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Integrated Effects of Tillage Intensity, Genotype, and Weather Variability on Growth, Yield, and Grain Quality of Winter Wheat in Maize–Wheat Rotation

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Abstract

The aim of the study was to compare grain yield, grain quality, and morphophysiological parameters of three winter wheat cultivars: Kilimanjaro, Hymalaya, and Ostroga. The cultivars were grown in crop rotation after grain maize harvest, using three tillage systems: conventional (C), reduced (R), and no-tillage (N). A three-year field experiment was conducted in southeastern Poland. Compared to no-tillage, the use of conventional and reduced systems resulted in higher grain yield, increased leaf area index and relative chlorophyll content, and higher gas exchange parameters. In the conventional system, the highest grain yield was achieved by cvs. Hymalaya and Ostroga, while in no-tillage and reduced, it was cv. Hymalaya. Compared to no-tillage, the conventional system resulted in higher values of grain quality parameters, while simultaneously reducing ash content, and the reduced system promoted a better gluten index. Interactions between cultivar and tillage system demonstrated good grain quality in terms of protein, falling number, and gluten index. Gluten content above 25.0% was found in grains of cvs. Kilimanjaro and Hymalaya in the reduced and conventional systems, and cv. Ostroga in the conventional system. The dry and semi-drought periods in the 2018/2019 season were conducive to more favorable grain quality parameter values: protein, gluten, falling number, and ash. However, the resulting grain was characterized by a lower gluten index and lower physical parameters. Cvs. Hymalaya and Ostroga are recommended for cultivation in conventional and reduced tillage systems, and cv. additionally for no-tillage systems. Growing the cv. Kilimanjaro in no-tillage and reduced tillage systems, and the cv. Ostroga in a no-tillage system, will result in lower grain yields.

Keywords: winter wheat; cultivars; soil tillage; yield; morphophysiological traits; grain quality; weather conditions

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1. Introduction

Common wheat (*Triticum aestivum* L.) is one of the main cereal crops cultivated in the world and in Europe [1]. Poland is the third largest wheat producer in the European Union, with a cultivated area of 2.4 million hectares and a production of 12.4 million tons in 2024 [2]. Compared to other major cereal crops, wheat plays a key role in maintaining global food security [3]. Wheat is a source of not only protein, carbohydrates, and fat, but also of health-promoting substances such as fiber, B vitamins, folic acid, and many macro- and micronutrients [4].

Wheat grain yield and quality depend primarily on soil and climatic requirements (temperature, rainfall), cultivar genotype, and agrotechnical practices, among which crop rotation and soil tillage play an important role [5–7]. The value of pre-crop plants is determined by the quantity and quality of crop residues, as they influence the physical, chemical, and biological properties of the soil. Wheat is a cereal species with high pre-crop requirements [8]. Higher wheat grain yield and quality were observed when the pre-crop plants included legumes (pea, faba bean, soybean), sugar beets, and winter rapeseed, as they improve soil conditions and have a positive phytosanitary impact [9]. However, these pre-crops pose an increased risk of leaching of mineral nitrogen accumulated in the soil (up to 100 kg N ha^{-1}) in winter, as nitrogen uptake by winter wheat in autumn is limited and usually does not exceed 20 kg N ha^{-1} [10].

In Europe, cereal-based crop rotations are widely used for economic reasons, resulting in wheat being grown after cereals or in monoculture. This leads to increased weed infestation, which usually causes reduced wheat growth and lower grain yields with poorer quality parameters. Winter wheat is usually grown in short rotations after winter rapeseed and very often after grain maize (*Zea mays* L.), using reduced tillage systems. After growing maize for grain, a large amount of nutrients, such as potassium, nitrogen, phosphorus, magnesium, calcium, and trace elements, remain in the field. The highest amounts of these nutrients are released in the first year, which positively impacts the yield and quality of the following crop. To enable sowing winter wheat after grain maize, it is important to thoroughly crush the remaining crop residue and completely incorporate it into the soil [11,12].

The results of some studies indicate that after maize, wheat grain yield under reduced tillage (RT) and no-tillage (NT) conditions may be lower or similar compared to conventional tillage (CT) [13]. Reduced (R) and no-tillage (N) systems are expected not to compromise grain quality and yield under certain conditions. However, the remaining plant residues after corn harvest in the reduced system should be thoroughly mixed with the soil to allow for precise wheat sowing [14].

In reduced (R) or no-till (N) systems, plant residues left in the field retain significant amounts of water in the soil [15]. Partly due to soil moisture conservation and faster mineralization of plant residues, better wheat grain yields have been demonstrated in crop rotation than in monoculture in the no-tillage system and in the reduced system in relation to the conventional one [16,17].

The genotype of a cultivar has a decisive influence on yield potential only if the cultivar is well adapted to the agroclimatic conditions of a given region. The different responses of wheat cultivars to variable hydrothermal and agrotechnical factors may result from their genetic resistance to biotic and abiotic stresses [18]. Tillage practices, in interaction with the cultivar genotype, can modify these stresses. This may affect the course of physiological processes and thus the productivity of wheat [19].

Hybrid wheat cultivars are bred to achieve satisfactory yields and grain quality under various environmental stresses and to adapt them to desired agronomic conditions [20]. The vigor of these cultivars, genetically derived from different parental lines, influences their more favorable agronomic and environmental traits. Hybrid cultivars are characterized by faster growth rates, higher and more stable grain yields, and better resistance to stressful agronomic and environmental conditions [21,22].

Sparse studies indicate that awned wheat cultivars may have higher yields and better grain quality than awnless cultivars [23,24]. Ear awns are active photosynthetic organs that supply significant amounts of assimilates to the kernels. They do not lose their activity during periods of drought, so awns are better able to cope with this stress [25].

Furthermore, compared to the flag leaf, the chloroplasts of the ear awns remain intact and active during the late grain filling period, which typically occurs in wheat cultivation after late harvested pre-crops [26].

The aim of the study was to determine the extent to which reduced (R) or no-tillage (N) systems, in relation to conventional tillage (C), affect the yield, grain quality, and morphophysiological parameters of winter wheat cultivars grown in maize–wheat rotation. The research hypothesis assumed the interactions of cultivars and tillage systems in shaping the grain yield and the values of the studied traits. Current climate changes with a shortage of rainfall, and, at the same time, progress in the breeding of wheat cultivars makes research on the integrated effect of tillage intensity and cultivar genotype in shaping the parameters of wheat growth, yield, and quality important. It is therefore expected that the obtained results will draw farmers' attention to the appropriate selection of winter wheat cultivars grown after the harvest of grain maize for less intensive tillage systems.

2. Materials and Methods

2.1. Experiment Site and Design

A field experiment was conducted in 2018–2021 at the Advisory Center in Boguchwała (49°59′ N, 21°56′ E; altitude 222 m), southeast Poland. The experiment had a randomized block design with two factors and 3 replications. The area of a single experimental plot was 18 m^2 (1.5 × 12 m). In each growing season the number of plots was 27, with a total area of 486 m^2 (Figure S1).

The experiment included two research factors:

I. Tillage system (TS): conventional (C), reduced (R), no-tillage (N), (Table 1).

Table 1. Tillage system characteristics.

Tillage System (TS)	Cultivation Treatments
Conventional	Mulching straw, disking (12 cm depth), presowing plowing (20 cm depth)
Reduced	Mulching straw, disking (15 cm depth), stubble cultivator (20 cm depth)
No-tillage	Mulching straw, sowing directly into the stubble with (seeder with double disk coulters)

II. Winter wheat cultivars (C): cv. Kilimanjaro (common), cv. Hymalaya (hybrid), cv. Ostroga (common), [27], (Table 2).

Table 2. Tested wheat cultivars.

Cultivars (C)	Quality Class	Thousand Grain Weight (g)	Plant Height (cm)	Ear	Breeding/Country
Kilimanjaro	A	46.7	85	Awnless	RAGT Semences GmbH, Torun, Poland
Hymalaya	A	42.2	78	Awnless	Saaten-Union GmbH, Estrées-Saint-Denis, France
Ostroga	A	48.1	87	Awned	DANKO GmbH, Wielkopolskie, Poland

A—high quality.

In Poland, the tested cultivars are considered quality bread varieties (group A), with genetically determined processing quality of grain intended for baking bread. Furthermore, these cultivars tolerate delayed sowing dates well, which allows them to be grown after various preceding crops, including late harvests. The selection of the cultivars was based on the COBORU (Słupia Wielka, Poland) recommendations [28].

The preceding crops (previous crop − main crop) were grown simultaneously, in a two-year maize—winter wheat rotation system, in which each crop returned to the same field after a one-year break.

The preceding crop, i.e., maize grown for grain (cv. Toutati, breeding—Lidea SAA GmbH, France), was harvested in the third decade of September and the first decade of October. Winter wheat was sown at a rate of 350 (cvs. Kilimajaro and Ostroga) and 200 (cv. Hymalaya) seeds per m^{-2}. Sowing was performed in the second decade of October at a row spacing of 14 cm, at a depth of 3–4 cm.

Phosphorus (superphosphate—46% P_2O_5) and potassium (potassium salt—60% K_2O) fertilization were applied once in the fall. Phosphorus (P) and potassium (K) fertilization rates were 75 and 128 kg ha^{-1} in 2018, 120 and 182 kg ha^{-1} in 2019, and 150 and 145 kg ha^{-1} in 2020, respectively, while the nitrogen fertilization rate was 180 kg ha^{-1} (ammonium nitrate—34%). Nitrogen was applied in 3 doses: 70 kg ha^{-1} in spring (21–23 BBCH), 60 kg ha^{-1} at the stem elongation (32–33 BBCH), and 50 kg ha^{-1} at the earing stages (54–56 BBCH). Foliar fertilization with Plonvit Z was also applied twice at a dose of 1.0 L ha^{-1} at BBCH stages 31–39.

The use of other agrochemicals in the individual study years depended on the occurrence of weeds, diseases, and pests (Table 3). Mineral fertilization and plant protection products were applied to wheat in accordance with the recommendations of the Institute of Plant Protection and Biotechnology (IOR-PIB) in Poznań, Poland [29], and according to the BBCH scale [30].

Table 3. Plant protection products used during the wheat growing period.

Active Ingredients (Product)	Dose (L ha^{-1})/* Development Phase
mecoprop, MCPA, dicamba (Herbicide)	2.0/24–25
iodosulfuron-methyl-sodium, 2,4-D (Herbicide)	1.0/24–25
protioconazole, spiroksamin, tebuconazole (Fungicide)	1.0/32–33
propiconazole, cyproconazole (Fungicide)	0.5/54–56
lambda-cyhalothrin (Insecticide)	0.35/54–56
trinexapac-ethyl (Growth regulator)	0.35/54–56

* BBCH scale [30].

2.2. Soil and Weather Conditions

The experiment was conducted on a clayey soil classified as Fluvic Cambisol (*CMfv*) according to the WRB [31]. In the 2018/2019 and 2020/2021 growing seasons, the soil pH (in 1.0 mol/L) was neutral, while in 2019/2020 it was slightly acidic. Both the organic carbon and N_{min} (in 0.01 mol/L $CaCl_2$ solution) contents were low [32,33]. The content of available phosphorus and potassium (in 0.04 mol/L $C_6H_{10}CaO_6$ solution) was high, and that of magnesium (in 0.0125 mol/L $CaCl_2$) was medium [34,35].

The content of soluble forms of iron, zinc, manganese, and copper was extracted in 1.0 mol/L HCl [36]. During the study years, the content of iron, manganese, and copper was medium. In the 2018/2019 and 2020/2021 seasons, the content of zinc was considered medium, while in 2019/2020 it was low (Table 4).

Table 4. Soil composition (0–35 cm).

Specification	Growing Seasons		
	2018/2019	2019/2020	2020/2021
pH (KCl)	6.85	6.15	7.06
Organic Carbon (%)	1.11	1.25	1.35
N_{min} (kg ha^{-1})	57.0	60.1	58.1
Nutrients (mg kg^{-1})			
Phosphorus	215.0	128.1	72.0
Potassium	265.1	170.1	248.1
Magnesium	123.0	135.5	220.6
Iron	1889.0	2713.0	2332.4
Zinc	13.9	6.3	12.4
Manganese	219.4	159.1	175.8
Copper	7.0	8.6	9.1

Weather data were obtained from the meteorological station located at the Advisory Center in Boguchwała, where the field experiments were conducted. For the spring and summer growing seasons, values of the Sielianinov hydrothermal index (K) were calculated, and their interpretations were provided [37] (Figure 1).

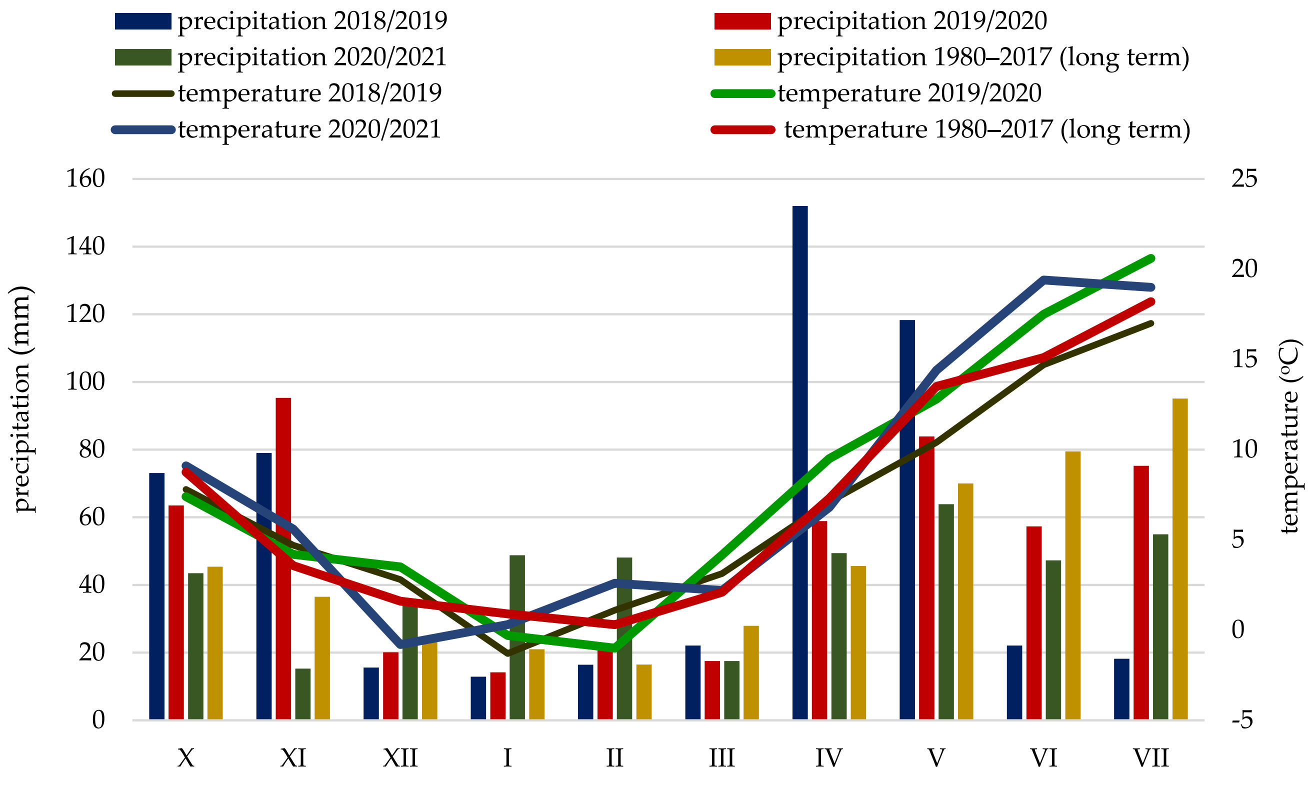

Figure 1. Weather conditions during the seasons of 2018–2021 and in the long-term period 1980–2017.

The 2018/2019 growing season was characterized by higher temperatures in October and December as well as in January and February, ranging from 0.8 to 1.2 °C compared to the multi-year average. In the 2019/2020 and 2020/2021 seasons, the highest temperatures were recorded in June, with these temperatures being 2.4 and 4.3 °C higher than the multi-year average. April in the 2018/2019 season saw the highest rainfall (152.0 mm), while July had the largest rainfall shortfall compared to the multi-year total, amounting to

76.9 mm. Also, in the 2019/2020 and 2020/2021 seasons, the lowest rainfall compared to the multi-year total occurred in June and July.

Hydrothermal conditions, defined as excessive moisture, occurred in April 2019 and 2021 as well as in May 2019. A drought occurred in June 2019 and a semi-drought in July 2019 and 2021. Furthermore, semi-drought periods occurred in April and June 2020. The optimal hydrothermal conditions occurred in May and June in the 2021 season (Table 5).

Table 5. The Sielianinov index (K) in the April–July period.

Specification	Growing Seasons			Long-term 1980–2017
Month	**2018/2019**	**2019/2020**	**2020/2021**	
April	excessive moisture	semi-drought	excessive moisture	excessive moisture
May	excessive moisture	optimal	optimal	optimal
June	drought	semi-drought	optimal	optimal
July	semi-drought	optimal	semi-drought	excessive moisture
Mean	excessive moisture	semi-drought	optimal	optimal

2.3. Yield Assessment

Wheat was harvested at full grain maturity (89–92 BBCH) using a plot combine in the third decade of July. Wheat grain yield was determined at 15% moisture and expressed in t ha^{-1}.

2.4. Morphophysiological Measurements

One LAI (leaf area index) measurement was performed above the crop, and three measurements were performed inside the wheat canopy according to the Hicks and Lascano method [38]. LAI measurements were performed with an LAI 2000 instrument (LI-COR, Lincoln, NE, USA). SPAD (soil–plant analysis development) and gas exchange measurements were performed randomly on selected plants according to the Blackmer and Schepers [39] and Nobel [40] methods. Chlorophyll content measurements were performed on 15 plants using an SPAD-502P Konica Minolta instrument (Tokyo, Japan).

The gas exchange parameters were as follows: net photosynthetic rate (Pn), transpiration rate (E), stomatal conductance (Gs), and intracellular CO_2 concentration (Ci). The measurements were performed at the flowering stage of wheat (65 BBCH). Gas exchange measurements were performed on 2 plants using a portable LCpro-SD system (ADC BioScientific Ltd., Hoddesdon, UK). Water use efficiency (WUE) was calculated as the ratio of PN to E.

2.5. Wheat Quality Parameters

Wheat grain was assessed for basic quality parameters. The scope of chemical analyses included the assessment of ash content (A) and protein content (P) determined according to the Kjeldahl method on a Kjeltec 8200 analyzer (Foss, Hillerød, Sweden). Wet gluten content (WG) and gluten index (GI) were determined using a Glutomatic 2200 device (Perten Instruments, Hägersten, Sweden), and falling number (FN) was determined by the Hagberg–Perten method using a Falling Number 1400 device (Perten Instruments, Hägersten, Sweden). The analyses were performed in accordance with AACC methods [41].

The scope of the physical properties tests included the determination of hectoliter weight (HW) using a 1-liter measuring container [42], and thousand grain weight (TGW) was calculated using a grain counter, subtracting 2 × 500 grains. The TGW result is given as a value determined from the weights obtained for the individual replications, after conversion to 14% moisture [43]. A mechanical sorter with a 2.5 × 2.0 mm mesh screen was used to determine the grain uniformity (GU) value. A 100 g grain sample was sieved, weighed, and the GU result was expressed as a percentage [44]. Grain vitreousness (GV) was determined using a farinotome [45]. Grain physical parameters were determined using equipment from Sadkiewicz Instruments, Bydgoszcz, Poland.

2.6. Statistical Analysis

The results were statistically analyzed using Statistica 13.3.0 statistical software (TIBCO Software Inc., Palo Alto, CA, USA). Tukey's test was used to verify the significance of differences at the level of $p \geq 0.05$. To check the analyzed data, the Shapiro–Wilk normality test was used. ANOVA was used to compare the effects of the studied factors: cultivation system (n = 3), cultivar (n = 3), year (n = 3), and their interaction effects on the studied traits. In order to verify the detected regularities and relationships between yield, morphophysiological measurements, and wheat quality parameters, Pearson correlation coefficients were calculated (p = 0.05).

3. Results and Discussion

3.1. Grain Yield

Grain yield was significantly dependent on the tillage system, cultivar, and weather conditions in each year of the study (Table 6).

Table 6. The effect of the experimental factors on the wheat yield, LAI, and SPAD index (mean for 2018–2021).

Factor		Grain Yield (t ha^{-1})	Leaf Area Index	Soil–Plant Analysis Development
Tillage System (TS)	**Cultivar (C)**			
Conventional		8.25 ± 0.60 a	5.41 ± 0.96 a	37.9 ± 5.7 a
Reduced		8.02 ± 0.52 a	5.26 ± 0.86 a	36.5 ± 6.5 ab
No-tillage		7.66 ± 0.62 b	4.39 ± 0.69 b	35.2 ± 7.7 b
	Kilimanjaro	7.54 ± 0.45 c	4.85 ± 0.96 b	35.2 ± 8.8 c
	Hymalaya	8.45 ± 0.62 a	5.22 ± 0.75 a	38.0 ± 4.5 a
	Ostroga	7.94 ± 0.45 b	4.97 ± 0.69 b	36.4 ± 5.7 b
Year (Y)	2018/2019	7.51 ± 0.69 c	4.86 ± 0.71 b	34.5 ± 9.1 c
	2019/2020	7.87 ± 0.61 b	5.01 ± 0.63 a	36.7 ± 5.7 b
	2020/2021	8.55 ± 0.59 a	5.18 ± 0.87 a	38.5 ± 6.4 a
Mean		7.98	5.02	36.5
TS		***	***	***
C		***	*	***
Y		***	*	***
TS × C		**	**	**
TS × Y		*	*	*
C × Y		*	**	ns
TS × C × Y		ns	ns	ns

Values marked with the same letter do not differ significantly at p = 0.05 in Tukey's test. Respectively a–c: * < 0.05; ** < 0.01; *** < 0.001; ns: not significant; ± standard deviation (SD).

A significant increase in grain yield was demonstrated after the use of conventional and reduced tillage systems, compared to the no-till system. However, the differences in grain yield between the conventional and reduced tillage systems were statistically insignificant. According to Sip et al. [16], the average wheat yield was higher in the reduced system than in the conventional system, with a statistically significant difference of 0.27 t ha^{-1}.

Furthermore, the study by Jaskulska et al. [13] showed that the use of the reduced system reduced the winter wheat yield by 5.0% in relation to the conventional system, with the yield being 0.65 t ha^{-1} higher after the winter rapeseed pre-crop than after maize. Some studies indicate that the wheat yield reduction in the no-tillage system in relation to the conventional system can range from 11.3 to 24.7% [46,47]. Under certain habitat conditions, reduced-till and no-till systems do not always increase yields, but their implementation is less costly [46].

One of the key factors influencing grain yield is the selection of the appropriate cultivar for the climatic conditions in a given area, which was also confirmed in the conducted research [16,48]. Šíp et al. [16] showed that variable environmental conditions (weather conditions and experimental location) caused greater variation in the grain yield of 13 tested winter wheat cultivars than tillage systems. In turn, Mitura et al. [48] report that wheat grain yield depends on the genotype of the cultivars and the better adaptation of winter cultivars, which are characterized by a longer growing period, to weather conditions. The highest average yield was obtained by cv. Hymalaya (8.45 t ha^{-1}). The yield was significantly lower for cv. Ostroga (7.94 t ha^{-1}) and the lowest for cv. Kilimanjaro (7.54 t ha^{-1}).

The variability in the effect of the wheat cultivars on grain yield in the tillage systems demonstrated in our study was also confirmed by the results of previous studies [14,16]. The TS × C interaction showed that in the conventional system the highest grain yield was achieved by cvs. Hymalaya (8.62 t ha^{-1}) and Ostroga (8.42 t ha^{-1}), while in reduced and no-tillage, cv. Hymalaya achieved 8.56 and 8.19 t ha^{-1}, respectively (Figure 2).

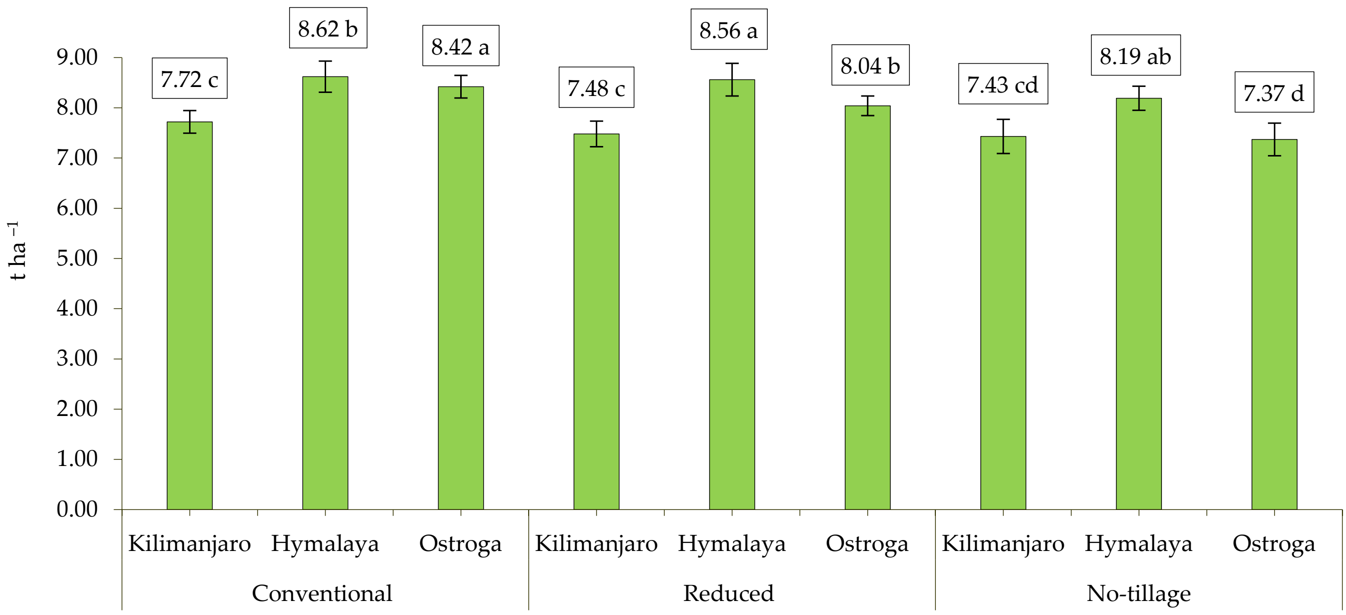

Figure 2. Grain yield (interaction of tillage system × cultivars). Values marked with the same letter do not differ significantly at p = 0.05 in Tukey's test.

The lowest grain yield was recorded in no-tillage cultivation, which was 7.37 t ha^{-1} for cv. Ostroga and 7.43 t ha^{-1} for cv. Kilimanjaro. Cv. Hymalaya achieved a similar grain yield in the conventional and reduced systems, but slightly lower in no-tillage. The yield of cv. Kilimanjaro was similar across all the tillage systems. In cv. Ostroga, the grain yield was found to be 4.5 to 12.5% higher in the conventional system compared to reduced and no-tillage. This demonstrates that, due to its higher grain yield, the hybrid cv. Hymalaya can be recommended for R and N tillage systems and cv. Ostroga for the R system. These results indicate that hybrid cultivars, compared to common cultivars, achieve more stable grain yields under variable agrotechnical conditions such as delayed sowing date or reduced tillage [20]. Moreover, in our own research, as observed visually, cv. Hymalaya hybrid was characterized by a faster growth rate in the initial stages of development, a well-developed root system, and a higher productive tillering coefficient than cvs. Kilimanjaro and Ostroga. Therefore, the cv. Hymalaya can be recommended for cultivation in more difficult conditions, i.e., for reduced (R) and no-tillage (N) cultivation. Wheat cultivars recommended for reduced tillage (R) and no-tillage (N) should be characterized by rapid growth in the initial stages of development and better utilization of available water during growth [49–51].

A longer growing season and better adaptation to climatic conditions usually mean that winter wheat cultivars have higher yields than spring cultivars [48]. This has been proven by our research, in which the highest grain yield, among the study years, was achieved in the 2020/2021 season when temperature and precipitation conditions were similar to the multiannual data. In the 2018/2019 and 2019/2020 seasons, which experienced periods of drought and semi-drought, the grain yield was 8.0 to 12.2% lower than in the 2020/2021 season. According to Li et al. [25], soil moisture deficiency in dry years adversely affects physiological processes, resulting in lower grain yields.

3.2. Leaf Area Index (LAI)

In this study, the highest LAI values were observed at the wheat flowering stage, ranging from 3.93 in strip tillage (ST) to 4.23 in conventional tillage (C). In our study, no-tillage resulted in a lower LAI in relation to the conventional and reduced systems, by 16.5% (R) and 18.9% (C), respectively. However, the differences in LAI between the conventional and reduced systems were insignificant (Table 6). The LAI in wheat can vary widely from 4.41 to 9.46, and there is a close relationship between the LAI value during the period of intensive growth of the wheat flag leaf and grain [46,52]. The research by Lepiarczyk et al. [53] shows that tillage systems significantly influenced the leaf area of wheat. The LAI values at the heading stage in wheat treated with conventional tillage compared to reduced tillage were 22.3% higher and correlated with grain yield. However, research by Różewicz et al. [18] only showed a trend toward higher LAI values at specific development stages in wheat treated with conventional tillage (C) than in strip tillage (ST).

Cv. Hymalaya achieved higher LAI values compared to the other cultivars, ranging from 4.8 (cv. Ostroga) to 7.1% (cv. Kilimanjaro). All the cultivars grown in the no-tillage system had significantly lower LAI values, ranging from 4.22 (cv. Ostroga) to 4.53 (cv. Hymalaya). The highest LAI values were achieved by cv. Hymalaya in the conventional (5.64) and reduced (5.49) systems, followed by cv. Ostroga in the conventional (5.42) and reduced system (5.27), respectively. The studies conducted by other authors generally show significant inter-cultivar differences for this trait [46,54] or no such relationships [18] (Figure 3).

As reported by Barbosa et al. [55], wheat cultivars demonstrate different biomass production strategies depending not only on agrotechnical factors but also on soil and hydrothermal conditions, which influence the cultivar variation in LAI values. In the conducted study, especially in the 2020/2021 season when more favorable moisture conditions prevailed, higher LAI values were observed. Therefore, when forecasting grain yield of individual wheat cultivars based on LAI values, it is necessary to take into account photosynthetic variables related to water stress in growing seasons with a rainfall deficiency [56].

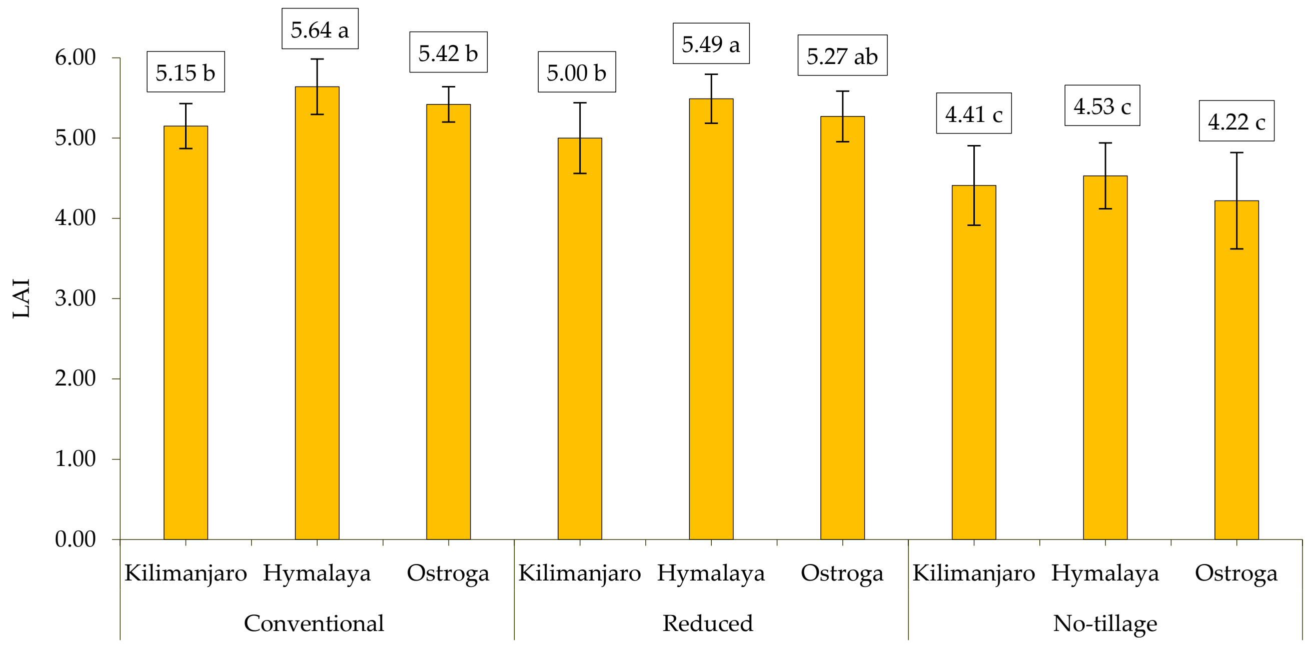

Figure 3. Leaf area index (interaction of tillage system × cultivars). Values marked with the same letter do not differ significantly at $p = 0.05$ in Tukey's test.

3.3. Soil–Plant Analysis Development (SPAD)

In the conducted study, the conventional system promoted an increase in SPAD values compared to the reduced system, but the differences observed were not statistically significant (Table 6). Lower SPAD values were observed in the reduced system (36.5) and the lowest in the no-tillage system (35.2), although these values were also not statistically different. Šip et al. [16] reported that the conventional system, in relation to reduced and no-tillage, resulted in better nitrogen utilization, which may contribute to higher chlorophyll values in the wheat flag leaf. Hury et al. [57] indicated that nitrogen fertilization and cultivar genotype had a significantly greater effect on SPAD values than tillage systems (C vs. R). Cv. Kilimanjaro had the lowest SPAD content in relation to cvs. Ostroga and Hymalaya, by 3.3 and 7.4%, respectively. The highest SPAD values were observed in cvs. Hymalaya and Ostroga plants in the conventional system and cv. Hymalaya in the reduced system. However, the lowest SPAD was obtained in cvs. Ostroga and Kilimanjaro in the no-tillage system (Figure 4).

As reported by Barutçular et al. [58], high chlorophyll content is a desirable trait, which means that more carbohydrates are available for grain formation in wheat cultivars with higher chlorophyll content. Differences in SPAD values between wheat cultivars may result from variations in measurement conditions and leaf structural differences, which cause different effects of chlorophyll reflection and/or scattering of light [59,60]. Typically, drought stress reduces chlorophyll content, inhibits plant growth, and ultimately reduces wheat grain yield [61]. This was also observed in our study, where rainfall deficiency in the 2018/2019 season significantly reduced the chlorophyll content in wheat. Conversely, more favorable moisture conditions in the 2020/2021 season resulted in an increase in SPAD values.

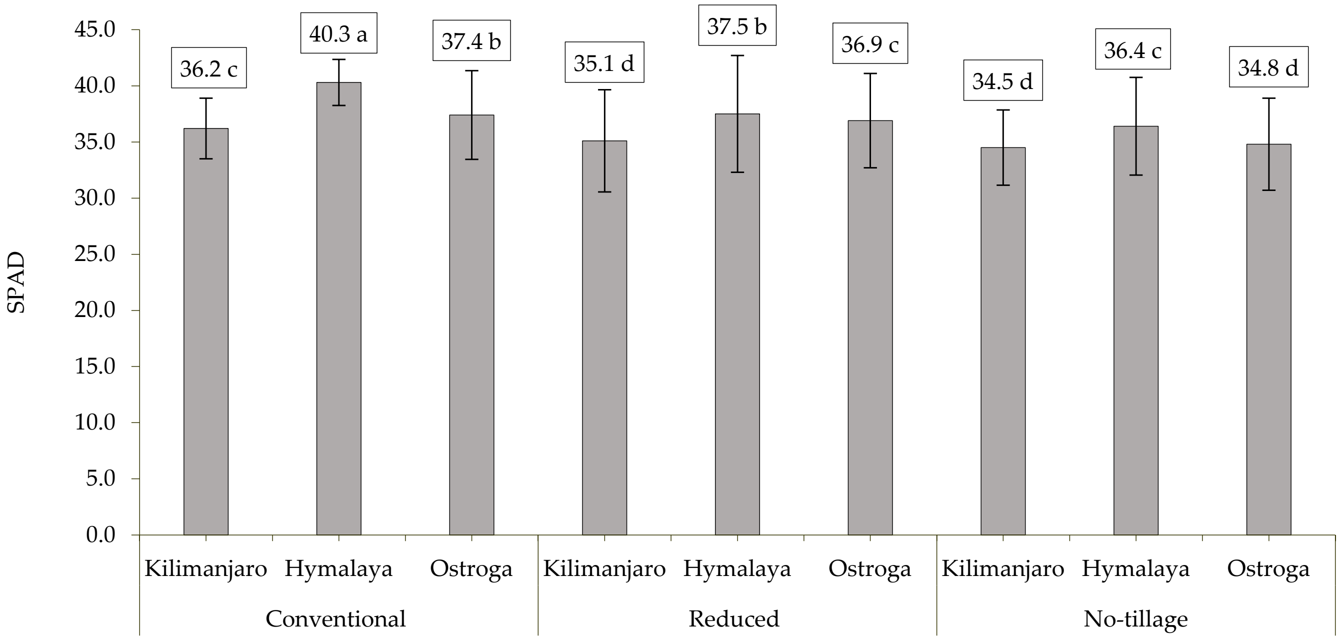

Figure 4. Soil–plant analysis development (interaction of tillage system × cultivars). Values marked with the same letter do not differ significantly at $p = 0.05$ in Tukey's test.

3.4. Gas Exchange

Measurements of gas exchange parameters can provide real-time insight into the efficiency of key photosynthetic enzymes, allowing optimization of both photosynthesis and transpiration rates in wheat [62]. The conventional system promoted more efficient gas exchange, as evidenced by the highest values of the photosynthetic rate, stomatal conductance, transpiration rate, and intracellular CO_2 concentration parameters (Table 7).

The increase in Pn values in the conventional system in relation to the reduced- and no-tillage systems was similar, reaching 6.0 and 7.3%, respectively. No statistically significant differences were found between the conventional and reduced systems for the Gs parameter, or between reduced and no-tillage for Pn and E.

Higher photosynthetic rates (Pn) in the conventional system may be associated with better soil aeration and therefore with more intensive organic matter mineralization processes and greater nitrogen availability [63]. Insufficient supply of soil nitrogen in reduced or no-tillage systems (R and N) limits the availability of CO_2 and reduces its fixation, which decreases photosynthetic efficiency and the Pn and Gs indices [64]. The Pn values in the tested cultivars ranged from 13.7 to 14.5 μmol (CO_2) m^{-2} s^{-1}. Cv. Kilimanjaro exhibited significantly the lowest Pn values in relation to the other cultivars. For the Gs, E, and Ci parameters, the highest values were found for cv. Hymalaya. In regard to Gs and Ci, no significant differences were found between cvs. Kilimanjaro and Ostroga. Cvs. Hymalaya and Ostroga also had similar Pn values, while cvs. Hymalaya and Kilimanjaro had similar E values. Of the analyzed study years, the highest values of the photosynthetic rate, stomatal conductance, transpiration rate, and intracellular CO_2 concentration parameters were observed in the 2021/2022 season and the lowest in the 2018/2019 season.

Różewicz et al. [18] reported that the cultivar's effect on net photosynthesis (Pn) was observed at the flag leaf stage and early heading stage of wheat, whereas at the full heading stage, the inter-cultivar differences for this trait were no longer significant. According to Wasaya et al. [65], the current trend is to look for wheat cultivars with higher chlorophyll content, which retain more photosynthetic pigments under both mild and severe drought conditions, thus maintaining higher stomatal conductance (Gs) and net photosynthesis (Pn). The highest Pn, E, and Gs values were obtained for cvs. Hymalaya and Ostroga in the conventional system. The Pn parameter was lowest in the reduced- and no-tillage systems for cv. Kilimanjaro and in the no-tillage system for cv. Ostroga.

Table 7. The effect of the experimental factors on the selected gas-exchange indicators (mean for 2018–2021).

Factor		Photosynthetic Rate (mmol (CO_2) m^{-2} s^{-1})	Stomatal Conductance (mol (H_2O) m^{-2} s^{-1})	Transpiration Rate (mmol (H_2O) m^{-2} s^{-1})	Intracellular CO_2 Concentration (µmol (CO_2) m^{-2} s^{-1})	Water Use Efficiency (mmol mol^{-1})
Tillage System (TS)	**Cultivar (C)**					
Conventional		15.0 ± 0.8 a	0.530 ± 0.332 a	3.74 ± 0.72 a	326 ± 45 a	4.01 ± 0.74 b
Reduced		14.1 ± 1.2 b	0.515 ± 0.025 a	3.28 ± 0.68 b	314 ± 39 b	4.29 ± 0.80 a
No-tillage		13.9 ± 0.6 b	0.428 ± 0.367 b	3.21 ± 0.92 b	303 ± 74 c	4.34 ± 0.88 a
	Kilimanjaro	13.7 ± 0.7 b	0.475 ± 0.124 b	3.51 ± 0.76 a	299 ± 69 b	3.91 ± 1.21 c
	Hymalaya	14.7 ± 0.9 a	0.511 ± 0.324 a	3.53 ± 1.21 a	333 ± 61 a	4.16 ± 0.93b
	Ostroga	14.5 ± 1.2 a	0.486 ± 0.214 b	3.18 ± 1.31 b	311 ± 55 b	4.57 ± 0.68 a
Conventional	Kilimanjaro	14.6 ± 1.5 b	0.504 ± 0.181 b	3.59 ± 1.10 ab	301 ± 39 b	4.06 ± 0.96 c
	Hymalaya	15.3 ± 1.2 a	0.553 ± 0.214 a	3.91 ± 0.83 a	350 ± 42 a	3.91 ± 0.88 c
	Ostroga	15.2 ± 0.6 a	0.531 ± 0.145 a	3.72 ± 1.24 a	328 ± 21 a	4.09 ± 0.75 c
Reduced	Kilimanjaro	13.2 ± 0.7 c	0.490 ± 0.325 b	3.39 ± 0.83 b	290 ± 35 c	3.90 ± 1.12 c
	Hymalaya	14.3 ± 0.8 b	0.538 ± 0.045 a	3.21 ± 0.59 c	335 ± 62 a	4.45 ± 1.10 b
	Ostroga	14.7 ± 1.1 b	0.516 ± 0.214 b	3.24 ± 0.95 c	316 ± 74 b	4.53 ± 0.78 b
No-tillage	Kilimanjaro	13.5 ± 0.9 c	0.430 ± 0.214 c	3.57 ± 1.41 ab	306 ± 45 b	3.78 ± 1.23 d
	Hymalaya	14.6 ± 0.7 b	0.442 ± 0.324 c	3.48 ± 0.69 b	315 ± 62 b	4.19 ± 1.12 b
	Ostroga	13.7 ± 0.9 c	0.411 ± 0.254 d	2.58 ± 0.58 d	288 ± 55c	5.31 ± 0.89 a
Year (Y)	2018/2019	13.7 ± 0.9 b	0.475 ± 0.223 b	3.17 ± 1.40 b	293 ± 38 c	4.30 ± 1.01 a
	2019/2020	14.3 ± 0.8 b	0.490 ± 0.201 a	3.50 ± 0.86 a	316 ± 48 b	4.09 ± 0.78 a
	2020/2021	15.0 ± 0.6 a	0.507 ± 0.125 a	3.55 ± 0.68 a	334 ± 52 a	4.22 ± 0.96 a
Mean		14.3	0.491	3.41	314	4.21
TS		**	*	**	***	**
C		*	*	**	*	**
Y		**	*	*	**	ns
TS × C		**	**	*	**	*
TS × Y		ns	ns	*	*	ns
C × Y		ns	ns	ns	*	ns
TS × C × Y		ns	ns	ns	ns	ns

Respectively a–d: * < 0.05; ** < 0.01; *** < 0.001; ns: not significant; ± standard deviation (SD).

For the Gs parameter, all the cultivars grown in the no-tillage system showed the lowest values in relation to the reduced and conventional systems. The lowest E index was observed for cv. Ostroga in the reduced and no-tillage systems and for cv. Hymalaya in the reduced system. The highest Ci parameter was found for cv. Himalaya in the conventional system (350 mmol L^{-1}), and the lowest for cvs. Kilimanjaro and Ostroga in no-tillage (290 and 288 mmol L^{-1}).

Water use efficiency (WUE) is an important parameter that can be used when selecting wheat cultivars that are recommended for cultivation in drought-prone regions [66]. In our study, the WUE values ranged from 3.91 (cv. Kilimanjaro) to 4.57 mmol mol^{-1} (cv. Ostroga). WUE in the reduced and no-tillage systems was 6.5 and 7.6% higher than in the conventional system, but was not differentiated by study year. In the no-tillage system, cv. Ostroga had significantly the highest and cv. Kilimanjaro had significantly the lowest WUE parameter in relation to the conventional and reduced systems. The WUE values in the no-tillage and reduced systems for cv. Hymalaya were 6.7 and 12.1% higher than in the conventional system. In the study by Różewicz et al. [18], the highest value of this parameter, i.e., 6.70, was also found in reduced tillage treatments at the beginning of wheat earing. Tillage reductions may alleviate drought stress during the growing season under dry conditions [67].

3.5. Selected Chemical and Physical Parameters of Wheat Grain

Currently, the milling and processing industries require raw materials in the form of cereal grains with appropriate quality parameters. The good technological value of wheat grain is determined by the basic and most important chemical parameters (ash, protein, wet gluten, gluten index, falling number) and physical parameters (hectoliter weight, thousand grain weight, grain uniformity, grain vitreousness) [48,68,69].

Ash content (A) in wheat grain was significantly dependent on the tillage system (TS). The difference in A content in the no-tillage system in relation to the conventional system was 7.5%. No significant differences were found for this trait between the conventional and reduced systems, or between the reduced and no-tillage systems (Table 8).

Table 8. The effect of the experimental factors on the chemical parameters of wheat grain (mean for 2018–2021).

Factor		Ash (g kg^{-1})	Protein (g kg^{-1})	Wet Gluten (%)	Gluten Index (%)	Falling Number (s)
Tillage System (TS)	Cultivar (C)					
Conventional		18.6 ± 1.8 b	130.0 ± 11.2 a	27.6 ± 4.3 a	88 ± 9 ab	318 ± 59 a
Reduced		19.1± 1.8 ab	126.5 ± 10.7 b	26.2 ± 3.8 a	91 ± 14 a	288 ± 48 b
No-tillage		20.1 ± 1.7 a	124.3 ± 9.5 b	23.2 ± 3.1 b	84 ± 12 b	292 ± 46 b
	Kilimanjaro	20.9 ± 1.7 a	134.2 ± 10.5 a	28.3 ± 3.9 a	89 ± 7 a	313 ± 71 b
	Hymalaya	18.6 ± 1.8 b	124.8 ± 6.8 b	24.8 ± 4.4 b	88 ± 8 a	330 ± 65 a
	Ostroga	18.2 ± 1.9 b	121.7 ± 7.9 c	23.8 ± 3.8 b	86 ± 10 a	255 ± 60 c
Conventional	Kilimanjaro	20.3 ± 2.2 b	139.1 ± 10.1 a	31.1 ± 4.9 a	87 ± 8 b	329 ± 76 b
	Hymalaya	18.3 ± 1.8 d	127.4 ± 8.6 c	26.1 ± 4.5 c	90 ± 15 ab	347 ± 62 a
	Ostroga	17.3 ± 1.7 e	123.6 ± 7.5 d	25.5 ± 4.0 c	89 ± 8 ab	278 ± 60 d
Reduced	Kilimanjaro	21.0 ± 2.0 a	132.7 ± 9.7 b	29.0 ± 5.2 b	93 ± 10 a	305 ± 66 c
	Hymalaya	18.0 ± 1.7 d	123.0 ± 8.4 d	25.6 ± 3.4 c	90 ± 11 ab	323 ± 75 b
	Ostroga	18.1 ± 1.7 d	123.7 ± 7.9 d	24.1 ± 2.9 d	89 ± 9 ab	235 ± 69 e
No-tillage	Kilimanjaro	21.5 ± 2.3 a	130.8 ± 9.5 b	24.9 ± 3.5 d	88 ± 8 b	304 ± 69 c
	Hymalaya	19.5 ± 1.8 c	124.1 ± 9.7 d	22.8 ± 4.7 e	84 ± 7 c	320 ± 70 b
	Ostroga	19.4 ± 1.9 c	117.9 ± 7.9 e	21.8 ± 3.5 e	80 ± 8 d	253 ± 56 d
Year (Y)	2018/2019	20.2 ± 2.3 a	134.3 ± 9.9 a	27.1 ± 3.1 a	86 ± 5 b	324 ± 49 a
	2019/2020	19.5 ± 1.7 a	127.0 ± 8.8 b	25.3 ± 2.9 b	90 ± 13a	301 ± 64 b
	2020/2021	18.2 ± 1.6 b	119.5 ± 8.7 c	24.5 ± 3.7 b	87 ± 8 b	272 ± 52 c
Mean		19.3	126.9	25.7	88	299
TS		**	**	**	*	**
C		*	***	**	ns	***
Y		**	**	*	**	**
TS × C		**	*	*	**	**
TS × Y		ns	ns	ns	ns	ns
C × Y		*	*	ns	ns	ns
TS × C × Y		ns	ns	ns	ns	ns

Respectively a–e: * < 0.05; ** < 0.01; *** < 0.001; ns: not significant; ± standard deviation (SD).

A reduction in ash in wheat grain by 1.9 g kg^{-1} (8.6%) in the conventional system in relation to the no-tillage system was also demonstrated by Woźniak and Rachoń [70]. In terms of A content, the grain of the tested wheat varieties differed in the following order: cv. Kilimanjaro > cv. Hymalaya > cv. Ostroga.

The cv. Kilimanjaro grain had a significantly higher A content in the no-tillage and reduced systems. The lowest was found in the cv. Ostroga grain from the conventional system. The increased ash content from the no-tillage system in relation to the conventional system could have been related to the finer wheat grain. The fine grain is characterized by a poorer ratio between the endosperm and the seed coat, which accumulates large amounts of minerals, including ash [71].

In contrast to ash content (A), significantly higher protein (P) and gluten (WG) contents, and falling number (FN) were obtained in the conventional system compared to no-tillage. The P and FN contents did not differ statistically between the reduced and no-tillage systems, and the WG levels were similar between the conventional and reduced systems. The gluten index (GI) of wheat grain was higher in the reduced system and the lowest in the no-tillage system. Similarly to our own research, a decrease in P and WG content in wheat grain in reduced or no-tillage systems (especially in N) was also demonstrated in some studies [72,73]. However, as other studies have shown, tillage systems did not significantly differentiate basic wheat quality traits such as P and WG content [68,69].

The research by Różewicz et al. [74] shows that the quality parameters (WG, GI, FN) of wheat grain did not depend on the tillage system used but were related to the cultivar genotype and weather conditions during the growing season. In our study, a significant effect of the cultivar on the parameters studied was demonstrated, with the exception of the gluten index. The GI differences between the cultivars ranged from 86 (cv. Ostroga) to 89 (cv. Kilimanjaro) and were insignificant. Cv. Kilimanjaro had the highest ash (A), protein (P), and gluten (WG) values in grain.

The cultivar factor had a significant impact on falling number (FN), with cv. Hymalaya exhibiting the highest FN, while cv. Ostroga exhibited the lowest. Previous studies also confirmed high values of grain quality parameters in cvs. Kilimanjaro [75] and Hymalaya [76], indicating their good potential for use for consumption purposes. Cv. Kilimanjaro had significantly the highest P and WG content in the conventional system and GI content in the reduced system. However, the A and P content in the grain of this cultivar did not differ statistically between the reduced and no-tillage systems. As in the case of cv. Kilimanjaro, the no-tillage system increased A content in the grain of cvs. Hymalaya and Ostroga compared to the conventional and reduced systems. Among the cultivars, the lowest P, WG, and GI values were observed in cv. Ostroga in the no-tillage system, FN in the RT system, and A in the conventional system. In the case of cvs. Hymalaya and Ostroga, the lowest WG content was found in the grain from the no-tillage system, which also had the lowest GI values.

Ahmadi et al. [77] demonstrated a higher WG content in the conventional system with phosphorus fertilization, while the no-tillage system increased GI values in wheat grain in relation to the conventional one. The research conducted by Šíp et al. [16] indicated no interaction between the tillage system (TS) and the cultivar (C) with regard to the grain quality parameters (P, WG, GI, FN). According to Hofmeijer et al. [78], lower soil compaction in the conventional system may lead to increased nitrogen uptake by wheat plants.

Wheat grain used for flour production should have a minimum protein content (P) of 115.0 g kg^{-1} (preferred content 125.0 g kg^{-1}) and a wet gluten (WG) content of at least 25.0 to 27.0%. However, wheat grain of quality class A should have a protein content of 14.0 g kg^{-1} [69,79]. In our own research, the requirements for P content were met by all the cultivars, while the WG levels were met by grains of cvs. Kilimanjaro and Hymalaya grown in the conventional and reduced systems, and of cv. Ostroga in the conventional system. Hu and Shang [80] report that high-quality wheat cultivars usually contain less wet gluten (WG) but have higher GI values. In regard to the GI and FN parameters, the grain of all the tested wheat cultivars met the requirements, regardless of the tillage system. The GI values ranged from 80 to 93, and FN from 235 to 347 s.

In addition to the tillage system (TS) and the genetic factor of the cultivar (C), the year (Y) also had a significant effect on the grain quality parameters. According to Mitura et al. [48], a higher protein content in grain is possible when, during the growing season, April and May are warm and humid, which favors the accumulation of nitrogen in the plant, and June is warm, which influences the deposition of protein substances in the grain.

In our study, in the 2018/2019 season, the protein content in grain was higher by 5.4 and 11.1%, respectively, compared to the other seasons of 2019/2020 and 2020/2021. Generally, the dry period in June and the semi-drought period in July in the 2018/2019 season promoted higher values of the quality parameters (A, WG, FN), although the resulting grain had a lower GI. A higher GI value was observed in the 2019/2020 season, while the other seasons did not differ significantly in terms of this trait.

Hernandez-Espinosa et al. [81] demonstrated that both drought and heat stress during the wheat growing season led to higher gluten content and strength due to higher protein content in the grain. The influence of weather conditions on protein content and other parameters of wheat grain quality was also demonstrated in other studies conducted [71,74,77].

Statistical analysis of the grain physical parameters revealed significant differences depending on the tillage system (TS), wheat cultivar (C), and their interaction (TS $\times$ C), as well as the year (Y) (Table 9). Compared to the no-tillage system, wheat grain from the conventional system had significantly higher HW, TGW, and GU values. This difference was 2.8 kg hl^{-1} (HW), 2.7 g (TGW), and 5.7% (GU), respectively. The HW, TGW, and GU parameters did not differ statistically between the conventional and reduced systems, or between the reduced and no-tillage systems. No effect of tillage system on grain vitreousness (GV) values was found. Woźniak and Rachoń [70] obtained similar results regarding GU, but they did not demonstrate an effect of tillage systems on HW and TGW.

Różewicz et al. [74] obtained significantly lower TGW values for reduced tillage (R) and strip tillage (ST) treatments by 3.3 and 7.9%, respectively, in relation to conventional tillage (C). Ahmadi et al. [77] did not find such a relationship for TGW. However, as reported by Maali and Agenbag [82] and Šíp et al. [16], higher nitrogen mineralization intensity with increasing tillage intensity in the conventional system, in relation to reduced and no-tillage, may influence TGW. The HW and TGW values in the wheat cultivars ranged from 75.5 (cv. Ostroga) to 77.0 kg hl^{-1} (cv. Kilimanjaro) and from 38.8 (cv. Ostroga) to 41.2 g (cv. Hymalaya). The GU value ranged from 88.8 (cv. Hymalaya) to 90.7% (cv. Kilimanjaro). The study by Mitura et al. [48] also indicates high variability in HW, TGW, and GU. The range of values, especially for TGW (28.4–31.0 g) and GU (64.4–79.8%), deviated from the values obtained in our study, but the authors believed that it was typical for spring wheat cultivars.

Among the basic parameters determining the quality of wheat cultivars is grain vitreousness (GV), which is one of the characteristic features of endosperm determined based on the grain cross-section [83]. In this present study, the GV of the wheat cultivars ranged from 56 to 65%. Cvs. Kilimanjaro and Hymalaya had significantly the highest GV, while cv. Ostroga had the lowest. According to Jańczak-Pieniążek et al. [84], grain vitreousness of the wheat cultivars ranged from 40 to 77%, with differences in the stability of this trait depending on the grain protein content of the cultivars and the nitrogen dose applied. According to Dziki et al. [85], wheat cultivar genotypes with higher protein content create a more compact protein matrix, which leads to increased grain vitreousness.

Table 9. The effect of the experimental factors on the physical parameters of wheat grain (mean for 2018–2021).

Factor: Tillage System (TS)	Factor: Cultivar (C)	Hectoliter Weight (kg hl^{-1})	Thousand Grain Weight (g)	Grain Uniformity (%)	Grain Vitreousness (%)
Conventional		77.5 ± 8.1 a	41.0 ± 5.3 a	91.0 ± 7.3 a	64 ± 4 a
Reduced		76.0 ± 6.6 ab	40.3 ± 4.9 ab	86.9 ± 8.8 ab	62 ± 2 a
No-tillage		74.7 ± 8.5 b	38.3 ± 5.6 b	85.3 ±9.7 b	60 ± 8 a
	Kilimanjaro	77.0 ± 7.2 a	39.5 ± 8.4 ab	90.7 ± 11.5 a	65 ± 7 a
	Hymalaya	75.5 ± 8.1 ab	41.2 ± 7.1 a	88.8 ± 9.5 a	64 ± 6 a
	Ostroga	75.7 ± 5.6 b	38.8 ± 6.4 b	83.8 ± 4.2 b	56 ± 4 b
Conventional	Kilimanjaro	78.1 ± 4.2 a	42.2 ± 3.8 a	95.7 ± 10.1 a	69 ± 7 a
	Hymalaya	77.0 ± 5.7 b	41.4 ± 4.1 ab	89.0 ± 8.7 b	67 ± 6 ab
	Ostroga	77.5 ± 6.7 a	39.4 ± 4.3 c	88.3 ± 9.5 b	55 ± 5 e
Reduced	Kilimanjaro	77.2 ± 4.8 b	38.8 ± 7.8 cd	86.3 ± 7.8b c	65 ± 8 bc
	Hymalaya	75.6 ± 3.9 bc	42.0 ± 7.2 a	88.7 ± 10.6 b	63 ± 9 c
	Ostroga	75.3 ± 4.7 bc	40.0 ± 6.1 bc	85.7 ± 7.9 c	58 ± 5 de
No-tillage	Kilimanjaro	75.8 ± 3.9 b	37.7 ± 5.8 d	90.0 ± 4.5 b	63 ± 4 c
	Hymalaya	74.0 ± 5.6 c	40.3 ± 7.1 b	88.7 ± 6.4 b	62 ± 10 cd
	Ostroga	74.4 ± 6.7 c	37.0 ± 8.5 d	77.3 ± 9.7 d	55 ± 8 e
Year (Y)	2018/2019	75.4 ± 4.8 b	38.7 ± 5.3 b	84.4 ± 7.6 b	66 ± 8 a
	2019/2020	75.9 ± 7.6 ab	40.1 ± 4.1 a	88.9 ± 6.7 a	60 ± 7 a
	2020/2021	77.0 ± 6.7 a	40.8 ± 7.1 a	89.9 ± 4.1 a	59 ± 4 a
Mean		76.1	39.8	87.7	62
TS		*	*	**	ns
C		*	*	**	**
Y		*	*	*	ns
TS × C		*	*	*	*
TS × Y		ns	ns	ns	ns
C × Y		ns	ns	ns	ns
TS × C × Y		ns	ns	ns	ns

Respectively a–e: * < 0.05; ** < 0.01; ns: not significant; ± standard deviation (SD).

In our research, the TS × C interaction showed that of the tested varieties, the highest values of the physical parameters (HW, TGW, GU, GV) in the conventional system were found in grain from cv. Kilimanjaro, and the lowest in cv. Ostroga in the no-tillage system. Higher TGW was confirmed in the conventional system only for cv. Kilimanjaro. However, TGW for cvs. Hymalaya and Ostroga was higher in the reduced system. Similar values of this parameter were found for these cultivars in the conventional and no-tillage systems as well as in the conventional and reduced systems. This indicates the influence of cultivar differences in TGW of wheat, which was also confirmed by the results of other authors [74,78]. The values of GU for cv. Hymalaya and GV for cv. Ostroga under the no-tillage system were not statistically different compared to the conventional and reduced systems. In general, the N system, compared to C and R, reduced the GU, GV, and HW values (except for cv. Kilimanjaro) and TGW (except for cv. Hymalaya), and to a lesser extent, the GU and GV values in wheat from the no-tillage system in relation to the conventional one. The results of Haliniarz et al. [47] also indicate lower, although not statistically confirmed, HW and GU values for wheat from the N system compared to C.

In our study, lower values of the HW, TGW, and GU parameters were found for grain harvested in the 2018/2019 season. In that season, after high rainfall (from 118.3 to 152.0 mm) in April and May, its deficiency occurred in June and July, with the rainfall ranging from 72.2 to 80.9% compared to the long-term rainfall total. According to Cosentino et al. [86], limited rainfall and temperatures higher than 31 °C during the flowering and early grain filling phases of wheat can reduce some physical parameters of the grain, including TGW, by up to 1.17 g. According to Djouadi et al. [87], under dry conditions in the no-tillage system, reduced nitrogen mineralization results in lower nitrogen availability compared to the conventional system, which may result in lower HW and GU values. Weather conditions in the 2019/2020 and 2020/2021 seasons were conducive to more favorable HW, TGW, and GU parameters. However, similarly to the studies by Woźniak and Stępniowska [88], no TS × Y interaction was demonstrated for the tested parameters, and the effect of the study years on GV values was insignificant. The study conducted by Cacak-Pietrzak [69] also indicates a significant effect of weather on the HW, TGW, and GU values of wheat.

3.6. Correlation Among Variables

In the study, grain yield (GY) was significantly correlated with LAI (r = 0.714) and SPAD (r = 0.845) as well as with the gas exchange parameters Pn (r = 0.804), Gs (r = 0.714), E (r = 0.470), and Ci (0.932). Significant correlations were found between LAI and SPAD. These parameters were also significantly correlated with gas exchange parameters (Pn, Gs, E, Ci). Additionally, correlations were found between Pn, Gs, E, and Ci.

According to Wasaya et al. [65], similar relationships between wheat grain yield and LAI, SPAD, and gas exchange parameters are possible under good irrigation or mild water stress conditions. The correlations between Pn, E, and Gs explain that higher Gs can improve CO2 access to the leaf chloroplast and have an effect on the increase in Pn and E [87]. The highly significant correlation between Gs and E (r = 0.910) obtained in the study by Tshikunde et al. [89] indicates that the transpiration rate (E) was largely dependent on stomatal conductance (Gs), which was also shown in our own study. In turn, Chen and Hao [90] obtained a negative correlation of the Gs parameter (r = 0.879) at the heading stage and weak correlations of Pn, E, Gs, and WUE (r = 0.575) at the heading, flowering, and grain filling stages with the grain yield of wheat cultivars (Table 10).

This yield was positively correlated with grain number per unit of area (r = 0.855), harvest index (r = 0.885), and thousand grain weight (r = 0.879). In our study, positive but much weaker correlations were obtained between GY and WUE (r = 0.292) and with TKW (r = 0.583) and HW (r = 0.536). In contrast, the negative correlation of GY and HW with A, P, and GV indicates that as grain yield increases, the quality parameters decrease due to nitrogen dilution in the grain. The increase in grain yield causes the available nitrogen (N) to be diluted, which leads to a decrease in N concentration and a deterioration in grain quality characteristics, especially protein content (P), which is a major problem in the breeding of wheat cultivars. In the higher grain yield mass, there is usually a different grain size, which results in a reduction in grain vitreousness (GV) and the content of ash (A), being a component of the grain seed coat [91,92]. According to Chen and Hao [90], the higher grain yield of both old and new wheat cultivars was positively correlated with the number of grains per unit area (r = 0.855), the yield index (r = 0.885), and the thousand grain weight (r = 0.879). These latter grain quality traits (A, P, GV) were positively correlated with each other (r = 0.503–0.749). Higher FN values were usually associated with increased GV, P, and WG values. A significant correlation between FN and GV and between A, P, and WG was reported by Mitura et al. [48]. Flour with a gluten index (GI) above 60 and a falling number (FN) of at least 200 s usually ensures good baking quality [69].

Table 10. Pearson correlation coefficients (r) between measured parameters.

Traits	GY	LAI	SPAD	Pn	Gs	E	Ci	WUE	A	P	WG	GI	FN	HW	TGW	GU
LAI	0.714 **															
SPAD	0.845 **	0.689 **														
Pn	0.804 **	0.590 *	0.740 **													
Gs	0.714 **	0.659 **	0.689 **	0.589 *												
E	0.470	0.463	0.560*	0.382	0.793 **											
Ci	0.932 **	0.702 **	0.848 **	0.742 **	0.782 **	0.509 *										
WUE	0.292	−0.282	−0.280	0.235	−0.282	−0.195	−0.230									
A	−0.715 **	−0.616	−0.776	−0.761	−0.616	−0.199	−0.692	−0.080								
P	−0.514 *	−0.078	−0.552	−0.372	−0.078	0.044	−0.505	−0.201	0.674 **							
WG	−0.247	0.306	−0.171	−0.235	0.307	0.151	−0.222	−0.280	0.375	0.661 **						
GI	0.027	0.510 *	0.146	−0.042	0.510	0.400	0.123	−0.460	0.022	0.237	0.441					
FN	−0.067	0.131	−0.131	−0.211	0.130	0.184	0.019	−0.255	0.379	0.581 *	0.535 *	0.244				
HW	0.536 *	0.378	0.164	0.239	0.379	0.314	0.083	−0.224	−0.452	−0.357	0.419	0.425	−0.003			
TGW	0.583 *	0.429	0.440	0.266	0.429	0.154	0.429	−0.112	−0.272	0.207	0.249	0.195	0.062	0.355		
GU	0.346	0.439	0.423	0.351	0.439	0.639 *	0.425	−0.545	−0.055	0.144	0.381	0.427	0.273	0.429	0.432	
GV	−0.302	0.065	−0.236	−0.269	0.065	0.108	−0.275	−0.255	0.503 *	0.749 **	0.673 **	0.325	0.772 **	0.137	0.071	0.251

Respectively: * < 0.05; ** < 0.01. GY: grain yield, LAI: leaf area index, SPAD: soil–plant analysis development, Pn: photosynthetic rate, Gs: stomatal conductance, E: transpiration rate, Ci: intracellular CO_2 concentration, WUE: water use efficiency, A: ash, P: protein, WG: wet gluten, GI: gluten index, FN: falling number, HW: hectoliter weight, TGW: thousand grain weight, GU: grain uniformity, GV: grain vitreousness.

According to Oyeyinka and Ini-Abasy [93], the relationship between FN and WG can be used in studies to determine the range of enzymatic activity in wheat grain. A low falling number (FN) indicates increased enzymatic activity, which degrades starch and proteins. This reduces the grain's ability to absorb water, resulting in a lower falling number, and decreases gluten quality. Higher FN values ensure good quality bread with adequate volume and texture, but flours with a very high FN may result in an undesirable dry texture [94].

4. Conclusions

Grain yield and quality parameters of winter wheat cultivars depended on various experimental factors and study years. The yield levels in the conventional and reduced systems were similar, while no-tillage resulted in grain yield reductions of 0.36 and 0.59 t ha^{-1}, respectively, in relation to the reduced and conventional systems.

Higher yields (8.55 t ha^{-1}) were achieved in the 2021/2022 season. Increased LAI (5.26–5.41) and SPAD (36.5–37.9) values and higher gas exchange parameters were observed after the use of reduced and conventional systems. The conventional system resulted in higher values of grain quality parameters in relation to no-tillage. The grain vitreousness (GV) value did not depend on tillage systems or study years. The gluten index (91%) of wheat grain was higher when the reduced system was used.

In the conventional system, the highest grain yield was obtained by cvs. Hymalaya (8.45 t ha^{-1}) and Ostroga (7.94 t ha^{-1}), followed by cv. Hymalaya (8.56–8.62 t ha^{-1}) in the no-tillage and reduced system. The dry period in June and the semi-drought period in July in the 2018/2019 season were conducive to more favorable grain quality parameter values: protein (134.3 g kg^{-1}), gluten (27.1%), falling number (324 s), and ash (20.2 g kg^{-1}). Although the resulting grain had a lower gluten index (86%) and physical parameters. Significant differences in quality parameter values were observed among the wheat cultivars tested. Due to their higher grain yield and better morphophysiological parameters, cv. Hymalaya and cv. Ostroga are recommended for cultivation in all tillage systems, including the conventional and reduced systems. All the tested cultivars met the criteria for use as a raw material for baking flour production in terms of protein content (P), falling number (FN), and gluten index (GI). However, the gluten content (WG) criterion was met by cvs. Kilimanjaro and Hymalaya grown in the conventional and reduced systems, while the WG criterion was met by cv. Ostroga in the conventional system. Nevertheless, among the cultivars tested, cv. Kilimanjaro distinguished itself with the best grain quality parameters, especially in the conventional and reduced systems, although it was characterized by relatively low yields.

Due to their higher grain yield and better morphophysiological parameters, cvs. Hymalaya and Ostroga are recommended for cultivation in conventional and reduced tillage systems. In addition, the cv. Hymalaya can be recommended for no-tillage systems. However, growing cv. Kilimanjaro in no-tillage (7.43 t ha^{-1}) and reduced (7.48 t ha^{-1}) systems, and cv. Ostroga in no-tillage (7.37 t ha^{-1}) systems, will result in lower grain yields.

The results of our research can be used by farmers in selecting wheat cultivars recommended for cultivation in various climatic and agrotechnical conditions as well as by processors interested in high-quality grain for the production of bread and other baked goods.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agriculture15192069/s1, Figure S1: The scheme of the experiment. K: cv. Kilimanjaro, H: cv. Hymalaya, O: cv. Ostroga, R: replication.

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