

Article

Selected Chemical Parameters of Cereal Grain Influencing the Development of *Rhyzopertha dominica* F.

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Abstract: The increasing food crisis in times of ecological threats has challenged conventional agriculture to transform into a more efficient and sustainable agri-food system. The global priority of these activities has become, among others, the responsible and effective use of already produced food. This study aimed to assess the impact of the natural resistance of cereal grains to consumption by storage pests. The study presented here analyzed the impact of selected chemical factors from the grain of six species of cereals (wheat, triticale, rye, barley, oat, corn) on the development of one of the most dangerous storage pests—the lesser grain borer *Rhyzopertha dominica* F. The increased development of this beetle on the tested grain was determined based on the number of progeny, the mass of dust produced, and the loss of grain mass. Moreover, the correlations between the above-mentioned development parameters of the pest and the content in the grain of dry matter, crude ash, total protein, crude fat, starch, and water-soluble carbohydrates (WSCs) were examined. The results showed that the tested pest developed most intensively on barley and triticale grains and was least abundant on oat and corn grains. Chemical analysis of the selected grain showed that the low number of the *R. dominica* progeny population was correlated with a higher crude fat content and a lower total protein content in the cereal grain, and therefore, these chemical properties could affect the development of the pest. Knowledge of these relationships can be used in cereal breeding programs and when recommending cereals for more extended storage. This directly translates into improved local and global nutritional and food security. Moreover, it may also contribute to the reduction of pesticide use at the storage stage, which is one of the basic requirements for agricultural production in a sustainable agriculture system.

Keywords: fatty acids; food attractiveness; food security; grains; natural resistance; proteins; storage pests



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1. Introduction

The escalating global food demand, a consequence of rapid global population growth, is the most pressing challenge of the 21st century [1–3]. The strategy of agricultural production increase, primarily focused on expanding crop area and yield, has proven inadequate in achieving sustainable global food security. This approach has also led to unprecedented environmental degradation [4–6]. In the wake of economic, ecological, social, and epidemiological crises, a significant rise in global malnutrition occurred in 2022 (7.9% in 2019 and 9.2% in 2022) [1]. Global production surpasses demand; thus, the food system crisis is not due to a food deficit [7,8]. This issue stems from a malfunctioning agri-food chain, particularly improper food distribution, food waste, and lack of purchasing power [9–11].

The European Union's implementation of the green transformation in agricultural policy necessitates changes at various levels. The objectives in this context (ecological transformation leading to the achievement of climate neutrality in the European Union by 2050) are fundamental but challenging to accomplish. Furthermore, with the gradual adoption of the Common Agricultural Policy (CAP) guidelines, the evolving world and its issues are reshaping the priorities of these initiatives, broadening their scope [12–14]. Hence, more efficient and sustainable solutions are being sought to ensure economic growth while safeguarding the natural environment [15].

Annually, over 30% of food produced for consumption is lost, posing ethical, environmental, and economic challenges [16,17]. Primarily, this leads to the squandering of resources that could feed 735 million undernourished people worldwide, and its production also generates unnecessary greenhouse gas emissions [15,18,19]. Therefore, reducing food waste is a crucial aspect of the resolution signed by all UN member states: 'Transforming our world: 2030 Agenda for Sustainable Development'. This declaration aims to eradicate global hunger by 2030, partly by halving food waste. However, rationalizing these losses applies to discarded food and minimizing losses during production, processing, storage, and distribution [20].

Cereals, the basic raw materials of the food industry, are the main link in global nutritional and food security, and Poland is among the leading producers in Europe [10,21,22]. Despite the undisputed role of cereals, they are among the most frequently lost and wasted agricultural products [23]. In grain production, over 80% of all losses occur at the grain storage stage. Therefore, protecting the cereals at this stage is one of the most essential elements of the undertaken global transformation of sustainable food systems [10,23,24].

During storage, up to 10% of stored agricultural produce may be damaged by storage pests [25,26]. The losses caused by such pests are not limited only to the loss of grain mass. Insects feeding on stored cereals also cause contamination (e.g., with molts, feces, and dead individuals). As a result of their feeding, the temperature of the stored material also increases, which favors the development of mold, the appearance of which leads to a reduction in the commercial value of the stored grain [27,28].

Transitioning from an intensive agricultural production system to a sustainable one involves minimizing chemical pest control methods. So far, these substances have been the basis for proper and long-term storage. These methods are effective but dangerous to human health and the natural environment [29,30]. Also, reducing the use of pesticides increases the likelihood of pest invasions [31,32]. A global pest that threatens stored cereals is the lesser grain borer *Rhyzopertha dominica* F. [33–35]. Entomological observations regarding this species' behavior and food preferences can help develop sustainable cereal storage patterns aimed at, among others, preventing losses and ensuring sustainable economic development.

Based on previous research and observations of storage pests [36–38], a research hypothesis was put forward that assumes that the development of *R. dominica* depends on the range of natural resistance of grains of individual species, which results from, among other aspects, the chemical composition of the grains, in particular the content of protein and fatty acids. An attempt was made to analyze the above relationships by examining the existence and nature of the relationship between the examined chemical properties of grains and the development of *R. dominica*.

2. Materials and Methods

2.1. Materials

Entomological material (*Rhyzopertha dominica* (F., 1792) (Coleoptera: Bostrichidae)) came from mother breeding conducted at the Department of Entomology, Phytopathology and Molecular Diagnostics (University of Warmia and Mazury in Olsztyn, Poland) on winter wheat grain, Korweta variety.

The research was conducted on grains of 6 cereal species purchased directly from the breeder:

- Winter wheat, Hondia variety, *Triticum aestivum* L. subsp. *aestivum* (DANKO Breeding Plant);
- Winter triticale, Transfer variety, *xTriticosecale* Wittm. ex A. Camus (Strzelce Breeding Plant);
- Hybrid rye, KWS Dolaro variety, *Secale cereale* L. (KWS Lochów Polska Breeding Plant);
- Spring barley, Stratus variety, *Hordeum vulgare* L. (Strzelce Breeding Plant);
- Common oats, Bingo variety, *Avena sativa* L. (Strzelce Breeding Plant);
- Corn, Rosomak variety, *Zea mays* L. (Smolice Breeding Plant).

Selected cereal grains, varieties recommended for cultivation in northern Poland, were conditioned in a SANYO MLR 350-H incubator for seven days (30 °C, humidity 70%, total darkness) to obtain equilibrium values. After obtaining the optimal humidity level, 20 g of grains were weighed on a laboratory scale (model: WPS220/C/2, manufacturer: Radwag, Radom, Poland) and placed in vidinur dishes. The breeding containers were equipped with ventilation holes with a diameter of 10 mm, secured with a chiffon mesh (container diameter 80 mm, height 30 mm). On the first day of the experiment, ten individuals of *R. dominica* (3–4 days old and with a sexual ratio of 1:1) were placed on the isolated plant material, which was then removed after 21 days of feeding. The pest's progeny population was then counted every seven days until all progeny were obtained. The experimental methodology was established based on previous research and observations regarding the development of *R. dominica* [34,39] (Figure 1).



Figure 1. Grain damage caused by *Rhyzopertha dominica*. Fot. Olga Kosewska.

2.2. Chemical Properties of Grain

Chemical analysis of the grains of the tested cereals was carried out at the Department of Animal Nutrition and Feed Sciences (University of Warmia and Mazury in Olsztyn, Poland). The dry matter content was determined using the drying method. The samples prepared immediately before the determination were weighed (5 g), crushed, and dried in a dryer at 105 °C until a constant weight was obtained (5–8 h). The crude ash content was measured using the gravimetric method by air combustion of a dry grain sample (5 g) in a muffle furnace (temperature 500–550 °C, time 5–6 h) and determining the mass of the sample before and after ashing. Based on the amount of total nitrogen (N), determined using the Kjeldahl method and then converted into total protein ($N \times 6.25$), the total protein content of the six cereal species examined was determined (Polish Standard: PN-ISO 5983.2000 [40]). Crude fat from the tested grains was extracted using the Soxhlet method (Polish Standard: PN-ISO 6492: 2005 [41]). The starch content was tested in a polarimeter according to Polish Standard PN-R-64785:1994 [42], and the water-soluble carbohydrate (WSC) content was determined according to Polish Standard PN-R-64784:1994 [43].

The protein content in the analyzed grains was determined using the methodology of the Department of Processing and Chemistry of Plant Raw Materials (University of Warmia and Mazury in Olsztyn, Poland). The analysis divides proteins according to their amino acid composition, which determines their solubility:

- Albumins (water-soluble proteins);
- Globulins (proteins soluble in dilute salt solutions);
- Prolamins (proteins soluble in aqueous alcohols);
- Glutelins (proteins soluble in dilute acids or bases) [44].

The extraction of albumins + globulins, prolamins, and glutelins was conducted, according to Wieser and Kieffer [45]. The protein content of each extract was determined spectrophotometrically (FLUOstar Omega, BMG LabTech, Ortenberg, Germany) at $\lambda = 595$ based on the Bio-Rad Bradford Protein Assay using bovine serum albumin (Bio-Rad, Hercules, CA, USA) for quantification of albumins and globulins and the gliadin standard (Sigma-Aldrich, Poznań, Poland) for quantification of prolamin and glutelin fraction of proteins.

Calibration curves were prepared for protein concentration up to 5 mg/mL (R^2 above 0.98). Gliadins and glutelins were determined using the Osborn method [46].

2.3. Statistical Analysis

The nature of the data distribution regarding the number of progeny, the loss of grain mass, the mass of dust produced by beetles, and the selected chemical parameters of the tested cereal grain were assessed using the Shapiro–Wilk W test. Data that were not normally distributed (progeny, dust mass, mass loss, dry mass, total protein, crude fat, starch, and WSCs) were subjected to logarithmic transformation ($\ln x + 1$). A one-factorial analysis of variance ANOVA was used to assess the significance of differences in the studied variables between cereal varieties. Groups of average tested parameters related to the development of *R. dominica*, which do not differ statistically, are marked with the same letter index: a, b, c... (Tukey HSD test).

To assess the similarity of the chemical composition of the examined cereal species for total protein, crude ash, starch, dry matter, crude fat, and WSCs, a dissimilarity analysis was performed based on the Bray–Curtis matrix, and dendrograms were then created using the Wald method. A redundancy analysis technique (RDA) was used to graphically assess the relationship between parameters describing the development of *R. dominica* (progeny, mass of dust, and loss of mass) and the chemical composition of the grain of the studied cereal species [47]. The RDA method was selected by calculating the lengths of the gradients (SD) for each analysis performed. Statistical calculations and their graphical interpretation were performed using the following programs: Statistica 13.1, Canoco 4.51, and PAST 2.17b.

3. Results

3.1. Developmental Parameters of *R. dominica*

Parameters related to the intensity of *R. dominica* development on a grain of selected cereal species were examined by assessing the number of progeny of beetles of the pest ($F = 81.47$, $p = 0.00$), the mass of dust produced ($F = 92.54$, $p = 0.00$), and the loss of grain mass ($F = 55.65$, $p = 0.00$). A one-factorial analysis of variance ANOVA showed that the differences between the means describing pest development on different cereal species were statistically significant (Table 1).

Table 1. Results of statistical significance tests (ANOVA) for parameters describing the development of *R. dominica* on the grain of the tested cereal species.

	df *	F Values	p **
Progeny of beetles	5	81.47	0.00
Mass of dust	5	92.54	0.00
Loss of grain mass	5	55.65	0.00

* Degrees of freedom. ** The value of the test probability p .

The highest number of *R. dominica* progeny was found on barley grain (average 258.9 individuals) (Figure 2a). Smaller numbers of progeny individuals were found on

the grain of triticale (203.1), wheat (156.3), and rye (133.2), but Tukey's HSD test classified them into the same homogeneous group (c). Significantly fewer beetle progeny were found in combination with oat grain (58.1, homogeneous group b), and the lowest number was recorded on corn grain (2.9, homogeneous group a) (Figure 2).

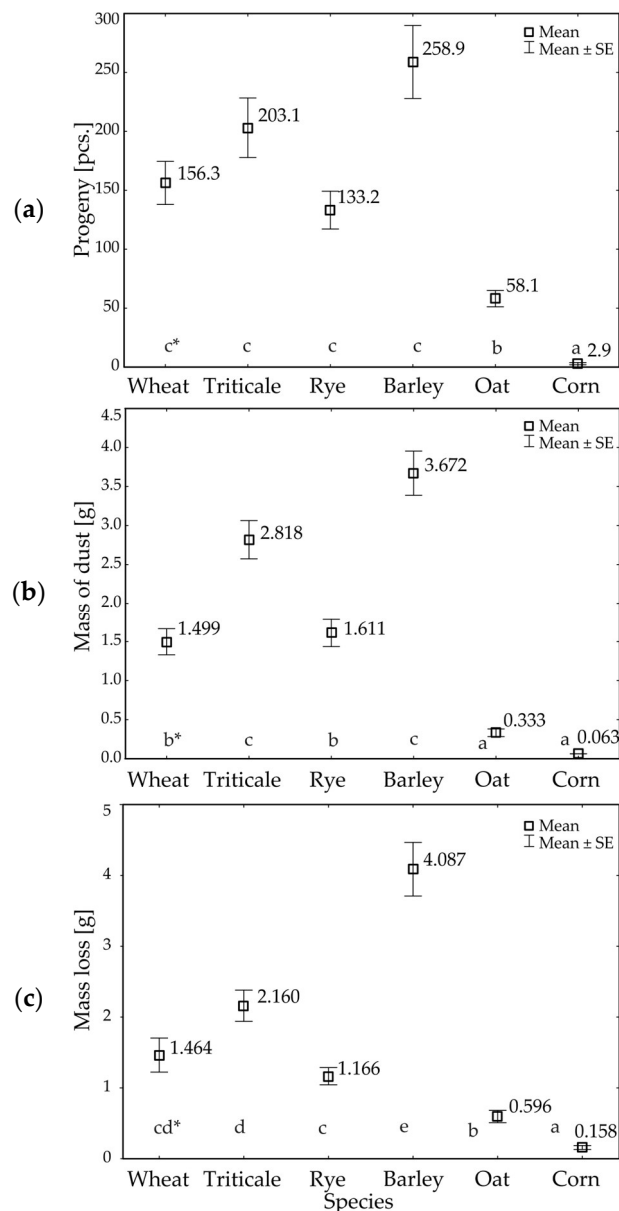


Figure 2. Average number of progeny beetles of *R. dominica* (a), mass of produced dust (b), and grain mass loss (c) observed on the grain of the studied cultivars (* means followed by the same letter do not differ—Tukey's HSD test).

The mass of dust produced by feeding beetles and the loss of grain mass are parameters correlated with the number of progeny. These relationships were confirmed in the research results. The highest dust mass was found in combination with barley grain (average 3.672 g) and triticale (2.818 g) (Figure 2b). Lower values of this parameter were recorded in combination with rye grain (1.611 g) and wheat grain (1.499) and the lowest values were in combination with oat grain (0.333 g) and corn grain (0.063 g). However, these combinations showed the most minor losses in grain mass. The loss was, on average, 0.596 g on oat grain and corn grain 0.158 g (Figure 2c). Combined with rye grain, the value of this parameter was, on average, 1.166 g, wheat—1.464 g, and triticale—2.160 g. The highest average loss

of grain mass, resulting from the feeding of *R. dominica*, was found in combination with barley grain (4.087 g) (Figure 2c).

3.2. Chemical Properties of the Tested Cereal Grain

The grain of the studied cereal species was analyzed in terms of its chemical composition. It was found to differ significantly in terms of dry matter content ($F = 757.42$, $p = 0.00$), crude ash ($F = 254.79$, $p = 0.00$), total protein ($F = 421.00$, $p = 0.00$), crude fat ($F = 660.25$, $p = 0.00$), starch ($F = 14190.98$, $p = 0.00$), and WSCs ($F = 6834.16$, $p = 0.00$) (Table 2).

Table 2. Results of statistical significance tests (ANOVA) for the content of selected chemical substances contained in the grain of the examined cereal species.

	df *	F Values	p **
Dry matter	5	757.42	0.00
Crude ash	5	254.79	0.00
Total protein	5	421.00	0.00
Crude fat	5	660.25	0.00
Starch	5	14,190.98	0.00
WSCs	5	6834.16	0.00

* Degrees of freedom. ** Test probability value p .

Wheat grain was characterized by the highest dry matter content (89.59) and total protein (12.4) among the examined cereal species. It also had a low crude fat content (0.60) (Table 3).

Table 3. Average values of the chemical composition of grains for the examined cereal species.

	Wheat		Triticale		Rye		Barley		Oat		Corn	
Dry matter	89.59 ± 0.09	e *	86.22 ± 0.08	b	89.05 ± 0.07	d	86.52 ± 0.06	c	86.40 ± 0.04	bc	85.24 ± 0.01	a
Crude ash	1.6 ± 0.00	c	1.49 ± 0.02	b	1.65 ± 0.04	c	1.87 ± 0.02	d	2.2 ± 0.02	e	1.28 ± 0.01	a
Total protein	12.4 ± 0.04	d	11.63 ± 0.06	c	11.72 ± 0.04	c	10.67 ± 0.06	b	9.15 ± 0.11	a	9.32 ± 0.03	a
Crude fat	0.60 ± 0.03	a	0.5 ± 0.03	a	0.48 ± 0.02	a	0.56 ± 0.02	a	3.03 ± 0.18	b	4.53 ± 0.07	c
Starch	61.17 ± 0.06	d	59.83 ± 0.05	c	59.78 ± 0.09	c	51.82 ± 0.04	b	44.44 ± 0.06	a	62.8 ± 0.06	e
WSCs	2.65 ± 0.01	c	3.61 ± 0.01	d	6.92 ± 0.01	f	4.02 ± 0.02	e	2.3 ± 0.03	b	1.87 ± 0.01	a

* a, b, c . . . groups of average tested parameters related to the development of *R. dominica*, which do not differ statistically (Tukey HSD test).

Triticale grain had a relatively high content of starch (59.83), total protein (11.63), and a low content of crude fat (0.5). Rye grains were characterized by the highest WSC content in the group (6.92), high total protein (11.72), dry matter (89.05), and low crude fat content (0.48). Barley grains were also characterized by a low content of these compounds (0.56) and a relatively high content of crude ash (1.87). In the case of oat grains, the highest content of crude ash was found (2.2), and the lowest amounts of total protein (9.15) and starch (44.44) were in the tested group. Compared to other species, corn kernels had the highest content of crude fat (4.53) and starch (62.8), and the lowest contents of other ingredients (Table 3).

R. dominica developed the least on corn and oat grains, and the most on barley and triticale. Cluster analysis was used to determine what chemical factors of the grain could influence this process. This analysis made it possible to compare the tested cereal grains in terms of the similarity of their chemical composition (Figure 3).

The chemical factor that could have influenced the low number of progeny generation of *R. dominica* was the content of total protein and crude fat. Regarding total protein content, the dendrogram distinguished two groups of cereal species. The first included oats, corn, and barley; the second included triticale, rye, and wheat. In the case of crude fat, two species with high natural resistance to *R. dominica* (corn and oats) formed a separate group on the dendrogram, differing from other cereal species. The grain's content of crude ash, dry matter, and starch was not correlated with resistance to beetle feeding because similar dendrograms placed oat and barley grains in one group. In the case of WSCs, oat and

barley grains formed one group with wheat, but they were also very similar to the group formed by triticale and barley (Figure 3). The results of grouping cereal species in terms of their similarity in chemical composition and susceptibility to feeding by *R. dominica* revealed that the low number of the generation of the pest developing on oats and corn may result from total protein and crude fat content. Therefore, the tested grain was also analyzed regarding its fatty acid content and the type of proteins. The analysis of variance (ANOVA) showed that the tested cereal grains differ significantly in terms of fatty acids and protein content (Table 4).

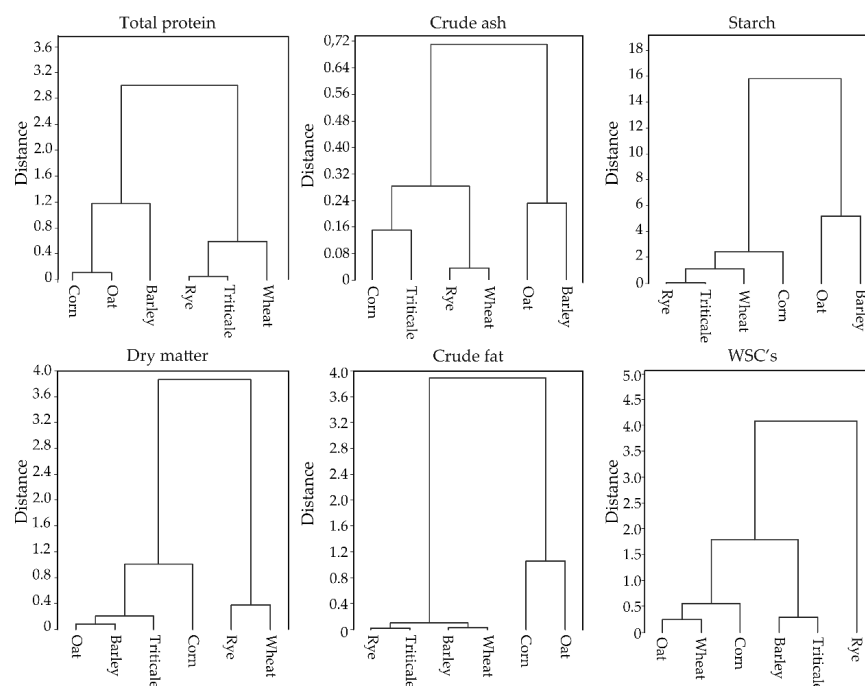


Figure 3. Dendrograms show the general similarity of the examined cereal grains depending on the groups of examined chemical substances. A dissimilarity matrix was prepared based on the Bray–Curtis similarity measure.

Table 4. Results of statistical significance tests (ANOVA) for the content of selected chemical substances contained in the grain of the examined cereal species (wheat, triticale, rye, barley, oats, corn).

	df *	F Values	p **
Fatty acids/Name of Acid			
C 14:0/myristic acid	5	199.98	0.00
C 15:0/pentadecanoic acid	5	83.87	0.00
C 16:0/palmitic acid	5	945.12	0.00
C 16:1/palmitoleic acid	5	109.26	0.00
C 17:0/margaric acid	5	92.1	0.00
C 17:1/margaroleic acid	5	217.87	0.00
C 18:0/stearic acid	5	114.44	0.00
C 18:1/oleic acid	5	4061.95	0.00
C 18:2/inoleic acid	5	614.30	0.00
C 18:3/ α -linoleic acid	5	12,384.3	0.00
C 20:0/araquinic acid	5	89.89	0.00
C 21:0/henicosanoic acid	5	1756.2	0.00
Proteins			
Albumins + globulins	5	101.48	0.00
Prolamins	5	557.23	0.00
Glutelin	5	645.22	0.00

* Degrees of freedom. ** Test probability value *p*.

Twelve fatty acids differing in the length of carbon chains were determined in the grains of the studied species (Table 5). The most significant amounts (in % of the sum of fatty acids) were linoleic acid (C 18:2), the content of which in grain ranged from 28.36 (oats) to 64.39 (wheat). High contents of pentadecanoic acid (C 16:0) (from 8.91 in corn to 22.12 in barley), oleic acid (C 18:1) (from 11.60 in triticale to 46.84 in oats), and α -linoleic acid (C 18:3) (from 0.31 in oats to 6.85 in rye) were found. The content of other fatty acids did not exceed 3%. The cluster analysis grouping grains of the examined cereal species in terms of their similarity in fatty acid content revealed that the composition of these compounds is very similar in oat and corn grains (Figure 4). The remaining species form a separate group in the dendrogram (Table 5).

Table 5. Average content of fatty acids and proteins in the grain of cereal species.

	Wheat		Triticale		Rye		Barley		Oat		Corn	
C 14:0 *	0.07 ± 0.01	b	0.18 ± 0.01	c	0.24 ± 0.01	d	0.26 ± 0.00	d	0.18 ± 0.02	c	0.01 ± 0.00	a
C 15:0	0.05 ± 0.01	b	0.14 ± 0.01	c	0.13 ± 0.01	c	0.11 ± 0.01	c	0.01 ± 0.01	a	0.01 ± 0.01	a
C 16:0	16.59 ± 0.06	b	18.39 ± 0.03	c	18.16 ± 0.04	c	22.12 ± 0.03	d	21.45 ± 0.02	d	8.91 ± 0.18	a
C 16:1	0.08 ± 0.01	b	0.10 ± 0.01	c	0.18 ± 0.01	e	0.07 ± 0.01	ab	0.15 ± 0.01	d	0.05 ± 0.00	a
C 17:0	0.07 ± 0.01	b	0.11 ± 0.01	c	0.12 ± 0.00	c	0.07 ± 0.01	b	0.02 ± 0.01	a	0.02 ± 0.01	a
C 17:1	0.02 ± 0.00	b	0.20 ± 0.01	c	0.32 ± 0.01	d	0.07 ± 0.01	bc	0.05 ± 0.01	b	0.01 ± 0.01	a
C 18:0	0.91 ± 0.02	a	1.36 ± 0.01	b	2.03 ± 0.01	d	1.62 ± 0.01	c	1.87 ± 0.08	d	1.44 ± 0.04	b
C 18:1	13.66 ± 0.09	c	11.60 ± 0.04	a	17.87 ± 0.05	d	12.93 ± 0.09	b	46.84 ± 0.96	f	39.19 ± 0.07	e
C 18:2	64.39 ± 0.12	e	61.273 ± 0.03	e	52.54 ± 0.09	c	57.07 ± 0.08	d	28.36 ± 0.82	a	49.48 ± 0.27	b
C 18:3	3.63 ± 0.04	c	5.66 ± 0.01	e	6.85 ± 0.01	f	4.74 ± 0.08	d	0.31 ± 0.01	a	0.51 ± 0.01	b
C 20:0	0.10 ± 0.01	a	0.17 ± 0.01	b	0.26 ± 0.01	c	0.25 ± 0.01	c	0.15 ± 0.01	b	0.26 ± 0.01	c
C 21:0	0.44 ± 0.00	b	0.81 ± 0.01	e	1.3 ± 0.01	f	0.68 ± 0.02	d	0.63 ± 0.01	c	0.11 ± 0.01	a
Albumins + globulins	4.03 ± 0.02	d	4.00 ± 0.05	d	3.96 ± 0.11	d	2.87 ± 0.01	b	3.61 ± 0.07	c	2.61 ± 0.07	a
Prolamins	2.17 ± 0.01	c	1.49 ± 0.08	b	1.02 ± 0.05	a	3.87 ± 0.02	e	3.38 ± 0.02	d	2.24 ± 0.06	c
Glutelin	4.25 ± 0.07	d	3.05 ± 0.05	b	2.39 ± 0.06	a	3.45 ± 0.05	c	6.24 ± 0.01	e	6.49 ± 0.09	e

Full name of fatty acids in Table 4. * a, b, c... groups of average tested parameters related to the development of *R. dominica*, which do not differ statistically (Tukey HSD test).

The second chemical component influencing the lower development of *R. dominica* in oats and corn was total protein content. It was found that the proteins of the examined cereal species included albumins + globulins ($F = 101.48$, $p = 0.00$), prolamins ($F = 557.23$, $p = 0.00$), and glutelin ($F = 645.2$, $p = 0.00$), and their content was significantly different (Table 4). In the case of oat and corn grains, they were distinguished from other species by the high content of glutelins (oats: 6.24; corn: 6.49) (Table 5).

A thorough analysis was conducted to comprehensively understand the relationship between the development parameters of *R. dominica* and the general chemical composition of cereal grains. This included a correspondence analysis (RDA) and identifying selected chemical factors related to increased resistance to feeding by this pest. The results, as shown in Figure 4, reveal the correlations between the development parameters of *R. dominica* and the general chemical composition of grains for the examined cereal species. The species with low pest progeny (oats, corn) are depicted in the row chart's upper left quadrant. The closed axis also illustrates the higher crude fat content in the grain. The axis corresponding to the increasing crude ash content correlates with the barley grain, while for triticale, it correlates with the increased content of starch and WSCs in the grain. The axis indicating the number of progeny generated for *R. dominica* and the mass of dust produced correlates with the grain's high dry matter content and total protein (Figure 5).

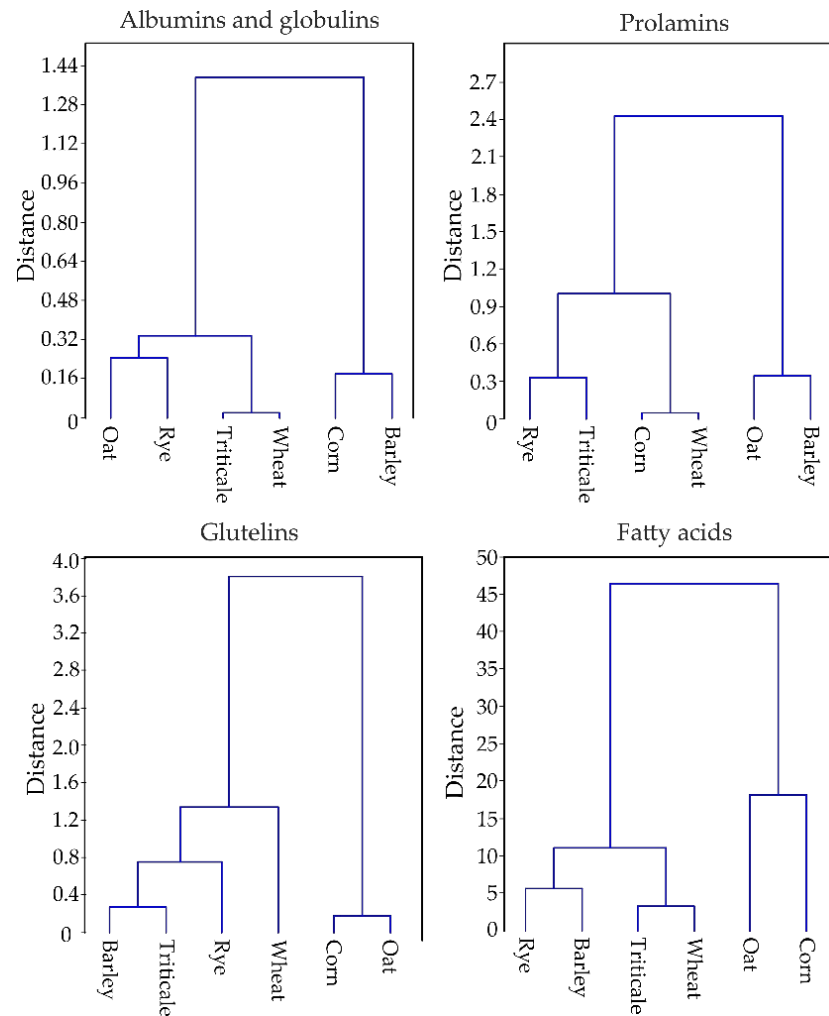


Figure 4. Dendrograms show the general similarity of the examined cereal grains depending on the groups of fatty acids and protein content. A dissimilarity matrix was prepared based on the Bray–Curtis similarity measure.

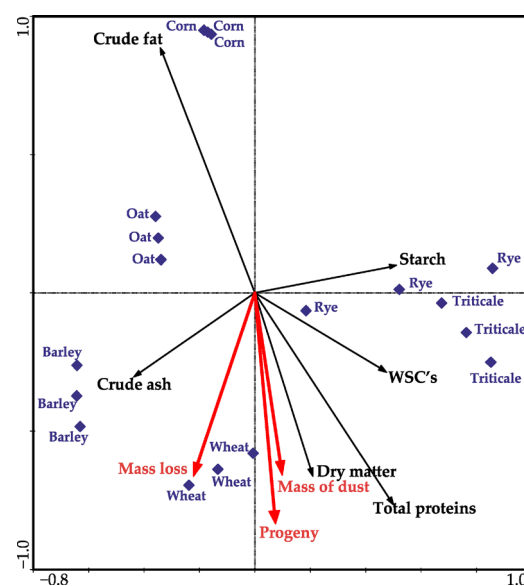


Figure 5. Redundancy analysis diagram (RDA) presenting correlations between analyzed parameters for the development of *R. dominica* and the chemical characteristics of grains.

Analysis of the connections between the parameters describing the development of *R. dominica* and the composition and content of fatty acids is presented in Figure 5. The axes describing the intensity of the development of the pest (progeny, mass of dust, and loss of mass) are correlated with the axes indicating the increased content of C 14:0 and C 16:0. They are located in the lower left quadrant of the ordination chart, which also contains barley and wheat grains. The triticale grain, on which *R. dominica* formed numerous progeny populations, is characterized by a high content of C 17:1 fatty acid. Corn and oats are located on the opposite side of the ordination chart, away from the other species, and correlate with increasing C 18:1 fatty acid content (Figure 6).

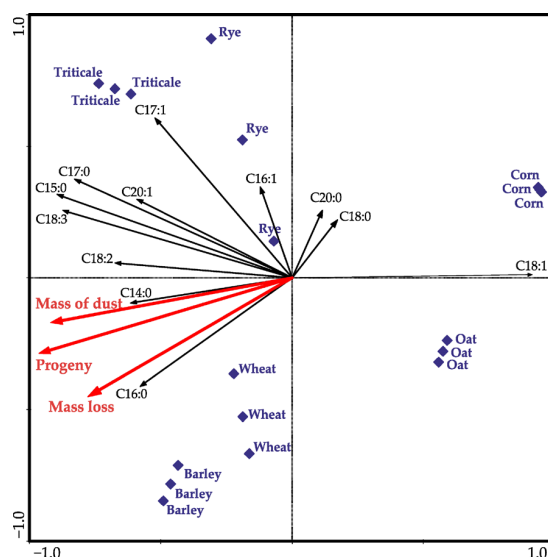


Figure 6. Redundancy analysis diagram (RDA) presenting correlations between analyzed parameters for the development of *R. dominica* and the content of fatty acids in the analyzed grain cultivars.

Analyzing the ordination chart showing the relationship between the parameters describing the development of *R. dominica* and the composition of proteins in the grain of the examined cereal species, it was observed that the low intensity of the pest's development is correlated with a high content of proteins from the glutelin group (Figure 7). Grain varieties with low resistance to pest feeding (high progeny, mass of dust, and loss of mass values) are significantly separated from each other on the RDA chart. The increasing content of prolamins in grains correlates with barley, while the increasing content of albumins and globulins correlates with triticale (Figure 7).

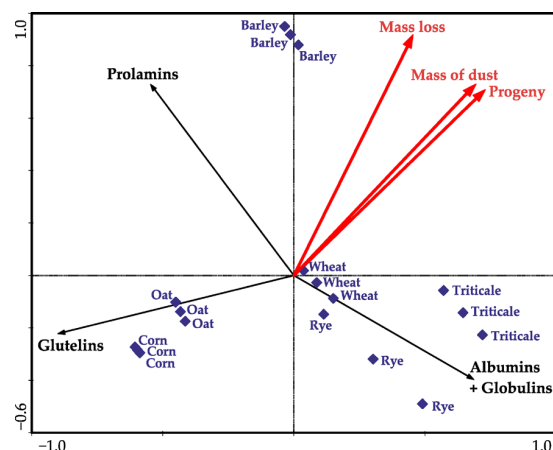


Figure 7. Redundancy analysis diagram (RDA) presenting correlations between analyzed parameters for the development of *R. dominica* and the protein content in the analyzed grain cultivars.

4. Discussion

Plant protection is vital in developing a sustainable future for agriculture [30,48]. In an era of searching for ecological solutions, particular attention is paid to the natural resistance of crop plants, which may also be crucial when storing cereal grains. Knowing and understanding the chemical basis determining the natural defense mechanisms of plants can complement the permitted plant protection methods in a sustainable agriculture system and may also become the primary method of preventing the invasion of storage pests [48,49].

R. dominica is a cosmopolitan pest of stored food products, mainly cereals [50–52]. Due to its high adaptability and reproductive potential, this insect can colonize and then damage the grain of many cereal species [50–52]. In our study, *R. dominica* developed on six cereal species, and its feeding and development on the tested grains showed statistically significant differences (Table 1). The heterogeneity of the physico-chemical composition of grains is a decisive factor influencing the development of storage pests. However, these mechanisms have not been fully understood, and their understanding and use in practice constitute one of the most significant challenges of modern sustainable agriculture [37,38,52–56].

The highest number of progeny for the tested pest was observed on barley (average 258.9 individuals), which was also characterized by the highest mass of dust produced and the highest average loss of grain mass (Figure 2). According to the post hoc test, these cereals formed a joint homogeneous group with triticale (203.1), wheat (156.3), and rye (133.2). Inverse relationships (low number of progeny resulting in low loss of grain mass and low dust mass), and thus, the highest natural resistance, were characteristic of oat (58.1) and corn (2.9) grains, forming separate homogeneous groups (Figure 2). Perišić [52], in his research on this pest among grains of wheat, barley, oats, rye, and triticale, observed the highest mortality for the original population and a low number of the progeny population also in oats. However, Hendrival [57], similarly to our study, showed lower susceptibility of corn to feeding by *R. dominica* than wheat (Figure 2).

Differences in the development of the tested beetle may result from the natural defense mechanisms of the inhabited cereal grains, which are shaped in particular by their chemical properties. Chemical composition is crucial to determining a plant's attractiveness to insects [28,48,58]. The influence of chemical composition (dry matter, crude ash, total protein, crude fat, starch, and WSCs) on the feeding of *R. dominica* in the grain of the studied cereal species showed significant differences (Tables 2 and 3, Figure 3). Our previous research also showed that the most critical chemical factors determining the development of *Sitophilus granarius* L. considered one of the most dangerous warehouse pests on wheat, are starch [37] and crude fat [38]. In our research on the influence of the chemical composition of common millet (*Panicum miliaceum* L.) on the development of *Tribolium confusum* Duv., a stimulating effect of increased crude fat concentration on the defense reactions of millet was also demonstrated [36]. Analysis of the chemical composition of oats and corn showed the highest average values of crude fat in their grains (corn 4.53, oats 3.03; wheat 0.6, barley 0.56; triticale 0.5; rye 0.48) (Table 3). A detailed analysis of fatty acids contained in wheat grains during studies with *S. granarius* showed that the higher C 18:1 and C 20:1 fatty acids may attract *S. granarius*. The higher content of C 15:0, C 16:1, and C 18:3 fatty acids may deter this pest [38]. However, in studies on *T. confusum*, we demonstrated an influence on the intensity of its development of C 18:2 fatty acid [36]. Both cereal species (oats and corn) differed significantly in terms of fatty acid content from other cereals, as revealed by the cluster analysis (Tables 4 and 5, Figure 4). In the grains with the lowest degree of infection in the experiment with *R. dominica*, the highest content of fatty acid C 18:1 was observed. The influence of fat contained in cereal grains on the feeding of warehouse pests was also demonstrated by Mebarkia et al. [58] and Niewiada et al. [59].

The most critical problems of the modern world include producing food in larger quantities and improving its quality. The diseases of the 21st century are primarily diet-related diseases, including the increasingly common gluten-dependent diseases (including celiac

disease, Duhring's disease, wheat allergy, and non-celiac gluten sensitivity (NCGS)) [60–62]. Despite its unique properties (binding values), gluten is the direct cause of increasing diseases [60–63]. Cereal grains are one of the primary plant protein sources in the human diet [64,65]. Their amount varies (from 5 to 15% of dry matter). Moreover, it depends on many factors, including the plant species [63,64,66,67]. Substitutes for cereals with a high gluten content (e.g., wheat, triticale) may be gluten-free cereals (containing less than 20 mg of gluten per kilogram of product) [61,68,69]. In our experiment, the cereals least damaged by the tested pest (oats, corn) have a low total protein content correlated with the highest glutelin content among the tested cereals (Table 3, Figure 7). Our results are consistent with the published results of Astuti et al. [70], who showed that the low protein content in flour products reduced the feeding and development efficiency of *Tribolium castaneum* (Herbst). In the studies of Syed et al. [71], lower numbers and limited vital parameters of *R. dominica* were correlated with lower protein contents. Dukić [72], in his research on the attractiveness of cereals for *T. castaneum*, concluded that the proportions of protein and carbohydrates that shape the food preferences of storage pests are significant. The studies of Perišić et al. [52] also demonstrated the influence of gluten content on the susceptibility of cereal grains to feeding by *R. dominica*. In their observations regarding *S. granarius*, Nietupski et al. [73] observed correlations between the protein content in grains and the development of this pest, showing that albumins, globulins, and glutenins inhibit it [72]. The research by Kosewska et al. [74] shows that the type and quality of food significantly influences the development of the microbiome of *Sitophilus oryzae* L. The authors also found that the composition of the microbiome changes with the development of the pest generations, adapting to the type of food. Understanding this relationship in the case of *R. dominica* will allow for a better understanding of what factors related to the chemical composition of cereal grains may affect the development of the pest. This knowledge may lead to new perspectives in storage control strategies for *R. dominica*.

5. Conclusions

This entomological study showed that the development of *R. dominica* on the six examined cereal species was differentiated. The pest's most intensive development was observed on barley and triticale grains and the weakest on oat and corn grains. The grains of the examined cereal species differed in their chemical composition. Chemical analysis of the grains of species characterized by a small population of the pest's offspring (oats, corn) showed that they contained higher amounts of crude fat and lower total protein content, with the highest content being proteins from the glutelin group. On the other hand, the high content of C 18:1 most likely stimulates the defensive reactions of oats and corn against storage pests. The natural resistance of cereals is an important element of their safe storage, and therefore, further research is required on this subject.

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References

- Food and Agriculture Organization of the United Nations World Food Situation. Available online: <https://www.fao.org/home/en> (accessed on 10 January 2024).
- Miladinov, G. Impacts of Population Growth and Economic Development on Food Security in Low-Income and Middle-Income Countries. *Front. Hum. Dyn.* **2023**, *5*, 1121662. [\[CrossRef\]](#)
- Galanakis, C.M. The Future of Food. *Foods* **2024**, *13*, 506. [\[CrossRef\]](#)
- Pretty, J. Intensification for Redesigned and Sustainable Agricultural Systems. *Science* **2018**, *362*, eaav0294. [\[CrossRef\]](#)
- Kopittke, P.M.; Menzies, N.W.; Wang, P.; McKenna, B.A.; Lombi, E. Soil and the Intensification of Agriculture for Global Food Security. *Environ. Int.* **2019**, *132*, 105078. [\[CrossRef\]](#) [\[PubMed\]](#)
- Beltran-Pea, A.; Rosa, L.; D'Odorico, P. Global Food Self-Sufficiency in the 21st Century under Sustainable Intensification of Agriculture. *Environ. Res. Lett.* **2020**, *15*, 095004. [\[CrossRef\]](#)
- Hodges, R.J.; Buzby, J.C.; Bennett, B. Postharvest Losses and Waste in Developed and Less Developed Countries: Opportunities to Improve Resource Use. *J. Agric. Sci.* **2011**, *149*, 37–45. [\[CrossRef\]](#)
- Wijerathna-Yapa, A.; Pathirana, R. Sustainable Agro-Food Systems for Addressing Climate Change and Food Security. *Agriculture* **2022**, *12*, 1554. [\[CrossRef\]](#)
- Canali, M.; Amani, P.; Aramyan, L.; Gheoldus, M.; Moates, G.; Östergren, K.; Silvennoinen, K.; Waldron, K.; Vittuari, M. Food Waste Drivers in Europe, from Identification to Possible Interventions. *Sustainability* **2016**, *9*, 37. [\[CrossRef\]](#)
- Łaba, S.; Cacak-Pietrzak, G.; Łaba, R.; Sulek, A.; Szczepański, K. Food Losses in Consumer Cereal Production in Poland in the Context of Food Security and Environmental Impact. *Agriculture* **2022**, *12*, 665. [\[CrossRef\]](#)
- Rayees, A.; Shafiya, H.; Showkat, A.; Syed, N.; Yendrambamb, D.; Kounser, J.; Salma, U.; Mohammad Javed, A.; Sait, E.; Barkat, H.; et al. Sustainability-Oriented Innovation in the Agri-Food System: Current Issues and the Road Ahead. *Technol. Forecast. Soc. Chang.* **2022**, *179*, 121653.
- Doukas, Y.E.; Salvati, L.; Vardopoulos, I. Unraveling the European Agricultural Policy Sustainable Development Trajectory. *Land* **2023**, *12*, 1749. [\[CrossRef\]](#)
- Cheba, K.; Bąk, I.; Szopik-Decpzyńska, K.; Ioppolo, G. Directions of Green Transformation of the European Union Countries. *Ecol. Indic.* **2022**, *136*, 108601. [\[CrossRef\]](#)
- Cheba, K.; Bąk, I.; Pietrzak, M.B. Conditions of the Green Transformation. The Case of the European Union. *Technol. Econ. Dev. Econ.* **2023**, *29*, 438–467. [\[CrossRef\]](#)
- Food and Agriculture Organization of the United Nations (FAO). *The State of Food Security and Nutrition in the World 2023*; International Fund for Agricultural Development: Rome, Italy, 2023; ISBN 9789251372265.
- FAO. *Food Loss and Food Waste: Causes and Solutions*; FAO: Rome, Italy, 2011; ISBN 9781788975391.
- Flanagan, K.; Robertson, K.; Hanson, C. *Reducing Food Loss and Waste: Setting a Global Action Agenda*; World Research Institute: Washington, DC, USA, 2019. [\[CrossRef\]](#)
- Scherhauser, S.; Moates, G.; Hartikainen, H.; Waldron, K.; Obersteiner, G. Environmental Impacts of Food Waste in Europe. *Waste Manag.* **2018**, *77*, 98–113. [\[CrossRef\]](#)
- Campoy-Muñoz, P.; Cardenete, M.A.; Delgado, M.D.C.; Sancho, F. Food Losses and Waste: A Needed Assessment for Future Policies. *Int. J. Environ. Res. Public Health* **2021**, *18*, 11586. [\[CrossRef\]](#) [\[PubMed\]](#)
- United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development. In *Arsenic Research and Global Sustainability—Proceedings of the 6th International Congress on Arsenic in the Environment, AS 2016, Stockholm, Sweden, 19–23 June 2016*; UN: New York, NY, USA, 2016; pp. 12–14. [\[CrossRef\]](#)
- 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. [\[CrossRef\]](#)
- Tufail, T.; Ul Ain, H.B.; Hussain, M.; Farooq, M.A.; Nayik, G.A.; Ansari, M.J. Cereals: An Overview. In *Cereal Grains: Composition, Nutritional Attributes, and Potential Applications*; CRC Press: Boca Raton, FL, USA, 2023; 336p, ISBN 9781000831849.
- Kumar, D.; Kalita, P. Reducing Postharvest Losses during Storage of Grain Crops to Strengthen Food Security in Developing Countries. *Foods* **2017**, *6*, 8. [\[CrossRef\]](#)
- Tadesse, M. Post-Harvest Loss of Stored Grain, Its Causes and Reduction Strategies. *Food Sci. Qual. Manag.* **2020**, *96*, 26–35. [\[CrossRef\]](#)
- Klejdzysz, T.; Ignatowicz, S.; Kubasik, W.; Gorzala, G.; Olejarski, P.; Horoszkiewicz, J.; Jajor, E.; Korbas, M.; Pruszyński, G.; Pruszyński, S.; et al. *Metodyka Integrowanej Ochrony Magazynów Zbożowych Dla Doradców [Methodology of Integrated Protection of Grain Storage for Advisers]*; Instytut Ochrony Roślin—Państwowy Instytut Badawczy: Poznań, Poland, 2017; ISBN 978-83-64655-31-9.
- Ahmad, R.; Hassan, S.; Ahmad, S.; Nighat, S.; Devi, Y.K.; Javeed, K.; Usmani, S.; Ansari, M.J.; Erturk, S.; Alkan, M.; et al. Stored Grain Pests and Current Advances for Their Management. In *Postharvest Technology—Recent Advances, New Perspectives and Applications*; IntechOpen: London, UK, 2021; pp. 1–37.
- 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. [\[CrossRef\]](#)
- 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. [\[CrossRef\]](#)

29. Alldrick, A.J. Chemical Safety of Cereal-Based Foods: Risk Management Considerations. *Qual. Assur. Saf. Crops Foods* **2014**, *6*, 3–14. [\[CrossRef\]](#)
30. Hamel, D.; Rozman, V.; Liška, A. Storage of Cereals in Warehouses with or without Pesticides. *Insects* **2020**, *11*, 846. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Tudi, M.; Ruan, H.D.; Wang, L.; Lyu, J.; Sadler, R.; Connell, D.; Chu, C.; Phung, D.T. Agriculture Development, Pesticide Application and Its Impact on the Environment. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1112. [\[CrossRef\]](#)
32. Cooper, J.; Dobson, H. The Benefits of Pesticides to Mankind and the Environment. *Crop Prot.* **2007**, *26*, 1337–1348. [\[CrossRef\]](#)
33. Kordan, B.; Żuk-Golaszewska, K.; Nietupski, M.; Słomka, W. Żyto Mieszańcowe Jako Siedlisko Rozwoju Wołka Zbożowego (*Sitophilus granarius* L.) i Kapturnika Zbożowca (*Rhyzopertha dominica* F.). *Prog. Plant Prot./Postępy Ochr. Roślin* **2009**, *49*, 4.
34. Mebarkia, A.; Guechi, A.; Mekhalif, S.; Makhoul, 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. [\[CrossRef\]](#)
35. Nietupski, M.; Bujak, E.; Kordan, B. Development of the Lesser Grain Borer (*Rhyzopertha dominica* F.) on Malt Barley and Fodder Barley Grain. *Prog. Plant Prot.* **2013**, *53*, 59–63. [\[CrossRef\]](#)
36. Ludwiczak, E.; Nietupski, M.; Laszczak-Dawid, A.; Gabryś, B.; Kordan, B.; Purwin, C. Influence of Chemical Composition and Degree of Fragmentation of Millet Grain on Confused Flour Beetle (*Tribolium confusum* Duv.) Infestation. *Agriculture* **2023**, *13*, 2178. [\[CrossRef\]](#)
37. Kordan, B.; Nietupski, M.; Ludwiczak, E.; Gabryś, B.; Cabaj, R. Selected Cultivar-Specific Parameters of Wheat Grain as Factors Influencing Intensity of Development of Grain Weevil *Sitophilus granarius* (L.). *Agriculture* **2023**, *13*, 1492. [\[CrossRef\]](#)
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. Gołębiowska, Z. The Feeding and Fecundity of *Sitophilus granarius* (L.), *Sitophilus oryzae* (L.), and *Rhyzopertha dominica* (F.) in Wheat Grain. *J. Stored Prod. Res.* **1969**, *5*, 143–155. [\[CrossRef\]](#)
40. PN-ISO 5983:2000; Animal Feeding Stuffs—Determination of Nitrogen Content and Calculation of Crude Protein Content—Kjeldahl Method. Polski Komitet Normalizacyjny: Warsaw, Poland, 2000.
41. PN-ISO 6492:2005; Animal Feeding Stuffs—Determination of Fat Content. Polski Komitet Normalizacyjny: Warsaw, Poland, 2005.
42. PN-R-64785:1994; Pasze—Oznaczanie Zawartości Skrobi Metodą Polarymetryczną. Polski Komitet Normalizacyjny: Warsaw, Poland, 1994.
43. PN-R-64784:1994; Feeds—Determination of Sugar Content. Polski Komitet Normalizacyjny: Warsaw, Poland, 1994.
44. Nucia, A. Białka Gluteninowe—Charakterystyka i Ich Wpływ Na Właściwości Reologiczne Pszenicy. Praca Przeglądowa. *Agron. Sci.* **2018**, *73*, 5–16. [\[CrossRef\]](#)
45. Wieser, H.; Kieffer, R. Correlations of the Amount of Gluten Protein Types to the Technological Properties of Wheat Flours Determined on a Micro-Scale. *J. Cereal Sci.* **2001**, *34*, 19–27. [\[CrossRef\]](#)
46. Osborne, T.B. *The Vegetable Proteins*, by Thomas B. Osborne; Longmans: London, UK, 1924; Volume 44. [\[CrossRef\]](#)
47. 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.
48. Chandrashekar, A.; Satyanarayana, K.V. Disease and Pest Resistance in Grains of Sorghum and Millets. *J. Cereal Sci.* **2006**, *44*, 287–304. [\[CrossRef\]](#)
49. 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. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Sheeba, T.; Bai, M.R. Feeding Preference and Reproductive Fitness of *Rhyzopertha dominica* (Fabricius, 1792) in a Choice-Based Feed Paradigm. *Indian J. Sci. Technol.* **2021**, *14*, 850–857. [\[CrossRef\]](#)
51. Edde, P.A. Corrigendum to “A Review of the Biology and Control of *Rhyzopertha dominica* (F.) the Lesser Grain Borer” [Journal of Stored Products Research 48 (2012) 1–18]. *J. Stored Prod. Res.* **2012**, *48*, 105. [\[CrossRef\]](#)
52. Perišić, V.; Perišić, V.; Vukajlović, F.; Pešić, S.; Predojević, D.; Đekić, V.; Luković, K. Feeding Preferences and Progeny Production of *Rhyzopertha dominica* (Fabricius 1792) (Coleoptera: Bostrichidae) in Small Grains. *Biol. Nyssana* **2018**, *9*, 55–61. [\[CrossRef\]](#)
53. Kordan, B.; Gabryś, B.; Załuski, D.; Zdunowski, K. Podatność Wybranych Gatunków Zbóż Na Żerowanie Trojszyka Ulca (*Tribolium confusum* DUV.). *Prog. Plant Prot./Postępy Ochr. Roślin* **2011**, *51*, 1559–1562.
54. Ajayi, E.O.; Oladipupo, S.O.; Ajisafe, O. Influence of Processing and Substrate Variety on Survival and Development of *Tribolium confusum* (Coleoptera: Tenebrionidae). *Arch. Phytopathol. Plant Prot.* **2019**, *52*, 356–370. [\[CrossRef\]](#)
55. Wong, N.; Lee, C.-Y. Relationship between Population Growth of the Red Flour Beetle *Tribolium Castaneum* and Protein and Carbohydrate Content in Flour and Starch. *J. Econ. Entomol.* **2011**, *104*, 2087–2094. [\[CrossRef\]](#)
56. Nemati-Kalkhoran, M.; Razmjou, J.; Borzoui, E.; Naseri, B. Comparison of Life Table Parameters and Digestive Physiology of *Rhyzopertha dominica* (Coleoptera: Bostrichidae) Fed on Various Barley Cultivars. *J. Insect Sci.* **2018**, *18*, 31. [\[CrossRef\]](#) [\[PubMed\]](#)
57. Hendrival, H.; Afriani, D.; Aryani, D.S. Susceptibility and Damage Cereals to Infestation *Rhyzopertha Dominica* (F.) (Coleoptera: Bostrichidae) in Storage. *J. Agro* **2019**, *6*, 57–65. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Mebarkia, A.; Rahbé, Y.; Guechi, A.; Bouras, A.; Makhoul, 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) Agricultural Experimental Station of the Field Crop Institute of Setif-Algeria. *Agric. Biol. J. N. Am.* **2010**, *1*, 571–578.

59. Piasecka-Kwiatkowska, D.; Gawlak, M.; Niewiada, A.; Nawrot, J.; Warchlewski, J.R.; Fornal, J.; Grundas, S. Wpływ Chemicznych Właściwości Ziarna Trzech Odmian Pszenicy Na Intensywność Zerwania i Tempo Rozwoju Populacji Wołka Zbożowego (*Sitophilus granarius* L.). *Prog. Plant Prot.* **2005**, *45*, 1688255.
60. Rajnincová, D.; Špaleková, A.; Gálová, Z.; Romanová, K. The Protein Profile of Cereals, Pseudocereals and Legumes. *J. Food Sci. Technol. Mysore* **2019**, *7*, 49–53.
61. Comino, I.; De Lourdes Moreno, M.; Real, A.; Rodríguez-Herrera, A.; Barro, F.; Sousa, C. The Gluten-Free Diet: Testing Alternative Cereals Tolerated by Celiac Patients. *Nutrients* **2013**, *5*, 4250–4268. [[CrossRef](#)]
62. Al-Toma, A.; Volta, U.; Auricchio, R.; Castillejo, G.; Sanders, D.S.; Cellier, C.; Mulder, C.J.; Lundin, K.E.A. European Society for the Study of Coeliac Disease (ESsCD) Guideline for Coeliac Disease and Other Gluten-Related Disorders. *United Eur. Gastroenterol. J.* **2019**, *7*, 583–613. [[CrossRef](#)]
63. Rosell, C.M.; Barro, F.; Sousa, C.; Mena, M.C. Cereals for Developing Gluten-Free Products and Analytical Tools for Gluten Detection. *J. Cereal Sci.* **2014**, *59*, 354–364. [[CrossRef](#)]
64. Bouchard, J.; Malalgoda, M.; Storsley, J.; Malunga, L.; Netticadan, T.; Thandapilly, S.J. Health Benefits of Cereal Grain-and Pulse-Derived Proteins. *Molecules* **2022**, *27*, 3746. [[CrossRef](#)] [[PubMed](#)]
65. Laskowski, W.; Górska-Warsewicz, H.; Rejman, K.; Czczotko, M.; Zwolińska, J. How Important Are Cereals and Cereal Products in the Average Polish Diet? *Nutrients* **2019**, *11*, 679. [[CrossRef](#)] [[PubMed](#)]
66. Urošević, D.; Knežević, D.; Branković, G.; Novoselskaya-Dragovich, A.Y.; Kudryavtsev, A.M.; Matković Stojšin, M.; Mićanović, D.; Zečević, V. Protein Content and Amino Acid Composition in Seed of Bread. *Orig. Sci. Artic. Protein* **2023**, *55*, 301–318.
67. Geirsdóttir, Ó.G.; Pajari, A.M. Protein—A Scoping Review for Nordic Nutrition Recommendations 2023. *Food Nutr. Res.* **2023**, *67*, 1–15. [[CrossRef](#)]
68. Cenni, S.; Sesenna, V.; Boiardi, G.; Casertano, M.; Russo, G.; Reginelli, A.; Esposito, S.; Strisciuglio, C. The Role of Gluten in Gastrointestinal Disorders: A Review. *Nutrients* **2023**, *15*, 1615. [[CrossRef](#)] [[PubMed](#)]
69. Union Commission Implementing Regulation (EU) No 828/2014 of 30 July 2014 on the Requirements for the Provision of Information to Consumers on the Absence or Reduced Presence of Gluten in Food Text with EEA Relevance. 2014. Available online: https://eur-lex.europa.eu/eli/reg_impl/2014/828/oj (accessed on 17 January 2024).
70. Astuti, L.P.; Rizali, A.; Firnanda, R.; Widjayanti, T. Physical and Chemical Properties of Flour Products Affect the Development of *Tribolium castaneum*. *J. Stored Prod. Res.* **2020**, *86*, 101555. [[CrossRef](#)]
71. Syed, M.I.S.; Chaudhary, F.K.; Prithiv, R.V.; Prabakaran, V. Role of Physico-Chemical Parameters in Stored Wheat for Resistance to *Rhyzopertha dominica* (Coleoptera: Bostrychidae) Role of Physico-Chemical Parameters in Stored Wheat for Resistance to *Rhyzopertha dominica*. *Environ. Ecol.* **2023**, *41*, 1235–1240.
72. Đukić, N.; Radonjić, A.; Popović, B.; Kljajić, P.; Pražič-Golić, M.; Andrić, G. The Impact of the Protein-Carbohydrate Ratio in Animal Feed and the Initial Insect Population Density on the Development of the Red Flour Beetle, *Tribolium castaneum*. *J. Stored Prod. Res.* **2022**, *97*, 101983. [[CrossRef](#)]
73. Nietupski, M.; Ciepielewska, D.; Fornal, Ł. Wpływ Źródnicowania Chemicznego Białek w Ziarnie Wybranych Odmian Pszenicy Na Rozwój Szkodników Magazynowych. *Prog. Plant Prot./Postępy Ochr. Roślin* **2006**, *46*, 420–423.
74. Kosewska, O.; Przemieniecki, S.W.; Koronkiewicz, S.; Nietupski, M. Effect of Different Chemical Properties of Cereal Grains on the Foraging and Microbiome of the Rice Weevil (*Sitophilus oryzae* L.). *Int. Agrophys.* **2024**, *38*, 165–176. [[CrossRef](#)]

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