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Selected Cultivar-Specific Parameters of Wheat Grain as Factors Influencing Intensity of Development of Grain Weevil *Sitophilus granarius* (L.)

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Abstract: Wheat, the main source of protein in the human diet, is a staple food in many countries. The yields and technological quality of wheat grain depend on both the yielding potential of wheat and the properties of wheat grain that allow its safe storage. To a large extent, losses during storage are caused by storage pests. Grains of 46 wheat cultivars were used in the study (samples weighing 20 g of each variety in 10 replications), on which the development of the grain weevil *Sitophilus granarius* (L.) (Coleoptera: Curculionidae) was observed (20 insects aged 3–4 days; sex ratio of 1:1). The laboratory study was carried out at constant temperature (27 OC) and humidity (75% relative humidity). The laboratory study demonstrated that the physicochemical parameters of grain (hardness, glassiness, flouriness, content of protein, sugars, starch, and crude fat), which are cultivar-dependent, can act as regulators of the development of the grain weevil. The main aim of the study was to develop recommendations regarding the breeding of wheat cultivars resistant to the foraging of S. granarius and which could therefore produce grain for longer storage, and to distinguish those that are more sensitive to the grain weevil and whose grain should therefore be supplied to the market more quickly. Knowledge of the resistance or susceptibility of individual cereal varieties to the feeding of storage pests may be useful in integrated grain storage management. Among the 46 wheat cultivars studied, five cultivars with the highest and five cultivars with the lowest susceptibility to foraging by *S. granarius* were identified. The highest inherent tolerance to the grain weevil was displayed by the following cultivars: KWS Livius, Bogatka, Speedway, Platin, and Julius; in contrast, the cultivars Askalon, Bamberka, Ostroga, Forum, and Muszelka proved to be the most sensitive. The chemical and physical analysis of the selected cultivars revealed a significant, positive correlation between the intensity of the development of the grain weevil, the content of starch and crude fat in the grain, and grain hardness and flouriness.

Keywords: storage pests; wheat varieties; storage; *Triticum* L.; grains; food attractiveness

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1. Introduction

The majority of food products are based on cereals, of which three species (rice, wheat, and maize) provide over 60% of all consumed calories globally [1]. Because of their considerable economic importance, cereals are among the most common crops grown worldwide and are the main food in countries with a temperate climate [2–7]. The area of wheat cultivation accounts for 30.6% of the world's cereal area (maize 26.7%, rice 22.6%), and the world production of wheat in 2022 exceeded 800 million tons [1]. Wheat plays a key role in providing adequate quantities and quality of food. Wheat production, crop acreage, and the quality of harvested yields have increased in recent years due to the optimal selection of habitat, varieties, and agricultural technology [1,8]. However, the intensification of wheat production does not satisfy the increase in demand for wheat driven by the growing human population [7,9–11]. Wheat is characterized by varied yields [4], and the rising demand for wheat necessitates the continual maximization of its production. The demand for highly yielding crops while adhering to the guidelines of the European Green Deal, instituted by the European Commission in 2019, entails constant balancing between food security and food safety [12]. The initial growth in the productivity of *Triticum* L. was achieved through technological change, which was stimulated by extensive investment in agricultural development [13]. The transformation of agriculture under the European Green Deal imposed extreme restrictions on the use of agricultural chemicals [2,14,15].

The controlled hybridization of cereals focuses on improving the crops' yield potential, protein content in the grain, and resistance to diseases and adverse climatic conditions [16]. However, the high use value of cultivars depends on both the harvested yield and the possibility of safe and long-term storage of this yield [17]. Cereal grain losses during storage in countries with low plant cultivation and sanitary culture can peak at as high as 50%, which indicates that the storage process significantly influences food security [15]. The process of storage is influenced by many factors, e.g., storage facilities (silos, granaries), and physical factors (temperature and humidity), among which the feeding of storage pests plays an important role. The grain weevil *Sitophilus granarius* (L.) (Coleoptera: Curculionidae) is one of the most harmful and common pests of cereal grains in temperate regions [18–20]. In Poland, annual losses of grain mass during storage due to foraging by the grain weevil oscillate around 5% [21]. The damage caused by *S. granarius* consists of direct loss of grain mass due to the pest's consumption and indirect loss due to secondary contamination with molts, feces, or the dead bodies of the grain weevil. Moreover, infestation of the grain by this insect increases the temperature and moisture of the stored material, which contributes to the accelerated development of mold, including highly toxic species, thereby causing further depreciation in the grain value [19,22].

Due to the gradual departure from chemical methods of combating storage pests, which are effective but dangerous to human health and life, alternative solutions are sought for the inherent resistance of grains of particular varieties of kernels. [15,18,23–25]. The vulnerability of individual cultivars of cereals to infestation by the grain weevil has been the subject of numerous studies. However, no conclusive results have been achieved, and the wide diversity among wheat varieties indicates the need for further research in this area. Further knowledge of the physicochemical properties of wheat grains may help us gain insight into the impact of these cultivar-specific variables on foraging by insects. Such insight can therefore be included in an integrated system for stored grain management [26,27].

The research hypothesis in this study was that the development of the grain weevil on stored wheat grain depended on the grain's physical and chemical properties in a given cultivar. This dependence was analyzed by:

- Evaluation of selected physical properties of the grain (hardness, thousand kernel weight TKW, glassiness, flouriness);
- Evaluation of selected chemical properties of the grain (total protein, crude fat, sugars, and starch);
- Evaluation of the rate of development (abundance of offspring generation, mass of generated dust, loss of grain mass, and grain susceptibility index) of *S. granarius* on the studied grain;
- Evaluation of occurrence and nature of the dependencies between the analyzed physico-chemical parameters of the grain and the development rate of *S. granarius*.

2. Materials and Methods

2.1. Materials

The laboratory experiment involved 46 cultivars. The analyzed grains originated from the Cultivar Testing Experimental Station in Radostów (southern Poland). The specimens of *S. granarius* used in the experiment came from mass breeding carried out for 10 years at the Department of Entomology, Phytopathology, and Molecular Diagnostics (University of Warmia and Mazury in Olsztyn, Poland). The maintenance breeding was carried out on the grain of the winter wheat cultivar Korweta. The genetic material was renewed every two years.

2.2. Bioassays

The analyzed grain was conditioned in an incubator for seven days to obtain its equilibrium moisture content. The experiment was carried out in complete darkness in a SANYO MLR 35O-H plant growth cabinet under constant temperature and humidity conditions (27 OC, 75% humidity) [18,27]. Entomological observations of the development of the grain weevil were conducted on vinidur dishes (80 mm diameter, 30 mm height) with a ventilation hole (10 mm) secured with chiffon mesh. A 20-gram sample of undamaged grains of each cultivar was placed in each dish, and 20 specimens of adult grain weevils (aged 3–4 days, 1:1 male to female ratio) were then placed on the grain. The sex of the weevils was identified by examining the proportions of the rostrum and the shape of the fifth and sixth abdominal sternites [28]. After the experiment, the mass of grains and the mass of dust were weighed on a WPS220/C/2 laboratory balance (Radwag, Radom, Poland). After eight weeks, the live material and the substrate on which the insects had been foraging were evaluated (mass of produced dust, loss of grain mass). The duration of the experiment was set according to previous observations and studies on the development of the grain weevil [29]. Gołębiowska [29] noticed that most of the new-generation adults of S. granarius emerge, on average, between 8 and 9 weeks from the oviposition. Based on the results of the analysis (development of *S. granarius* regarding the number of offspring individuals, mass of dust, and loss of grain mass), ten wheat cultivars were selected for the next stage of the experiment (five cultivars of the highest and five cultivars of the lowest susceptibility to foraging by the grain weevil). The kernels of these cultivars were then submitted for chemical (content of protein, sugars, starch, and crude fat) and physical (hardness, glassiness, and flouriness) analyses. The experiment was composed of 10 replications for each wheat cultivar.

2.3. Physicochemical Properties of Grain

The tests on the physical properties of grains from the analyzed wheat cultivars were completed in the Department of Heavy Duty Machines and Research Methodology, University of Warmia and Mazury in Olsztyn. A Mecmesin MultiTest 1-i device with a capacity of 500 N and a compression speed of 10 mm/min was used to determine the hardness of the grain. For the observations, an assumption was made that the value of the force needed to crush a kernel entirely corresponded to the kernel's hardness. The glassiness of kernels was determined by the visual evaluation of the structure of the endosperm in a crosssection of 50 randomly chosen kernels dissected with a farinotom knife. Glassy kernels were those with a completely glassy endosperm or that were glassy over at least 34 percent of the cross-section. The thousand kernel weight (TKW) was determined using an LN-S-50 seed counter. The grain susceptibility index was calculated from the formula given by Dobie and Kilminster [30].

Values for the chemical parameters of the selected wheat cultivars were determined at the Department of Animal Nutrition and Feed Science, University of Warmia and Mazury in Olsztyn. The protein content was determined using the Kjeldhal method. Measurements of the content of sugars were conducted according to Polish Norm PN-R-64784:1994. The content of starch was measured using the polarimetric method in line with Polish Norm PN-R- 64785:1994; finally, the content of crude fat was determined using the Soxhlet method, as specified in Polish Norm PN-ISO-6492: 2005.

2.4. Statistical Analysis

The data concerning the development of the grain weevil (abundance of offspring generation, mass of produced dust, loss of grain mass, and grain susceptibility index) on

46 wheat cultivars were submitted to an analysis of distribution using the Shapiro–Wilk test. The results showed that these data did not display a normal distribution. Hence, they underwent logarithmic transformation (ln), and the significance of differences between the analyzed variables in the experimental objects with wheat cultivars was determined with a one-factorial ANOVA test. Groups of means of the analyzed parameters associated with the development of *S. granarius* which were not statistically different were denoted with the same letter: a, b, c . . . (the HSD Tukey test). The results obtained at this stage enabled us to identify ten cultivars that differed in susceptibility to *S. granarius*. Two groups of five cultivars, each characterized by high and low inherent resistance to foraging by the grain weevil, respectively, were selected. In order to determine the dependencies between the physicochemical parameters of the grain of these ten wheat cultivars and the rate of development of *S. granarius*, the Pearson linear correlation coefficients r were calculated at the test probability p ($p < 0.05$ as statistically significant). The relationships were presented visually using ordinance techniques [31]. RDA (Redundancy Analysis) was used at a gradient length of SD = 0.1. Differences between the wheat cultivars regarding the physicochemical parameters of wheat kernels were illustrated with the help of nonmetric multidimensional scaling (NMDS), using Bray–Curtis's similarity measure. The Statistica 13.1, Canoco 4.51, and Past 2.01 software programs supported all statistical calculations and their visual interpretation.

3. Results

The analysis of variance demonstrated the significance of differences between the examined wheat cultivars and the chosen parameters describing the intensity of the development of the grain weevil. The number of offspring, the mass of produced dust, the loss of grain mass, and the grain susceptibility index were all significantly differentiated by the cultivar as a factor (Table 1).

Table 1. Results of a one-factorial ANOVA for the abundance of offspring generation of *S. granarius*, mass of produced dust, loss of kernel mass, and grain susceptibility index determined for wheat cultivars.

	df	**ANOVA**	***p***
		F Value	
Progeny of weevils	45	27.20	0.00
Mass of dust	45	15.84	0.00
Loss of grain mass	45	18.15	0.00
Grain susceptibility index	45	27.00	0.00

Groups of means describing a given *S. granarius* development parameter are presented in Table 2. The HSD Tukey test ordered the means into homogenous groups with similar development parameter values. Based on this test, ten wheat cultivars were selected for further research:

- Five cultivars with the lowest inherent resistance to foraging by the grain weevil (the most numerous offspring generation), which were: Askalon, Bamberka, Ostroga, Forum and Muszelka;
- Five cultivars with the highest inherent resistance to foraging by the grain weevil (the least numerous offspring generation), which were: KWS Livius, Bogatka, Speedway, Platin and Julius (Table 2).

The grain of the selected wheat cultivars, which differed in susceptibility to foraging by *S. granarius* underwent chemical and physical analyses. The significance of differences in terms of the tested parameters among the analyzed wheat cultivars was submitted to statistical analysis, and the ANOVA results are presented in Table 3. The differences in these values between the chosen wheat cultivars proved statistically significant (Table 3).

Table 2. Mean values of the parameters describing the intensity of the development of grain weevil on 46 wheat cultivars.

Cultivar	Mean Number of Progeny		Mass of Dust (g)		Loss of Grain Mass (g)		Grain infestation Indicator (%)	
Julius	125.6	a *	0.66	a	4.95	a	8.62	a
Platin	126.2	b	0.71	b	5.09	ab	8.62	a
Speedway	126.6	b	0.74	b	5.60	b	8.63	a
Bogatka KWS	140.3	c	0.61	a	5.55	b	8.82	ab
Livius	159.7	d	0.78	b	5.60	b	9.05	b
Praktik	165.0	d	0.91	cd	6.34	c	9.10	c
Forkida	166.9	d	0.93	cd	6.18	c	9.13	c
Fregata	167.8	d	0.86	c	5.94	bc	9.15	c
Estivus	169.8	d	1.13	fg	7.08	d	9.14	c
KWS Magic	175.1	e	1.20	h	7.07	d	9.20	c
Natula	175.8	e	1.02	de	6.40	cd	9.22	d
Fakir	176.0	e	1.11	f	7.17	de	9.21	cd
Tonacja	176.4	e	1.06	e	7.01	d	9.23	de
Jantarka	179.0	e	0.99	d	6.17	c	9.24	e
Meister	183.9	f	1.03	de	7.12	de	9.30	ef
Patras	184.0	f	0.94	cd	6.99	d	9.31	ef
Artist	185.6	f	0.96	d	6.89	d	9.32	ef
Torrild	185.7	f	0.97	d	6.73	d	9.32	ef
Pengar	186.0	f	1.14	g	6.74	d	9.23	de
Fidelius	187.7	fg	1.12	fg	7.37	f	9.35	ef
Figura	190.3	fg	1.14	g	7.48	f	9.37	ef
Tulecka	191.0	fg	1.14	g	7.29	e	9.38	ef
Kws Ozon	193.2	fg	1.08	ef	8.04	g	9.40	ef
Legenda	193.5	fg	1.07	e	7.26	e	9.39	ef
Operetka	193.5	fg	1.21	h	7.53	f	9.36	ef
Kepler	195.4	fg	1.05	e	7.13	de	9.41	ef
Astoria	206.0	g	1.24	hi	7.44	f	9.46	f
Toras	210.3	h	1.15	g	7.36	e	9.52	fg
Smuga	211.8	h	1.22	h	8.16	gh	9.55	g
Kredo	231.7	hi	1.52	jk	8.81	i	9.71	hi
Skagen	232.2	hi	1.47	j	8.79	i	9.70	h
Sailor	233.1	hi	1.16	g	8.53	h	9.70	h
Banderola	236.3	hi	1.34	i	7.98	g	9.71	h
Arktis	236.4	hi	1.41	ij	8.66	i	9.71	i
Oxal	241.0	i	1.35	i	8.57	hi	9.77	ij
Markiza KWS	241.0	i	1.17	g	8.61	hi	9.78	j
Dacanto	258.8	ij	1.53	jk	9.50	j	9.92	j
Muszelka	267.6	ij	1.63	lm	10.77	l	9.97	j
Lavantus	268.4	ij	1.62	l	9.92	k	9.98	j
Arkadia	269.1	ij	1.60	kl	9.99	kl	9.97	j
Mulan	275.0	j	1.59	kl	10.05	kl	10.03	jk
Linus	285.6	j	1.55	k	9.38	ij	10.10	k
Forum	306.0	k	1.68	m	10.06	kl	10.20	k
Ostroga	347.3	k	2.17	mn	11.78	m	10.41	kl
Bamberka	369.4	l	2.18	mn	12.11	mn	10.54	l
Askalon	375.2	l	2.40	o	12.33	n	10.55	l

* means in columns followed by the same letter do not differ—Tukey's HSD test.

Values for the analyzed physical and chemical parameters of the selected wheat kernels are presented in Table 4. The HSD Tukey test was run to evaluate the similarity of these parameters for the given wheat cultivars. The test divided the wheat cultivars into groups in which the value of a given parameter was similar (Table 4).

Table 3. Results of one-factorial ANOVA describing the significance of differences at levels of the tested wheat cultivars' selected physical and chemical parameters.

	df	ANOVA	p *
		F Value	
Hardness (N)	9	13.25	0.00
Thousand kernel weight (TKW) (g)	9	557.00	0.00
Glassiness (%)	9	7.55	0.00
Flouriness (%)	9	5.06	0.00
Total protein (%)	9	240.36	0.00
Crude fat (%)	9	3.36	0.01
Sugars (%)	9	126.20	0.00
Starch (%)	9	102.55	0.00

* Value of the test probability p.

Table 4. Mean values of the analyzed physical and chemical parameters describing the chosen wheat cultivars.

Variety	Hardness (N)		TKW (g)		Glassiness (%)		Flouriness (%)		Total Protein (%)		Crude Fat (%)		Sugars (%)		Starch (%)	
Bogatka	36.87	c *	54.04	b	30.00	b	70.00	a	10.65	a	1.09	ab	3.35	e	63.59	a
Muszelka	41.13	bc	42.81	g	23.33	b	76.67	a	9.92	b	0.87	a	4.01	d	61.55	c
Platin	89.73	b	44.09	f	33.33	b	66.67	a	9.68	c	1.11	ab	3.90	d	58.83	d
Ostroga	120.87	a	55.95	a	16.00	b	84.00	a	9.47	cd	1.42	a	3.82	d	63.51	a
KWS Livius	121.08	a	53.90	b	21.33	b	78.67	a	8.78	e	1.25	ab	5.90	a	59.27	d
Bamberka	121.90	a	49.02	d	15.33	b	84.67	a	8.97	e	1.43	a	4.05	d	61.16	c
Forum	132.37	a	45.50	e	28.00	b	72.00	a	9.54	c	1.26	ab	5.24	b	61.23	c
Julius	133.90	a	50.32	c	67.33	a	33.33	b	9.31	d	1.26	ab	5.22	b	61.33	c
Askalon	135.50	a	45.14	e	31.33	b	68.67	a	8.90	e	1.24	ab	3.86	d	62.70	b
Speedway	136.70	a	49.52	cd	9.33	b	90.67	a	8.37	f	1.41	a	4.57	c	61.02	c

* means in columns followed by the same letter do not differ—Tukey's HSD test.

In order to detect the presence of a dependence between the intensity of the development of *S. granarius* and a given trait describing a physical or chemical property of the grain from a given wheat cultivar, the Pearson linear correlation coefficient r was determined (Table 5).

Table 5. Values of Pearson's linear correlation coefficient (r) between the offspring of the *S. granarius* population and the physical and chemical characteristics of wheat grains.

	Adults	
	r	p *
Adults	-	-
Hardness [N]	0.21	0.26
TKW [g]	−0.16	0.40
Glassiness [%]	−0.29	0.12
Flouriness [%]	0.29	0.13
Total protein [%]	−0.12	0.54
Crude fat [%]	0.19	0.32
Sugars [%]	−0.26	0.16
Starch [%]	0.43	0.02

* The value of the test probability p.

The RDA ordination diagram displays relationships between the physicochemical parameters of the kernels of the analyzed wheat cultivars and the selected variables: the abundance of offspring generation and the quality group of wheat grain (quality groups A and B) ($p < 0.05$). The first ordination axis, describing 76.6% of the variance, was correlated with the quality group of wheat grain (QG). This factor also correlated with the high content of total protein in kernels (Figure 1). The second factor (the abundance of the offspring generation of *S. granarius*) was strongly correlated with the second ordination axis. Cultivars with the lowest resistance to foraging *S. granarius* (Askalon, Bamberka, and Ostroga) were located in the lower right-hand quadrant of the ordination diagram, close to vectors describing the increase in the grain content of starch, fats, and the hardness of kernels. These physicochemical parameters could additionally be positively correlated with an increase in the susceptibility of grain to foraging by *S. granarius* (Figure 1).

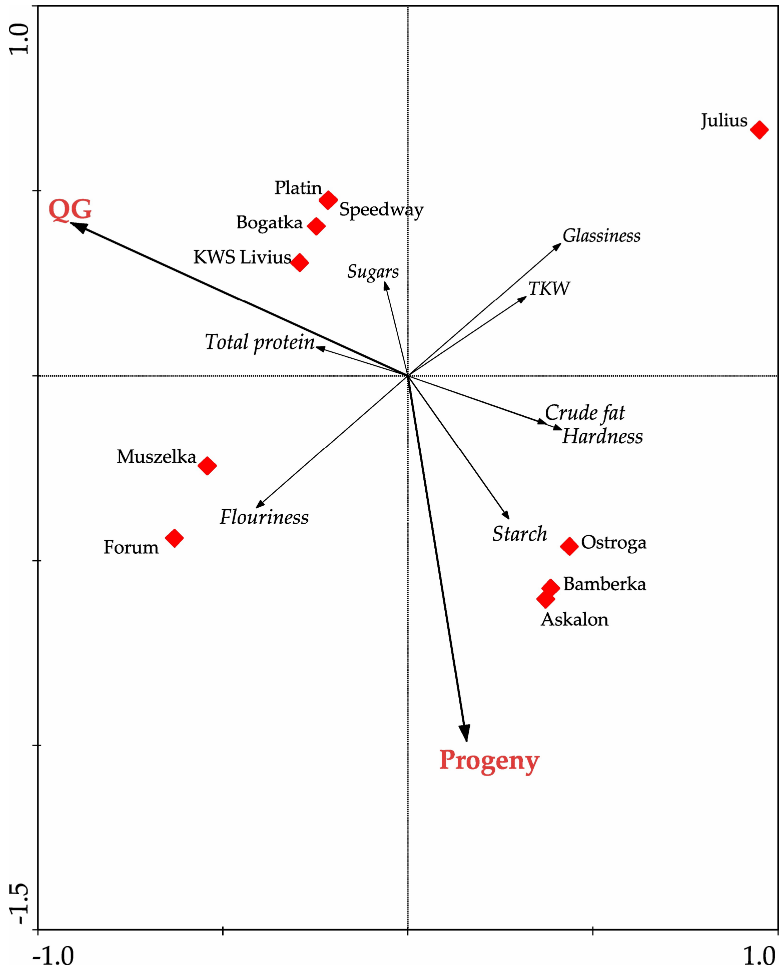

Figure 1. Redundancy analysis diagram (RDA) presenting correlations between analyzed parameters pertaining to the development of *S. granarius* (number of progeny and QG) and the physical and chemical characteristics of wheat cultivars.

The nonmetric multidimensional scaling (NMDS) analysis was applied to confirm the similarity between the chosen wheat cultivars in terms of their physical and chemical properties. The NMDS diagram (Figure 2) presents the chemical properties of the analyzed wheat grain groups in its center, with the wheat cultivars identified as being most susceptible to foraging by *S. granarius* (stress = 0.1; ANOSIM R = 0.98, $p < 0.00$). The NMDS diagram displaying the cultivars with respect to the physical parameters of grain (Figure 3) shows the presence of two groups of cultivars (stress = 0.1; ANOSIM R = 0.57, $p < 0.00$). Apart from the cultivars susceptible to foraging by *S. granarius* (Forum, Bamberka, Ostroga, and Askalon), there are cultivars that are not resistant to the grain weevil (Speedway, KWS Livius, Platin, and Julius). The other group in the NMDS diagram is composed of two cultivars: Muszelka (resistant) and Bogatka (not resistant). This may indicate that the physical parameters of the kernels distinguished in this study are not significantly correlated with their resistance to foraging by *S. granarius*. It can therefore be assumed that the inherent resistance of wheat grain is more strongly correlated with the chemical composition of the kernels than with their physical characteristics (Figures 2 and 3).

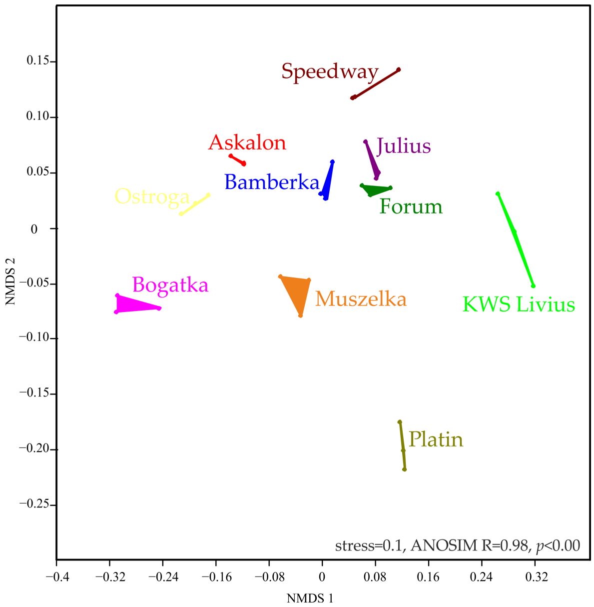

Figure 2. NMDS diagram describing similarities of wheat cultivars with respect to chosen chemical characteristics of grain.

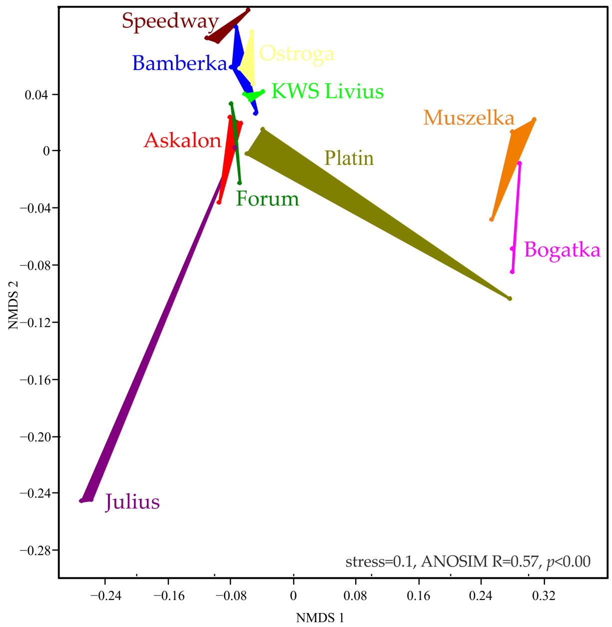

Figure 3. NMDS diagram describing similarities of wheat cultivars with respect to the chosen physical characteristics of grain.

4. Discussion

According to the Polish Research Centre for Cultivar Testing, which deals with seed science and legal protection of crops, there were 214 wheat cultivars registered in Poland in 2022 [32]. Creative breeding of cultivars is a long and multistage process based on which each cultivar is assigned a detailed description. Breeders of cereal crops, when introducing a new cultivar to the market, provide such information as agricultural characteristics (including yields, winter hardiness, and tolerance to diseases) and technological characteristics (including the content of protein, gluten, glassiness, and productivity) [26,32]. However, the detailed characteristics of cultivars do not provide any information on the cultivar's resistance to foraging by storage pests. Therefore, in the face of high losses during grain storage [15], it is essential to determine the resistance of grain to such pest insects.

The aim of this study was to determine the competitive potential of 46 wheat cultivars regarding foraging by the grain weevil. The dynamics of the development of *S. granarius* mainly depend on three factors: temperature, moisture of the kernels, and type of food [19]. Unlike live plant tissues, stored grain does not possess typical defensive substances [18]. The chemical composition of kernels from particular cultivars of wheat may differ significantly. Varying concentrations of chemical compounds accumulated in grain can be a factor in either attracting or repelling storage pests [15,18,21,33,34]. The research completed to date has demonstrated that the level of infestation by the grain weevil is to a large extent dependent on the kernels' physical characteristics, for example, the hardness of the endosperm and the grain coat or the smoothness of the kernel's surface [15,34]. Some studies indicate that other factors that determine the presence of the grain weevil on grain are the waxes on the surface of wheat kernels [35] and the chemical compounds contained in essential oils found in the cuticle [36]. Nawrot et al. [18] draw attention to the complexity of this process, which depends on the physicochemical and biochemical properties of grain as well as its physical characteristics and technological treatments. Knowledge of these dependences helps to distinguish and then recommend sowing such wheat cultivars that correspond well to the chosen technologies and intended use of the grain. Cultivars characterized by higher resistance to foraging by storage pests can be recommended as those producing grain for longer storage. In turn, cultivars that are more susceptible to damage caused by the grain weevil can be grown for grain intended for prompt delivery to the market and hence for shorter storage.

The significance of wheat cultivar-specific factors on foraging by the grain weevil has been the subject of previous studies. The susceptibility of certain cultivars and the factors that affect them have not yet been determined unambiguously [15,27,34,37–40]. In our experiment, the abundance of the offspring generation, the mass of produced dust, the loss of grain mass, and the grain susceptibility index showed statistically significant differences among the wheat cultivars (Table 1). The abundance of the offspring generation, reflecting the attractiveness of a given habitat, and the intensity of foraging by *S. granarius*, determined on the basis of the amount of dust produced, are the basic parameters describing the susceptibility of particular cultivars [39]. Analysis of the offspring generation and the amount of dust produced by foraging insects on 46 wheat cultivars showed very large discrepancies. Among the tested cultivars, the highest average number of offspring as well as the highest mass of dust were determined for the Askalon (375.2 individuals of grain weevil; 2.3983 g of dust), Bamberka (369.4 indiv.; 2.1749 g), and Ostroga (347.3 indiv.; 2.1658 g) cultivars, while the smallest values for these parameters were observed for the Julius (125.6 indiv.; 0.6586 g) and Platin (126.2 indiv.; 0.7084 g) cultivars (Table 2). Apart from the direct loss of grain mass due to foraging by storage pests, the large amounts of dust generated by such insects have a negative impact on the aeration of the stored grain material, which, in consequence, adds to a higher likelihood of the development of mold [41]. Another indicator that confirmed the susceptibility to foraging by *S. granarius* was the loss of grain mass. The smallest average mass loss was determined for the cultivar Julius (4.9485 g), and the highest was for cv. Askalon (12.3287 g), where the grain mass loss reached 61% (Table 2).

Analysis of the values of the examined physical and chemical properties of the cultivars with the highest (Askalon, Bamberka, Ostroga, Forum, Muszelka) and lowest (Julius, Platin, Speedway, Bogatka, KWS Livius) susceptibility to foraging by *S. granarius* revealed the significance of differences (Tables 3 and 4; Figures 2 and 3). The Julius cultivar, characterized by the lowest grain susceptibility index (8.6%), calculated on the basis of the abundance of offspring progeny and time of its development, was also distinguished by high hardness and glassiness (Tables 2 and 4). The susceptibility of cultivars with low glassiness to foraging by the grain weevil has been demonstrated experimentally by Nawrot [42]. On the other hand, the hardness of grains is considered to be the main parameter of wheat quality, not only because of the crop's intended use but also in view of its resistance to foraging by storage insects [43,44]. Higher susceptibility of cultivars with less hard grain to infestation by the grain weevil has been shown by several researchers, including Nietupski et al. [39], Nawrot [42], Piasecka-Kwiatkowska et al. [45], and Mebarkia [40]. Such dependencies have also been confirmed in a study on the rice weevil *Sitophilus oryzae* L. foraging on rice grains [46]. In our research, we did not obtain unequivocal confirmation that an increase in grain hardness of the tested wheat cultivars is significantly positively correlated with an increase in the resistance to foraging by *S. granarius* (Table 5).

Mebarkia [15] points to the content of protein in wheat grain as the main determinant of selecting food by the grain weevil. Analysis of the relationships between the intensity of the development of the grain weevil and the total protein content in the grain of the ten selected cultivars revealed a negative correlation (Table 5). The cultivars identified as more resistant to foraging by *S. granarius* were characterized by a higher content of total protein (Figure 1). In a study of the relationships between the varied chemical composition of proteins in cereal grains and the development of storage pests, Nietupski et al. [47] demonstrated a correlation between the content of particular protein fractions and foraging by *S. granarius*, and showed that the development of the grain weevil might be hindered by such protein fractions as albumins, globulins, and glutenins. Niewiada et al. [33] and Mebarkia et al. [15] determined a significant relationship between the intensity of foraging by the grain weevil and the fat content of kernels. In our study, grains with the highest total fat content (Bamberka 1.43 % and Ostroga 1.42 %) belonged to the group of cultivars on which the grain weevil developed the best (Table 4). The grain of all wheat cultivars contains large amounts of starch, which has a versatile use in food production and industries. Starch makes up over 70% of the kernel and its exact content depends on genetic traits, environmental conditions, and agritechnological treatments [48,49]. Starch consists of two polymers of glucose residues: amylose (average 25%) and amylopectin (average 75%) [50,51]. The content of starch in the wheat cultivars tested in our study was positively correlated with the abundance of offspring generation (Table 5). Literature data indicate that the weevil develops better on grains with high flouriness [33,42]. Our research did not confirm these relationships. On the grain of varieties characterized by high flouriness, a low number of progenies of *S. granarius* (Speedway variety 126.6 indiv.) was found, as well as a high number (Bamberka variety 369.4 indiv. and Ostroga 347.3 indiv) (Table 4). The chemical and physical properties of wheat grains may be related to their inherent resistance to feeding by storage pests. Knowledge of these factors can be used in the breeding of resistant wheat cultivars, which can directly translate into a reduction in the use of pesticides in the storage of cereal grains, and thus food safety and environmental protection. Therefore, research on the factors determining the inherent resistance of wheat grain to *S. granarius* foraging should be conducted in a broader context, considering the identification of food by the pest (physical and chemical factors perceived by imagines looking for food), and then food digestion.

5. Conclusions

The development of the grain weevil on the analyzed kernels of 46 wheat cultivars (varieties recommended for cultivation in the northern region of Poland) was distinctly varied. The highest inherent resistance to this insect was shown by KWS Livius, Bogatka, Speedway, Platin, and Julius, which is why these cultivars can be recommended for the long storage of grain. The most numerous offspring generations of the grain weevil were observed on grain of the Askalon, Bamberka, Ostroga, Forum, and Muszelka cultivars, and hence these cultivars can be recommended for prompt technological processing of grain. Based on the results of this study, the main cultivar-specific characteristic of wheat kernels affecting the inherent resistance to grain weevil is most probably the chemical composition of the grain, particularly the starch content.

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References

1. Food and Agriculture Organization of the United Nations World Food Situation. Available online: https://www.fao.org/home/en (accessed on 6 April 2023).
2. de Sousa, T.; Ribeiro, M.; Sabença, C.; Igrejas, G. The 10.000-Year Success Story of Wheat! *Foods* **2021**, *10*, 2124. [CrossRef] [PubMed]
3. Grote, U.; Fasse, A.; Nguyen, T.T.; Erenstein, O. Food Security and the Dynamics of Wheat and Maize Value Chains in Africa and Asia. *Front. Sustain. Food Syst.* **2021**, *4*, 617009. [CrossRef]
4. Iwanska, M.; Paderewski, J.; Stepien, M.; Rodrigues, P.C. Adaptation of Winter Wheat Cultivars to Different Environments: A Case Study in Poland. *Agronomy* **2020**, *10*, 632. [CrossRef]
5. Central Statistical Office Statistical Analyses. *Agriculture in 2021*; Central Statistical Office Statistical Analyses: Warsaw, Poland, 2022.
6. Różewicz, M. Production and Supply of Cereal Grains in Poland and Their Importance and Use in Polish Economy. *Pol. Tech. Rev.* **2021**, *2*, 18–23.
7. Reynolds, M.P.; Braun, H.-J. Wheat Improvement. In *Wheat Improvement: Food Security in a Changing Climate*; Springer International Publishing: Cham, Switzerland, 2022; pp. 3–15. ISBN 9783030906726.
8. Crespo-Herrera, L.A.; Crossa, J.; Huerta-Espino, J.; Autrique, E.; Mondal, S.; Velu, G.; Vargas, M.; Braun, H.J.; Singh, R.P. Genetic Yield Gains in CIMMYT'S International Elite Spring Wheat Yield Trials by Modeling the Genotype × Environment Interaction. *Crop Sci.* **2017**, *57*, 789–801. [CrossRef] [PubMed]
9. Guarin, J.R.; Martre, P.; Ewert, F.; Webber, H.; Dueri, S.; Calderini, D.; Reynolds, M.; Molero, G.; Miralles, D.; Garcia, G.; et al. Evidence for Increasing Global Wheat Yield Potential. *Environ. Res. Lett.* **2022**, *17*, 124045. [CrossRef]
10. Food and Agriculture Organization of the United Nations. *The State of the World's Land and Water Resources for Food and Agriculture*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2021; p. 82.
11. Bapela, T.; Shimelis, H.; Tsilo, T.J.; Mathew, I. Genetic improvement of wheat for drought tolerance: Progress, challenges and opportunities. *Plants* **2022**, *11*, 1331. [CrossRef]
12. Parlament Europejski Zielony Ład: Klucz Do Neutralnej Klimatycznie i Zrównoważonej UE. Available online: https://www.europarl.europa.eu/news/pl/headlines/society/20200618STO81513/zielony-lad-klucz-do-neutralnej-klimatycznie-i-zrownowazonej-ue?&at_campaign=20234-Green&at_medium=Google_Ads&at_platform=Search&at_creation=RSA&at_goal=TR_G&at_audience=europejski (accessed on 11 April 2023).
13. Pardey, P.G. A Strategic Look at Global Wheat Production. Productivity and R&D Developments. *Czech J. Genet. Plant Breed.* **2011**, *47*, S6–S19. [CrossRef]
14. Fetting, C. The European Green Deal. *Eur. Comm.* **2020**, *53*, 24.
15. Mebarkia, A.; Rahbé, Y.; Guechi, A.; Bouras, A.; Makhlouf, M.; Sciences, F.; Insa, I.; Biology, F.; Pasteur, B.L.; Mebarkia, C.A. Susceptibility of Twelve Soft Wheat Varieties (*Triticum aestivum*) to *Sitophilus granarius* (L.) (Coleoptera: Curculionidae). *Agric. Exp. Stn. Field Crop Inst. Setif-Alger.* **2010**, *1*, 571–578.
16. Feledyn-Szewczyk, B.; Cacak-Pietrzak, G.; Lenc, L.; Stalenga, J. Rating of Spring Wheat Varieties (*Triticum aestivum* L.) According to Their Suitability for Organic Agriculture. *Agronomy* **2020**, *10*, 1900. [CrossRef]
17. Basavaraja, H.; Mahajanashetti, S.; Udagatt, N.C. Economic Analysis of Post-Harvest Losses in Food Grains in India: A Case Study of Karnataka. *Agric. Econ. Res. Rev.* **2007**, *20*, 117–126.
18. Nawrot, J.; Piasecka-Kwiatkowska, D.; Gawlak, M. The Effect of Some Biochemical and Technological Properties of Wheat Grain on Granary Weevil (*Sitophilus granarius* L.) (Coleoptera: Curculionidae) Development. In Proceedings of the 9th International Working Conference on Stored Product Protection, São Paulo, Brazil, 15–18 October 2006; pp. 400–407.
19. Boniecki, P.; Koszela, K.; Świerczyński, K.; Skwarcz, J.; Zaborowicz, M.; Przybył, J. Neural Visual Detection of Grain Weevil (*Sitophilus granarius* L.). *Agriculture* **2020**, *10*, 25. [CrossRef]

20. Kučerová, Z.; Aulický, R.; Stejskal, V. Outdoor Occurrence of Stored-Product Pests (Coleoptera) in the Vicinity of a Grain Store—Short Communication. *Plant Prot. Sci.* **2005**, *41*, 86–89. [CrossRef]
21. Piasecka-Kwiatkowska, D.; Zielinska-Dawidziak, M.; Nawrot, J.; Gawlak, M. Wpływ Czasu Żerowania Chrząszczy Wołka Zbożowego (*Sitophilus granarius* L.) Na Ziarnie Pszenicy Na Masę Ziaren i Zawartość Wyekstrahowanego Białka. *Prog. Plant Prot.* **2011**, *51*, 1000–1005.
22. Metodyka Integrowanej Ochrony Magazynów Zbożowych Dla Doradców; Klejdysz, T.; Mrówczyński, M. (Eds.) *Zakład Transferu Wiedzy i Innowacji*; Instytut Ochrony Roślin—Państwowy Instytut Badawczy: Poznań, Poland, 2017; ISBN 9788364655319.
23. Germinara, G.S.; De Cristofaro, A.; Rotundo, G. Bioactivity of Short-Chain Aliphatic Ketones against Adults of the Granary Weevil, *Sitophilus granarius* (L.). *Pest Manag. Sci.* **2012**, *68*, 371–377. [CrossRef]
24. Keszthelyi, S.; Lukács, H.; Gibicsár, S.; Rolbiecki, R.; Pál-Fám, F. Action of Different Exposures of Chilled Atmospheric Treatments on the Mortality of Granary Weevil and Embryo Viability of the Treated Wheat. *Agronomy* **2023**, *13*, 597. [CrossRef]
25. Lukács, H.; Pál-Fám, F.; Varga-Visi, É.; Rolbiecki, R.; Percze, A.; Keszthelyi, S. Impact of Short-Term Atmospheric Heat Transfer on the Survival of Granary Weevil in Stored Winter Wheat. *Agronomy* **2022**, *12*, 1313. [CrossRef]
26. Lemic, D.; Mikac, K.M.; Genda, M.; Jukic, Ž.; Živković, I.P. Durum Wheat Cultivars Express Different Level of Resistance to Granary Weevil. Sitophilus Granarius (Coleoptera; Curculionidae) Infestation. *Insects* **2020**, *11*, 343. [CrossRef]
27. Kordan, B.; Skrajda-Brdak, M.; Konopka, I.; Cabaj, R. Phenolic and Lipophilic Compounds of Wheat Grain as Factors Affecting Susceptibility to Infestation by Granary Weevil (*Sitophilus granarius* L.). *J. Appl. Bot. Food Qual.* **2019**, *72*, 64–72. [CrossRef]
28. Halstead, D.G. External Sex Differences in Stored-Products Coleoptera. *Bull. Entomol. Res.* **1963**, *54*, 19–34. [CrossRef]
29. Gołębiowska, Z. The Feeding and Fecundity of *Sitophilus granarius* (L.). *Sitophilus oryzae* (L.). *Rhyzopertha dominica* (F.) Wheat Grain. *J. Stored Prod. Res.* **1969**, *5*, 143–155. [CrossRef]
30. Dobie, P.; Kilminster, A.M. The Susceptibility of Triticale to Post-Harvest Infestation by Sitophilus Zeamais Motschulsky. *Sitophilus oryzae* (L.) and *Sitophilus granarius* (L.). *J. Stored Prod. Res.* **1978**, *14*, 87–93. [CrossRef]
31. Ter Braak, C.J.R.; Smilauer, P. *CANOCO Reference Manual and User's Guide to Canoco for Windows: Software for Canonical Community Ordination (Version 4)*; Microcomputer Power: Ithaca, NY, USA, 1998.
32. Centralny Ośrodek Badania Odmian Roślin Uprawnych. *Lista Odmian Roślin Rolniczych Wpisanych do Krajowego Rejestru w Polsce/Polish National List of Agricultural Plant Varieties*; Centralny Ośrodek Badania Odmian Roślin Uprawnych: Słupia Wielka, Poland, 2022; pp. 1–99.
33. Niewiada, A.; Nawrot, J.; Klockiewicz- Kamińska, E. Wpływ Właściwości Fizykochemicznych Ziarna Pszenicy Różnych Odmian Na Proces Składania Jaj Przez Samice Wołka Zbożowego (*Sitophilus granarius* L.). *Postępy W Ochr. Roślin* **2003**, *43*, 836–839.
34. Nawrot, J.; Gawlak, M.; Szafranek, J.; Szafranek, B.; Synak, E.; Warchalewski, J.R.; Piasecka-Kwiatkowska, D.; Błaszczak, W.; Jeliński, T.; Fornal, J. The Effect of Wheat Grain Composition. Cuticular Lipids and Kernel Surface Microstructure on Feeding. Egg-Laying. and the Development of the Granary Weevil (*Sitophilus granarius* L.). *J. Stored Prod. Res.* **2010**, *46*, 133–141. [CrossRef]
35. Nawrot, J.; Polanska, A. Czynniki wpływajace na proces składania jaj przez wołka zbożowego. *Ochr. Roślin* **2000**, *44*, 9–10.
36. Germinara, G.S.; De Cristofaro, A.; Rotundo, G. Behavioral Responses of Adult Sitophilus Granarius to Individual Cereal Volatiles. *J. Chem. Ecol.* **2008**, *34*, 523–529. [CrossRef]
37. Niewiada, A.; Nawrot, J.; Szafranek, J.; Szafranek, B.; Synak, E.; Jeleń, H.; Wąsowicz, E. Some Factors Affecting Egg-Laying of the Granary Weevil (*Sitophilus granarius* L.). *J. Stored Prod. Res.* **2005**, *41*, 544–555. [CrossRef]
38. Nietupski, M.; Ludwiczak, E.; Cabaj, R.; Purwin, C.; Kordan, B. Fatty Acids Present in Wheat Kernels Influence the Development of the Grain Weevil (*Sitophilus granarius* L.). *Insects* **2021**, *12*, 806. [CrossRef]
39. Nietupski, M.; Ciepielewska, D.; Kordan, B.; Kozirok, W. Czy Twardość Ziarniaków Pszenicy Nowych Odmian Ma Związek z Rozwojem *Sitophilus granarius* L.? *Prog. Plant Prot./Postępy W Ochr. Roślin* **2003**, *42*, 833–855.
40. Mebarkia, A.; Guechi, A.; Mekhalif, S.; Makhlouf, M. Biochemical Composition Effect of the Some Cereal Species' on the Behaviour of *Sitophilus granarius* L. and *Rhyzopertha dominica* F. Species in Semi-Arid Zone of Setif, Algeria. *J. Agron.* **2009**, *8*, 60–66. [CrossRef]
41. Warchlewski, J.R.; Gralik, J.; Nawrot, J. Możliwości Zmniejszania Powodowanych Przez Szkodniki Owadzie Strat Magazynowanego Ziarna Zbóż. *Zesz. Probl. Postępów Nauk Rol.* **2000**, *47*, 85–96.
42. Nawrot, J. The Susceptibility of Grain Various Wheat Varietes and Cultivars to the Post Harvest Infestation by Granary Weevil (*Sitophilus granarius* L.). *Pr. Nauk. Inst. Ochr. Roślin* **1981**, *XXIII*, 133–141.
43. Pasha, I.; Anjum, F.M.; Morris, C.F. Grain Hardness: A Major Determinant of Wheat Quality. *Food Sci. Technol. Int.* **2010**, *16*, 511–522. [CrossRef]
44. Keskin, S.; Ozkaya, H. Effect of Storage and Insect Infestation on the Technological Properties of Wheat. *J. Food* **2015**, *13*, 134–139.
45. Piasecka-Kwiatkowska, D.; Gawlak, M.; Niewiada, A.; Nawrot, J.; Warchlewski, J.R.; Fornal, J.; Grundas, S. Wpływ Chemicznych Właściwości Ziarna Trzech Odmian Pszenicy Na Intensywnosc Zerowania i Tempo Rozwoju Populacji Wołka Zbożowego (*Sitophilus granarius* L.). *Prog. Plant Prot.* **2005**, *45*, 982–985.
46. Sahoo, G.; Sahoo, B.K. Grain Hardness and Protein Content of Milled Rice Grains and Their Relationship with Infestation of Rice Weevil *Sitophilus oryzae* L. (Coleoptera: Curculionidae). *ORYZA-Int. J. Rice* **2016**, *53*, 332–336.
47. Nietupski, M.; Ciepielewska, D.; Fornal, Ł. Wpływ Żróżnicowania Chemicznego Białek w Ziarnie Wybranych Odmian Pszenicy Na Rozwój Szkodników Magazynowych. *Prog. Plant Prot./Postępy W Ochr. Roślin* **2006**, *46*, 420–423.
48. Gąsiorowski, H. Weglowodany w Ziarnie Pszenicy i Przetworach Pszennych. *Przegląd Zbożowo-Młynarski* **2004**, *48*, 19–20.

49. Shevkani, K.; Singh, N.; Bajaj, R.; Kaur, A. Wheat Starch Production. Structure. Functionality and Applications—A Review. *Int. J. Food Sci. Technol.* **2017**, *52*, 38–58. [CrossRef]
50. Chen, G.; Liu, Y.; Lu, X.; Han, C.; Zhang, W.; Xu, Y.; Yan, Y. Biosynthesis and Regulation of Wheat Amylose and Amylopectin from Proteomic and Phosphoproteomic Characterization of Granule-binding Proteins. *Sci. Rep.* **2016**, *6*, 33111. [CrossRef] [PubMed]
51. Wang, Y.; Ral, J.-P.; Saulnier, L.; Kansou, K. How Does Starch Structure Impact Amylolysis? Review of Current Strategies for Starch Digestibility Study. *Foods* **2022**, *11*, 1223. [CrossRef] [PubMed]

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