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The Effect of Tillage Systems and Weed Control Methods on the Yield and Quality of Spelt Grain (*Triticum aestivum* ssp. *spelta* L.)

Sylwia Wesołowska [1], Dariusz Danilkiewicz [2], Dorota Gawęda [2], Małgorzata Haliniarz [2,*], Hubert Rusecki [2] and Justyna Łukasz [2]

[1] Institute of Soil Science and Environment Shaping, University of Life Sciences in Lublin, Akademicka 13, 20-950 Lublin, Poland
[2] Department of Herbology and Plant Cultivation Techniques, University of Life Sciences in Lublin, Akademicka 13, 20-950 Lublin, Poland
* Correspondence: malgorzata.haliniarz@up.lublin.pl

Abstract: The aim of this three-year field experiment was to determine how simplified (reduced) pre-planting tillage and different weed control methods impact the yield and selected quality parameters of spelt grain (*Triticum aestivum* ssp. *spelta* L.). Conventional tillage and three variants of reduced tillage (RT) were tested. The second experimental variable (weed control) had three variants: mechanical weed control (M), combined mechanical + chemical treatment at full herbicide rate (MC 100%), and combined mechanical + chemical treatment at 25%-reduced herbicide rate (MC 75%). The mechanical method consisted of harrowing the wheat crop in the fall and spring. The results showed that the wheat yields obtained under reduced pre-planting tillage were comparable to those under conventional tillage. However, the grain quality parameters proved to be worse under the reduced tillage regimes. Herbicide applications, both at full and reduced rates, significantly improved grain quality parameters and yields compared with mechanical-only weed control. In particular, the herbicide-treated crops boasted higher values of thousand-kernel weight and grain weight per ear.

Keywords: spelt; tillage systems; weed control method; yield; grain quality parameters

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1. Introduction

Spelt wheat (*Triticum aestivum* ssp. *spelta*) is one of the oldest subspecies of wheat and has been grown by humans since the Stone Age [1,2]. The increased demand for more nutritious and palatable food has sparked a growing interest in the cultivation of spelt wheat [3–5]. Spelt wheat has found its own niche in the food market thanks to its high content of high-quality protein and 80%+ digestibility [6]. Compared to common wheat, spelt wheat contains more unsaturated fatty acids (especially linoleic and linolenic acids) and phytosterols. In addition, its grain is rich in essential nutrients, such as fiber, carbohydrates, vitamins, and minerals. It is also a source of B1, B2, and PP vitamins, fat-soluble vitamins—A, D, E—and minerals such as potassium, iron, calcium, phosphorus, zinc, and copper [7–13].

Spelt wheat is also quite resistant to fungal diseases [14,15] and, thanks to its high tillering ability, tends to outcompete weeds better than common wheat [16,17]. These features make it a prime candidate for farming without the overuse of plant-health products and mineral fertilizers. However, one barrier to spelt farming in Poland lies in its lower yields compared with common wheat [3]. According to Feledyn-Szewczyk [16], the yields of spelt wheat are 17.5% lower than those of common wheat varieties. Its low and highly varied productivity has encouraged investigations into better technologies for achieving higher grain yields [10,18].

In Poland, as in other European countries, spelt wheat is mostly grown in organic and low-input farms [12]. Due to the low production efficiency, the resultant crop often fails to meet the high quality standards set for wheat grain [19].

Most studies in the literature have looked at spelt cultivation in the context of organic farming [12,20–22]. There is a dearth of research exploring the performance of this crop in conventional farms that employ chemical plant-protection products. It would therefore seem advisable to identify optimal agrotechnical technologies for producing high-quality spelt grain with the use of chemical plant-protection products. It is also important to examine whether spelt production is viable under different cultivation schemes, especially with regard to systems that limit tillage and use methods that do not overturn the soil. Research to date suggests that limiting or eliminating tillage enhances soil quality by improving its structure while increasing bioactivity and water retention capacity [23–25]. Reduced tillage also brings commercial benefits. Reduced-tillage and no-till systems can reduce production costs and boost cost efficiency by reducing energy and labor needs compared with conventional tillage [26–28].

Producing high-quality cereals and fully realizing their yield capacity is possible if the crops are given optimal conditions in which to grow [29–31]. This can be achieved by using appropriate agrotechnical measures, including optimal chemical protection of plants and appropriate tillage schemes. Tillage modifies the quality and productivity of the grain, as any changes to the physical, chemical, and biological properties of the soil affect the growth and development parameters of the crop [32–36].

The objective of this study was to determine how simplified (reduced) pre-planting tillage regimes and different methods of weed control affect the yields and selected quality traits of spelt wheat grain grown under the weather and soil conditions of the middle Lubelskie region (Poland).

2. Materials and Methods

2.1. Location of the Experiment and Soil/Climatic Conditions

The present field experiment on the cultivation of winter spelt wheat was carried out in the years 2012–2015 on the Experimental Farm in Czesławice (57.3079 N; 22.2482 E) owned by the University of Life Sciences in Lublin (Poland).

The experiment was established on a loess-derived grey-brown podzolic soil (good wheat soil complex) with a slightly acidic pH. The soil was rich in available K, P, and Mg, with average levels of organic matter (Table 1).

Table 1. Selected chemical properties of the soil in a layer of 0–30 cm.

Years	The Humus Content (%)	pH in 1 M KCl	The Content of Ingredients (mg per 100 g Soil)		
			P_2O_5	K_2O	Mg
2012	1.56	5.46	23.3	27.7	8.8
2013	1.51	5.48	28.1	22.3	9.2
2014	1.61	5.61	37.5	41.5	10.2

Precipitation and air temperature data were sourced from the Czesławice Meteorological Station, located near the experimental site, and are given in Table 2. Mean air temperatures in the 2013/2014 and 2014/2015 growing seasons were similar, exceeding the multi-year norm by 0.9 °C and 1.0 °C, respectively. The mean air temperature for the 2012/2013 growing season was the same as the multi-year norm. Low rainfall in September 2012 adversely affected pre-planting cultivation. In October 2012, there were optimal conditions for plant germination and growth. In the spring of 2013, snow cover remained until 8 April, with precipitation being greater than the multi-year norm (which delayed spring crop maintenance). In 2013, the plant growth-spurt months (May and June) were characterized by higher mean daily temperatures and total rainfall compared to historical data. In the second wheat-growing season (2013/2014), October 2013 was an exceptionally dry month, but the spring of 2014 was exceptionally wet—which provided the plants with sufficient water for growth. The fall of 2014 (third growing season) proved to be extremely

dry. While April was near average in terms of precipitation, May was characterized by extremely heavy rainfall. June and August in the last year of the experiment (2015) proved to be very dry.

Table 2. The rainfall and mean monthly air temperature in the growing season of spelt wheat, according to the Meteorological Station in Czesławice (Poland).

Months	Years							
	2012/2013		2013/2014		2014/2015		LTA * 1963–2010	
	mm	°C	mm	°C	mm	°C	mm	°C
September	40.4	14.6	49.5	11.3	21.8	14.0	59.5	13.1
October	110.7	7.7	7.3	9.5	27.5	9.7	45.6	7.9
November	29.0	5.0	60.6	4.9	24.1	4.6	41.0	2.9
December	17.4	−3.4	13.7	1.7	57.8	−0.1	36.9	−1.3
January	60.3	−4.4	54.5	−2.9	50.9	1.0	30.3	−3.0
February	30.0	−1.3	5.8	0.3	15.8	−1.1	29.2	−1.7
March	37.6	−2.6	49.1	4.9	48.6	2.8	31.3	1.8
April	53.2	7.4	63.9	8.9	39.1	6.5	42.4	7.7
May	103.3	14.9	230.2	13.0	169.6	11.5	63.5	13.6
June	108.3	18.1	110.2	15.2	13.5	16.1	72.7	16.5
July	44.3	18.7	61.4	19.6	52.6	19.0	80.0	18.3
August	26.6	18.7	102.0	18.3	5.9	21.9	69.5	17.7
Sum/Mean (September–August)	661.1	7.8	808.2	8.7	527.2	8.8	601.9	7.8

* LTA—long-term average.

2.2. Experimental Design and Agronomic Practices

The two-factor field experiment on a winter spelt crop ('Rokosz' variety) was set up in a split-plot design in triplicate on 30 m^2 plots. The experiment investigated the following factors: I. Tillage system: CT—conventional tillage, RT1—reduced tillage, RT2—reduced tillage, RT3—reduced tillage; II. Weed control method: M—mechanical removal, MC (100%)—mechanical + chemical control at full herbicide rate, MC (75%)—mechanical + chemical control at 25%-reduced herbicide rate.

The conventional tillage scheme involved 10 cm skimming with a bed plough and soil preparation via two rounds of harrowing. The first harrowing was done immediately after the skimming, the second 10 days later. The pre-planting plowing was done 3 weeks before the anticipated date of sowing, to a depth of 20 cm. Simplified tillage was performed in three variants. In variant RT1, a round of post-harvest tillage was performed using a tine tiller consisting of an extirpator, a disk harrow section, and a string roller. The pre-planting plowing was done 3 weeks before the anticipated date of sowing. In variant RT2, a tine tiller was used to perform a round of post-harvest tillage, with pre-planting ploughing done 5 days before the anticipated date of sowing. In variant RT3, a tine tiller was used to perform a round of post-harvest tillage, with plowing done 5 days before the anticipated date of sowing, after which the soil was finished using a packer roller. In all of the tillage schemes used, the seeds were sown to a depth of 25 cm. Soil tillage was conducted using the same process across all sites, using a spring-tine cultivator with a string roller.

Weed control was the second experimental factor—variants included mechanical removal, combined mechanical + chemical control at 100% herbicide rate, and combined mechanical + chemical control at 25%-reduced herbicide rate. Mechanical weeding (M) involved fall and spring harrowing of the wheat crop using an Expom weeder. The fall

harrowing was performed during the 2-leaves-unfolded stage (BBCH 14), and the spring harrowing was done as a two-step cross-hatch pass using a medium tine, performed when the spelt was in full tiller (BBCH 25). For the mechanical + chemical control at full herbicide rate (MC 100%), a weeder was used in the fall during the 2-leaves stage (BBCH 14). Then, in the spring (tillering stage), the crop was treated with the herbicidal agents Chwastox Trio 540 SL (mecoprop, MCPA, dicamba) at 2 L ha^{-1} and Atlantis 12 OD (iodosulfuron-methyl-sodium, mesosulfuron-methyl) at 0.9 L ha^{-1}. The reduced-herbicide run with mechanical + chemical weed control (MC 75%) differed from the full-herbicide variant by the rates at which these herbicides were applied, which were reduced by 25% (nominally by 1.5 and 0.65 L ha^{-1}, respectively).

The spelt was sown at 130 kg ha^{-1} (350 seeds per 1 m^2) in the third ten-day of September 2012, 2013, and 2014 and harvested in the second ten-day of August 2013, 2014, and 2015. After the previous crop (winter wheat) was harvested, the field was limed with calcium magnesium oxide at 3 t ha^{-1} (1690 kg ha^{-1} CaO and 560 kg ha^{-1} MgO). The calcium fertilizers were mixed with the soil via skimming. Prior to the sowing, an NPK fertilizer (Polifoska 6) was applied at 300 kg ha^{-1} (18 kg N, 60 kg P_2O_5, 90 kg K_2O). The mineral fertilizers were mixed with the soil using the cultivator. The top-dressing of nitrogen (ammonium nitrate) was made in the spring during two agrotechnical periods: with spelt at full tiller (BBCH 25) (60 kg N ha^{-1}) and at the beginning of stem elongation (BBCH 33) (40 kg N ha^{-1}). During the flag-leaf stage (BBCH 39), foliar fertilization with Basfoliar 36 extra was performed at 12 L ha^{-1}. The fertilizer contained 27 g L^{-1} total N, 3.2 g L^{-1} MgO, 0.02 g L^{-1} B, 0.2 g L^{-1} Cu, 0.02 g L^{-1} Fe, 1 g L^{-1} Mn, 0.005 g L^{-1} Mo, and 0.01 g L^{-1} Zn, with all of the micronutrients in the form of IDHA chelate.

During the growing period, comprehensive chemical protective treatments were applied to the crop, which included fungicidal, insecticidal, and growth-control agents. During cultivation, a fungicide protection regime was employed, consisting of three treatments. The stem bases were treated with the protective agent Yamato 303 SE (thiophanate-methyl, tetraconazole) at 1.75 L ha^{-1} during the end-of-tillering stage (BBCH 29). The leaves and stems were treated with the protective agent Optan 183 SE (pyraclostrobin, epoxiconazole) at 1.5 L ha^{-1} during the advanced stem-elongation stage (BBCH 35). For protection of flag leaves and ears, Wirtuoz 520 EC was used (prochloraz, tebuconazole, proquinazid) at 1.25 L ha^{-1} during the flag-leaf sheath-swelling stage (BBCH 49). Decis mega 50 EW (deltamethrin) at 0.25 L ha^{-1} was used for insecticidal protection during the advanced stem-elongation stage (BBCH 35). The anti-lodging agent Antywylegacz płynny 675 SL (675 g L^{-1} chlormequat chloride) was used at 2.0 L ha^{-1} for growth control during the first node stage (BBCH 31).

2.3. Methods of Plant Analyses

The harvested spelt wheat grain was weighed separately for each plot, with the weights expressed on a per hectare basis. Length of stems, length of ears, number of grains per ear, and grain weight per ear were determined based on a random sample of 30 ears from each plot. Before the harvest of winter wheat, ear density per 1 m^2 was determined at two randomly selected sections (1 m $\times$ 0.25 m quadrats) of each plot. The thousand-kernel weight was calculated after wheat harvest (2 $\times$ 500 grains from each plot).

The following basic quality parameters were tested: total protein (%), wet gluten (%), Zeleny sedimentation value (mL), grain uniformity, bulk grain density (kg hL^{-1}), and falling numbers (s). All determinations were made according to the following standards: PN-EN ISO 24333:2012P (Cereals and cereal products—Sampling), PN-EN ISO 7971-3:2010P (Cereals—Determination of bulk density), PN-EN 15948:2015-05E (Cereals—Determination of moisture and protein—Method using Near-Infrared Spectroscopy in whole kernels), PN-EN ISO 3093:2010E (Wheat, rye, and their flours, durum wheat and durum wheat semolina—Determination of the falling number according to Hagberg–Perten), PN-EN ISO 5529:2010E (Wheat—Determination of the sedimentation index—Zeleny test), PN-EN ISO 5223:2016-02E (Test sieves for cereals—Determination of grain uniformity), PN-EN ISO

21415-2:2015-12E (Wheat and wheat flour—Gluten content—Part 2: Determination of wet gluten and gluten index by mechanical means).

2.4. Statistical Analysis

The results were subjected to analysis of variance (ANOVA). Significant differences were determined via Tukey's test at a significance level of $p < 0.05$. A three-way analysis of variance (ANOVA) was carried out to determine the effect of tillage systems, weed control methods, years of study, and the interactions thereof on spelt grain yield, selected spelt yield and crop structure indicators, and quality parameters. A total of 108 results (4 tillage systems × 3 weed control methods × 3 years × 3 replicates) were used for statistical calculations with regard to the analyzed parameters. The distribution conformity with normal distributions was verified with the Shapiro–Wilk test, while homogeneity of the variance was tested with the Bartlett's test. Computations were made using Statistica 14.0 software (TIBCO Software Inc., Tulsa, OK, USA). Only significant interactions between years of research and weed control methods or tillage systems are shown in the manuscript.

3. Results

3.1. Grain Yield and Yield Components of Spelt Wheat

The choice of tillage system had no significant effect on spelt grain yield (Table 3). On the other hand, the weed control method affected the yield. The mechanically weeded plot (M) produced significantly reduced yields (by 22.8 and 9.7%, respectively) compared to the plot mechanically + chemically weeded at full (100%) and reduced (75%) herbicide rates. The spelt was much more productive (17.0% higher yields) at full herbicide rate (100%) compared with the reduced-herbicide (75%) variant. The yields also varied significantly across the different years of study, with the lowest recorded for 2013. In turn, 2014 saw a marked increase in the yields (0.66 t ha^{-1}), while the significantly highest yield was obtained in 2015.

Table 3. Spelt wheat yield and crop and yield components depending on tillage system, weed control method (mean for 2013–2015), and years of research.

Specification	Grain Yield (t ha $^{-1}$)	Number of Ears (no. m^{-2})	Number of Grains per Ear (no.)	Grain Weight per Ear (g)	Thousand-Kernel Weight (g)	Length of Stem (cm)	Length of Ear (cm)
			Tillage system				
CT	6.24a	512.5a	34.3a	1.33a	36.8b	96.9a	10.6a
RT1	6.00a	480.1b	33.3a	1.25a	33.1c	92.7b	10.2bc
RT2	6.34a	495.3ab	33.2a	1.25a	36.9b	93.8b	10.4ab
RT3	6.44a	480.5b	32.2a	1.32a	39.9a	95.3ab	10.1c
			Weed control method				
M	5.51c	491.5a	32.9a	1.21b	32.5b	95.5a	9.3a
MC (100%)	7.14a	516.3a	36.3a	1.37a	39.1a	94.1a	12.0a
MC (75%)	6.10b	468.6a	30.6a	1.29ab	38.5a	94.5a	9.7a
			Years of research				
2013	5.68c	442.3b	31.2b	1.27a	36.6a	95.2a	11.9a
2014	6.34b	520.4a	34.8a	1.28a	37.3a	96.3a	9.5b
2015	6.75a	513.6a	33.8ab	1.31a	36.1a	92.6b	9.5b

CT—conventional tillage; RT1, RT2, RT3—reduced tillage: M—mechanical; MC (100%)—mechanical and chemical (dose of herbicides 100%); MC (75%)—mechanical and chemical (dose of herbicides 75%). Different letters denote significant differences ($p \leq 0.05$). The same letter represents not significantly different values ($p \leq 0.05$).

The number of spelt ears per 1 m^2 was significantly determined by the pre-planting cultivation scheme and year of study (Table 3). Reduced-tillage methods (RT1 and RT3) led to reduced numbers of ears (6.3 and 6.2% less, respectively) compared with conventional tillage (CT). Ear density proved to be the lowest during the first year of study (2013). The

parameter then rose progressively and significantly throughout the next two years, with a 17.7% increase in 2014 and 16.1% in 2015.

Significant differences in number of grains per ear were noted only between different growing seasons (Table 3). In 2013, the lowest number of grains per ear was marked. This parameter was significantly (11.5%) higher in 2014 than in 2013. The value for 2015 was similar to the other years.

The statistical analysis showed a significant effect of the weed control method on grain weight per ear (Table 3). The weight values were the highest when herbicides were applied at the prescribed rate (MC 100%). When no chemical protection agents were used (M), grain weight per ear was significantly (11.7%) lower than in the full-herbicide variant (CM 100%).

The experimental factors had a significant effect on the thousand-kernel weight (TKW) (Table 3). Variant RT3 performed the best in terms of TKW. The thousand-kernel weight was 17.0, 7.5, and 7.8% lower under RT1, RT2, and CT, respectively, compared with RT3. The TKW values were similar across the chemically treated variants, regardless of whether full or reduced herbicide rates were used. On the other hand, the mechanically weeded plots performed significantly worse, with the thousand-kernel weight being 16.9 and 15.6% lower than under MC 100% and MC 75%, respectively.

The length of the spelt stem was significantly determined by the tillage system (Table 3). All reduced-tillage sites produced significantly shorter stems than conventionally tilled (CT) ones. The shortest stems were found in variant RT1. The year of research also significantly influenced this feature. The 2015 crops performed the worst, with significantly lower length values. Stem lengths were similar between 2013 and 2014, diverging from the 2015 values by 2.7 and 3.8%, respectively.

Ear length was found to differ significantly with the tillage scheme and year of study (Table 3). The longest ears were produced in conventionally tilled (CT) plots. The shortest ears were found in the reduced-tillage variant RT3. The highest ear length values were recorded for 2013, dropping significantly (by 20.2%) in 2014 and 2015.

No effect of the interaction between the tillage and weed control method on the grain yield and crop components of spelt wheat was found (Figure 1).

The interaction between weed control method and year of study had a significant effect on the grain yields (Figure 2). The spelt wheat was more productive at full herbicide rate across all years of study. However, in 2015, the full-herbicide (MC 100%) and mechanical-control (M) plots produced equal yields of 7.17 t ha^{-1}. The mechanically weeded variant (M) performed the worst in 2013 and 2014.

The interaction between the protection method used and year of study significantly influenced the ear density (Figure 3). The crops grown during the first year of study using mechanical weeding had the lowest ear density. Conversely, the plots treated mechanically (M) or with herbicides at full rate (MC 100%) in 2014 and 2015 demonstrated the highest number of ears.

The thousand-kernel weight of spelt wheat values showed dependence on the choice of tillage system across the years of study (Figure 4A). RT1 performed poorest in this regard across all years of study. Reduced tillage RT3—where pre-planting plowing was performed 5 days before the date of sowing, followed by finishing with a packer roller—boosted the TKW across all growing seasons. The values obtained under the RT3 system were significantly higher than under RT1. The TKW was also significantly determined by the interaction between the protection method used and year of study (Figure 4B). The TKW values were similar between the full-herbicide (MC 100%) and reduced-herbicide (MC 75%) variants across all years of study and, in 2013 and 2014, were significantly higher than when purely mechanical weeding was applied (M).

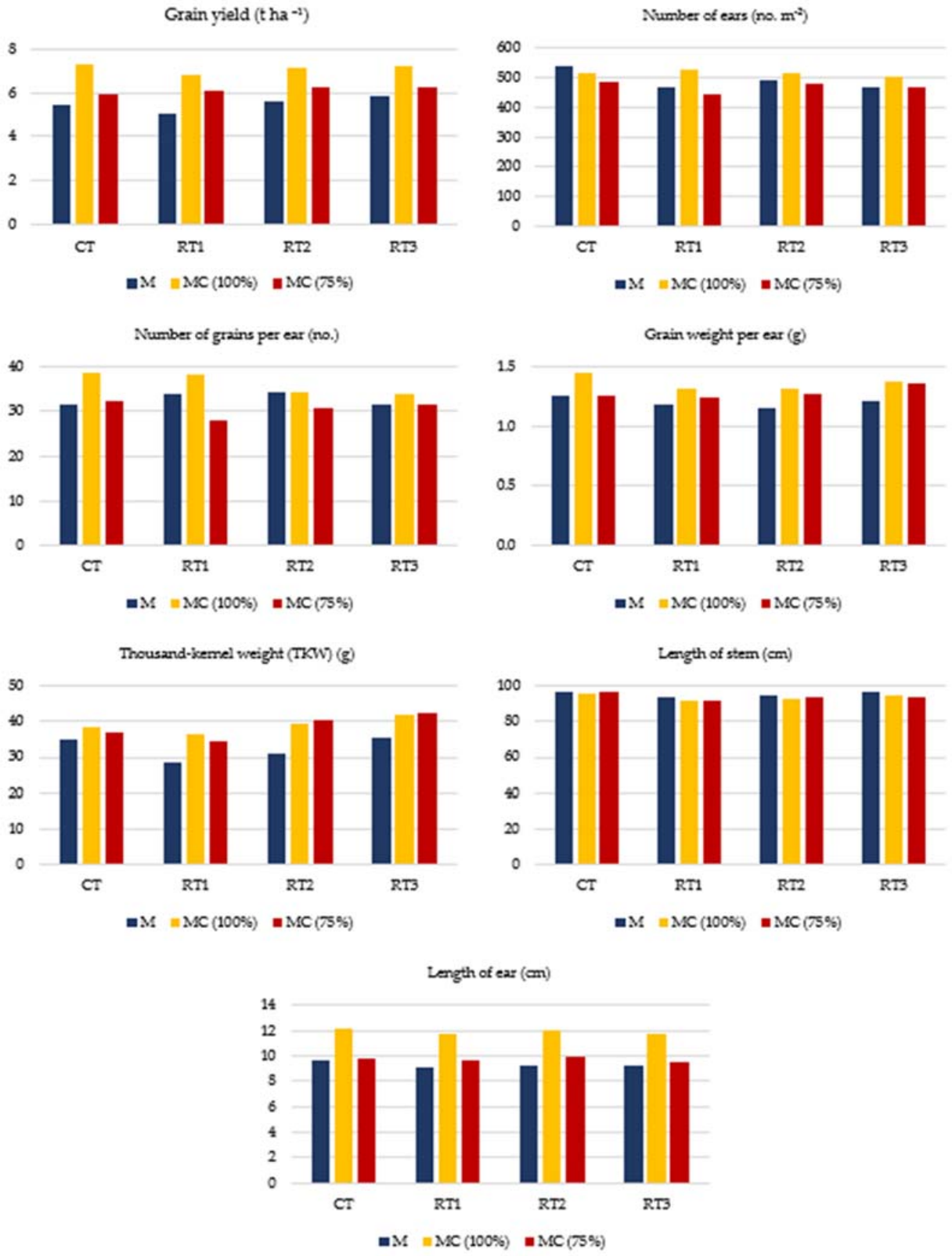


Figure 1. Interaction of the tillage system and weed control method in determining grain yield and crop components of spelt wheat.

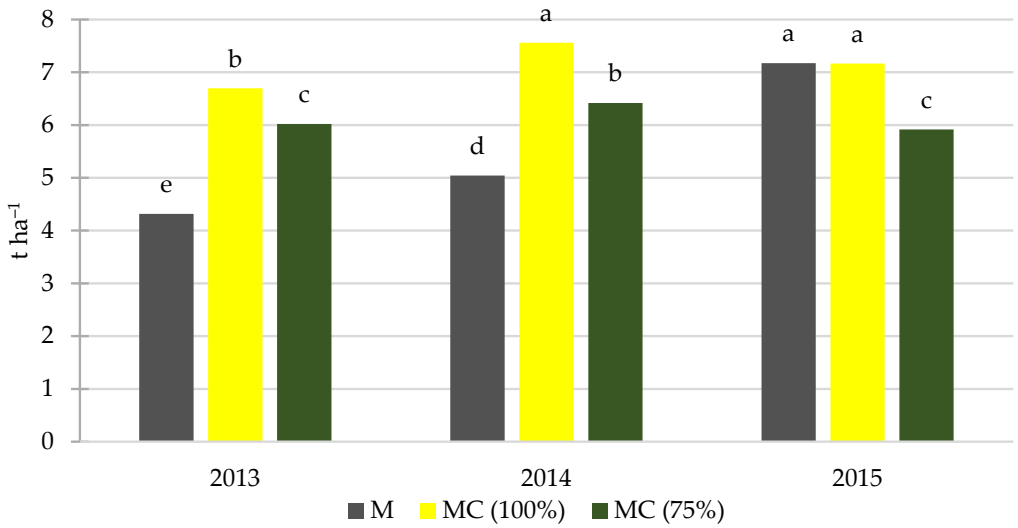


Figure 2. Interaction of the weed control methods and research years in determining spelt wheat grain yield. M—mechanical; MC (100%)—mechanical and chemical (dose of herbicides 100%); MC (75%)—mechanical and chemical (dose of herbicides 75%). Different letters denote significant differences ($p \leq 0.05$). The same letter represents not significantly different values ($p \leq 0.05$).

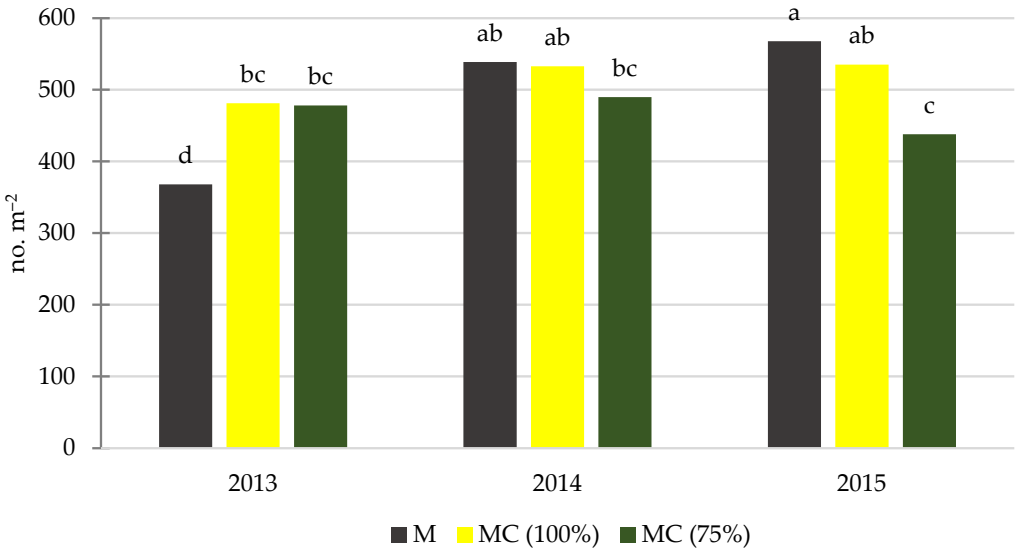


Figure 3. Interaction of the weed control methods and research years in determining number of ears of spelt wheat. M—mechanical; MC (100%)—mechanical and chemical (dose of herbicides 100%); MC (75%)—mechanical and chemical (dose of herbicides 75%). Different letters denote significant differences ($p \leq 0.05$). The same letter represents not significantly different values ($p \leq 0.05$).

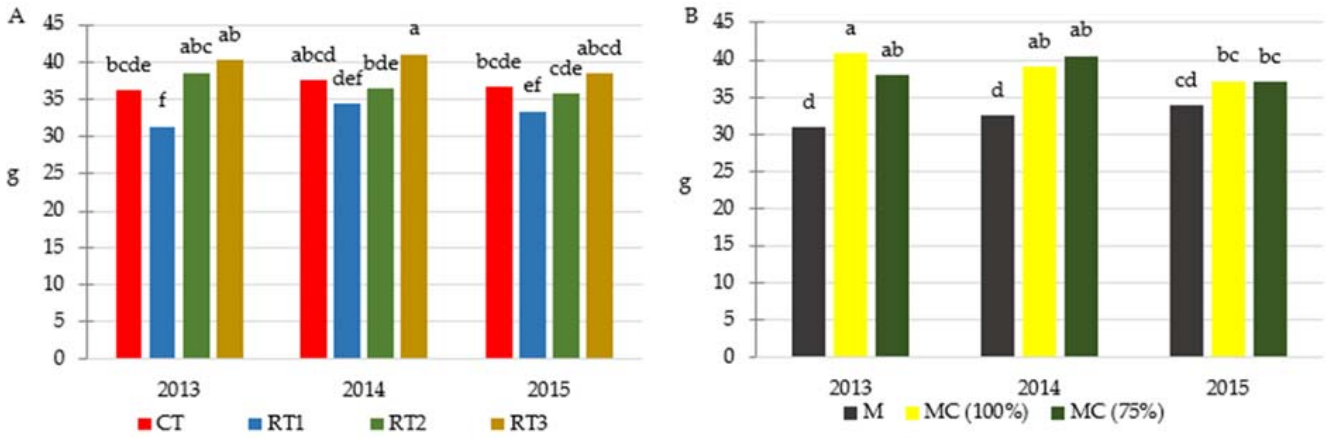


Figure 4. Interactive dependencies of the tillage systems (**A**), weed control methods (**B**), and research years in determining thousand-kernel weight of spelt wheat. CT—conventional tillage; RT1, RT2, RT3—reduced tillage; M— mechanical; MC (100%)—mechanical and chemical (dose of herbicides 100%); MC (75%)—mechanical and chemical (dose of herbicides 75%). Different letters denote significant differences ($p \leq 0.05$). The same letter represents not significantly different values ($p \leq 0.05$).

3.2. Quality Parameters of Spelt Wheat Grain

The tillage system, weed control method, and year of study had a significant impact on total protein content in spelt grain (Table 4). The lowest protein content was noted for grain harvested from field RT1. The CT variant and reduced-tillage variant RT2 produced crops with similar protein levels, 1.4% and 0.9% higher than RT1 grain, respectively, which represents a significant increase. Chemical weed control methods had a positive effect on grain protein content, regardless of the herbicide rate. The grain harvested in 2014 and 2015 had significantly higher levels of protein than the grain from the first harvest (2013).

Table 4. Selected quality features of spelt wheat grain depending on the tillage systems, weed control methods (mean for 2013–2015), and years of research.

Specification	Total Protein Content (%)	Wet Gluten Content (%)	Falling Number (s)	Zeleny Sedimentation Value (mL)	Grain Uniformity (%)	Bulk Grain Density (kg hL^{-1})
			Tillage system			
CT	12.8a	25.8a	317.2a	59.2a	82.5a	76.8a
RT1	11.4c	23.3c	284.2c	53.3c	76.2d	72.3c
RT2	12.3ab	25.5a	307.1ab	58.0ab	80.7b	75.7b
RT3	11.9bc	24.4b	299.3b	56.1b	79.0c	74.7b
			Weed control method			
M	11.0b	23.8b	291.4c	55.4b	74.4c	71.9c
MC (100%)	12.7a	25.6a	312.6a	58.9a	82.7a	78.4a
MC (75%)	12.5a	24.8ab	301.9b	55.6b	81.7b	74.4b
			Years of research			
2013	9.8b	23.5c	297.1a	54.0b	73.4b	71.2b
2014	13.4a	24.5b	302.0a	58.1a	81.7a	75.9a
2015	13.1a	26.2a	306.8a	57.8a	83.7a	77.6a

CT—conventional tillage; RT1, RT2, RT3—reduced tillage; M—mechanical; MC (100%)—mechanical and chemical (dose of herbicides 100%); MC (75%) mechanical and chemical (dose of herbicides 75%). Different letters denote significant differences ($p \leq 0.05$). The same letter represents not significantly different values ($p \leq 0.05$).

The tillage system, weed control method, and year of study significantly modified the gluten content of spelt grain (Table 4). The reduced-tillage plot RT1 produced grain with significantly reduced gluten content. The highest gluten levels were found in the CT crop, with similar values also recorded for the reduced-tillage field RT2. Mechanically

weeded plots were associated with the lowest gluten levels, though they were only slightly higher in the reduced-herbicide variant (MC 75%). Conversely, the full-herbicide variant (MC 100%) produced the most gluten-rich crop, though the values for this site did not significantly differ from those noted for the 25%-reduced herbicide rate. There were significant differences between gluten levels across the different years of study—the 2015 and 2013 crops had the highest and lowest gluten levels, respectively.

The falling number was another spelt quality parameter significantly determined by the tillage system and weed control method (Table 4). The reduced-tillage variants (with the exception of RT2) had significantly reduced falling numbers compared with conventional tillage (CT). The lowest and highest values were obtained for the M and MC 100% variants, respectively.

The Zeleny sedimentation value was modified by tillage systems, weed control method, and research years (Table 4). Regarding tillage systems, the highest value was noted for conventionally tilled (CT) plots. The RT1 and RT3 systems had markedly reduced values—10.0% and 5.2% lower than the CT system. Among the weed control methods tested, crops mechanically + chemically treated at full herbicide rate (MC 100%) performed the best in this regard, with Zeleny values significantly higher than in the other weeding variants. The sedimentation index proved to be the lowest for 2013, then rose in the subsequent years, with a 14.0% increase in 2015 and 11.3% in 2014.

Both of these experimental factors, as well as the year of study, had a significant effect on spelt grain uniformity (Table 4). All reduced-tillage variants (RT2) produced less uniform grain than conventional tillage (CT), with the lowest scoring variant being RT1. Out of all examined weed control methods, the full-herbicide treatment (MC 100%) was the most effective in improving grain uniformity. Comparing the years of research, the 2013 crop was the least uniform.

The tillage system significantly differentiated the bulk grain density (Table 4). All reduced-tillage schemes were associated with diminished density values compared with conventional tillage (CT). The lowest bulk grain density was noted for the RT1 system. The weed control method also had a significant effect on the density. Mechanically weeded plots (M) performed the worst in terms of this particular parameter. In 2013, the bulk grain density crop was the lowest.

The interaction between tillage system and weed control method had a significant effect on spelt grain uniformity and bulk grain density (Figure 5). The most uniform grain came from the conventionally tilled (CT) sites, treated at full (MC 100%) or reduced (MC 75%) herbicide rates. Wheat grain sourced from the reduced-tillage plot RT1, with mechanical weeding (M) used, exhibited the lowest bulk density values. Conversely, the highest density values were obtained when using full herbicide rates combined with reduced tillage RT2 or conventional tillage CT. The interaction between tillage system and weed control method had no significant effect on spelt grain protein content. However, protein levels did tend to be higher in chemically treated crops compared with the mechanically treated variant across all tillage types.

The interaction between weed control method and year of study had a significant effect on the total protein content, Zeleny sedimentation value, and bulk density of spelt wheat grain (Figure 6). Crops mechanically + chemically treated at full (100%) and reduced (75%) herbicide rates had similar protein levels in 2014 and 2015, significantly higher than those in mechanically weeded grain (M). Subjecting the crop to a combined mechanical/chemical treatment at full herbicide rate (CM 100%) significantly boosted the sedimentation value across all years of study. In terms of bulk density, in 2014 and 2015, the mechanically weeded variant and the full-herbicide variant (MC 100%) performed the worst and best, respectively. For 2013, there was no major difference in density between the reduced-herbicide variant (MC 75%) and mechanical-only variant methods (M). The full herbicide rate (MC 100%) significantly boosted the parameter against the mechanical-only weeded plots.

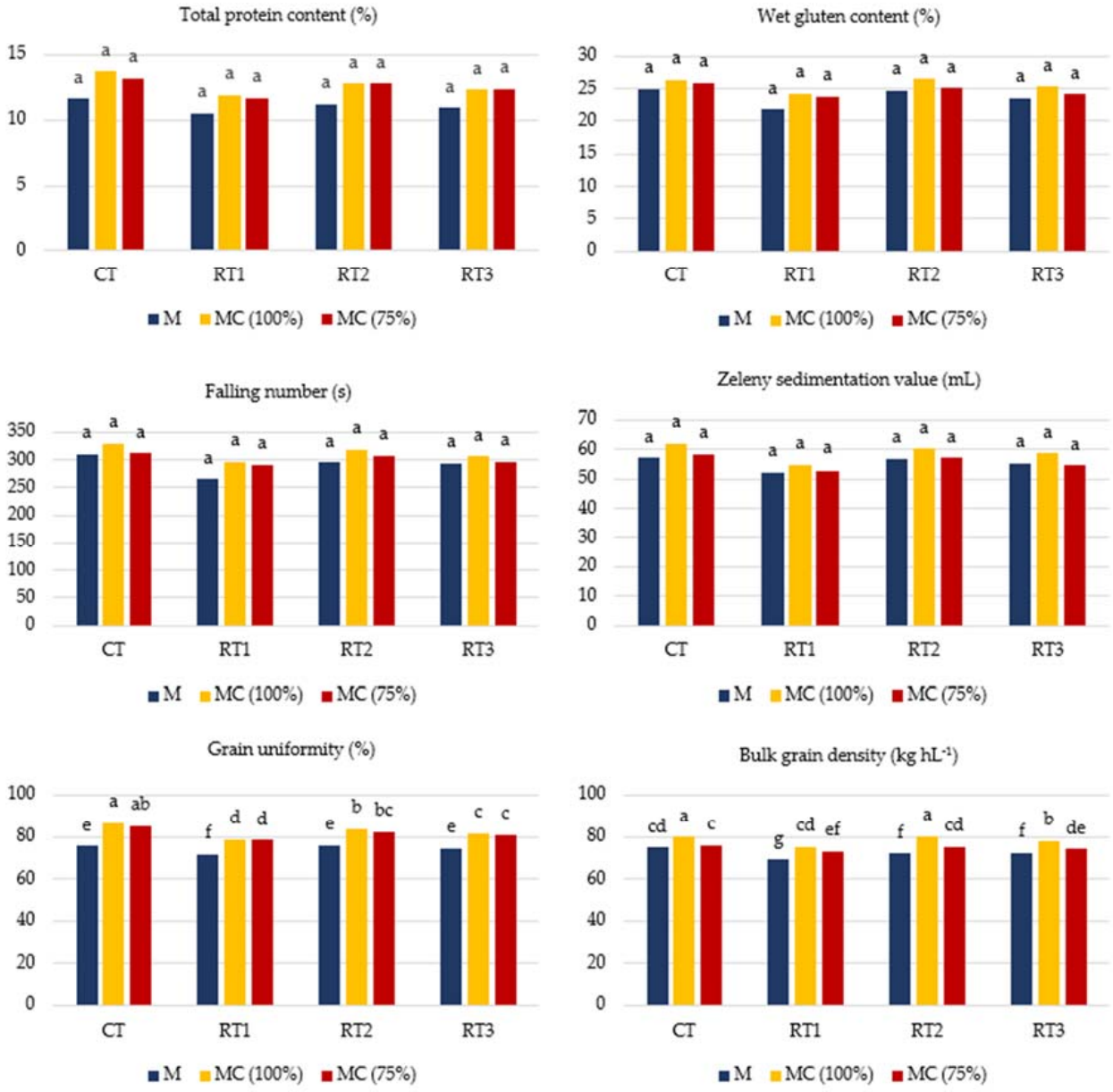


Figure 5. Interaction of the tillage systems and weed control methods in determining quality parameters of spelt wheat grain. CT—conventional tillage; RT1, RT2, RT3—reduced tillage; M—mechanical; MC (100%)—mechanical and chemical (dose of herbicides 100%); MC (75%)—mechanical and chemical (dose of herbicides 75%). Different letters denote significant differences ($p \leq 0.05$). The same letter represents not significantly different values ($p \leq 0.05$).

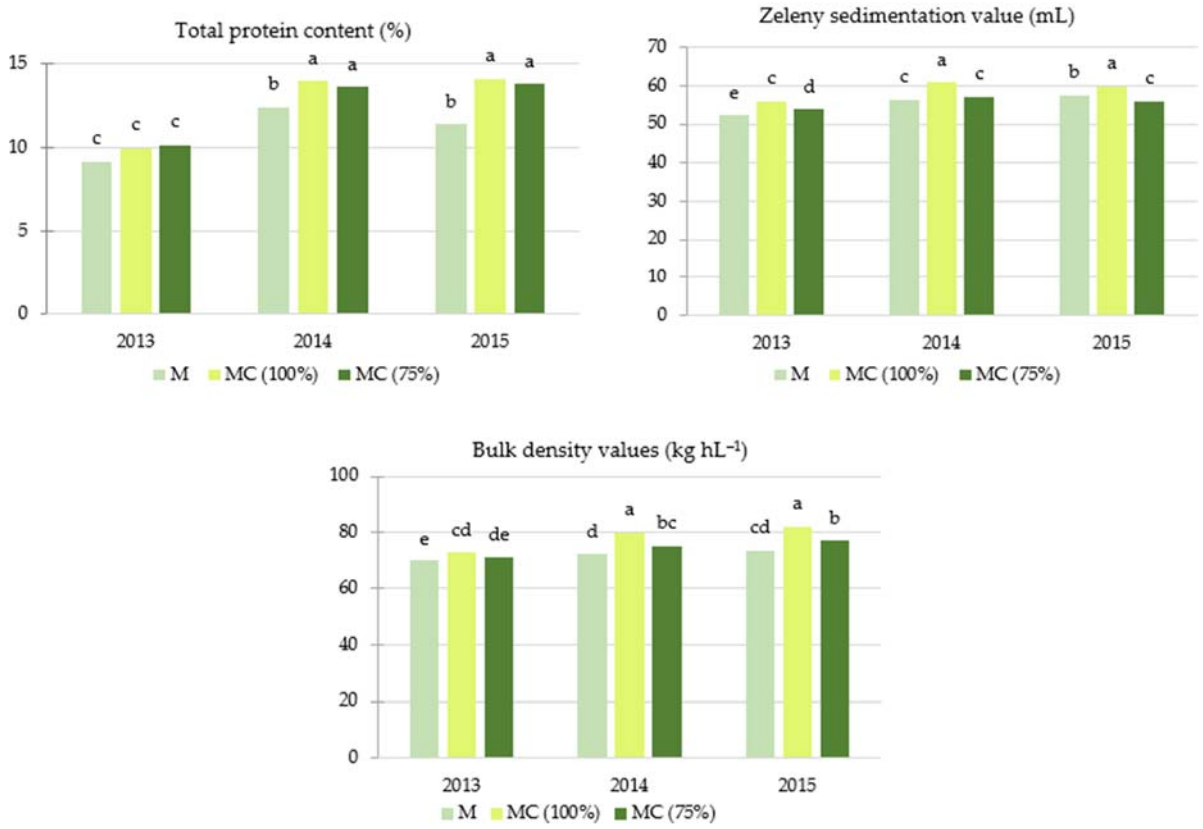


Figure 6. Interaction of the weed control method and research years in determining quality parameters of spelt wheat grain. M—mechanical; MC (100%)—mechanical and chemical (dose of herbicides 100%); MC (75%)—mechanical and chemical (dose of herbicides 75%). Different letters denote significant differences ($p \leq 0.05$). The same letter represents not significantly different values ($p \leq 0.05$).

4. Discussion

The results indicate that the weather was a major determinant of yields across the different years of study. The lowest yields were produced in 2013, then grew progressively larger throughout the next two years, reaching a peak in 2015. The high yields in 2015 could have been influenced by both weather conditions (Table 2) and the high abundance of nutrients in the soil (Table 1). The relatively low yield of spelt wheat in the first year of the study was most likely attributable to the persistent snow cover. This resulted in delayed herbicide application, after the weeds had already matured. Moreover, above-average rainfall in May and June impacted the effectiveness of weed control methods, especially on the mechanically weeded and reduced-herbicide plots. Major differences in spelt yields depending on the year were also noted by Jablonskytė-Raščė et al. [10]. Our own findings, as well as those of other authors, support the thesis that the relatively small and variable yields of spelt wheat—which are largely determined by weather trends during different growing seasons—present a barrier to spelt farming in Poland [37].

The variable yield of the spelt grain year-over-year was mainly expressed in the difference in ear density. The lowest ear density and yields were recorded in 2013. The present study indicates that simplified cultivation schemes that replace skimming with no-till methods (by using a tine tiller composed of an extirpator, a disk harrow section, and a string roller) do not significantly hamper yields across the different years of study. A study by De Vita et al. [34] suggests that no-tillage regimes can be beneficial in low-rainfall seasons. Reducing the intensity of cultivation causes an increase in the moisture content of the topsoil (0–10 cm) [24]. Therefore, eschewing conventional plow tillage or limiting the number of plow passes can boost crop yields during periods of weak precipitation [38].

In our experiment, only the 2014/2015 growing season had lower precipitation than the multi-year norm. However, the precipitation was consistent, with February 2014 and August 2015 (the harvest season) being the only drier months, which is why it had no major bearing on the growth and yield of wheat.

The results of our experiment show that the tillage scheme had no significant effect on grain yield, suggesting that tillage can be effectively limited by eschewing skimming and using a cultivator instead. Chetan et al. [33] obtained comparable yields under no-till and conventional tillage regimes. The authors surmise that the positive reaction of wheat to no-till schemes derives from the increased water retention capacity of the soil, allowing plants to keep drawing water from the soil during droughts. Other authors have provided conflicting reports on how reduced tillage impacts cereal yield. Rieger et al. [39] noted a significant decrease in winter wheat yields from reduced tillage. A study by Andruszczak [29] also showed that reduced-tillage spelt crops had much lower yields than conventionally tilled ones, mainly due to the reduced ear density per 1 m^2. Jug et al. [40] showed that no-till cultivation of winter wheat resulted in a decreased number of grains per ear. Lower cereal yields under no-till (NT) systems were also demonstrated by Grigoras et al. [41], as well as by Gawęda and Haliniarz [42]. Berner [43] found that reduced tillage of wheat (*Triticum aestivum* L.) and spelt (*Triticum spelta* L.) crops led to yields reduced by 14% ($p < 0.001$) and 8% ($p < 0.05$) compared with conventional tillage. However, an experiment by Ali et al. [44] showed the opposite, with the best performance achieved when durum wheat was grown under the NT system. The grain yield under NT was significantly higher than under CT, with the lowest values recorded for reduced tillage (RT). An experiment by Schlegel et al. [45] obtained higher yields of winter wheat (*Triticum aestivum* L.) under no-till (NT) and reduced-tillage (RT) regimes than under conventional ploughing (CT). The same authors also found that NT and RT systems were associated with higher moisture content compared with CT, which undoubtedly boosted wheat yields. Singh et al. [46] have noted that conventional plough tillage can be eschewed without sacrificing crop productivity, but only on fine-textured soils.

In our study, reduced tillage adversely impacted the tested parameters of spelt grain quality. Other authors disagree on how tillage methods affect the quality of cereal grains. Ali et al. [44] and Amato et al. [47] found that wheat grown using NT regimes contained much less protein than that cultivated under CT or RT. Gawęda and Haliniarz [42] found that CT performed much better than NT in terms of grain density and uniformity, while also resulting in a much lower gluten index. On the other hand, there was no major difference between the CT and NT systems in terms of the Zeleny sedimentation values and protein/gluten content of winter wheat grain. Woźniak [48] proves that reduced tillage contributes to a decrease in the content of protein and wet gluten as well as in grain test weight of spring wheat. The results of our experiment and the study by Woźniak and Rachoń [49] indicate an adverse effect of NT system on winter wheat grain uniformity, whereas Kraska et al. [50] and Peigné et al. [51] found no significant effect of tillage systems (CT vs. NT) on the aforementioned wheat grain quality parameters. Hury et al. [52] have reported that using a reduced-tillage system (with a disk harrow used in lieu of a plow) had virtually no effect on the physical quality parameters of winter spelt grain and flour. The only significant difference was noted for wet gluten content, which was significantly higher for the reduced-tillage variant than for the conventional one. In the study by Grigoras et al. [41], the average content of protein and gluten in wheat grain obtained in the NT system was higher than in the conventional system (CT), by 0.15% and 0.67%, respectively. An experiment by Andruszczak [29] showed that reduced tillage significantly improved the Zeleny sedimentation value and the protein/gluten content of wheat grain compared with conventional tillage. According to Žuljević et al. [53], the required wet gluten content is at least 25% for good baking quality of wheat products. In our study, similar gluten content was obtained only in conventional tillage (CT), reduced tillage RT2, and in the plot with the recommended herbicide rate (MC 100%).

Our findings indicate that the weed control method has a considerable effect on spelt wheat yields. Combined mechanical + chemical weed control, both at full and reduced herbicide rates, produced higher yields than purely mechanical methods (M). However, the yields were significantly better when the full herbicide dose was applied (MC 100%) compared with the 25%-reduced treatment (MC 75%). Our findings are corroborated by Haliniarz and Chojnacka [17], who found that the application of the full herbicide dosage led to significantly (10%) higher spelt grain yield than those obtained from the control plot (no herbicides). Andruszczak [29] also demonstrated improved yields (10% higher on average) of a winter spelt crop when comprehensive chemical protection was applied. In this particular study, the improvements were mostly evident in the ear density per 1 m^2. Chemical treatments had no significant effect on the length of ears, number and weight of grains per ear, or on the thousand-kernel weight. In contrast, our study did demonstrate that herbicide treatments boosted the thousand-kernel weight and grain weight per ear as compared against mechanical treatments. Haliniarz et al. [54] examined the yields of 'Rokosz' spelt wheat and found that the variety was much more productive when chemical protection agents were used rather than the more environmentally friendly methods.

The study shows that mechanical + chemical weed control, both at full and reduced (75%) herbicide rates, produced better quality grain than purely mechanical methods (M). The full-herbicide treatment variant (MC 100%) produced superior quality grain (with regard to all tested parameters) to the variant weeded by mechanical means only (M). The reduced-herbicide variant (MC 75%) showed significantly increased protein levels in grain, falling numbers, grain uniformity, and bulk grain density compared with harrowed-only plots (M). The present study indicates that the herbicide rate does not have a substantial impact on the protein/gluten content of wheat grain, with no major difference in these values between the full- and reduced-herbicide variants. The same pattern was identified by Haliniarz and Chojnacka [17], who demonstrated similar parameters for spelt crops given either full herbicide or 25%-reduced herbicide treatments. A study by Andruszczak [29] indicated that chemical crop protection significantly boosted the Zeleny sedimentation value and protein levels in grain but did not affect the gluten and starch content. Similarly, Rachoń et al. [55] found that higher rates of chemical crop protection improved the chemical composition of spelt, increasing the protein content of the grain.

5. Conclusions

The choice of tillage system had no significant effect on spelt grain yields but did impact some parameters of the crop structure. Conventional tillage (CT) performed the best in improving the number of ears per m^2. Most of the spelt grain quality parameters proved to be worse under reduced-tillage regimes. The only other variant comparable to CT in terms of the protein/gluten content of wheat grain, falling numbers, and Zeleny sedimentation value was RT2 (ploughed 5 weeks before sowing).

Using combined mechanical + chemical treatments at full herbicide rates or at a rate reduced by 25% improved yields against mechanical maintenance. Full herbicide application proved to stimulate grain weight per ear more effectively than mechanical crop control.

Combined mechanical + chemical weed control produced better quality spelt grain than purely mechanical methods (M). Out of the two, the full-herbicide treatment variant (MC 100%) proved to perform the best in this regard.

Yields, crop structure parameters, and grain quality parameters were determined by the weather conditions across the different years of study.

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