



The suitability of wheat grain and grain of three less common cereals as hosts for the rice weevil (*Sitophilus oryzae* [L.]) (Coleoptera: Curculionidae)

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ABSTRACT

The aim of the present study was to test the suitability of different grain commodities, i.e., common wheat (*Triticum aestivum*), millet (*Panicum miliaceum*), spelt (*Triticum aestivum* ssp. *spelta*), and buckwheat (*Fagopyrum esculentum*) as hosts for the rice weevil (*Sitophilus oryzae*). We monitored weevil mortality and progeny emergence. Two different amounts of grains (50 g and 100 g) were applied. The experimental units were stored at three temperatures (15, 20, and 25 °C) and at two relative humidities (RHs) (55 and 75%), for a total of six combinations. Mortality was assessed on the 7th, 14th and 21st days after exposure. After 56 days, we determined progeny emergence. We determined that weevil mortality was correlated to temperature, RH, grain commodity, grain quantity and exposure duration. In general, mortality counts were higher at lower grain quantities. The mortality and progeny emergence were highest in wheat grain, since wheat grain is the most suitable host. Progeny production (emergence) was highest at 25 °C. Only a few individuals emerged from buckwheat and millet.

1. Introduction

The rice weevil (*Sitophilus oryzae* [L.]) is an important polyphagous primary stored product insect that can cause damage to different grain commodities, such as wheat, maize, barley, sorghum and paddy rice (Bhandari et al., 2015; Athanassiou et al., 2017; Doherty et al., 2023; Majd-Marani et al., 2023). It has also been reported that the rice weevil can feed on various kinds of nuts and cereal-based products (Delobel and Grenier, 1993; Stejskal et al., 2004).

The rice weevil's preferences for wheat has been previously confirmed (Athanassiou et al., 2008; Mehta et al., 2021). Rice weevils can complete their life cycle in 39.1 days if reared on wheat (Devi et al., 2017). In such cases, females lay an egg directly into the cereal grain, and hatched larvae feed on the endosperm. Larvae and adults cause extensive damage by feeding outside and inside the grain (Majd-Marani et al., 2023).

Development and population increase of the rice weevil can be influenced by the host plant on which it was fed (Majd-Marani et al., 2023); therefore, further knowledge on the life cycle of this species is important for improving pest management programs. Majd-Marani et al. (2023) also reported studies on the resistance mechanisms of different cereal grains to *S. oryzae*. Therefore, grain physiochemical properties

such as grain size, grain hardness and moisture content are important factors determining the development of *S. oryzae* (Doherty et al., 2023; Majd-Marani et al., 2023).

Food security is an important goal, and plenty of research is focused on the provision of an adequate food supply. According to data from 2023 from the Slovenian Statistical Office (SiStat Database, 2023), wheat and spelt were produced on 27.564 ha of this country, millet was produced on 312 ha and buckwheat was produced on 4.430 ha. On the other hand, barley was produced on 22.546 ha, and wheat was produced on its own on 26.936 ha. Since insect species have been tested in Slovenian studies for several years (Rojht et al., 2010; Bohinc et al., 2020a), we wanted to study the mortality and progeny production of rice weevil on less common cereals.

In this study, we wanted to explore the suitability of different grains, namely, common wheat (*Triticum aestivum* L.), millet (*Panicum miliaceum* L.), spelt (*Triticum aestivum* L. ssp. *spelta* Thell.), and buckwheat (*Fagopyrum esculentum* Moench) as the host species for rice weevil adults and to obtain a detailed overview of the susceptibility to insect infestation of grains that are important for Slovenian production.

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2. Materials and methods

2.1. Insects

The adults of *S. oryzae* were reared in the Laboratory of Entomology, Chair of Phytomedicine, Agricultural Engineering, Field Crop Production, and Pasture and Grassland Management, located in the Biotechnical Faculty, in Ljubljana, Slovenia. The insects were originally obtained from the Pesticide and Environment Research Institute (Belgrade, Serbia) as part of a scientific cooperation between this Institute and the Biotechnical Faculty. Before being used in this experiment, the insects were maintained for 1.5 years at room temperature (22 ± 2 °C), with a RH of $55 \pm 5\%$ and continuously dark conditions, using wheat grains as their host.

2.2. Grain commodity and size

Different species of grains, namely common wheat (*Triticum aestivum*), millet (*Panicum miliaceum*), spelt (*Triticum aestivum* L. ssp. *spelta*), and buckwheat (*Fagopyrum esculentum*) were obtained from the Infrastructural Centre Jabolje of the Agricultural Institute of Slovenia, during the harvest season of 2022. Common wheat, millet, and buckwheat were used in the form of grains, but spelt was used in the form of spikelets. We also measured grain size (mm) by using a Motic SMZ-140 series stereomicroscope (supplier: MoticEurope, Spain). We first selected groups of 100 undamaged kernels in three replicates per grain variety and then performed measurements.

2.3. Bioassay procedure

The four different grain types (common wheat, millet, spelt, and buckwheat) in two different amounts (50 and 100 g) were used, creating a total of eight combinations, and nine repetitions were applied for each combination. The grains were weighed directly into 100 ml Erlenmeyer flasks, and then 30 adults of rice weevil were put into each flask. All adults were 2–4 weeks old, and their sex was undefined. The flasks were closed with a piece of breathable fabric to ensure the survivability of the weevils. The combinations were prepared six different times, and each combination was stored in different storage conditions. The six combinations of predetermined temperatures (15, 20, or 25 °C) and relative humidities (RHs) (55 or 75%) were used as the six experimental conditions. Weevil mortality was evaluated on the 7th, 14th and 21st days after exposure. The method used for this determination follows that of a similar experiment by Bohinc et al. (2018) and Bohinc et al. (2020b), with some adjustments and modifications.

2.4. Progeny test

On the 21st day, all the weevils were removed from the grains, and three experimental progeny test units were created from the nine experimental units of each treatment combination. The grains from three Erlenmeyer flasks were gathered into one glass jar, which was then closed with breathable fabric. The jars were stored for 8 weeks at room temperature (22 ± 2 °C) with RH of $55 \pm 5\%$ and continuously-dark conditions. After eight weeks, the number of emerging adult weevils was counted and evaluated. The method used for this progeny test follows that of a similar experiment by Bohinc et al. (2018), with some adjustments and modifications.

2.5. Data analysis

The mortality data are presented as the percentage of mortality and were then analysed by using repeated measures MANOVA. To present the mean mortality in different grains, mortality counts were analysed by using repeated measures MANOVA with grain quantity, grain commodity, and exposure duration as the repeated measures variables and

temperature and RH as the main effects. For the progeny test, the mean abundance of weevils was analysed by using repeated measures MANOVA with grain commodity, grain quantity as the repeated measures variable and temperature and RH as the main effects. The means for mortality counts (all bioassays) were separated by using the Tukey HSD test at the 5% level. The Statgraphics Centurion XVII (Statgraphics Centurion XVI, 2009) programme was used for the statistical analysis of the data. We calculated correlations using linear regression analysis ($y = kx + n$) between progeny emergence in all treatments and measurements of grain size in all types of grain (and repetitions). Calculations were made according to research published by Trdan et al. (2008).

3. Results

3.1. Mean mortality of rice weevil adults (general results)

All main effects and some interactions were significant, as presented in Table 1. In general, the mortality of rice weevil adults reached 10% when exposed to wheat grain. In the other three grain commodities, mortality did not reach 7%. When individuals were exposed to a lower grain quantity at 55% RH, less than 6.29% mortality was recorded in buckwheat, 7.8% in spelt, 5.2% in millet, and 4.8% in common wheat. At higher RH values and lower grain quantities, mortality was confirmed at 6.7% in buckwheat, 8.10% in spelt, 9.4% in millet and 16% in common wheat. When exposed to a higher grain quantity at 55% RH, 3.7% mortality of adults was confirmed in buckwheat, 5.24% in spelt, 5.96% in millet and 4.54% in wheat. At higher grain quantity and higher RH,

Table 1

Repeated measures ANOVA parameters for main effects and associated interactions for mortality level of *Sitophilus oryzae* adults (error df = 131).

Source	df	F	P
Source between variables			
All between	47	170.11	<0.05
Intercept	1	40.40	<0.05
Grain commodity	3	55.82	<0.05
RH	1	76.95	<0.05
Grain quantity	1	44.50	<0.05
Exposure duration	2	80.40	<0.05
Grain commodity x RH	3	88.98	<0.05
Grain commodity x grain quantity	3	3.38	<0.05
Grain commodity x exposure duration	6	1.47	0.1862
Grain commodity x RH x grain quantity	3	8.36	<0.05
Grain commodity x RH X exposure duration	6	3.74	<0.05
Grain commodity x grain quantity x exposure duration	6	0.59	0.7380
Grain commodity x RH X grain quantity x exposure duration	6	1.23	0.2899
RH x grain quantity	1	0.81	0.3678
RH x exposure duration	2	0.63	0.5349
RH x grain quantity x exposure duration	2	0.78	0.4601
Grain type x exposure duration	2	1.62	0.1992
Source within variables			
Within interactions	84	77.15	<0.05
Temperature	2	89.47	<0.05
Temperature x grain commodity	6	38.52	<0.05
Temperature x RH	2	142.17	<0.05
Temperature x grain quantity	2	14.40	<0.05
Temperature x exposure duration	4	10.57	<0.05
Temperature x grain commodity x RH	6	93.48	<0.05
Temperature x grain commodity x grain quantity	6	11.93	<0.05
Temperature x grain commodity x exposure duration	12	9.19	0.4513
Temperature x RH x grain quantity	2	15.65	<0.05
Temperature x RH x exposure duration	4	2.65	<0.05
Temperature x grain quantity x exposure duration	4	1.18	0.3167
Temperature x grain commodity x RH x grain quantity	6	11.68	<0.05
Temperature x grain commodity x RH x exposure duration	12	5.60	<0.05
Temperature x grain commodity x grain quantity x exposure duration	12	0.67	0.7789
Temperature x RH x grain quantity x exposure duration	4	0.50	0.7328

4.21% mortality of adults was recorded in buckwheat, 4.86% in spelt, 5.15% in millet and 14.03% in wheat.

When treatments were exposed to 15 °C, 10% adult mortality was recorded, while at 25 °C, the mortality of adults reached 5%. Seven days after exposure, less than 5% mortality of adults was recorded, while almost 8% mortality was recorded 14 days after exposure. After 21 days, almost 10% mortality of adults was confirmed.

3.2. Mean mortality of rice weevil adults at lower grain quantities

When adults were exposed to 55% RH and 15 °C, almost 25% mortality was recorded after day 21 in buckwheat, while mortality in wheat grains and millet did not reach 7%. Almost 12% mortality was recorded when weevils were exposed to spelt for three weeks.

When weevils were exposed to 20 °C and 55% RH for three weeks, almost 8% mortality was recorded in all grain commodities. In treatments exposed to 25 °C and 55% RH for three weeks, an average of 6% mortality was recorded in all grain commodities. All values are presented in Table 2.

On day 21 postapplication at 75% RH, 6% mortality of individuals was recorded at 15 °C when buckwheat was used. On the other hand, under the same conditions, more than 33% mortality was recorded when weevils were exposed to wheat grains. Less than 20% mortality was detected when individuals were exposed to wheat for three weeks at 20 °C and 75% RH. When individuals were exposed to wheat grains for three weeks at 25 °C, less than 5% mortality was recorded. Details are presented in Table 3.

3.3. Mean mortality of rice weevil adults at higher grain quantities

At 55% RH and all three temperatures, the mortality of individuals

Table 2
Mean mortality (±SE) of rice weevil adults exposed to 50 g of different grain types at 55% RH.

			buckwheat	spelt	millet	wheat
55% RH	15 °C	Day	4.44 ± 1.84	4.07 ±	3.33 ±	2.59 ±
		7	Ab	1.33 Aa	1.46 Aab	0.92 Aa
		Day	15.18 ± 3.14	15.18 ±	5.19 ±	3.71 ±
		14	Bb	2.72 Bb	1.67 Aa	1.03 Aa
		Day	18.27 ± 3.52	20.0 ±	5.26 ±	3.71 ±
		21	BCE	2.38 Bb	1.13 Aa	1.03 Aa
	20 °C	Day	2.22 ± 0.96	6.29 ±	2.59 ±	3.33 ±
		7	Ab	1.87 Ba	0.92 Aa	0.78 Aa
		Day	4.44 ± 1.24	7.03 ±	3.33 ±	4.44 ±
		14	ABa	1.79 Ba	1.24 Aa	0.96 ABab
		Day	7.62 ± 1.02	8.0 ±	7.18 ±	7.62 ±
		21	Ab	1.03 Ab	1.04 Aa	0.68 Ab
	25 °C	Day	0.74 ± 0.48	4.81 ±	5.18 ±	4.07 ±
		7	Aa	1.76 Ba	1.48 Bb	1.44 Ba
		Day	2.96 ± 1.29	8.52 ±	8.52 ±	6.29 ±
		14	Aa	2.29 Ba	2.23 Bb	1.51 Bb
		Day	4.75 ± 0.61	6.08 ±	5.77 ±	7.00 ±
		21	Aa	0.85 ABa	0.87 Aba	0.78 Bb

Between columns and within day of exposure, means followed by the same uppercase do not differ significantly by Tukey HSD test at $P = 0.05$. For comparison within columns, $df = 3,35$ (at 15 °C, for day 7, $F = 2.15$, $P = 0.06$; for day 14, $F = 17.17$, $P < 0.01$; for day 21, $F = 10.41$, $P < 0.01$ # at 20 °C, for day 7, $F = 7.65$, $P < 0.01$; for day 14, $F = 24.24$, $P < 0.01$; for day 21, $F = 9.15$, $P = 0.07$ # at 25 °C, for day 7, $F = 12.15$, $P < 0.01$; for day 14, $F = 3.19$, $P < 0.01$; for day 21, $F = 11.41$, $P < 0.01$).

Between each row and temperature, means followed by the same lowercase letter do not differ significantly by Tukey's HSD test at $P = 0.05$. For comparison within rows, $df = 2,26$ (in buckwheat, for day 7, $F = 12.50$, $P < 0.01$; for day 14, $F = 14.12$, $P < 0.01$; for day 21, $F = 13.58$, $P < 0.01$ # in spelt, for day 7, $F = 24.77$, $P < 0.01$; for day 14, $F = 0.12$, $P < 0.01$; for day 21, $F = 42.77$, $P < 0.01$ # in millet, for day 7, $F = 24.77$, $P < 0.01$; for day 14, $F = 11.12$, $P < 0.01$; for day 21, $F = 2.77$, $P = 0.07$ # in wheat, for day 7, $F = 4.12$, $P = 0.06$; for day 14, $F = 9.19$, $P = 0.075$; for day 21, $F = 2.77$, $P < 0.01$).

Table 3

Mean mortality (±SE) of rice weevil adults exposed to 50 g of different grain types at 75% RH.

			buckwheat	spelt	millet	wheat
75% RH	15 °C	Day	0.74 ± 0.50	3.33 ±	9.62 ±	16.67 ±
		7	Aa	1.36 Ba	2.38 Cb	2.99 Db
		Day	2.22 ± 0.96	7.40 ±	17.41 ±	32.96 ±
		14	Aa	2.06 Bb	2.34 Cc	3.39 Dc
		Day	5.59 ± 0.75	8.55 ±	21.15 ±	33.12 ±
		21	Aa	1.45 Aa	1.33 Bb	2.77 Cc
	20 °C	Day	11.85 ± 2.22	11.48 ±	10.37 ±	16.29 ±
		7	Ab	2.01 Ab	2.96 Ab	3.30 Ab
		Day	14.07 ± 2.60	12.96 ±	10.75 ±	18.89 ±
		14	Aba	1.95 Ac	3.08 Ab	3.73 Bb
		Day	19.48 ± 1.21	19.26 ±	11.74 ±	19.74 ±
		21	Bb	1.12 Bb	1.18 Aa	1.47 Bb
	25 °C	Day	0.74 ± 0.48	2.22 ±	1.11 ±	0.37 ±
		7	Aa	0.78 Ba	0.78 ABa	0.37 Aa
		Day	1.48 ± 0.58	3.33 ±	1.11 ±	1.85 ±
		14	Aa	1.11 Aa	0.78 Aa	0.58 Aa
		Day	4.22 ± 0.55	4.96 ±	4.07 ±	4.15 ±
		21	Aa	0.61 Aa	0.58 Aa	0.57 Aa

Between columns and within day of exposure, means followed by the same uppercase do not differ significantly by Tukey HSD test at $P = 0.05$. For comparison within columns, $df = 3,35$ (at 15 °C, for day 7, $F = 12.49$, $P < 0.01$; for day 14, $F = 11.12$, $P < 0.01$; for day 21, $F = 3.41$, $P < 0.01$ # at 20 °C, for day 7, $F = 14.19$, $P < 0.01$; for day 14, $F = 7.49$, $P < 0.01$; for day 21, $F = 7.15$, $P < 0.01$ # at 25 °C, for day 7, $F = 13.19$, $P < 0.01$; for day 14, $F = 19.33$, $P = 0.07$; for day 21, $F = 11$, $P = 0.11$).

Between each row and different temperatures, means followed by the same lowercase letter do not differ significantly by Tukey's HSD test at $P = 0.05$. For comparison within rows, $df = 2,26$ (in buckwheat, for day 7, $F = 13.10$, $P < 0.01$; for day 14, $F = 11.12$, $P < 0.01$; for day 21, $F = 17.90$, $P < 0.01$ # in spelt, for day 7, $F = 20.40$, $P < 0.01$; for day 14, $F = 13.11$, $P < 0.01$; for day 21, $F = 23.77$, $P < 0.01$ # in millet, for day 7, $F = 07.187$, $P < 0.01$; for day 14, $F = 11.12$, $P < 0.01$; for day 21, $F = 2.77$, $P < 0.01$ # in wheat, for day 7, $F = 20.12$, $P < 0.01$; for day 14, $F = 9.11$, $P < 0.01$; for day 21, $F = 9.77$, $P < 0.01$).

did not exceed 5% when all grain commodities were tested. Mortality counts were highest three weeks after exposure to 20 °C, when more than 7% mortality was recorded in all grain commodities. Details can be seen in Table 4. When individuals were exposed to 15 °C and 75% RH, mortality was highest in wheat grain, i.e., it was less than 2% on day 7, more than 43% on day 14 and more than 46% on day 21. On the other hand, mortality in millet ranged from 3% (day 7) to 6% (day 21), less than 1% (day 7) to 3% (day 21) in spelt and less than 1% (day 7) to 3% (day 14) in buckwheat. When individuals were exposed to 20 °C, mortality was the highest in spelt when exposed for three weeks. At 25 °C and 75% RH, mortality peaked at 6% after individuals were exposed to wheat grains for three weeks. Details are presented in Table 5.

3.4. Progeny production (general data)

According to Table 6, all main factors and their interactions have significantly influenced progeny production. A higher abundance of individuals was recorded at a higher grain quantity and at 25 °C. We also detected a significant influence of the higher RH on higher abundance. The mean number of newly emerged individuals was also the highest in wheat grain, and buckwheat and millet had the lowest mean number.

3.5. Progeny production in lower grain quantities

Regarding the mean number of weevils, these were significantly higher when treatments were based on wheat grain. The highest numbers were recorded at 25 °C, with almost 1600 individuals per 150 g of grain at 55% RH and almost 1200 individuals per 150 g of wheat grain at 75% RH. The lowest abundance of progeny occurred in buckwheat and millet. , This temperature was also the most suitable temperature for production when rice weevil adults were exposed to spelt (Table 7).

Table 4

Mean mortality ($\pm$ SE) of rice weevil adults exposed to 100 g of different grain types at 55% RH.

			buckwheat	spelt	millet	wheat
55% RH	15 °C	Day 7	1.85 $\pm$ 0.81	2.59 $\pm$	2.96 $\pm$	1.85 $\pm$
			Aab	0.74 Aa	1.29 Aa	0.58 Aa
		Day 14	4.07 $\pm$ 1.33	4.81 $\pm$	7.77 $\pm$	2.59 $\pm$
			Abb	0.97 Ba	1.82 Cb	0.74 Aa
	20 °C	Day 7	4.81 $\pm$ 1.40	4.07 $\pm$	5.92 $\pm$	3.77 $\pm$
			Aa	0.91 Bb	1.39 Aa	0.72 Aa
		Day 14	1.11 $\pm$ 0.55	4.07 $\pm$	3.71 $\pm$	0.74 $\pm$
			Aa	1.08 Bb	1.41 Ba	0.49 Aa
	25 °C	Day 7	1.48 $\pm$ 0.58	5.55 $\pm$	4.44 $\pm$	2.22 $\pm$
			Aa	1.46 Ba	1.36 Ba	0.78 Aa
		Day 14	7.03 $\pm$ 1.05	7.77 $\pm$	7.77 $\pm$	7.18 $\pm$
			Ab	1.02 Aa	1.03 Ab	1.04 Ab
	21	Day 7	3.333 $\pm$ 0.78	5.18 $\pm$	4.07 $\pm$	5.93 $\pm$
			Ab	1.49 Aa	0.92 Aa	1.21 Ab
		Day 14	4.81 $\pm$ 0.98	7.41 $\pm$	7.03 $\pm$	8.14 $\pm$
			Ab	1.33 Ba	1.17 Bb	1.25 Bb

Between columns and within day of exposure, means followed by the same uppercase do not differ significantly by Tukey HSD test at $P = 0.05$. For comparison within columns, $df = 3,35$ (at 15 °C, for day 7, $F = 22.49$, $P = 0.121$; for day 14, $F = 9.12$, $P < 0.01$; for day 21, $F = 3.41$, $P = 0.13$ # at 20 °C, for day 7, $F = 13.12$, $P < 0.01$; for day 14, $F = 12.01$, $P < 0.01$; for day 21, $F = 23.15$, $P = 0.06$ # at 25 °C, for day 7, $F = 13.19$, $P < 0.01$; for day 14, $F = 19.33$, $P < 0.01$; for day 21, $F = 11.32$, $P < 0.01$).

Between each row and different temperatures, means followed by the same lowercase letter do not differ significantly by Tukey's HSD test at $P = 0.05$. For comparison within rows, $df = 2,26$ (in buckwheat, for day 7, $F = 13.10$, $P < 0.01$; for day 14, $F = 11.12$, $P < 0.01$; for day 21, $F = 17.90$, $P < 0.01$ # in spelt, for day 7, $F = 13.40$, $P < 0.01$; for day 14, $F = 14.11$, $P < 0.01$; for day 21, $F = 6.77$, $P < 0.01$ # in millet, for day 7, $F = 12.43$, $P = 0.09$; for day 14, $F = 11.12$, $P < 0.01$; for day 21, $F = 12.24$, $P < 0.01$ # in wheat, for day 7, $F = 8.03$, $P < 0.01$; for day 14, $F = 9.11$, $P < 0.01$; for day 21, $F = 14.2$, $P < 0.01$).

3.6. Progeny production in higher grain quantities

Rice weevil adult abundance was the highest in treatments with wheat grain. At 25 °C and 55% RH, more than 1400 individuals were recorded; on the other hand, only 30 individuals were recorded in 300 g of grain at 15 °C and 55% RH. At 15 °C and 55% RH, fewer than 2 individuals were recorded in buckwheat and millet. When individuals were counted in spelt, the highest numbers were recorded at 25 °C at both RH values (Table 8).

3.7. Grain size and correlation between progeny emergence and grain size

According to our measurements, the less common grains in our research differ among themselves regarding size (in mm), with these being 10.56 ± 0.03 mm, 2.2 ± 0.02 mm, 5.47 ± 0.01 mm and 6.23 ± 0.01 mm for spelt, millet, buckwheat and wheat, respectively. The correlation between progeny emergence and grain size was $Y = -139.38 + 57.70 \times$ progeny, with a correlation coefficient of $r = 0.43$, which indicates a moderate correlation.

4. Discussion

Our study is based on testing the suitability of different grain commodities as host plants for *Sitophilus oryzae*.

As shown in previous studies (Bohinc et al., 2018; Bohinc et al., 2020a), we also identified a significant impact of temperature and relative humidity on the mortality and progeny production of individuals. Individuals in our study were not exposed to different inert powders (Eroglu et al., 2019; Bohinc et al., 2020a); therefore, we did not identify an impact of lower RH values on higher mortality. In our study, the highest difference in mortality percentage was recorded in wheat

Table 5

Mean mortality ($\pm$ SE) of rice weevil adults exposed to 100 g of different grain types within 75% RH.

			buckwheat	spelt	millet	wheat
75% RH	15 °C	Day 7	0.37 $\pm$ 0.37	0.74 $\pm$	2.96 $\pm$	1.85 $\pm$
			Aa	0.48 Aa	1.29 Aa	0.58 Aa
		Day 14	2.96 $\pm$ 1.70	2.96 $\pm$	5.55 $\pm$	43.33 $\pm$
			Aba	1.17 Aa	1.36 Ba	4.04 Cb
	20 °C	Day 7	2.96 $\pm$ 0.97	2.99 $\pm$	6.12 $\pm$	46.11 $\pm$
			Aa	0.77 Aa	0.25 Bb	6.20 Cb
		Day 14	6.26 $\pm$ 1.51	5.92 $\pm$	3.70 $\pm$	0.74 $\pm$
			Cb	1.21 BCb	1.41 Ba	0.49 Aa
	25 °C	Day 7	8.51 $\pm$ 1.93	9.62 $\pm$	6.27 $\pm$	8.15 $\pm$
			Ab	2.04 Ab	1.61 Aa	2.29 Aa
		Day 14	8.44 $\pm$ 1.06	10.17 $\pm$	8.0 $\pm$	8.29 $\pm$
			Ab	1.08 Ac	1.03 Ac	1.07 Aa
	21	Day 7	1.48 $\pm$ 0.81	2.59 $\pm$	4.07 $\pm$	5.92 $\pm$
			Aa	1.07 Aa	0.92 Aa	1.21 Ab
		Day 14	2.59 $\pm$ 0.92	4.07 $\pm$	4.85 $\pm$	5.92 $\pm$
			Aa	1.44 Aba	1.12 Ba	0.48 Ba

Between columns and within day of exposure, means followed by the same uppercase do not differ significantly by Tukey HSD test at $P = 0.05$. For comparison within columns, $df = 3,35$ (at 15 °C, for day 7, $F = 30.49$, $P = 0.15$; for day 14, $F = 3.12$, $P < 0.01$; for day 21, $F = 10.41$, $P < 0.01$ # at 20 °C, for day 7, $F = 16.12$, $P < 0.01$; for day 14, $F = 12.101$, $P = 0.074$; for day 21, $F = 23.15$, $P = 0.06$ # at 25 °C, for day 7, $F = 13.19$, $P = 0.055$; for day 14, $F = 7.33$, $P < 0.01$; for day 21, $F = 11.32$, $P < 0.01$).

Between each row and different temperatures, means followed by the same lowercase letter do not differ significantly according to Tukey's HSD test at $P = 0.05$. For comparison within rows, $df = 2,26$ (in buckwheat, for day 7, $F = 13.10$, $P < 0.01$; for day 14, $F = 11.12$, $P < 0.01$; for day 21, $F = 17.90$, $P < 0.01$ # in spelt, for day 7, $F = 13.40$, $P < 0.01$; for day 14, $F = 14.11$, $P < 0.01$; for day 21, $F = 6.77$, $P < 0.01$ # in millet, for day 7, $F = 12.43$, $P = 0.09$; for day 14, $F = 11.12$, $P < 0.01$; for day 21, $F = 12.24$, $P < 0.01$ # in wheat, for day 7, $F = 8.03$, $P < 0.01$; for day 14, $F = 9.11$, $P < 0.01$; for day 21, $F = 14.2$, $P < 0.01$).

Table 6

Repeated measures ANOVA parameters for main effects and associated interactions for abundance in progeny test of *Sitophilus oryzae* adults (error $df = 41$).

Source	df	F	P
Source between variables			
All between	15	145.11	<0.05
Intercept	1	189.78	<0.05
Grain commodity	3	233.59	<0.05
Grain quantity	1	31.62	<0.05
RH	1	120.15	<0.05
Grain commodity x RH	3	170.13	<0.05
Grain commodity x grain quantity	3	113.92	<0.05
Grain commodity x grain quantity x RH	3	99.13	<0.05
Source within variables			
Within interactions	26	89.74	<0.05
Temperature	2	45.07	<0.05
Temperature x grain commodity	6	77.77	<0.05
Temperature x grain quantity	2	61.13	<0.05
Temperature x RH	4	101.10	<0.05
Temperature x RH X grain commodity x grain quantity	12	88.78	<0.05

grain, being 5% at 55% RH and 16% at 75% RH. In other commodities, the mortality percentage differed less. Additionally, the highest progeny rates were recorded for wheat grain when exposed to 75%.

However, if fed on wheat rice, weevil adults can withstand RHs with values from 40 to 70%. Based on Lu et al. (2023), a lower humidity level can affect the activity of adult insects, as can also be seen in our study. A lack of internal water can cause death (Lu et al., 2023). According to Mason and McDonough (2012), rice weevils favour higher temperatures for their development, which was also confirmed in our study. Higher

Table 7

Mean abundance ($\pm$ SE) of *Sitophilus oryzae* adults in lower grain commodities (150 g).

Grain commodity	RH	T(°C)	Mean number ($\pm$ SE)
wheat	55	15	41.67 $\pm$ 5.78 D
		20	321.33 $\pm$ 35.68 D
		25	1566.33 $\pm$ 264.71 C
	75	15	1.0 $\pm$ 0.0 B
		20	591.67 $\pm$ 98.77 D
		25	1198.67 $\pm$ 83.33 D
buckwheat	55	15	1.33 $\pm$ 0.67 B
		20	9.33 $\pm$ 1.33 B
		25	15.33 $\pm$ 4.70 A
	75	15	2.67 $\pm$ 0.88 C
		20	22.33 $\pm$ 6.17 B
		25	22.00 $\pm$ 5.67 B
millet	55	15	0.0 $\pm$ 0.0 A
		20	1.00 $\pm$ 0.00 A
		25	11.67 $\pm$ 2.33 A
	75	15	0.00 $\pm$ 0.00 A
		20	2.00 $\pm$ 0.00 A
		25	14.67 $\pm$ 2.60 A
spelt	55	15	22.00 $\pm$ 4.04 C
		20	96.67 $\pm$ 25.98 C
		25	222.67 $\pm$ 48.07 B
	75	15	52.67 $\pm$ 9.94 D
		20	193.00 $\pm$ 37.22 C
		25	213.33 $\pm$ 18.95 C

Between grain commodities and RH values at the same temperature, means followed by the same uppercase do not differ significantly by Tukey's HSD test at $P = 0.05$. For comparison within rows ($df = 3,79$) (55% RH, at 15 °C, $F = 130.11$, $P < 0.05$; at 20 °C, $F = 50.42$, $P < 0.05$; at 25 °C, $F = 56.22$, $P < 0.05$ # 75% RH, at 15 °C, $F = 89.16$, $P < 0.05$; at 20 °C, $F = 63.42$, $P < 0.05$; at 25 °C, $F = 45.22$, $P < 0.05$).

Table 8

Mean abundance ($\pm$ SE) of *Sitophilus oryzae* adults in different grain commodities exposed to 300 g of grain.

Grain commodity	RH	T(°C)	Mean number ($\pm$ SE)
wheat	55	15	29.33 $\pm$ 13.17 C
		20	987.67 $\pm$ 192.67 D
		25	1465.67 $\pm$ 61.17 D
	75	15	1.33 $\pm$ 0.67 B
		20	1356.33 $\pm$ 106.73 D
		25	1944.33 $\pm$ 332.39 D
buckwheat	55	15	1.33 $\pm$ 0.33 B
		20	48.00 $\pm$ 6.11 B
		25	78.00 $\pm$ 14.50 B
	75	15	11.33 $\pm$ 8.33 C
		20	51.33 $\pm$ 18.41 B
		25	100.00 $\pm$ 11.54 B
millet	55	15	0.33 $\pm$ 0.33 A
		20	2.00 $\pm$ 0.57 A
		25	26.33 $\pm$ 8.81 A
	75	15	0.00 $\pm$ 0.00 A
		20	4.33 $\pm$ 2.33 A
		25	26.67 $\pm$ 1.76 A
spelt	55	15	113.67 $\pm$ 8.83 D
		20	312.33 $\pm$ 23.05 C
		25	371.67 $\pm$ 56.00 C
	75	15	147.33 $\pm$ 22.84 D
		20	359.33 $\pm$ 57.78 C
		25	417.67 $\pm$ 27.06 C

Between grain commodities and RH values at the same temperature, means followed by the same uppercase do not differ significantly by Tukey's HSD test at $P = 0.05$. For comparison within rows ($df = 3,79$) (55% RH, at 15 °C, $F = 73.11$, $P < 0.05$; at 20 °C, $F = 66.42$, $P < 0.05$; at 25 °C, $F = 70.22$, $P < 0.05$ # 75% RH, at 15 °C, $F = 88.16$, $P < 0.05$; at 20 °C, $F = 73.42$, $P < 0.05$; at 25 °C, $F = 62.22$, $P < 0.05$).

temperatures had a positive effect on the developmental rate, especially in wheat. The optimal temperature for development is 27.5 °C if the rice weevils feed on wheat (Lu et al., 2023). Based on our results, the temperature of 15 °C is estimated to be too low for *S. oryzae* survival and development. The result of the comparisons between the temperatures, in which half of the treatments show higher mortalities at 15 °C, also further supports this theory. As already mentioned by Golić et al. (2021), a temperature treatment of 5 °C can cause 96% mortality.

As already demonstrated by Danho et al. (2002), grain quantity can also influence progeny production. In their study, they examined the impact of grain quantity on the biology of maize weevil, and detected higher emergence at higher grain quantity. In our study, we obtained similar results, although our studies included the rice weevil. Regarding general data from our studies, a lower quantity of grain caused higher mortality.

We have also noticed several studies in which researchers have also noted the impact of different grain varieties (Leuschner et al., 2000; Doherty et al., 2023) or grain types (grain commodity) (Athanasios et al., 2008) on resistance towards *Sitophilus oryzae*.

According to Delobel and Grenier (1993), *S. oryzae* and two other weevils (*S. granarius* and *S. zeamais*) can feed on buckwheat. Since *Sitophilus* spp. larvae are too large to develop inside buckwheat; they pop out from kernels before finishing their growth, and hence, moulting is delayed. In our research, only single individuals had completed development in vials with buckwheat.

The same characteristic was previously reported for *Sitophilus granarius* by Nietupski et al. (2017). Therefore, physical factors deter *S. granarius* and *S. oryzae* from settling on buckwheat. Mortality levels, where buckwheat is included, are also very low. Other studies have demonstrated that resistant pericarp obstructs laying eggs and their emergence (Locatelli and Limonta, 1998).

Although wheat grain was the most favoured host in our study as was previously reported by Mentha et al. (2021), mortality rates were highest in this grain commodity as well. That the mortality rate can be the highest on wheat had already been recorded by Wakil et al. (2021), but these researchers had applied DE and *B. bassiana* in that study. Spelt was also described as one of the most resistant to storage pests (Gałęcki et al., 2019). In our case, the mortality of individuals was higher when they were exposed to a lower quantity of spelt spikelets. Spelt spikelets are also a factor of natural resistance, as they present a barrier (Gałęcki et al., 2019). In our research, a higher quantity of spelt had an impact on lower mortality and a higher number of progeny emergence (Danho et al., 2002).

De Groote et al. (2017) reported that grain size and grain colour could also be important factors of insect preference. Based on our study, we can confirm the previous finding that *S. oryzae* can accept large grains more quickly than small grains. We identified a positive correlation between kernel/grain size and progeny emergence, i.e., there is greater progeny emergence in larger kernels. Regarding size as a physical characteristic, millet is also not a suitable host. However, some individuals have emerged.

Therefore, we can conclude that several factors can influence the mortality of rice weevils. In addition to traditionally identified factors such as temperature and relative humidity mentioned in several studies, we can also confirm less-tested grain commodity and grain quantity. Grain commodity, as a present detail grain characteristic, is an important factor in our opinion. To conclude, wheat grain should be stored in combination with different plant protection methods, while buckwheat and millet can be easily stored on their own.

CRedit authorship contribution statement

Tanja Bohinc: Data curation, Methodology, Writing – original draft, Writing – review & editing. **Monica Novljan:** Investigation, Writing – original draft. **Polona Kovačič:** Methodology. **Eva Indihar:** Investigation. **Stanislav Trdan:** Project administration, Supervision, Writing –

review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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