers, the amount of CO_2 released from the plough-cultivated soil was significantly higher than from the strip-tilled soil. In the second to fourth periods, neither the use of microgranular fertilisers nor the presence of the gelling agent in them was found to have any significant effect on the CO_2 emissions from the soil.

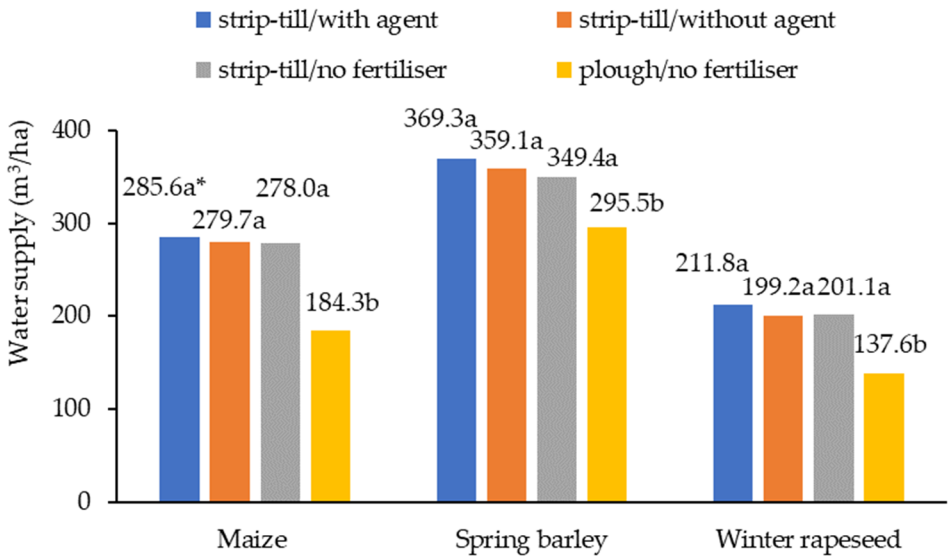

Figure 5. Water supply in the soil immediately after sowing plants, by soil tillage method (strip-till, plough) and application of microgranulated fertilisers with gelling agent (with agent, without agent); *—the letters being the same in columns of results for a given crop indicates a lack of statistically significant differences.

Table 5. CO_2 emission from soil (mg $CO_2/m^2/h$), by soil tillage method and application of microgranulated fertilisers with gelling agent.

Crop	Tillage Method/Gelling Agent in Fertiliser	Measurement Date			
		I	II	III	IV
Maize	strip-till/with agent	286 a *	473 a	322 a	275 a
	strip-till/without agent	274 a	482 a	313 a	288 a
	strip-till/no fertiliser	292 a	459 a	330 a	282 a
	plough/no fertiliser	614 b	511 b	447 b	361 b
Spring barley	strip-till/with agent	194 a	406 a	276 a	249 a
	strip-till/without agent	185 a	398 a	270 a	252 a
	strip-till/no fertiliser	201 a	422 a	281 a	239 a
	plough/no fertiliser	478 b	459 b	350 b	308 b
Winter rapeseed	strip-till/with agent	174 a	363 a	175 a	211 a
	strip-till/without agent	163 a	351 a	171 a	203 a
	strip-till/no fertiliser	170 a	349 a	184 a	204 a
	plough/no fertiliser	745 b	442 b	287 b	338 b

*—the letters being the same in columns of results for a given crop indicates a lack of statistically significant differences.

The pre-flowering biomass of strip-tilled spring barley and winter rapeseed was higher than that sown after ploughing. However, the weight of the above-ground parts of strip-tilled and conventionally ploughed maize plants did not differ significantly from one another (Figure 6). Microgranulated fertilisers with the gelling agent applied during sowing increased the pre-flowering mass of plants compared to the plants also grown using strip-till technology but either with microgranulated fertiliser without the gelling agent or without microgranulated fertiliser. Only the biomass of winter rapeseed after the application of Oilseed fertiliser with and without the gelling agent did not differ significantly from one another.

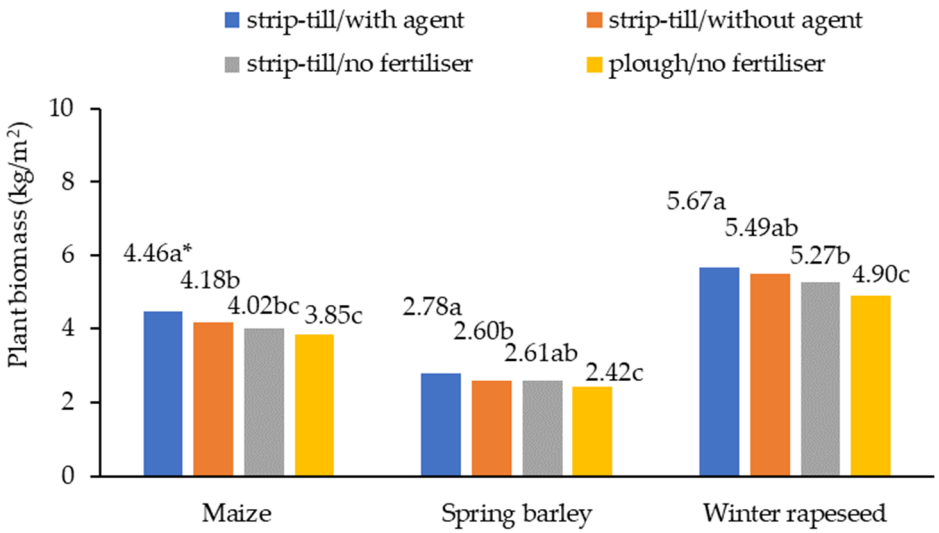

Figure 6. Pre-flowering plant biomass, by soil tillage method (strip-till, plough) and application of microgranulated fertilisers with gelling agent (with agent, without agent); *—the letters being the same in columns of results for a given crop indicates a lack of statistically significant differences.

The yield of each crop grown using conventional technology with ploughing and without microgranulated fertiliser was significantly lower than the yield of crops sown in strip-till (Figure 7). The application of microgranular fertiliser with a gelling component as compared to the fertiliser without the additive resulted in a significant increase in the yield of maize grain only. Each fertiliser with a gelling component, i.e., Maize, Grain, and Oilseed, increased the yield of maize, spring barley, and winter rapeseed, respectively, compared to the plants not fertilised with these fertilisers.

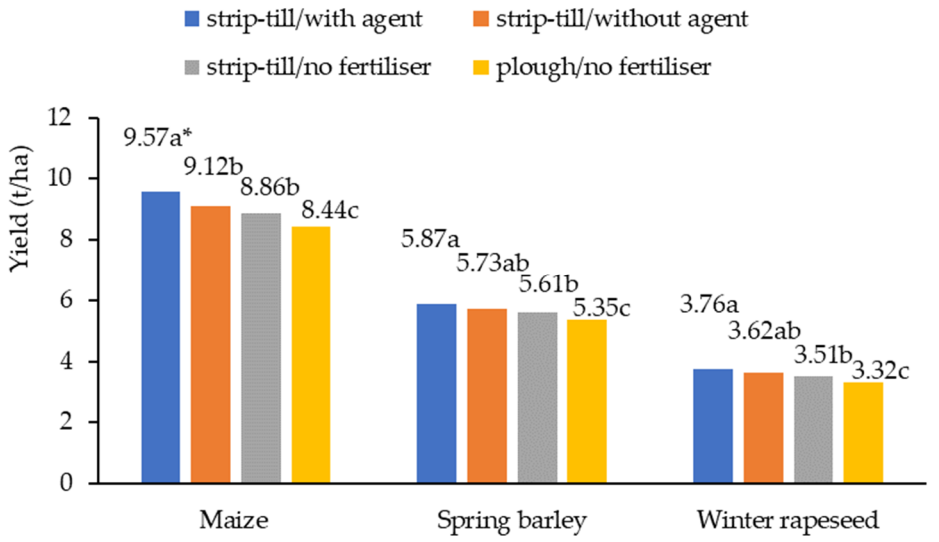

Figure 7. Crop yields, by soil tillage method (strip-till, plough) and application of microgranular fertilisers with gelling agent (with agent, without agent); *—the letters being the same in columns of results for a given crop indicates a lack of statistically significant differences.

After harvesting the crops grown conventionally with ploughing, there were significantly fewer microorganisms of all groups in the soil than after strip-till, regardless of whether microgranulated fertilisers were applied and regardless of their composition (Table 6). As compared to microgranulated fertilisers with no gelling agent, there were significant increases in the abundances of filamentous fungi and amylolytic microorganisms for the Maize microgranulated fertiliser with the gelling agent in the plots after maize

harvesting; filamentous fungi for the Cereal fertiliser in the spring barley plots after harvest; and total bacteria and cellulolytic and amylolytic microorganisms for the Oilseeds fertiliser in the plots after winter rapeseed harvesting. However, the same fertilisers, but without the gelling agent, increased the abundances of some microorganism groups in the soil compared to the strip-tilled soils not fertilised with microgranules. In these plots, after harvesting maize, there were more filamentous fungi and proteolytic microorganisms; in the plots after harvesting spring barley, there were more actinobacteria and cellulolytic microorganisms; and in the soil after harvesting winter rapeseed, there were more total bacteria and proteolytic microorganisms.

Table 6. Abundances of microorganisms in soil after harvest, by tillage method and application of microgranular fertilisers with gelling agent.

Microorganisms	Unit	Tillage Method/Gelling Agent in Fertiliser	Crop		
			Maize	Spring Barley	Winter Rapeseed
Total bacteria	cfu × 10^6	strip-till/with agent	2.63 a *	3.24 a	4.11 a
		strip-till/without agent	2.63 a	3.15 ab	3.88 b
		strip-till/no fertiliser	2.54 a	3.08 b	3.65 c
		plough/no fertiliser	2.26 b	2.91 c	3.20 d
Actinobacteria	cfu × 10^5	strip-till/with agent	6.33 a	4.83 a	4.57 a
		strip-till/without agent	6.17 a	4.86 a	4.44 ab
		strip-till/no fertiliser	6.26 a	4.67 b	4.26 b
		plough/no fertiliser	5.84 b	4.02 c	3.83 c
Filamentous Fungi	cfu × 10^4	strip-till/with agent	9.04 a	23.3 a	12.3 a
		strip-till/without agent	8.18 b	21.6 b	11.8 a
		strip-till/no fertiliser	7.41 c	21.9 b	11.7 a
		plough/no fertiliser	6.63 d	20.2 c	10.7 b
Cellulolytic microorganisms	cfu × 10^5	strip-till/with agent	6.67 a	17.6 ab	7.61 a
		strip-till/without agent	6.41 ab	17.8 a	7.29 b
		strip-till/no fertiliser	6.10 b	16.8 b	7.04 b
		plough/no fertiliser	5.09 c	14.6 c	5.81 c
Amylolytic microorganisms	cfu × 10^5	strip-till/with agent	3.65 a	6.51 a	6.02 a
		strip-till/without agent	3.37 b	6.23 a	5.70 b
		strip-till/no fertiliser	3.40 b	6.26 a	5.66 b
		plough/no fertiliser	3.06 c	5.67 b	5.12 c
Proteolytic microorganisms	cfu × 10^5	strip-till/with agent	4.84 a	8.36 a	9.14 a
		strip-till/without agent	4.89 a	8.55 a	9.01 a
		strip-till/no fertiliser	4.37 b	8.29 a	8.55 b
		plough/no fertiliser	3.90 c	7.36 b	7.47 c

*—the letters being the same in columns of results for a given group of microorganisms for a given crop indicates a lack of statistically significant differences.

4. Discussion

Observations and research results from recent decades confirm far-reaching unfavourable environmental changes both on a global scale and in various regions of the world, resulting in reduced agricultural productivity, lower quality of agricultural produce, and threats to the food security of the human population [58,59]. However, the response of agriculture to these changes is ambiguous. Negative effects can be reduced and positive ones enhanced, but this requires that current agricultural practices be adapted to the amount of atmospheric CO_2 and to the water and thermal conditions [60]. It is therefore justified to promote and implement conservation agriculture practices, especially in regions where intensive agriculture dominates. In European countries, especially in Poland, such practices account for a relatively small area to date [61,62]. Our own research was conducted in an area with a large rainfall deficit for field crop production. According to Kuśmierek-Tomaszewska and Żarski [63], the frequency of meteorological droughts in the period of intensive plant vege-

tation in central Poland is about 30.0%. However, the frequency of extreme droughts is 6.7%. In this region, as in Central Europe, dry periods occur mainly in spring and summer [64]. Water shortages for plants are exacerbated by rising air temperatures. Their increase in recent decades (1961–2018) is estimated at 0.33 °C per 10 years. The greatest temperature increase has occurred in the summer months, with a July increase of 0.48 °C per 10 years. A slightly smaller increase in temperature is observed in the winter months (0.46 °C per 10 years for January) and spring months (0.41 °C per 10 years for April) [65]. Therefore, the fact that strip-till cultivation is being increasingly implemented and popularised in this region should be considered positive [66].

The researched agricultural practices, I.e., strip-till and the application of microgranular starter fertilisers in accordance with the adopted research assumption, had a positive effect on some soil properties that are important factors in plant productivity. According to Maharjan et al. [67], an agro-ecosystem assessment of soil cultivation should take into account its impact on, among other things: soil bulk density, soil aggregates and structure, porosity, hydraulic properties, content of soil organic matter and nutrients, plant residues, weed diaspores, diversity and activity of soil organisms, and biochemical properties. Abandoning ploughing and field-wide soil fertilisation followed by sowing in multiple successive agrotechnical treatments in favour of a single pass of a multifunctional machine implementing strip-till technology had a positive effect on the soil properties in our own research. As a result of the use of this technology, water resources in the soil increased during the sowing and emergence of winter and spring plants, and CO_2 emissions from the soil decreased. As compared to conventionally-cultivated crops, the post-harvest soil of strip-tilled crops were more abundant in bacteria, actinobacteria, filamentous fungi, and cellulolytic, amylolytic, and proteolytic microorganisms. Reducing loosening, and especially eliminating ploughing with a mouldboard plough, improves the soil water conditions. Abdallah et al. [68] emphasise that conservation agriculture practices significantly reduce the evaporation from the soil surface. Mulch also helps reduce water losses from the soil [69,70]. In strip-till, inter-rows are mulched, and they account for up to two thirds or more of the field area [71,72]. Mulch on the surface and the higher water content in the soil keep the temperature lower, further reducing the water evaporation [73]. Licht and Al-Kaisi [74] indicate that the deep loosening of soil strips, unlike no-till, accelerates the warming of the soil, which, due to the excessive moisture, may be too cold for plant germination and emergence. The difference in the soil temperature in the upper 5 cm layer may be 1.0–1.4 °C. In turn, according to Blanco-Canqui et al. [75], deep soil loosening, e.g., in ploughing, increases water infiltration, and no-till cultivation does not always have a positive effect on the total porosity, hydraulic conductivity, or water retention in the soil.

A reduction in conventional tilling is associated with reduced soil respiration [76]. Soil CO_2 emissions depend on the tillage method and are generally lower in ploughless systems. A several-fold increase in CO_2 emissions from the soil in the first hours after its cultivation is indicated by Bregaglio et al. [77]. Al-Kaisi and Yin [78] found that for 20 days after soil tillage, total CO_2 emission was 26% lower after strip-tilling than after ploughing. In our own research, replacing conventional tillage with strip-till resulted in a greater than four-fold reduction in the emission of this greenhouse gas at the time of ploughing before sowing winter rape and a more than two-fold reduction in the same emissions during loosening tilling for maize and spring barley. The lower CO_2 emissions from the soil after strip-tilling also persisted in the later period. Twenty days after sowing the maize, spring barley, and winter rapeseed it was, respectively, 21.9%, 22.6%, and 39.6% lower than after ploughing.

Conservation tillage practices affect the soil composition and microbial diversity [79]. The reduced mechanical intervention in the soil, mulching, increased carbon sequestration, smaller changes in the amount and temperatures of water and air that typify conservation soil cultivation create favourable conditions for microorganisms [80,81]. Strip-till, like other methods of ploughless cultivation, usually increases the presence and activity of microorganisms in the soil [82,83]. In our own research, the number of total bacteria, acti-

nobacteria, filamentous fungi, and cellulolytic, amylolytic, and proteolytic microorganisms in the strip-tilled soil was significantly higher than in the soil after ploughing. The relative differences in bacteria abundances in the three consecutive years was 12.4%, 5.8%, and 14.1%—and 11.8%, 8.4%, and 9.3% for fungi. The abundances of some groups of microorganisms in strip-tilled soil depended on the type of starter fertiliser used. The addition of a gelling agent that changed the hydration of the microgranules and the moisture content of the adjacent soil layer, as demonstrated in the pot experiments, increased the number of filamentous fungi in the soil after the harvesting of maize and spring barley, and of the total bacteria and cellulolytic and amylolytic microorganisms after the harvesting of winter rapeseed. According to Mackay et al. [84], the composition of microbial communities in strip-tilled soil is similar to the composition of microbial communities in no-till soil, but it differs from the conventional tillage. The differences in microbial communities result from the differences in the carbon sources and pH of soils cultivated using different methods. The presence of specific groups of microorganisms is also influenced by many other abiotic factors, including fertilisation and the soil nutrient contents [85,86].

Given the current challenges facing modern agriculture, not only should new-generation fertilisers be a source of nutrients, but they should also have the capacity for a greater efficiency of use and reduce possible negative environmental impacts. Such functions are fulfilled via microgranulated starter fertilisers placed into a single sowing furrow along with seeds [87,88]. These fertilisers, which contain additional ingredients that, for example, slow the release of ingredients and influence soil properties and/or plant growth, are called "smart fertilisers" [89,90]. Such ingredients include hydrophobic matrix material, hydrophilic hydrogel, or poorly soluble inorganic compounds [91,92]. In our own research, as in the study [93,94], fertilisers contained an ingredient that had the ability to absorb large amounts of water and release it over a long time. The absorption of water by these fertilisers in the amount of >120% of the fertiliser mass and their keeping it within the granules explains why they remained on the surface of moist soil for 60–70 h and the 3–4 p.p. higher volumetric soil moisture in the pot tests compared to the use of fertilisers without the gelling agent. The weaker impact of these fertilisers on the soil water properties in the field conditions was probably due to the lower concentration of the fertiliser relative to the soil mass.

Laboratory tests and field experiments confirmed the possibility of adding gelling agents to the fertilisers indicated by Sarmah and Karak [95], not only to improve soil properties, but also to stimulate plant growth. The cited authors, after adding a superabsorbent hydrogel modified with starch in an amount of 0.25% to the soil, found a 120% increase in the soil's water retention capacity and an impact on the soil bulk density and porosity. Hydrogel applied with urea also increased the growth rate of chickpeas (*Cicer arietinum*). In our own research, the seedlings of corn and winter rapeseed grown in the presence of microgranulated fertilisers in the soil had a greater mass than those grown without fertiliser. However, the same fertilisers with the additional gelling agent increased the weight of seedlings of all tested plant species in the pots, as well as the pre-flowering weight of plants grown in the field conditions using strip-till technology. This technology allows similar or even higher yields to be obtained for lower expense and less environmental impact than conventional technology that used ploughing as the basic soil tillage, including in the region of the world where our own research was carried out [20,96–98]. Our research confirmed higher yields of maize, spring barley grain, and winter rapeseed grown under strip-till than using conventional technology. The yields of these plants were highest when microgranular fertilisers, especially those with a gelling component, were applied at the same time as sowing. Microgranulated fertiliser was also found to have a beneficial effect on the yield of winter rapeseed by Jankowski et al. [99], of wheat and barley by Bartzialis et al. [100], and of maize by Balawejder et al. [101]. These last cited authors indicate that the beneficial effect of the fertiliser on the growth and yield of maize did not result directly from the amounts contained in the nutrients, but from the mechanism of the fertiliser's action on the

soil and plants. Fertiliser containing protein fractions increased maize resistance to water stress during its vegetation period.

5. Conclusions

The challenge for modern intensive agriculture is to introduce alternative practices that can meet the food needs of a growing human population while reducing the environmental pressure in the changing climate conditions. One technology that can replace conventional crop cultivation that includes ploughing soil seems to be strip-till one-pass technology. According to the literature and previous research by the authors, this low-cost and environmentally friendly technology of soil tillage, fertilisation, and sowing in one pass of a multifunctional machine can provide similar or even higher yields than conventional cultivation with mouldboard ploughing. The present research confirmed higher productivity of both winter and spring plants with different sowing dates in a region with a high risk of drought. It was also shown that this technology allows basic soil fertilisers but also microgranulated fertilisers to be applied. These "smart" fertilisers containing a gelling agent improve the soil water conditions, biomass production, and plant yields. The cumulative effect of strip-till and microgranulated fertilisers, especially with the gelling agent, was expressed in a larger water supply in the soil, lower CO_2 emissions from the soil to the atmosphere and, in terms of the plants themselves, a higher mass of vegetative parts and seeds than the plants cultivated after ploughing. Innovative plant cultivation technologies with strip-till cultivation and the simultaneous application of microgranular fertilisers with a gelling agent also create conditions favourable to the soil microbiome. As a result of their use in the cultivation of maize, spring barley, and winter rape, the number of bacteria, actinobacteria, filamentous fungi, and cellulolytic, amylolytic, and proteolytic microorganisms in the soil increased. Strip-till and microgranulated fertilisers—especially those containing additives that increase the use of nutrients, improve soil properties, and stimulate plant growth—can be a production-effective, pro-environmental alternative to the current agricultural practices.

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