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ORIGINAL ARTICLE

The chemical grain composition of wheat and barley affects the development of the lesser grain borer (*Rhyzopertha dominica* F.) and the rice weevil (*Sitophilus oryzae* L.)

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Abstract

The lesser grain borer (*Rhyzopertha dominica* F.) and the rice weevil (*Sitophilus oryzae* L.) are stored grain pests that cause significant economic losses in grain storage. This study aimed to analyze the impact of the chemical composition of wheat and barley grain (e.g., protein, fatty acids and total antioxidant capacity) on the development of two species of storage pests and to determine the relationship between the analyzed variables. The study involved the evaluation of 10 wheat cultivars and 10 barley cultivars under laboratory conditions. The observations included assessing the beetles' progeny abundance, dust mass produced after feeding, and grain mass loss. The chemical composition of the tested wheat and barley cultivars was also determined, and the influence of different chemical compositions on insect development was investigated. The results of the experiment revealed diversity of resistance among cultivars to pest feeding. Larger populations of the lesser grain borer were observed on barley grains, while rice weevil populations were higher on wheat. Cultivars with higher protein and fat content were more susceptible to pest attacks. A connection between the amount of dust, grain mass loss, and the type of pest was also identified, indicating differences in feeding mechanisms and selective food preferences of these insects. The grain chemistry of wheat cultivars, including the content of fatty acids and antioxidants, significantly influenced the progeny abundance of *S. oryzae*, suggesting the potential of these components as natural barriers against storage pests. This study provides valuable insights for developing breeding strategies to enhance the natural resistance of new grain cultivars to these pests, contributing to the reduction of pesticide use. Statistical analyses confirmed the significance of differences in grain composition in varied resistance to the studied pests. The conclusions drawn from this work may help establish new storage and breeding practices, promoting sustainable agriculture and protecting natural resources.

Keywords: barley, food security, storage pests, *Sitophilus oryzae*, *Rhyzopertha dominica,* wheat

Introduction

Due to the significant risk caused by storage pests, stored products should be effectively protected against their destructive impact. This is especially important because as the average temperature increases, the development of pests is much faster, and the losses are more significant (Warchalewski *et al.* 2000). According to FAO data, global grain losses amount to approximately 10%. Feeding of storage insect pests on grain may lead to weight loss, fungal growth and loss of quality associated with an increase in the content of free fatty acids (Trematerra 2009).

In Poland and around the world, the rice weevil (*Sitophilus oryzae* L.) and the lesser grain borer (*Rhyzopertha dominica* F.) are among the most harmful primary pests (Nowaczyk *et al.* 2008; Edde 2012; Hagstrum and Flinn 2014; Nietupski *et. al* 2017; Saad *et al.* 2018; Draz *et al.* 2021; Vianna *et al.* 2023). Significant differences in grain colonization mechanisms are observed between the species mentioned above, especially in the context of oviposition processes and food intake by larvae. Female weevils bite a small hole in the kernel, where they deposit eggs, and then secure this place, the so-called "cork" – a sticky substance that they mix with the grain's starch. However, female lesser grain borers lay eggs on the surface of the grain, and the hatching larvae penetrate its structure, continuing their development there. In the primary larval stages, *R. dominica* can feed on dust generated by adults. The larvae then bite into the grain, taking advantage of existing damage caused by adults or natural cracks and damage to the grain structure (Gołębiowska 1969; Nietupski 2020).

Non-chemical methods cannot provide sufficient protection against the feeding of storage pests, and it is necessary to use chemical agents. Unfortunately, this approach is contrary to consumer expectations and the assumptions of the European Green Deal, which strive to maintain food security with minimal impact on the natural environment (Dal Bello *et al.* 2000; Derbalah and Ahmed 2011; Klejdysz and Mrówczyński 2017). From this perspective, a strategic approach is to reduce pest populations by developing plant genetic resistance. It is worth noting, however, that so far most breeding programs have focused mainly on improving seed yield and quality without increasing plant resistance to storage pests (Keneni *et al.* 2011; Kordan *et al.* 2023).

The type of food stored is significant, and certain factors determine the vulnerability of specific cereal varieties to foraging by storage pests. The physical qualities of kernels, such as grain hardness, glassiness, and thickness of the seed cover, as well as biochemical factors, play crucial roles. Grains with lower nutritional value are less attractive, which reduce egg laying and feeding range (Nawrot *et al.* 2010). Insects prefer grains with higher protein content and are free of substances that limit their development (Perisic *et al.* 2018). The development of storage pests, such as the rice weevil, may be influenced by the variety and amount of sugars contained in the product (Chippendale 1972). According to research conducted by Majd-Marani *et al.* (2023), the content of phenols and lipids in their food also significantly impacts the development of these pests. The analysis of the influence of the content of fatty acids in grain on the development of insects suggests that the presence of fats in cereal plants also plays a crucial role in shaping the storage stability of cereal products and may influence the feeding behavior of storage pests (Liu 2011).

This research aimed to gain a deeper understanding of the mechanisms of cereal resistance, focusing on a detailed study of the effects of individual grain chemical components on the development of storage pests: *R. dominica* and *S. oryzae*. It also aimed to develop innovative preventive methods against pest feeding in cereal stores, which are based on knowledge of the chemical composition of the grain. The study results can be used to develop new cereal cultivars with naturally enhanced pest resistance. Focusing on the ecological aspects of pest control, this study proposed alternatives to the use of pesticides, contributing to the development of sustainable agriculture. Additionally, it sought to investigate the impact of changes in farming and storage practices on reducing pest losses, which is important for agricultural efficiency and economics. With the objective of determining the influence of the chemical composition of wheat and barley grain on the development of the *R. dominica* and *S. oryzae*, specific research hypotheses were set:

– The specific biochemical composition of the grains, which includes, among other things, different protein, lipid, or carbohydrate contents, plays a crucial role in shaping the resistance of these grains to pest attacks. This hypothesis suggests that identifying specific biochemical components that enhance grain resistance or susceptibility will enable a deeper understanding of resistance mechanisms.

– Differences in grain chemical profiles affect feeding behavior, reproduction, and pest survival. Certain components may act as natural repellents, reducing pest foraging or attracting pests, increasing their abundance. This opens up the prospect of exploring the relationship between specific chemical components of grains and insect feeding preferences and survival strategies.

Materials and Methods

Materials

Entomological observations were conducted on grains of 10 wheat cultivars: Rotax, Kilimanjaro, Impresja, Lawina, Tybalt, Rusałka, Feeling, Varius, Telimena, and Mandaryna, as well as 10 barley cultivars: Radek, Ismena, Avatar, Flair, Trofeum, RGT Planet, Accordine, Amidala, KWS Dante, and RGT Baltic. The studied cultivars were categorized into functional types of grain, such as fodder and malting barley, and utility forms, such as spring and winter wheat. The examined grains originated from the Experimental Variety Assessment Station in Wrócikowo, Poland. These cultivars were chosen because they are commonly grown in northern Poland and have particular agronomic or quality characteristics that make them attractive to research. Individuals of the studied beetle species (*R. dominica* and *S. oryzae*) used in the experiment were obtained from mass breeding conducted in the Department of Entomology, Phytopathology, and Molecular Diagnostics at UWM in Olsztyn, where insect development is monitored, and the colony size is regulated. Young (1–2 days old) adult beetles were used for further experiments.

Experiment with different feed variants

In the experiment, the development of the lesser grain borer and the rice weevil on grains of selected cereal species was analyzed. The grains were conditioned in a breeding chamber for 7 days at 30°C and 80% RH and then sieved through a 1 mm mesh to separate the dust. In containers (with a ventilation hole) measuring 8 cm in diameter and 3 cm in height, 20 g of grain samples from each variety were placed. For each sample, 20 individuals of rice weevil or lesser grain borer were introduced at a sex ratio of 1:1. After 2 weeks, adult individuals were removed from the containers, and monitoring for the presence of emerging young progeny of beetle individuals began. The experiment concluded when no beetles were observed on the material within 10 days. Subsequently, measurements were taken for the mass of dust produced after beetle feeding, and the loss of grain mass was determined (using a WPS 220/C/2 laboratory scale). The experiment was conducted in a Sanyo MLR-350H climatic chamber under optimal conditions for the studied species, i.e., 30°C, 80% RH (Gołębiowska *et al.* 1976). The study was conducted in 10 repetitions.

Chemical analyses of grain

Dry mass was determined using the drying method. Crude ash was determined by burning an air-dry sample. The Kjeldahl method determined the total protein content, following standard PN-ISO 5983.2000. Crude fat was extracted using a Soxhlet extractor, following standard PN-ISO 6492: 2005 procedures. The crude fiber was determined by the classic Henneberg-Stohmann method for determining the raw fiber content of feed following the PN–EN ISO 6865.2002 standard. The anthrone method determined water-soluble sugars – WSC (Thomas 1977). The antioxidant capacity of samples was determined according to the Benzie and Strain method (1996) with some modifications. Ascorbic acid was used as the standard, and distilled water was used as the blank control. An adequately diluted sample or standard (0.1 ml) was added to a mixture of 4.0 mL of FRAP reagent. The mixture was incubated for 10 min in the dark, and the absorbance was measured at 593 nm against a blank prepared using distilled water. To prepare the calibration curve, the standards of ascorbic acid were used in the range from 0.01 to 0.2 mg · ml^{-1}.

Statistical analysis

The results, describing the chemical composition of the examined barley and wheat cultivars, as well as parameters related to beetle development (the abundance of the progeny, the mass of produced dust, and the loss of grain mass), were subjected to a distribution assessment using the Shapiro-Wilk test. Data that did not follow a normal distribution (antioxidants, dry mass, ash, protein, fiber) underwent logarithmic transformation ($ln\ x$+1). To assess the significance of differences in the examined variables across combinations of used grain cultivars, a one-way analysis of variance (ANOVA) was applied. Groups with statistically non-differentiating average values of examined parameters related to pest development were labelled with the same letter index: a, b, c... (Tukey's HSD test). Depending on their chemical composition, differences between the studied species and forms of grains were presented using non-metric multidimensional scaling (NMDS), using Bray-Curtis's measure of similarity. A non-parametric ANOSIM test (Clarke 1993) was applied for statistical assessment of differences. Graphical evaluation of the relationship between the chemical composition of grain and the abundance of the pest's progeny was conducted using ordination techniques – RDA (Braak and Šmilauer 1998). Statistical calculations and their graphical interpretation were performed using Statistica 13.1, Canoco 4.51, and Past 2.01.

Results

Data on the number of progeny generation, the weight of dust produced and grain weight loss, and the chemical properties of the grains tested are shown in Table 1.

Based on the analysis of variance (ANOVA) results, significant differences in the development of *R. dominica* and *S. oryzae* were observed, which were related to various factors such as species, grain type, and cultivar. Significant differences were observed in the number of progeny individuals, grain mass loss and dust mass in the case of the studied species and varieties. Factors such as the type of barley grain for both tested pest species and wheat variety for *S. oryzae* and some chemical properties did not differ statistically (Table 2).

The highest number of progeny individuals of *R. dominica* was observed on barley grains (mean 99.92). Significantly fewer *R. dominica* individuals were recorded on wheat grains (mean 42.39). Analyzing the

Table 1. Comparison of development parameters of *Rhyzopertha dominica* and *Sitophilus oryzae* developing on selected cultivars of wheat and barley and grain composition characteristics of the cultivars used in the experiment

Combination		Progeny of beetles [pcs.]		Mass of dust [g]		Loss of grain mass [g]		Dry matter	Crude Ash	Total Protein	Crude fat	Crude fiber	WSC	Antioxidants*
		Rd	*So*	*Rd*	*So*	*Rd*	*So*	[%]	[%]	[%]	[%]	[%]	[%]	[%]
Wheat		42.39 a**	262.05 b	0.44 a	0.26 b	0.71 a	10.26 b	89.08 b	1.75 a	12.57 b	1.61 a	2.72 a	3.13	0.0217 a
Barley		99.92 b	132.06 a	1.03 b	0.21 a	1.74 b	5.83 a	88.94 a	2.16 b	11.79 a	1.79 b	4.63 b	3.33	0.1276 b
Wheat:	spring	28.70 a	259.87	0.32 a	0.24	0.55 a	12.16 b	89.05	1.78	13.26 b	1.66	2.75	3.38 b	0.0240 a
	winter	62.93 b	265.33	0.63 b	0.27	0.96 b	7.41 a	89.14	1.70	11.54 a	1.53	2.68	2.76 a	0.0183 a
Barley:	brewery	91.32	137.50	0.94	0.22	1.59	5.86	88.91	2.14	11.96	1.80	4.52	3.71 b	0.1190 a
	fodder	108.52	126.62	1.12	0.19	1.88	5.81	88.97	2.18	11.61	1.78	4.74	2.94 a	0.1362 b
Cultivar of wheat	Feeling	14.80 ab	226.50 a	0.16 ab	0.19 a	0.26 ab	12.47 b	89.22 f	1.75 bc	13.80 e	1.90 e	2.75 b	2.89 ab	0.0158 a
	Impresja	104.20 e	268.70 a	0.88 d	0.23 ab	1.43 d	3.23 a	89.35 g	1.75 bc	12.00 c	1.75 de	2.65 ab	2.59 a	0.0211 ab
	Kilimanjaro	48.40 d	255.20 a	0.67 cd	0.33 b	0.87 c	11.88 b	88.81 b	1.60 a	11.15 b	1.55 c	2.80 b	2.67 a	0.0136 a
	Lawina	65.60 de	236.70 a	0.60 cd	0.26 ab	1.00 c	3.06 a	89.37 g	1.75 bc	10.65 a	1.50 c	2.70 ab	2.87 ab	0.0199 a
	Mandaryna	22.60 ab	253.70 a	0.30 b	0.24 ab	0.82 c	12.22 b	89.19 f	1.70 b	12.45 d	1.50 c	2.55 a	3.09 b	0.0241 ab
	Rotax	33.50 b	300.70 a	0.36 b	0.27 ab	0.54 b	11.46 b	89.04 d	1.70 b	12.35 cd	1.30 a	2.55 a	2.90 ab	0.0185 a
	Rusałka	9.40 a	293.30 a	0.10 a	0.27 ab	0.21 a	11.72 b	89.09 de	1.75 bc	13.15 a	1.35 b	2.65 ab	4.51 d	0.0319 b
	Telimena	34.20 c	231.50 a	0.44 c	0.25 ab	0.65 b	12.44 b	89.11 e	1.85 c	14.95 f	1.75 de	2.75 b	3.10 b	0.0236 ab
	Tybalt	36.00 c	275.50 a	0.38 b	0.29 ab	0.56 b	11.77 b	88.97 c	1.60 a	11.15 b	1.70 d	2.65 ab	3.37 c	0.0169 a
	Varius	55.20 de	278.70 a	0.52 c	0.22 ab	0.80 bc	12.35 b	88.71 a	2.00 d	14.05 e	1.75 de	3.15 c	3.35 c	0.0317 b
Cultivar of barley	Accordine	50.70 bc	193.10 de	0.55 ab	0.34 d	0.95 ab	12.26 d	88.43 a	2.20 bc	12.30 cd	1.95 d	4.60 cd	3.71 d	0.0748 a
	Amidala	112.80 d	105.10 bc	1.21 bc	0.19 b	2.05 bc	1.70 bc	89.06 d	2.20 bc	12.20 c	1.75 c	5.15 f	3.68 d	0.1283 bc
	Avatar	114.60 d	96.30 b	1.24 bc	0.14 ab	2.11 c	1.56 bc	89.05 d	1.95 a	12.55 d	1.45 a	4.35 c	3.24 c	0.1077 ab
	Flair	140.40 d	82.30 ab	1.44 c	0.13 ab	2.55 c	1.31 b	89.05 d	2.30 d	12.25 cd	1.60 b	4.95 ef	3.67 d	0.1189 b
	Ismena	105.50 c	154.60 d	1.19 b	0.28 cd	1.86 b	12.70 d	89.09 d	2.25 c	10.30 a	2.20 e	4.55 cd	2.74 b	0.1658 c
	KWS Dante	126.50 d	64.80 a	1.47 c	0.09 a	2.38 c	0.96 a	89.14 e	2.15 b	10.30 a	1.80 cd	5.00 ef	3.62 d	0.1395 bc
	Radek	16.80 a	216.50 e	0.28 a	0.25 c	0.43 a	12.19 d	88.83 c	2.20 bc	10.60 b	1.90 d	4.85 d	2.30 a	0.1473 bc
	RGT Baltic	147.00 d	137.90 c	1.21 bc	0.19 b	2.16 c	2.00 c	89.36 f	2.20 bc	12.50 cd	1.85 cd	3.80 a	3.92 d	0.1416 bc
	RGT Planet	19.60 b	186.60 de	0.27 a	0.30 d	0.43 a	12.36 d	88.55 b	1.95 a	12.50 cd	1.65 b	4.05 b	3.61 d	0.1109 ab
	Trofeum	165.30 d	83.40 ab	1.45 c	0.14 ab	2.47 c	1.27 ab	88.85 c	2.20 bc	12.35 cd	1.75 c	5.00 ef	2.78 b	0.1413 bc

So – *Sitophilus oryzae*, *Rd* – *Rhyzopertha dominica*, * – concentration of antioxidants in ascorbic acid equivalents, ** – means in columns followed by the same letter do not differ (Tukey's HSD test)

Table 2. Results of statistical analysis (ANOVA) for *Rhyzopertha dominica* and *Sitophilus oryzae* development parameters and selected chemical properties of the tested grains

	df		ANOVA F Value		*p**	
	Development parameters of *R. dominica* and *S. oryze* on species of grain: wheat and barley					
	Rd	*So*	*Rd*	*So*	*Rd*	*So*
Progeny of beetles	1	1	31.04	165.14	0.00	0.00
Loss of grain mass	1	1	57.48	60.61	0.00	0.00
Mass of dust	1	1	49.16	13.50	0.00	0.00
	Developmental parameters of *R. dominica* and *S. oryze* on wheat grain type					
	Rd	*So*	*Rd*	*So*	*Rd*	*So*
Progeny of beetles	1	1	21.55	0.07	0.00	0.79
Loss of grain mass	1	1	16.33	61.52	0.00	0.00
Mass of dust	1	1	20.39	2.83	0.00	0.10
	Developmental parameters of *R. dominica* and *S. oryze* on barley grain type					
	Rd	*So*	*Rd*	*So*	*Rd*	*So*
Progeny of beetles	1	1	0.49	0.47	0.49	0.50
Loss of grain mass	1	1	1.26	0.03	0.26	0.87
Mass of dust	1	1	1.33	2.19	0.25	0.14
	Developmental parameters of *R. dominica* and *S. oryze* on cultivars of wheat					
	Rd	*So*	*Rd*	*So*	*Rd*	*So*
Progeny of beetles	9	9	9.78	1.19	0.00	0.31
Loss of grain mass	9	9	7.64	197.47	0.00	0.00
Mass of dust	9	9	6.19	1.81	0.00	0.08
	Developmental parameters of *R. dominica* and *S. oryze* on cultivars of barley					
	Rd	*So*	*Rd*	*So*	*Rd*	*So*
Progeny of beetles	9	9	17.65	19.06	0.00	0.00
Loss of grain mass	9	9	11.78	329.09	0.00	0.00
Mass of dust	9	9	8.59	14.46	0.00	0.00
	Differences in selected chemical properties between species of grain					
Dry matter	1		5.42		0.02	
Crude ash	1		189.1		0.00	
Total Protein	1		6.31		0.02	
Crude fat	1		12.98		0.00	
Crude fibre	1		600.23		0.00	
WSC	1		1.95		0.17	
Antioxidants	1		539.90		0.00	
	Differences in selected chemical properties between cultivars of grain					
	wheat	barley	wheat	barley	wheat	barley
Dry matter	9	9	290.06	345.71	0.00	0.00
Crude ash	9	9	32.17	40.58	0.00	0.00
Total Protein	9	9	314.08	242.15	0.00	0.00
Crude fat	9	9	35.10	51.20	0.00	0.00
Crude fibre	9	9	20.30	81.54	0.00	0.00
WSC	9	9	52.36	61.64	0.00	0.00
Antioxidants	9	9	7.57	8.52	0.00	0.00

Table 2. Results of statistical analysis (ANOVA) for *Rhyzopertha dominica* and *Sitophilus oryzae* development parameters and selected chemical properties of the tested grains – *continuation*

	df		ANOVA F Value		*p**	
	Differences in selected chemical properties among types of cereal grains					
	wheat	barley	wheat	barley	wheat	barley
Dry matter	3	3	1.53	0.46	0.23	0.51
Crude ash	3	3	3.16	0.81	0.09	0.38
Total Protein	3	3	18.45	1.03	0.00	0.32
Crude fat	3	3	3.72	0.07	0.06	0.79
Crude fibre	3	3	1.29	2.21	0.27	0.15
WSC	3	3	14.37	32.75	0.00	0.00
Antioxidants	3		196.33		0.00	

*the value of the test probability *p*, So – *Sitophilus oryzae*, *Rd* – *Rhyzopertha dominica*

individual types and utility forms of the studied grains, fodder type barley exhibited the highest average abundance of *R. dominica* beetles (mean 108.52), while the lowest was found in spring wheat (mean 108.52). Examining individual cultivars, the wheat cv. Impresja proved to be the most favorable for the development of *R. dominica* progeny (mean 104.20) and for barley, the cv. Trofeum (mean 165.30) showed the highest average abundance. The cultivars were among those where the lesser grain borer produced the least numerous progeny, belonged cv. Rusałka wheat (mean 9.40) and cv. Radek barley (mean 16.80). Similarly, the mass of produced dust by feeding *R. dominica* beetles followed a similar pattern. The cultivars of barley, KWS Dante (1.47 g), Flair (1.44 g), and Trofeum (1.45 g), and the wheat cultivar Impresja (0.88 g) were among those where the pest generated the highest amounts of dust. In combination with wheat cultivars, significantly less dust was recorded. The lowest values among the tested variants were observed in the wheat cv. Rusałka (0.10 g) and Feeling (0.16 g). In the barley cultivars, the lowest amount of dust was noted for cv. RGT Planet (0.27 g). Similarly, results were obtained concerning the loss of grain mass; cultivars characterized by higher amounts of produced dust also showed a greater loss in grain mass (Table 1).

More rice weevil progeny individuals were observed on wheat grains (mean 262.05) than on barley grains (mean 132.06). Analyzing the individual types and utility forms of the studied grains, winter wheat exhibited the highest average abundance of *S. oryzae* beetles (mean 265.33), while the lowest was found in fodder-type barley (mean 126.62). The most numerous progeny among the studied wheat cultivars were recorded in Rotax cv. (mean 300.70), and the least numerous in Feeling cv. (mean 226.50). However, the studied wheat cultivars exhibited a similar abundance of *S. oryzae* progeny (the same homogeneous group). The pest formed fewer progeny on the examined barley cultivars, and the cultivar factor differentiated this development. The cultivar where *S. oryzae* formed the fewest progeny was the KWS Dante cv. (mean 64.80), and the most numerous was the Radek cv. (mean 216.50). Among the barley cultivars, cv. Accordine (0.34 g) and RGT Planet (0.30 g), along with the wheat cv. Kilimanjaro (0.33 g) the pest generated the greatest amount of dust. Minor dust, produced by all tested grain cultivars, was observed in the barley cv. KWS Dante (0.09 g), and in wheat, the Feeling cv. (0.19 g). Grain mass loss was higher for the studied wheat cultivars, as was the case with the abundance of the progeny (Table 1).

Analyzing the values of selected physicochemical parameters of wheat and barley grains, it was observed that a higher average content of crude ash, crude fat, crude fiber, WSC' and antioxidants characterized barley. Wheat, on the other hand, had higher protein and dry matter contents. Among all the tested varieties, the Telimena wheat cv. was characterized by the highest protein content (14.95%), the KWS Dante barley cv. had the highest crude fat content (2.20%), and the Amidala barley cv. had the highest crude fiber content (5.15%) (Table 1).

To confirm the similarity of selected wheat cultivars in terms of utility forms, fat content, and antioxidants, non-metric multidimensional scaling (NMDS) analysis was employed. The NMDS plot (Fig. 1A) illustrates the graphical division of wheat and barley cultivars into four groups, separated from each other on the ordination plot, reflecting their diversity in terms of the investigated chemical traits of the grain. In the context of the analysis of fatty acid and antioxidant contents, clear differences were observed in their concentrations among the examined grains. The antioxidant

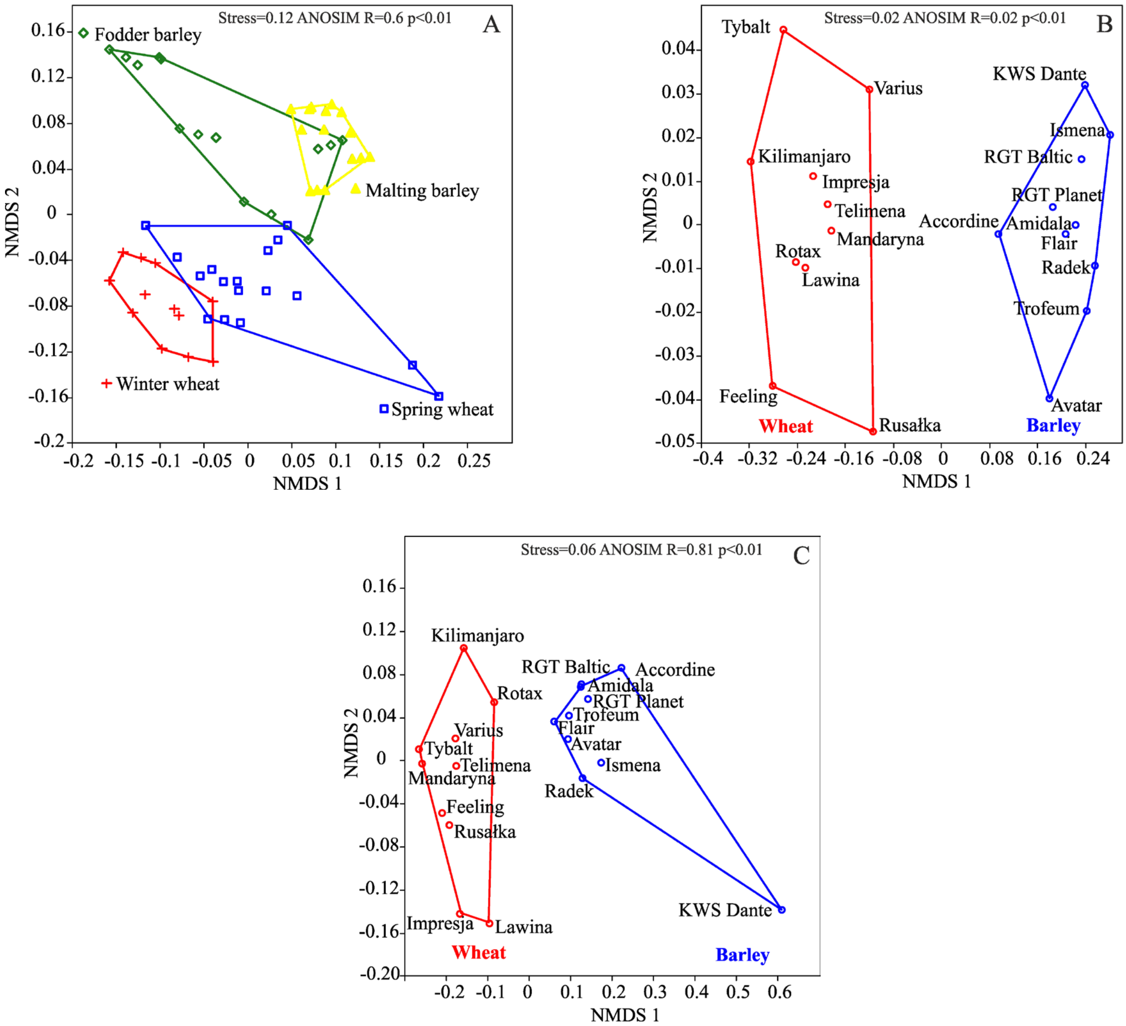

Fig. 1. NMDS diagram describing the similarity of the tested barley and wheat cultivars in terms of forms and types of grain (A), fatty acid content (B), antioxidant content (C)

content in wheat and barley cultivars was significantly different, as graphically presented in the NMDS plot (Fig. 1B). Similarly, the fat content analysis in wheat and barley cultivars was significantly different, as graphically depicted in the NMDS plot (Fig. 1C).

The grains of wheat and barley, on which the studied species of storage pests developed, were also subjected to an assessment of the fatty acid (FA) content. A total of 13 substances with different carbon chain lengths was found. The isolated fatty acids belonged to the group of saturated fatty acids (SFA) – 7 acids and unsaturated fatty acids (UFA) – 6 acids. The latter group included monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA). The most abundant fatty acids were C 18 : 2, C 16 : 0 and C 18 : 1. Their high content was found in KWS Dante cv. barley (C 16 : 0, C 18 : 1) and Mandaryna cv. and Tybalt cv. wheat (C 18 : 2). The grains with the the lowest fatty acid content belonged to the groups C 12 : 0 and C 17 : 1. The largest amounts of C 12 : 0 and C 17 : 1 were found in the grain of wheat cultivars Feeling, Varius, Telimena (C 12 : 0) and barley cultivar Ismena (C 17 : 1). The remaining cultivars were characterized by a content lower than 0.06 for C 12 : 0 and 0.28 for C 17 : 1 (Table 3).

To accurately determine the correlation between the chemical composition of the examined grains and the development of *R. dominica* and *S. oryzae*, redundancy analysis (RDA) was used. Based on the redundancy analysis results (Fig. 2A), a strong correlation was observed between the variables, namely the abundance of *S. oryzae* progeny and the first ordination axis. This factor was positively correlated with the fatty acid content in the grains while negatively correlated with the soluble carbohydrate content (WSC). On the other hand, high protein content correlated with the vector describing the progeny of *R. dominica*. For wheat varieties (Fig. 2B), the first ordination axis was correlated with the abundance of *R. dominica* progeny, a parameter also correlated with high fiber content. The second ordination axis was, however, correlated with the progeny abundance of *S. oryzae*

Table 3. The mean content of fatty acids in tested grain cultivars (in % of the sum of fatty acids)

Species and utility type	Cultivar	Fatty Acid												
		lauric acid	myristic acid	pentadeca- noic acid	palmitic acid	palmitoleic acid	margaric acid	margaroleic acid	stearic acid	oleic acid	inoleic acid	α-linoleic acid	araquinic acid	godoleic acid
		C12:0	C14:0	C15:0	C16:0	C16:1	C17:0	C17:1	C18:0	C18:1 c9	C18:2	C18:3	C20:0	C20:1
Winter wheat	Rotax	0.02	0.18	0.15	21.25	0.16	0.12	0.14	1.97	12.95	57.24	4.84	0.22	0.77
	Kilimanjaro	0.01	0.20	0.27	19.75	0.15	0.20	0.18	4.06	12.41	57.62	4.23	0.23	0.70
	Impresja	0.03	0.19	0.19	18.79	0.16	0.19	0.16	2.59	17.35	56.10	3.31	0.22	0.71
	Lawina	0.02	0.22	0.26	18.78	0.21	0.21	0.19	4.28	15.44	55.27	3.76	0.29	1.07
	Tybalt	0.02	0.15	0.13	17.34	0.16	0.13	0.14	1.67	14.66	60.27	4.50	0.17	0.67
Spring wheat	Rusałka	0.01	0.16	0.14	18.79	0.16	0.12	0.09	1.97	15.71	58.07	3.90	0.18	0.68
	Feeling	0.07	0.19	0.13	18.73	0.16	0.12	0.09	1.76	15.42	58.64	3.84	0.16	0.69
	Varius	0.06	0.18	0.18	18.55	0.16	0.14	0.10	2.24	13.57	58.96	4.96	0.19	0.71
	Telimena	0.06	0.18	0.13	19.72	0.14	0.13	0.11	1.81	14.29	58.58	4.01	0.19	0.65
	Mandaryna	0.02	0.13	0.12	17.95	0.17	0.11	0.09	1.54	14.56	60.30	4.17	0.14	0.68
Fodder spring barley	Radek	0.03	0.29	0.20	23.23	0.22	0.13	0.13	3.13	13.94	51.80	5.71	0.27	0.91
	Ismena	0.02	0.34	0.17	24.24	0.14	0.12	0.29	2.52	14.31	50.69	5.93	0.27	0.96
	Avatar	0.03	0.33	0.14	23.89	0.12	0.13	0.12	2.52	14.26	52.69	4.59	0.31	0.87
	Flair	0.02	0.42	0.18	23.38	0.12	0.12	0.11	2.11	13.64	53.83	4.77	0.33	0.95
	Trofeum	0.02	0.32	0.15	23.95	0.11	0.12	0.08	2.39	13.48	53.05	5.08	0.30	0.95
Brewery spring barley	RGT Planet	0.03	0.36	0.18	24.63	0.12	0.12	0.09	2.73	12.77	52.21	5.54	0.28	0.94
	Accordine	0.03	0.38	0.18	26.66	0.13	0.10	0.11	2.68	13.27	50.14	4.99	0.31	1.04
	Amidala	0.02	0.33	0.15	24.89	0.11	0.10	0.09	2.36	13.05	52.68	4.96	0.31	0.95
	KWS Dante	0.02	0.47	0.17	32.32	0.15	0.10	0.11	2.63	16.77	42.56	3.19	0.39	1.14
	RGT Baltic	0.01	0.33	0.13	25.00	0.12	0.10	0.08	2.11	13.29	52.63	5.01	0.29	0.92

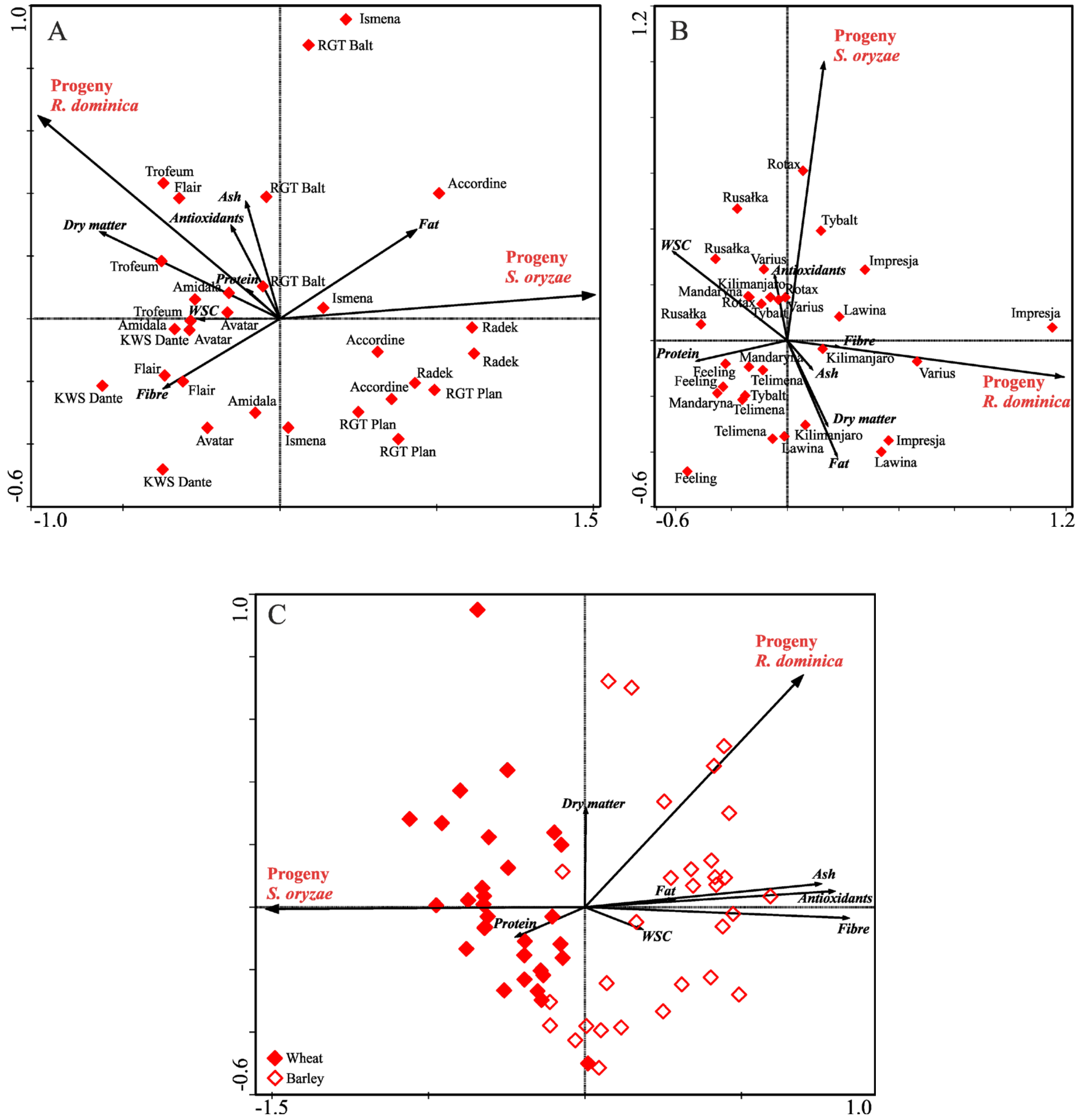

Fig. 2. RDA diagram presenting the relationship between the tested parameters related to the development of *R. dominica* and *S. oryzae* and the content of chemical components in the used varieties of barley grain (A), wheat (B) or both tested grain species (C) (the red rhomboids in Figure A indicate the barley cultivars tested and in Figure B, the wheat)

(Fig. 2B). The chemical composition of barley and wheat was also assessed according to factors describing the intensity of the development of the studied species of storage pests (Fig. 2C). The progeny abundance of *R. dominica* was strongly correlated with barley grain. In contrast to *R. dominica*, progeny of *S. oryzae* was correlated with wheat grain. An increase in the progeny abundance of *S. oryzae* was correlated with the rising protein content in the examined wheat cultivars.

Discussion

Rhyzopertha dominica and *S. oryzae* exhibited significant variability in their reproductive and feeding habits (Howe 1952; Baker 1988; Kłyś 2006; Edde 2012). In this study, we collected data that confirmed the better growth of *R. dominica* on barley cultivars, while *S. oryzae* showed better development on the wheat-tested cultivars (Fig. 2C). Food is a crucial biotic factor influencing the development of storage insect pests. The chemical composition of the tested wheat and barley grains differed (Table 1), which may be a factor in luring and repelling insects (Kordan *et al.* 2023). The analysis of variance (ANOVA) showed significant differences in the development of *R. dominica* and *S. oryzae* (Table 2). In the case of progeny development, the observed significant differences between the examined species and varieties of wheat and barley grains emphasize the influence of biological factors on the development of storage pests. The loss of grain mass and the amount of dust produced also differed significantly, which indicates the comprehensive impact of the factors studied on the harmful effects of feeding by storage insects. In the analysis of the chemical properties of grains, significant differences were found between cereal species and cultivars, the exception being the WSC content between the tested cereal species. This highlights chemical diversity as an important factor influencing interactions between storage pests and their environment.

The results of the study by Nietupski *et al.* (2021) suggest that the intensity of development in *S. granarius* is significantly correlated with a higher content of both saturated and unsaturated fatty acids in the grain. In a study conducted by Duarte *et al*. (2021) on *Tribolium castaneum*, it was shown that the fatty acid composition of the different developmental stages of this insect shows significant differences, which may indicate the complex influence of these components on their life cycle. It was also shown that saturated and unsaturated fatty acids play a significant role in developing cereal storage pests such as *R. dominica* and *S. oryzae*. Kerbel *et al.* (2024) showed that olive pomace oils, rich in various fatty acids, have activity against these pests. This indicates that the fatty acid composition of the diet of these beetles may directly affect their development. Xue *et al*. (2024), in a study on *R. dominica*, highlight the importance of regulating fatty acid synthase expression in pest adaptation to different temperature conditions. The implication is that biochemical mechanisms involved in fatty acid metabolism are important for pest survival in a changing environment. This research suggests that saturated and unsaturated fatty acids can influence various aspects of pest life, including their ability to adapt to their environment, their feeding preferences and even their resistance to control methods. As part of the research conducted by Kordan *et al.* (2019), it was noted that the content of fatty acids affects the basic life functions of *S. granarius*. It was shown that the survival of this insect was influenced by fatty acids such as C 18 : 1 and C 18 : 2. Similar relationships were observed during our experiment in the case of *S. oryzae*, which developed much better on wheat cultivars that were characterized by a higher content of C 18 : 2 fatty acid (Table 1, 3). The assessment of the relationship between the content of fatty acids and parameters describing the development of *S. oryzae* on barley grain was carried out based on RDA. This analysis showed a relationship between parameters describing the development of *S. oryzae* and the total content of fatty acids in the grain. In the case of *R. dominica*, the number of progeny individuals was strongly correlated with the protein content (Fig. 1A). The protein content in individual cultivars could significantly impact the development of the lesser grain borer. Protein is an important nutrient for insects, providing them with essential amino acids for growth. Gourgouta *et al.* (2024) indicate that a high protein content in the food can accelerate the development of insect larvae, with direct consequences for the rate of development of pest populations in cereal stores. Similarly, Bendjedid *et al.* (2024) noted that pest colonization of flour could significantly reduce its protein content, which affects the quality of the final product. Similar results to those in this study were obtained by Mariey *et al.* (2023), who investigated the effect of phenol addition on the development of *R. dominica* feeding on different barley cultivars. In the mentioned study, the authors observed that the feeding intensity of *R. dominica* was correlated with the total protein and carbohydrate content. Moreover, they also showed that the addition of phenol at a concentration of 0.4 g ai · kg^{-1} grains (“ai” indicates active ingredient) was toxic to *R. dominica.*

In research conducted by Majd-Marani *et al.* (2023), it was observed that the chemical composition of food plays an important role in shaping the development of insects, especially in the context of the content of phenols and lipids. Lipids in grains can affect their nutritional properties and the plants’ defense mechanisms against biotic and abiotic stresses, influencing their flavor and aroma (Rahman *et al.* 2023). Analysis of the life cycle of the rice weevil showed significant relationships between the developmental time, longevity, fecundity of insects and the amount of phenols in the consumed diet. An important observation in this study is the lower number of progeny individuals of *S. oryzae* on cereal cultivars characterized by higher antioxidant activity (Majd-Marani *et al*. 2023). Moreover, we confirmed that the lower number of *S. oryzae* progeny was caused by higher antioxidant activity (Table 1). The research of Sahu *et al.* (2021) provides information on the content and antioxidant activity of phenols in wheat, which is relevant in the context of our study. We can infer that the higher phenolic content of the wheat grains studied by Sahu *et al.* (2021) could potentially affect the development and population of storage pests, such as *S. oryzae*, through mechanisms similar to those described by Majd-Marani *et al.* (2023).

In the context of our research on the effects of grain chemistry on storage pests, the results of Lee *et al.* (2023), who described changes in phenolic metabolites in wheat at different growth stages, are relevant. These data complement our understanding of grain resistance mechanisms, which is crucial for pest management strategies. Phenols, which are important secondary metabolites in grains, can include a wide range of compounds, such as ferulic acid, p-coumaric acid and various flavonoids and tannins, which play a role in protecting plants from pests and diseases and in attracting insects (Al-Khayri *et al.* 2023).

In the case of the lesser grain borer, it was shown that the development of progeny on grains of various wheat cultivars is correlated with the fiber content (Fig. 1B), which may suggest that higher food hardness is not a problem for this insect. This may be because the original food source for this species was most likely wood and dried fruit (Jia *et al.* 2008). However, high hardness was a significant barrier to the development of *S. oryzae*, thus protecting the grain from significant infection by this insect. This is confirmed by the fact that the hardness and size of grains have a key impact on resistance to feeding by insect storage pests (Thakkar and Parikh *et al.* 2020; Bergvinson 2014).

Similar conclusions were reached by Nietupski *et al.* (2017), who, in their research on the influence of physicochemical properties of achenes of buckwheat cultivars on the development of *S. granarius* and *R. dominica*, found that increased fiber content may adversely affect the development of *S. granarius*. However, it showed a positive correlation (r = 0.89) with the number of progeny individuals of *R. dominica*. Also, Singh and Sharma (2021), in their study on the susceptibility of different wheat cultivars to *R. dominica* feeding, showed that the pest invasion of all cultivars had a positive correlation with the crude fiber content.

Conclusions

Rhyzopertha dominica and *S. oryzae* showed different development on the tested cereal varieties. The highest resistance to *R. dominica* feeding among the tested barley cultivars was shown by the Radek cultivar, while among the wheat cultivars, the highest resistance to *S. oryzae* feeding was shown by the Rusalka cultivar. It was seen that the tested wheat and barley cultivars differed chemically. These differences were related to the content of antioxidants, fatty acids and proteins, which may influence the intensity of pest development. The increase in the number of *S. oryzae* progeny was correlated with the increasing protein content in the tested wheat cultivars and the increasing content of fatty acids in the tested barley cultivars. The increase in the number of progeny of *R. dominica* was correlated with the increasing fiber content in the tested wheat cultivars and the increasing protein content in the tested barley cultivars. These results are important for understanding plant resistance mechanisms and developing effective pest control strategies in the context of breeding cultivars with increased natural resistance.

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