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Reduced Tillage, Application of Straw and Effective Microorganisms as Factors of Sustainable Agrotechnology in Winter Wheat Monoculture

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Abstract: In the aspect of the sustainable development of agrocenoses, the proper management of plant residues remaining after harvesting, the appropriate selection of tillage and maintaining high microbiological activity of soil are particularly important. Therefore, a four-year two-factor experiment with winter wheat monoculture was conducted. The objective of this study was to compare the effects of 18 cultivation technologies variants on weed infestation and yield structure of winter wheat grown in a 4-year monoculture. Six methods of tillage and management of residues after harvesting forecrops (first factor) and the use of microbiological preparations (second factor) were tested. The experiment showed that simplified tillage (elimination of plowing) had an adverse effect on the weed infestation of the field and most of the tested plant characteristics, including the yield. In terms of yield, the best solution was to leave the forecrop straw mulch on the field surface until plowing was carried out before sowing, regardless of the use of microbiological preparations. The application of preparations containing effective microorganisms brought beneficial effects only when the shredded straw of the forecrop was mixed with the soil using a grubber.

Keywords: crop production; sustainable agriculture; post-harvest residues; weed infestation

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1. Introduction

Wheat is one of the most important crops for global food security, both in the developing as well as in the developed world [1–3]. In some countries, the area under wheat is so large that it is grown in monoculture or cereal rotations [4–6]. Cereal monocultures result in deterioration of the biological properties of the soil [7–9]. Moreover, they lead an to increased occurrence of pests and fungal diseases, which in turn results in increased costs of canopy protection and reduced yield [10,11].

Taking into consideration the growing world population, there is an increasing demand for food production [12,13]. Moreover, population growth will force us to limit animal production and increase human consumption of crop foods [14,15]. This direction of change, although it will help to meet the food needs of the human population, will result in a decrease in farm animals' number and, as a consequence, a reduction in the production and use of farmyard manure. As a result of such changes, a deterioration of the biological properties of the soil may be expected [16–18]. Therefore, to maintain a high level of soil productivity and on the other hand sustainable agrotechnology, it is necessary to look for alternative methods to improve its biological activity. The use of preparations containing effective microorganisms may be an important factor to achieve these goals [19–21]. Also, post-harvest residues of previous crops, straw incorporation and especially green manure from catch crops have a very positive effect on biological soil activity and let us maintain sustainable agrotechnology, even in conditions without using farmyard manure [22–24]. Improving the soil biological properties, connected with mulching the soil, leads to positive changes in soil physical properties. This is important especially in soils with reduced tillage, where straw mulch may decrease bulk density and increase its porosity [25]. Moreover, straw mulching has the potential to increase soil water storage in conditions with low precipitation [25,26]. Under conditions of high rainfall, straw mulching can significantly reduce erosion processes on the soil surface [27].

Mulching the soil with straw or green manure enables us to improve soil conditions for wheat growth and as a result avoid the yield reduction often caused by reduced tillage [25,28]. The straw mulch leads to an improvement in soil chemical properties through increasing the concentration of available forms of macronutrients (N, P, K) and organic carbon in the top layers of soil [29–31]. According to Shao et al. [32], nutrients from straw mineralization may be an effective source of nitrogen, phosphorus and potassium, replacing 10% N, 9% P_2O_5 and 58% K_2O from fertilizer application.

The negative aspects of mulching the soil with straw include the possibility to increase pests and diseases infestation in main crops [25,33,34]. Shao et al. [32] stated that incorrect direct straw-returning practices may have negative effects for crop health and the number of pests and may also reduce the crop germination rate. However, the results of research on this issue are not clear. In the study by Silva-Filho et al. [35], a decrease in *Myzus persicae* landing on the kale plants was stated. The authors explained it by the higher temperature in the mulched plots, as well as the physiological changes in the kale plants.

A significant problem occurring in cereal crop rotations and monocultures is the excessive development of weeds [36,37]. Weeds may be strong competition for wheat and significantly reduce grain yield [38–40]. According to Minhas et al. [41], the soil tillage system is an important factor influencing weed infestation. Zero tillage promotes weed infestation due to minimum soil disturbance, whereas conventional tillage technique suppresses it. Factors improving biological soil properties may be useful in reducing weed infestation. According to Lamparski and Kotwica [42], in cereal crop rotation, effective microorganisms help with the degradation of shredded straw applied during post-harvest tillage. As a result, a reduction in weed infestation occurs.

The hypothesis assumed is that testing many various tillage methods and straw management combined with the application of microbiological preparations will allow us to choose the optimal variant of winter wheat monoculture agrotechnology. In the context of this hypothesis, the objective of this study was to compare the effects of 18 cultivation technologies variants on the weed infestation and yield structure of winter wheat grown in a 4-year monoculture.

2. Materials and Methods

2.1. Experiment Site

The presented material is part of broader research located in the same place. Part of the results regarding spring wheat have been published [19] in the same Special Issue "Approaches to Promote Wider Emergence of Sustainable Agricultural Production" of Agronomy. The second part regarding winter wheat is the subject of this publication. Due to the above, some elements of the methodology of both studies are the same—this includes the location of the experience and weather conditions. The spatial design of the experiment and the size of the plots were also the same.

The field experiment was located in Central Europe (52°55′58″ N 18°05′55″ E). The research lasted four growing seasons and was carried out in 2010–2014. It was a static experience—carried out throughout the entire research cycle in the same place. The experiment was located on Luvisol soil [43]: sand 41.4%, silt 52.3%, clay 6.3%.

2.2. Experiment Design

The experiment was located for four years in exactly the same place—winter wheat monoculture. The field experiments were carried out in the randomized split-plot design, with four replications. A single plot area was 200 m^2 (8 m × 25 m).

Experimental factors:

Factor A—tillage method and straw management (the text also uses the abbreviation "tillage method" interchangeably):

- Crushed straw + post-harvest grubber + plowing—A1;
- Crushed straw + post-harvest grubber + before sowing grubber—A2;
- Straw mulch + plowing—A3;
- Straw mulch + grubber—A4;
- Straw removed (stubble), no tillage (direct sowing)—A5;
- Straw removed + grubber + plowing (traditional tillage—control)—A6.

Factor B—applying microbiological preparations:

- EM-1 (B1);
- UG_{max} (B2);
- Control—without the use of microbiological preparations (B3).

In total, there were 18 experimental objects. The experiment was carried out in 4 replications, giving 72 experimental plots. In each of the four years of the experiment, each object was located in exactly the same place—a static experiment.

Explanations:

- Crushed straw—in 2010, winter rapeseed straw, in subsequent years winter wheat straw; crushed during harvesting by a harvester;
- Crushed straw + post-harvest grubber—crushed straw of the forecrop mixed with the soil using a grubber to a depth of 25 cm. Performed immediately after harvesting the forecrop;
- Before sowing grubber—grubber applied two weeks before sowing (second week of September);
- Grubber—Grubber Lemken Terra Cult vibro;
- Plowing—plowing to a depth of 20 cm in the second week of September; Kverneland EM 100 reversible plow/4 furrow/with Packomat;
- Mulch—shredded forecrop straw left on the soil surface;
- Straw removed (stubble)—straw collected and transported outside the field;
- No tillage (direct sowing)—the soil was not disturbed from harvesting the forecrop to sowing. Sowing was performed directly into the stubble field. Horsch seeder equipped with disc coulters and kneading rollers was used;
- EM-1—application 20.0 $dm^3 \cdot hm^{-2}$ on crushed straw or stubble—https://greenland.pl/produkt/preparat-em-1/, accessed on 27 March 2024;
- UG_{max}—application of 1.0 $dm^3 \cdot hm^{-2}$ on crushed straw or stubble—http://bogdan.agro.pl/, accessed on 27 March 2024.

2.3. Precipitation and Air Temperature

The distribution of temperature and precipitation in the years of research was determined based on the results of standard meteorological measurements. The sums of monthly average air temperatures in the years 2010–2014 were referred to the period 1949–2009 and presented in the form of deviations (Table 1). Similarly, monthly rainfall totals from 2010 to 2014 were compared to averages from 1949 to 2009 (Table 2).

The precipitation and air temperature presented in Tables 1 and 2 were commented on in more detail in a previously published manuscript based on the same series of experiments [19].

2.4. Elements of Agrotechnical Practises

Certified seed material of winter wheat variety 'Bogatka' was sown at a density of 400 grains$\cdot m^2$ at the turn of September and October at a spacing of 10.2 cm, to a depth of 4 cm. For sowing, a 4 m (working width) cultivation and sowing unit with an active cyclotiler section and a Horsch seeder equipped with disc coulters and kneading rollers was used. During direct sowing, the active sections of the cyclotiler were disconnected.

Table 1. Average monthly temperatures [°C] in the years of study and deviations from the years 1949–2009.

	Years					Means	Deviations from the Long-Term Means				
Months	**2010**	**2011**	**2012**	**2013**	**2014**	**1949–2009**	**2010**	**2011**	**2012**	**2013**	**2014**
January	−7.7	−0.5	−0.1	−3.5	−3.0	−2.3	−5.4	1.8	2.2	−1.2	−0.7
February	−2.4	−5.2	−5.2	−0.9	2.1	−1.5	−0.9	−3.7	−3.7	0.6	3.6
March	2.2	2.1	4.5	−2.9	5.5	1.9	0.3	0.2	2.6	−4.8	3.6
April	7.8	10.5	8.4	7.0	9.9	7.4	0.4	3.1	1.0	−0.4	2.5
May	11.4	13.4	14.4	14.2	13.2	12.8	−1.4	0.6	1.6	1.4	0.4
June	16.7	17.7	15.2	17.3	16.0	16.2	0.5	1.5	−1.0	1.1	−0.2
July	21.7	17.6	18.8	18.8	21.5	18.0	3.7	−0.4	0.8	0.8	3.5
August	18.5	17.7	17.6	18.2	17.3	17.4	1.1	0.3	0.2	0.8	−0.1
September	12.2	14.3	13.3	10.7	14.3	13.2	−1.0	1.1	0.1	−2.5	1.1
October	5.6	8.4	7.5	8.2	9.7	8.2	−2.6	0.2	−0.7	0.0	1.5
November	4.1	2.6	4.5	4.8	4.3	3.1	1.0	−0.5	1.4	1.7	1.2
December	−6.9	2.7	−2.5	1.8	0.6	−0.5	−6.4	3.2	−2.0	2.3	1.1

Table 2. Monthly rainfall sums [mm] in the years of study and deviations from the years 1949–2009.

	Years					Means	Deviations from the Long-Term Means				
Months	**2010**	**2011**	**2012**	**2013**	**2014**	**1949–2009**	**2010**	**2011**	**2012**	**2013**	**2014**
January	22.0	33.0	62.9	44.0	23.5	24.3	−2.3	8.7	38.6	19.7	−0.8
February	20.1	14.5	29.6	31.3	18.0	19.1	1.0	−4.6	10.5	12.2	−1.1
March	28.6	11.7	15.4	14.7	49.7	24.6	4.0	−12.9	−9.2	−9.9	25.1
April	33.8	13.5	26.5	13.6	40.7	27.6	6.2	−14.1	−1.1	−14.0	13.1
May	92.6	38.4	25.4	91.7	65.7	42.4	50.2	−4.0	−17.0	49.3	23.3
June	18.1	100.8	133.8	49.0	44.9	53.5	−35.4	47.3	80.3	−4.5	−8.6
July	107.4	132.5	115.6	79.0	55.4	71.6	35.8	60.9	44.0	7.4	−16.2
August	150.7	67.7	51.8	56.6	57.3	51.4	99.3	16.3	0.4	5.2	5.9
September	74.7	37.0	25.1	64.1	25.9	40.9	33.8	−3.9	−15.8	23.2	−15.0
October	2.3	13.2	40.3	18.6	18.0	33.3	−31.0	−20.1	7.0	−14.7	−15.3
November	115.0	9.0	53.7	28.5	24.5	31.8	83.2	−22.8	21.9	−3.3	−7.3
December	39.9	46.2	27.2	19.1	69.3	31.7	8.2	14.5	−4.5	−12.6	37.6

Before pre-sowing, mineral fertilization was applied: N—40 kg·hm^{-2} (ammonium sulphate), P_2O_5 30 kg·hm^{-2} (granulated superphosphate), K_2O—90 kg·hm^{-2} (potassium salt). In early spring, nitrogen was applied twice: in the BBCH 32 phase—80 kg·N·hm^{-2}, and in the BBCH 51 phase—60 kg·N·hm^{-2}.

Herbicyd Atlantis 12OD (0.45 dm^3·hm^{-2} iodosulfuron methyl sodium + mesosulfuron methyl) together + the Sekator 125OD (0.15 dm^3·hm^{-2} amidosulfuron + iodosulfuron methyl sodium) + Esteron 600EC (0.45 dm^3·hm^{-2} 2,4-D) was applied in the in autumn. In early spring, growth regulator Moddus 250 EC (0.8 dm^3·hm^{-2} trineksapak etylu), was applied in the BBCH 31–32 phase. Fungicide protection: Swing Top 183 SC (1.5 dm^3·hm^{-2} dimoksystrobina + epoksykonazol) applied in the BBCH 37–39 phase. Pesticides were applied using a sprayer AMAZONE UX5200 24 m.

2.5. Samples and Measurements

During the wheat growing season, biometric characteristics of plants from all plots were assessed: chlorophyll index SPAD[1], leaf area index (LAI)[2], ear density BBCH 89; after harvest: weight of a thousand grains, grains per ear, grain yield.

1. Yara N-tester™ https://www.yara.my/contentassets/6d5ba39b1a364a33be1e4e6b6b2a2be1/n-tester-instruction-manual.pdf/, accessed on 27 March 2024;
2. Plant canopy analyzer Li 2000 (Li Cor, Lincoln, NE, USA). https://licor.app.boxenterprise.net/s/q6hrj6s79psn7o8z2b2s, accessed on 27 March 2024.

2.6. Data Analysis

The data were subjected to statistical analysis—a two-way analysis of variance—separately for each growing season, and a synthesis was performed for the four years.

The ANOVA synthesis mixed model, i.e., with vegetation seasons—random, experimental factors—fixed has been used. The split-plot design model of ANOVA was used. The first-order factor was the management of organic matter before sowing and tillage; the second-order factor was the microbiological preparation. Tukey's post-hoc test ($LSD_{0.05}$) was used to assess the significance of differences between the mean values of each feature. The ANAWAR 5.3 statistical package based on Microsoft Office 2021 was used to statistically analyze the data.

3. Results

3.1. Significance of the Influence of Factors

Years of research (weather variability) have modified the impact of tillage on most of the measured features, i.e., weed infestation, chlorophyll index, leaf area index LAI, ear density, weight of a thousand grains and grain yield. However, the mixed model of synthesis ANOVA showed that, despite this variability, all winter wheat traits tested in the experiment were significantly determined by the tillage method (Table 3). However, there was no interaction of weather conditions with the microbiological preparations' application for any measured feature. A significant influence of the second tested factor, i.e., applying microbiological preparations, was found only for the chlorophyll index. However, the interaction of both factors was demonstrated in the case of total weed density, chlorophyll index SPAD, ear density, grains per ear and grain yield.

Table 3. Significance of the influence of factors and their interactions on the features of winter wheat plants.

Feature	Years × Factor		Factor		Years × Factor Interaction	Factor Interaction
	A	B	A	B		
Density of *Capsella bursa-pastoris*	+	−	+	−	−	−
Density of *Viola arvensis*	+	−	+	−	−	−
Density of *Stellaria media*	+	−	+	−	−	−
Density of *Chenopodium album*	+	−	+	−	−	−
Density of *Apera spica-venti*	+	−	+	−	−	−
Density of *Avena fatua*	+	−	+	−	−	−
Density of other weed species	+	−	+	−	−	−
Total weed density	+	−	+	−	−	+
Chlorophyll index SPAD (BBCH 33–44)	+	−	+	+	−	+
Chlorophyll index SPAD (BBCH 51–52)	+	−	+	+	−	+
Chlorophyll index SPAD—mean	−	−	+	+	−	+
Leaf area index LAI (BBCH 37–39)	−	−	+	−	−	−
Leaf area index LAI (BBCH 49–51)	−	−	+	−	−	−
Leaf area index LAI (BBCH 75–87)	−	−	+	−	−	−
Leaf area index LAI—mean	+	−	+	−	−	−
Ear density	+	−	+	−	−	+
Weight of a thousand grains	+	−	+	−	−	−
Grains per ear	−	−	+	−	−	+
Grain yield	+	−	+	−	−	+

(+)—significant impact; (−)—no significant impact.

3.2. Weed Infestation

The most abundant weed species were *Viola arvensis*, *Stellaria media*, and *Apera spica-venti;* these three weed species accounted for an average of 62.4% of all weeds (Table 4). Until the herbicide treatment, segetal vegetation was most numerous in the no-till variant A5, and its density was 2.13 times higher than in the control A6. There is a pronounced, although not always statistically confirmed, regularity that the facilities where the tillage variants with plowing (A1, A3, A6) were used were less infested with weeds than those without plowing. The indicated regularity of the influence of the tillage method is generally confirmed for most weed species. The most abundant weed was the *Viola arvensis*, and its average density was 28.5 pcs.m^{-2}. Its density was reduced most strongly by the use of plowing in the control variant A6, although it was not significantly lower than in the remaining facilities with plowing: A1, A3. Similar relationships were found for the second most abundant weed, *Stellaria media*. It should be noted, however, that while in the case of the no-plow tillage variants, the number of these species was very similar, in the case of the plowed variants, the number of *Stellaria media* was smaller than that of the *Viola arvensis*. *Chenopodium album* responded slightly differently to tillage, as its significant reduction compared to the other treatments was found in the control A6, where the density did not differ significantly only in comparison to the A1 variant. For clarification, it should be noted that the weed density was determined in the autumn of the year preceding the year of harvesting; hence, the years 2010–2013 are given in the Table 4 title and 2011–2014 in the case of other features.

Table 4. The influence of the tillage method for winter wheat on the number of weeds [pcs.m^{-2}], averages for 2010–2013.

Weed Species	Tillage Method and Straw Management						Mean	$LSD_{0.05}$
	A1	A2	A3	A4	A5	A6		
Viola arvensis	25.0 $_{CD}$ *	30.6 $_{ABC}$	26.8 $_{BCD}$	34.5 $_{AB}$	35.7 $_{A}$	18.3 $_{D}$	28.5	8.9
Stellaria media	19.4 $_{CD}$	29.9 $_{ABC}$	23.0 $_{BCD}$	31.9 $_{AB}$	35.0 $_{A}$	14.6 $_{D}$	25.6	11.5
Chenopodium album	7.9 $_{AB}$	11.1 $_{A}$	10.3 $_{A}$	10.6 $_{A}$	11.4 $_{A}$	4.5 $_{B}$	9.3	3.6
Apera spica-venti	16.8 $_{BC}$	27.6 $_{AB}$	17.8 $_{BC}$	31.4 $_{A}$	33.5 $_{A}$	13.9 $_{C}$	23.5	11.2
Avena fatua	5.2 $_{C}$	6.8 $_{ABC}$	5.6 $_{BC}$	8.6 $_{AB}$	9.5 $_{A}$	3.8 $_{C}$	6.6	3.1
Capsella bursa-pastoris	7.3 $_{BC}$	10.1 $_{AB}$	7.7 $_{BC}$	11.6 $_{A}$	13.1 $_{A}$	5.7 $_{C}$	9.3	3.6
Others	23.8 $_{ABC}$	19.9 $_{BC}$	23.0 $_{BC}$	25.3 $_{AB}$	28.4 $_{A}$	17.0 $_{C}$	22.9	6.3
Weeds Total	104.1 $_{CD}$	133.6 $_{ABC}$	112.4 $_{BCD}$	152.1 $_{AB}$	165.8 $_{A}$	77.7 $_{D}$	124.3	43.4

* The data marked with different letters (in the lines) were significantly different at $p = 0.05$, according to Tukey's test.

3.3. Chlorophyll Index SPAD

The experiments showed that the application of microbiological preparations significantly determined the SPAD index (Table 5). It was found that, on average, winter wheat plants treated with these preparations were characterized by higher values of this indicator compared to the control, i.e., without the application of microorganisms. It should be noted, however, that this resulted from the fact that the microbiological factor generated a significant difference only in the case when shredded forecrop straw was left in the field and mixed with the soil using a grubber. In the remaining variants of tillage and straw management, the application of microbiological preparations was insignificant for the SPAD index. These dependencies were confirmed in both dates of measurement of the indicator in question and in the case of average values. The obtained results indicate that in each of the terms, as well as on average for the terms, the highest values of the SPAD index were obtained for the tillage method A3, but they were at a similar level as when using traditional tillage (A6).

3.4. Leaf Area Index LAI

The leaf area index measured in three development phases of winter wheat, as well as on average for the phases, obtained the highest values for the A3 tillage variant (Table 6). However, it was best visible at the first marking date (BBCH 37–39). In the BBCH 49–51 phase, a similar effect was also achieved for the variant with traditional tillage (A6), and in the BBCH 75–87 phase (and for the mean) in the A1 variant. It should be recalled that in these variants (A1, A3, A6), the basic tillage procedure was plowing. In this comparison, in terms of the discussed feature, the lowest values were obtained in the variant with direct sowing A5, although statistically, on average it did not differ from the variants A2, A4 or A6.

Table 5. Values of the SPAD index of winter wheat in the BBCH 32–55 phase depending on the tillage methods and the application of microbiological preparations (average 2011–2014).

Applying Microbiological Preparations [B]	Management of Organic Matter before Sowing and Tillage [A]						Mean [A]
	A1	A2	A3	A4	A5	A6	
			BBCH 32–37				
EM	456 $_{ABa}$	441 $_{ABCa}$	504 $_{Aa}$	405 $_{BCa}$	382 $_{Ca}$	469 $_{ABa}$	443 $_{a}$
UG_{max}	474 $_{Aa}$	439 $_{ABa}$	496 $_{Aa}$	402 $_{BCa}$	370 $_{Ca}$	466 $_{ABa}$	441 $_{a}$
Control	406 $_{Cb}$	400 $_{Cb}$	497 $_{Aa}$	411 $_{BCa}$	378 $_{Ca}$	475 $_{ABa}$	428 $_{b}$
Mean [B]	445 $_{BC}$	427 $_{BCD}$	499 $_{A}$	406 $_{CD}$	377 $_{D}$	470 $_{AB}$	437
$LSD_{0.05}$ A = 53.6; B = 10.6; B/A = 35.0; A/B = 64.8							
			BBCH 51–55				
EM	501 $_{ABa}$	464 $_{BCa}$	568 $_{Aa}$	444 $_{BCa}$	419 $_{Ca}$	514 $_{ABa}$	485 $_{a}$
UG_{max}	513 $_{ABa}$	475 $_{BCab}$	569 $_{Aa}$	440 $_{BCa}$	419 $_{Ca}$	508 $_{ABa}$	487 $_{a}$
Control	446 $_{BCb}$	436 $_{Cb}$	572 $_{Aa}$	452 $_{BCa}$	417 $_{Ca}$	517 $_{ABa}$	473 $_{b}$
Mean [B]	487 $_{BC}$	458 $_{BCD}$	570 $_{A}$	445 $_{CD}$	418 $_{D}$	513 $_{AB}$	482
$LSD_{0.05}$ A = 63.7; B = 10.3; B/A = 34.6; A/B = 73.2							
			Mean				
EM	479 $_{ABCa}$	453 $_{ABCa}$	536 $_{Aa}$	425 $_{BCa}$	400 $_{Ca}$	491 $_{ABa}$	464 $_{a}$
UG_{max}	493 $_{ABa}$	457 $_{ABCDa}$	533 $_{Aa}$	421 $_{BCDa}$	395 $_{Da}$	487 $_{ABCa}$	464 $_{a}$
Control	426 $_{BCb}$	418 $_{BCb}$	535 $_{Aa}$	432 $_{BCa}$	398 $_{Ca}$	496 $_{ABa}$	451 $_{b}$
Mean [B]	466 $_{ABC}$	443 $_{BC}$	535 $_{A}$	426 $_{BC}$	398 $_{C}$	491 $_{AB}$	460
$LSD_{0.05}$ A = 83.7; B = 10.9; B/A = 24.9; A/B = 87.3							

Data marked with different capital letters indicate significant differences (p = 0.05) between the crop variants A1–A6 (horizontal comparison of means). Data marked with different lowercase letters indicate significant differences (p = 0.05) between microbiological preparations—EM, UGmax and control (vertical comparison of means).

Table 6. LAI index for winter wheat for development phases depending on tillage variants (average 2011–2014).

BBCH	Management of Organic Matter before Sowing and Tillage [A]						Mean	$LSD_{0.05}$
	A1	A2	A3	A4	A5	A6		
37–39	2.93 $_{B}$	2.86 $_{BC}$	3.31 $_{A}$	2.75 $_{BC}$	2.67 $_{C}$	2.94 $_{B}$	2.91	0.256
49–51	3.64 $_{BC}$	3.41 $_{CD}$	4.00 $_{A}$	3.46 $_{BC}$	3.19 $_{D}$	3.77 $_{AB}$	3.58	0.355
75–87	3.4 $_{AB}$	3.48 $_{A}$	3.52 $_{A}$	3.52 $_{A}$	3.22 $_{BC}$	3.16 $_{C}$	3.38	0.215
Mean	3.32 $_{AB}$	3.25 $_{BC}$	3.61 $_{A}$	3.24 $_{BC}$	3.03 $_{C}$	3.29 $_{BC}$	3.29	0.298

Data marked with different capital letters indicate significant differences (p = 0.05) between the crop variants A1–A6 (horizontal comparison of means).

3.5. Grain Yield Components

There was no significant effect of applying microbiological preparations on the elements of the yield structure; however, in the case of shaping the ear density and grain weight in the ear, an interactive effect of this factor with the management of organic matter before sowing and tillage was found (Table 7). However, this interaction was limited only to the significant impact of the application of microorganisms in conditions when shredded straw was mixed with soil in the field (A1 and A2). In these objects, a higher ear density was recorded after the application of EM and UG_{max} preparations than in the control (by 3.33% and 3.74%, respectively) and a significantly higher grain weight in the ear after the application of EM than in the control (7.44%).

In the case of ear density, the number of grains per ear and grain weight per ear, the highest values were obtained in the A3 tillage variant, although they were not always significantly higher than other variants. The diversity of ear density under the influence of different tillage methods reached 91 pcs.m^{-2}, i.e., 17.7%—the difference between A3 and A5. The analogous difference for the number of grains in the ear was 2.4 pcs. (7.1%). In the case of grain weight in the ear, extreme differences were noted between the objects A3 and A4 (0.11 g, i.e., 8.3%). In the case of grain size, the highest value was obtained for the A5 variant, although it did not differ significantly from the A3 variant.

Table 7. Values of the yield structure elements depending on the tillage variants and the application of microbiological preparations (average 2011–2014).

Applying Microbiological Preparations [B]	Management of Organic Matter before Sowing and Tillage [A]						Mean [A]
	A1	A2	A3	A4	A5	A6	
			Ear density [pcs.m^{-2}]				
EM	497_{ABa}	487_{ABa}	517_{Aa}	458_{BCa}	428_{Ca}	443_{Ca}	472_{a}
UG_{max}	499_{ABa}	483_{ABa}	513_{Aa}	462_{BCa}	421_{Ca}	441_{Ca}	470_{a}
Control	481_{ABb}	465_{BCb}	514_{Aa}	462_{BCa}	424_{Ca}	451_{BCa}	466_{a}
Mean [B]	492_{AB}	478_{ABC}	515_{A}	461_{BCD}	424_{D}	445_{CD}	469
$LSD_{0.05}$			A = 39.6; B = n.s. B/A = 15.9; A/B = 42.2				
			Grains per ear [pcs.]				
Mean [B]	33.2_{AB}	32.4_{BC}	33.8_{A}	31.9_{C}	31.4_{C}	32.3_{BC}	32.5
$LSD_{0.05}$			A = 1.12; B = n.s. B/A = n.s.; A/B = n.s.				
			Weight of a thousand grains [g]				
Mean [B]	40.8_{BC}	40.4_{C}	43.0_{AB}	41.3_{BC}	45.0_{A}	43.0_{AB}	42.2
$LSD_{0.05}$			A = 2.42; B = n.s. B/A = n.s.; A/B = n.s.				
			Grains per ear [g]				
EM	1.30_{Aa}	1.29_{ABa}	1.33_{Aa}	1.21_{Ba}	1.30_{Aa}	1.27_{ABa}	1.28_{a}
UG_{max}	1.28_{ABab}	1.27_{ABab}	1.30_{Aa}	1.21_{Ba}	1.29_{ABa}	1.25_{ABa}	1.27_{a}
Control	1.21_{Bb}	1.20_{Bb}	1.33_{Aa}	1.21_{Ba}	1.33_{Aa}	1.28_{ABa}	1.26_{a}
Mean [B]	1.26_{B}	1.25_{BC}	1.32_{A}	1.21_{C}	1.31_{AB}	1.27_{AB}	1.27
$LSD_{0.05}$			A = 0.06; B = n.s. B/A = 0.07; A/B = 0.09				

Data marked with different capital letters indicate significant differences (p = 0.05) between the crop variants A1–A6 (horizontal comparison of means). Data marked with different lowercase letters indicate significant differences (p = 0.05) between microbiological preparations—EM, UGmax and control (vertical comparison of means).

3.6. Grain Yield

Based on four years of research, it was found that, on average for the tillage method (Figure 1), in terms of yield, the A3 variant was the best, consisting in leaving the forecrop straw mulch on the field surface until plowing before sowing—this allowed us to obtain a yield of 6.2 Mg·hm^{-2}. The least favorable in terms of yield were the variants A2, A4 and A5, in which the yield was lower than the A3 variant, respectively, by 22.5%, 22.7% and 27.8%. It should be mentioned that variants A2, A4 and A5 were tillage methods that did not use plowing.

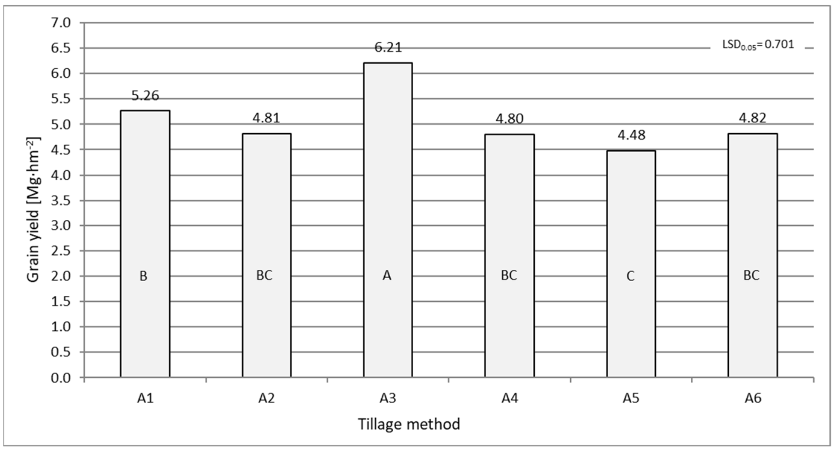

Figure 1. Winter wheat grain yield [Mg·hm^{-2}], depending on tillage method (average from 2011 to 2014). A–C—different letters indicate significant differences (p = 0.05). A1–A6—crop variants.

Using microbiological preparations (average) did not determine the yield of winter wheat at a level that could be statistically confirmed (Figure 2). Only a slight, approximately 2%, tendency in higher yields was found after the use of microbiological preparations.

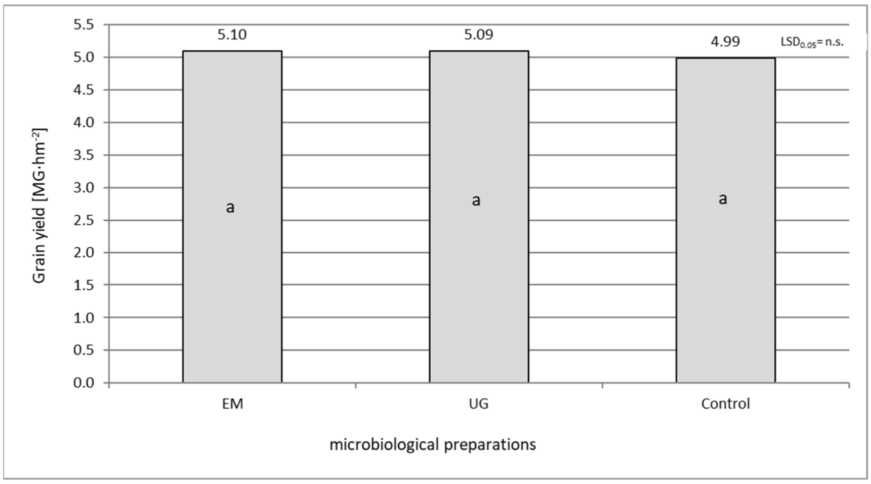

Figure 2. Winter wheat grain yield [Mg·hm^{-2}], depending on applying microbiological preparations (average from 2011 to 2014). a—different letters indicate significant differences (p = 0.05).

Both tested factors had an interactive effect on grain yield. The grain yield of winter wheat in monoculture among 18 compared objects ranged from 4.42 to 6.26 Mg·hm^{-2}—on average for the four years of research (Figure 3). It turned out that applying microbiological preparations was important only when the forecrop straw, crushed after harvest, was mixed with the soil using a grubber—this resulted in a significant increase in grain yield compared to the control object (without the application of these preparations). In the remaining variants (A3–A6) of the tillage method, the application of effective microorganisms did not significantly affect the yield.

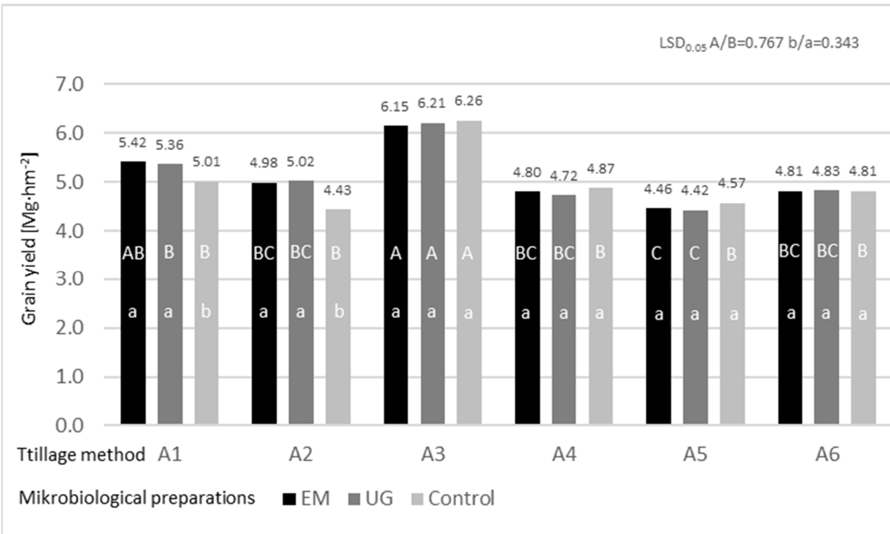

Figure 3. Winter wheat grain yield [Mg·hm^{-2}], depending on the tillage method and the applied microbiological preparations (average from 2011 to 2014). Data marked by different capital letters indicate significant differences (p = 0.05) between the tillage variants A1–A6. Data marked by different lowercase letters indicate significant differences (p = 0.05) between EM, UG_{max} and control.

4. Discussion

This study confirmed the unfavorable impact of tillage simplifications on the number of weeds in winter wheat, known from numerous scientific studies [44–46]. In the study by Woźniak [45], a greater number of weeds and their higher biomass occurred in winter wheat grown using a reduced tillage system than in conventional tillage. In our own research, a particularly heavy weed infestation of wheat was found in the treatment with zero tillage (A5). Increased weed infestation in untilled areas may result from the formation and spreading of seeds by weeds after the harvesting of plants grown as a previous crop for wheat. Similar relationships were obtained in studies by Mohler et al. [47] and Chauhan et al. [48]. Similarly to the study by Gawęda et al. [44], no tillage contributed to an increase in the occurrence of *Viola arvensis*, *Stellaria media*, *Avena fatua* and *Capsella bursa-pastoris*. An increase in the number of these weeds was also observed under reduced tillage conditions (A4). Wacławowicz et al. [46] pointed out that the usage of reduced or no tillage may contribute to an increase in weed infestation, especially if there is heavy rainfall in May and the air temperature is below the long-term average. In our own research, the lowest weed infestation of winter wheat was obtained in a treatment without straw and with conventional post-harvest and pre-sowing tillage. However, this did not result in wheat yield, which was the highest in the treatment with plowed straw mulch of the previous crop, characterized by average weed infestation; it should be noted that the number and biomass of weeds were determined before applying herbicides. This indicates the importance of straw as a fertilizer, especially when it is plowed. According to Wang et al. [49], straw fertilization allows for a reduction in the dose of mineral fertilizers. Shao et al. [32] stated that straw may replace 10% of N from mineral fertilizers. This is important because excessive mineral fertilization may limit the biological activity of the soil by reducing the diversity of root endophytic bacteria and the abundance of potential biocontrol bacteria such as Bacillus, Streptomyces and Burkholderia, and it can inhibit the biosynthesis of antibiotics that increase the occurrences of wheat crown rot. However, the method of introduction of straw into the soil is important for its impact on the growth and development of subsequent plants. Straw mixed with the soil only using a grubber had a negative impact on grain germination, which usually resulted in a significantly lower ear density compared to objects with plow tillage. Relatively good results were obtained when the grubber was used twice (A2), while direct sowing did not enable us to obtain conditions favorable to germination. According to Winkler et al. [50], the reduced technologies of tillage may slow down the germination of seeds. The authors stated that in reduced tillage, the action of inhibitory substances may negatively affect germination rate. Slowed-down germination can affect the quality of crops. It may increase the harmfulness of soil pathogens to plants. Conventional tillage technology mitigates these negative consequences. As a result, the grain yield of winter wheat in our own research obtained in the treatment with plowed straw was significantly higher than in the reduced or zero tillage conditions. Generally, the response of winter wheat to the use of microbiological preparations was weaker than the response to the method of tillage and the use of shredded straw fertilization. A positive effect of microbiological preparations on the development and yield of wheat was found only in objects with shredded straw (A1 and A2). This beneficial interaction of biological preparations with shredded straw could be related to the acceleration of the microbiological decomposition of shredded straw and faster activation of the ingredients contained in it. This is indicated by the positive effect of microbiological preparations on the SPAD index in the A1 and A2 objects in the stem elongation phase, and also in the case of the EM object in the earing phase. A similar effect of EM in conventional tillage was obtained under the same soil and weather conditions for spring wheat [19]. These findings are consistent with the results of Janusauskaite and Kadziene [51], in which simplified tillage systems had a negative impact on the value of the SPAD index in winter wheat compared to a plow tillage system. However, in general, this impact is not clear. In the study by Yadav et al. [52], reduced tillage and zero tillage had a positive effect on the value of the SPAD index. In our own research, higher values of both the SPAD and LAI indexes were found in plow tillage conditions compared to no-tillage (A5) conditions, whereas in reduced tillage conditions, intermediate values of these indices were obtained. The reason for this variable impact of cultivation technology on plant nutritional indicators may be the interaction of plow tillage and the use of straw for fertilization, which was removed from the experimental plots in the zero-tillage treatment. The use of microbiological preparations combined with the use of shredded straw as a fertilizer resulted in a significant increase in ear density, and in the treatment with EM also an increase in the weight of grain in the ear, compared to the control without microbiological preparations. In the case of using mulch made of unshredded straw and in objects without straw, microbiological preparations did not affect the value of the SPAD index or any structural elements of wheat yield. Direct sowing resulted in a higher weight of 1000 grains compared to full post-harvest and pre-sowing tillage using shredded straw. This could be due to the well-known negative correlation of this feature with the ear density and the number of grains in the ear [53–56].

5. Conclusions

Four-year studies of winter wheat monoculture showed that the tillage method determined all the tested biometric features of winter wheat as well as the weed infestation of the field for all weed species. A significant impact of applying microbiological preparations was found only for the chlorophyll index. However, the interaction of both factors was demonstrated in the case of several features, including grain yield. The grain yield of winter wheat for 18 compared experimental objects was in the range of 4.42–6.26 $Mg \cdot hm^{-2}$ (average for four years of the research). In terms of yield, the best solution was to leave the forecrop straw mulch on the field surface until plowing was carried out before sowing without the application of microbiological preparations. The conducted field experiments showed that the elimination of plowing as the basic method of tillage had an adverse effect on the weed infestation of the field and most of the tested plant characteristics, including the yield. The application of preparations containing effective microorganisms brought beneficial effects only when the shredded straw of the previous crop was mixed with the soil using a grubber.

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